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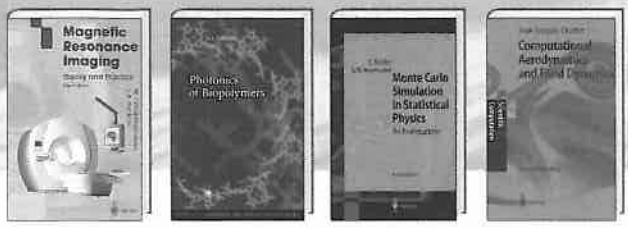

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NEWS AND VIEWS

Special issue overview

Nigel J. Mason, Special Issue Editor, The Open University, UK

The articles in this issue are a clear testament to the vitality of the field of atomic and molecular physics and the continued ingenuity of its researchers. The last decade has seen extraordinary developments in the field providing some of the most exciting advances in modern physics, advances that have a direct consequence on our understanding of the world around us. The breadth and excitement of the field are demonstrated in this special issue, suggesting that many exciting developments await us in the coming century.

The ability to cool, trap and manipulate atoms, culminating in the formation of Bose-Einstein condensates, is pioneering new instrumentation on the atomic and nanoscale with the prospect of developing quantum computing, cryptography and teleportation—pioneering the next great advance in technology. Hinds et al. demonstrate how new 'atom chips' may be developed from BECs for the development of atom/optical devices and operational quantum computers. Masnou-Seeuws and Pillet describe how the techniques for cold atoms are being used to form cold molecules, opening the door on a new world of low temperature chemistry.

The ability to understand, manipulate and control physico-chemical processes at the molecular level has long been the 'holy grail' of physical and chemical sciences. Single molecule engineering requires selective bond cleavage in target molecules to allow management of the local site chemistry. Research has revealed that it is possible to influence the excitation and dissociation of molecules through the manipulation of electron interactions at the individual molecular level. Field et al. discuss 'cold collisions', which emphasise the coherent wave nature of matter.

In the life sciences the role of electron-driven processes has only recently been recognised. For example, in contrast to previous hypotheses radiation damage in the DNA of living systems has now been shown to arise primarily from collisions of very low energy secondary electrons through dissociative electron attachment to the components of DNA molecules or to the water around them. Gohlke and Illenberger discuss recent experiments suggesting that such a process may provide a direct low energy process for the degradation of DNA by resonant electron attachment to basic molecular components suggesting that single strand damage is site specific and proceeds through discrete molecular bond rupture.

The ability to build new materials and structures is dependent upon our ability to study how elementary processes change during the transition from isolated particle behaviour in a low pressure gas to many body interactions in the condensed phase. The ability to prepare clusters has led to the emergence of a new branch of physical chemistry in which the properties and reactions of a given species may be studied as a function of its size, cluster shape and cluster composition. Connerade, Solov'yov and Greiner view progress in this fast moving field over the last decade while Campbell discusses an interesting class of clusters known as 'fullerenes', compounds that may lead to the ability to design and build structures from the nanoscale to macroscale.

Molecular dynamics underpins the whole field of chemical physics with applications from astronomy to radiation biology. The development of ultrashort pulse and intense lasers is enabling us to study the behaviour of atomic and molecular systems in fields of atomic strength. L'Huillier reviews the progress in this field and how it may lead to the development of new bright x-ray sources to study biological systems. Schmidt-Bocking, Dorner and Ullrich describe how the development of the COLTRIMS technique is providing us with unparalleled information of the fragmentation of many particle systems using ions, electrons and photons as projectiles. Winter and Aumayr review how atomic and molecular physics is used to understand condensed matter phenomena and in particular how potential sputtering may possibly be used to produce nanodots on silicon oxide surfaces, providing a new methodology for nanolithography.

Gianturco introduces us to antimatter and the formation of positronium, a hydrogen like species composed of one electron and one positron. With the development of intense sources of positrons experimental investigations of the antimatter world are becoming possible, opening the possibility of new types of chemistry, studies that may even have an impact on our understanding of how the universe was formed!

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Ultracold Molecules

Françoise Masnou-Seeuws and Pierre Pillet
Laboratoire Aimé Cotton, Orsay, France

Why cold molecules?

Up to very recently, the coldest molecules in laboratory were at temperatures around 1K, either in supersonic beams, or on helium nanodroplets. The availability of even colder temperatures would open the route to many new applications. We may cite:

- precision measurements: determination of lifetimes with possible estimation of parity non-conservation effects; measurement of an upper limit of the dipole moment of the electron as a critical test of elementary particle physics beyond the standard model [1]. Both in the case of atoms and molecules, the use of cold matter is improving the ultimate sensitivity of such measurements.
- condensation of complex systems, for instance achievement of a molecular condensate. Many experimental and theoretical groups are presently working in that direction.
- coherent control of molecule formation, towards ultracold chemistry.
- interferometry with molecules [2].

For neutral molecules, major progress have been realized since 1997, along three main directions, using either non-optical or optical cooling techniques:

- In the helium buffer gas cooling technique, developped in Harvard by John Doyle and collaborators, [3], hot molecules -for instance introduced by laser ablation- are thermalized with a cold helium buffer gas inside a dilution refrigerator, at temperatures well below 1K (typically, 400 mK). This technique is related to the "sympathetic cooling" techniques at ultracold temperatures, widely used by the experimental groups working on Bose-Einstein condensation. The physical process of sympathetic cooling where a hot object is cooled via collisions with a cold one is easy to understand.
- Another technique relies upon Stark deceleration of dipolar molecules in a supersonic beam. The basic idea of deceleration is to have a sequence of electrodes (≈100 stages) making a static electric field that alternatively increases and decreases. Molecules in a specific rotational level are decelerated by the Stark effect when they propagate from a weak field to a strong one. The cycle is repeated, and each stage is removing kinetic energy from the beam equal to the increase in Stark shift. Although this idea has been known for many years, it was demonstrated only in 1999 by G. Meijer and his group: details on the method have been published recently [4]. The Stark deceleration technique is similar in principle to the acceleration techniques developed in particle accelerators, but of couse the size of the instruments is much smaller, less than 1m. Recently, a tabletop *storage ring for molecules* has been achieved. and temperatures below 1 mK have been reached.
- Optical techniques are benefitting from the major progress in laser cooling and trapping of atoms. Direct laser cooling of molecules is not efficient, since it requires a large number of optical pumping cycles between the same two levels, whereas a molecule is a multi-level system. The solution [5–7] consists in first cooling the atoms with laser light, then making a molecule from two atoms via the photoassociation reaction. Next, the radiative dexcitation process must be guided to stabilize this excited molecule into a bound vibrational level of the ground electronic state. This technique is yielding molecules that are translationally cold ($T \leq 100\ \mu K$), the population being spread into many vibrational levels. Further laser cooling should be implemented to obtain vibrationnally cold molecules.

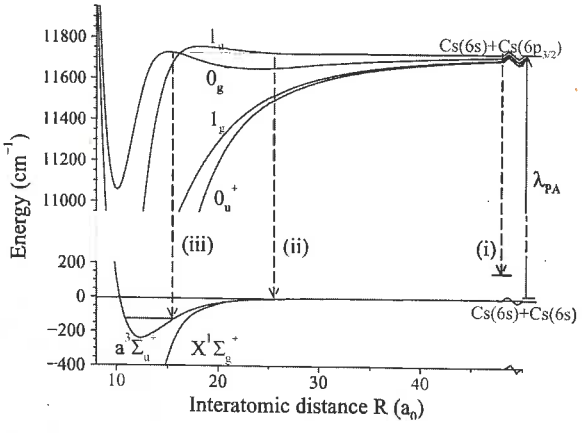
We should also mention that groups working in ion traps are capable of cooling molecular ions down to 100 mK, using sympathetic cooling. In the following, we shall focus on optical cooling techniques, yielding ultracold molecules at temperatures below 100 μK.

Making molecules via photoassociation of laser-cooled atoms and stabilization: mechanisms.

In the photoassociation reaction [8] a pair of ultracold ground-state alkali atoms absorbs a photon, at frequency $\nu_{PA} = \nu_0 - \Delta$, red-detuned relative to the resonance line,

$$A(ns)+A(ns)+h(\nu_{PA}) \rightarrow A_2^*(\Omega_{u,g}(ns+np_{1/2,3/2});v,J)\ , \qquad (1)$$

creating a molecule in an excited electronic state $\Omega_{u,g}$. The corresponding potential displays an asymptotic $\sim R^{-3}$ behaviour, since at large distances an excited atom and a ground state atom interact via dipole-dipole interaction. This potential extends to much larger distances than the $\sim R^{-6}$ ground state potential. The reaction is efficient at low detunings Δ, forming molecules in very excited vibrational levels v. In contrast the rotational quantum number J remains small due to the very low kinetic energy of the colliding atoms in the initial state which limits the reaction to small centrifugal barriers. The photoassociated molecule is a *long range molecule*, which looks like a pair of atoms at very large distances more than a usual molecule. Indeed, during a vibration period, the relative motion is taking place most of the time in the



▲ **Fig. 1:** Formation of an excited molecule by photoassociation of two cesium ground state atoms. (i) In most cases, this short-lived molecule decays back into a pair of cold atoms. Spontaneous emission → dissociation.(ii) 1_u "speed bump" → stabilization by spontaneous emission to a bound level of the ground state.(iii) 0_g^- "speed bump" → stabilization by spontaneous emission to a bound level of the lower triplet state.

features

asymptotic region governed by the very weak R^{-3} potential, the time spent in the inner region being comparatively very short. At small distance, the relative motion is accelerated by the chemical forces and reflected on the steep potential wall. Therefore when this excited molecule decays by spontaneous emission, it is likely to dissociate into a pair of ground state cold atoms. Stabilization by spontaneous emission into a bound level of the ground electronic state requires very particular situations. The first scheme was found accidentally for Cs [5], and confirmed for Rb [7], and is schematized in Fig. 1. Due to the presence of a double well potential with a very gentle slope, the vibrational motion in the region of intermediate distances is delayed, so that there is a non negligible probability of stabilization by spontaneous emission into a bound level of the ground state.

This scheme is fortuitous, since for lighter alkali dimers the double well is located at even larger internuclear distances where decay into bound levels of the ground state is impossible. However, once we have understood that the key effect is to slow down the vibrational motion in the intermediate region, many other schemes can be found. For instance a resonant coupling scheme, demonstrated for Cs_2 $0_u^+(P_{1/2,3/2})$ coupled channels [9], can be present in many molecules. Besides, schemes using induced emission could be very efficient, so this research domain is only opening.

Formation and trapping of cold molecules: experiment

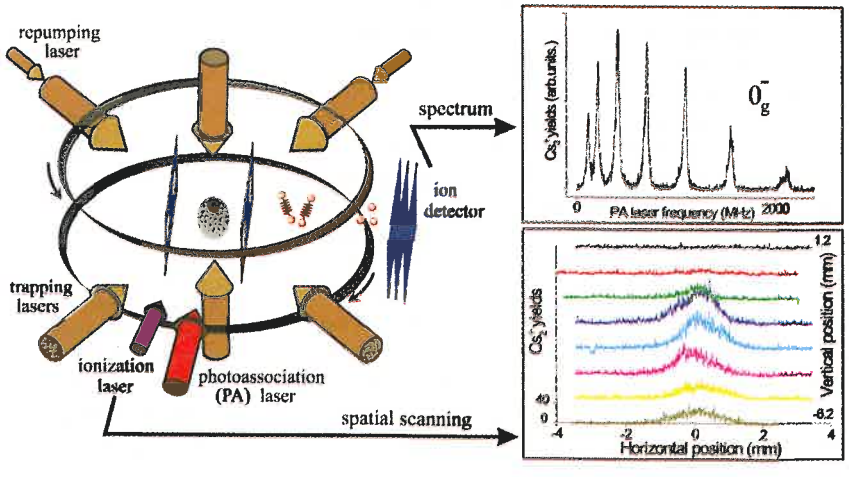
Most of the experiments of photoassociation are performed by using the basic tool of any experiment with cold atoms: a magneto-optical (MOT). Figure 2 shows a schema of the experimental setup of a vapor-loaded cesium MOT. The atomic cloud is illuminated with a continuous-wave laser of frequency ν_{PA} to produce the resonant photoassociation reaction. In most of the photoassociation configurations considered experimentally, the electronically excited Cs_2^* molecules dissociate by giving a pair of atoms which escape outside of the trap (see arrow (i) in Fig. 1). Trap-losses can be analyzed by recording the fluorescence yield due to the cooling laser beams. Formation of cold ground-state molecules after emission of a photon with frequency ν_{SP}, for instance

$$Cs_2^*(0_g^-(6s + 6p_{3/2}); v, J)\ Cs_2(a^3\Sigma_u^+; v', J') + h\nu_{SP},$$

yields molecules in the lower triplet state (see arrow (iii) in Fig. 1). They can be detected by photoionization, using a pulsed dye laser beam. The Cs_2^+ molecular ions are then selectively detected through a time-of-flight mass spectrometer. The upper inset of Fig.2 shows a typical rotational progression obtained by scanning the frequency of the photoassociation laser around the resonance for $v = 6$. One important application of such spectra is accurate determination of the excited potential, leading, through C_3 coefficient in the asymptotic C_3/R^3 expansion, to unprecedented accuracy in atomic lifetimes. In these experimental conditions, rates of formation can reach up 0.2 molecule per atom and per second, meaning several millions of molecules formed per second for an initial atomic cloud with several tens millions of atoms [10]. The cold molecules being unsensitive to the MOT trapping forces are falling down because of gravity. The analysis of their ballistic expansion allows to determine their temperature which is found identical to that of the atomic cloud, i.e. in the microkelvin range [5].

Two hundred thousand molecules can be accumulated and trapped in a time of 100 ms of photoassociation process.

To accumulate and to store the formed cold molecules is a necessary condition for further applications. The use of a CO_2 laser to create a quasi-electrostatic trap is an interesting possibility, already demonstrated for the molecules present in the MOT [11], and which should be confirmed for those obtained via photoassociation. Another way has been investigated, via a mixed atomic and molecular trap, constituted by a Cs vapor-cell MOT and a quadrupolar magnetic Cs_2 trap, using the same magnetic field gradient. The atomic cloud is produced at the intersection of the three pairs of mutually othogonal, counter propagating $\sigma^+ - \sigma^-$ lasers beams, at the zero magnetic field point of a pair of anti-Helmholtz coils, but here the magnetic field gradient of 6mT/cm is chosen four times larger than for an usual



▲ **Fig. 2:** Experimental setup of the molecular trap. The upper inset shows a typical photoassociation spectrum (note the resolution), the lower one represents the spatial analyzis of the molecular cloud.

MOT. With such experimental conditions, we obtain an atomic cloud of 10^7 atoms in a volume with a radius of 200 μm and at a temperature of 25 μK. The magnetic field gradient is now large enough to trap the molecules in the triplet sate $a^3\Sigma_u^+$, by compensating the gravity. Only molecules formed with a magnetic moment opposite to the local magnetic field can be accumulated and trapped. Two hundred thousand molecules can be accumulated and trapped in a time of 100 ms of photoassociation process. The lifetime of the trapped molecular cloud ~1s is limited by the backgroud gas pressure. The spatial analysis of the molecular cloud performed by photoionization is shown in the below-inset of Figure 2.

Its dimension of a few millimeters is much larger than the atomic cloud. The complete analyzis demonstrates a molecular temperature of 30 ± 10 μK.

Conclusion

The mechanism of formation of cold molecules via photoassociation opens a wide field of possibilities for an ultracold photochemistry. Combining that technique with other methods used to obtain cold molecular samples can increase the number of possibilities. The progresses in the experiments should be focussed on the control the final channel in the formation of cold molecules. Use of Feshbach resonances and of stimulated Raman photoassociation can provide tricks for such an aim. The recent success of Bose-Einstein condensation of cesium obtained in the group of Rudi Grimm opens also promising possibilities to go towards Bose-Einstein condensation of a molecular gas.

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Cold encounters: Electrons and molecules

David Field[1], Nykola Jones[1] and Jean-Pierre Ziesel[2]
[1] University of Aarhus, Aarhus, Denmark
[2] University Paul Sabatier, Toulouse, France

Cold collisions give a special insight into quantum dynamics, since cold encounters emphasise the coherent wave nature of matter. In cold collisions particles may pass ghost-like through each other or pursue a superposition of energetically forbidden trajectories, in a manner alien to a classical vision of natural phenomena. Cold electron collisions have the additional attraction that they occur in the natural world, in planetary atmospheres and in the interstellar medium, as well as in industrially important plasmas for device fabrication.

A cold collision is one in which the de Broglie wavelength of the projectile is very much greater than the physical dimensions of the target species. Two parallel experimental developments have aroused strong interest in cold collisions. The first is the achievement of Bose-Einstein condensation, which depends for its success to a very large degree on an appreciation of the nature of the scattering of cold alkali atoms [1,2]. The second, on which we dwell here, has been the study of the interaction of cold electrons with molecules, made possible by the development of new cold electron sources [3-6].

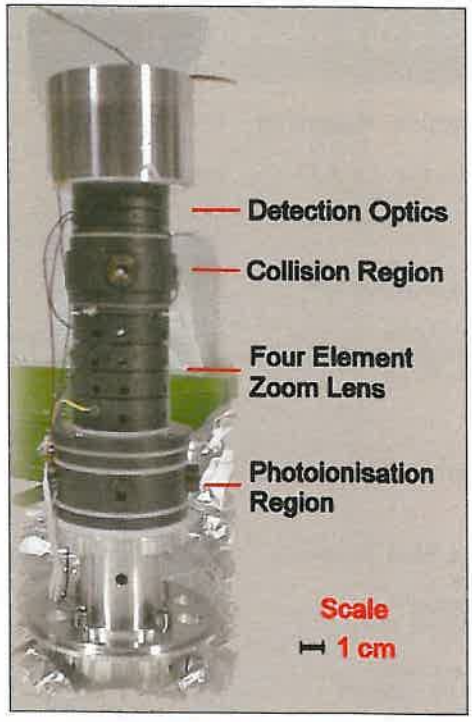
How cold is cold?

The de Broglie wavelength of an electron with kinetic energy of 10 meV (1 meV = 8.0655 cm^{-1} = 96.485 $Jmol^{-1}$) is 12.3 nm, equivalent, for comparison with atom-atom collisions, to a Rb atom at a temperature of 500 μK. When cold electrons encounter molecules, they can be elastically scattered, they can excite rotation and vibration in the targets or they can cause the formation of negative ion products, a process called dissociative attachment (DA).

Experiments

Two types of experiment have been developed. The first are those that form cold electrons or Rydberg atoms *in situ* with a target gas to study exclusively DA [3,4,5,7]. The exquisite precision of recent DA measurements is illustrated by data in [8], involving CH_3I + electron → I^- + CH_3, showing how the cross-section for I^- production is strongly affected by vibrational motion in CH_3I through "vibrational Feshbach resonance".

The second type of experiment uses electron beams and involve elastic and inelastic scattering, as well as DA. The apparatus with which the great majority of these data have been acquired is shown in Figure 1 [6]. Electrons are formed by the threshold photoionisation of Ar at 15.76 eV, using synchrotron radiation from the ASTRID storage ring, University of Aarhus. A beam of electrons, with a resolution which may be better than 1 meV, passes through gas at room temperature, and the attenuation of the beam yields the scattering cross-section. A great variety of species has been studied with this apparatus, ranging from the simplest diatomics, H_2, N_2, O_2 to more complex molecules such as benzene, hexafluorobenzene and still larger species such as naphthalene or anthracene. These studies have revealed a number of fascinating quantum scattering phenomena, some known or strongly suspected from theory, such as powerful rotational excitation in polar molecules with cross-sections of several thousand $Å^2$, others unknown and which remain largely unexplained.



▲ Fig. 1: The cold electron experiment on the ASTRID storage ring (Aarhus). The apparatus may be immersed in a magnetic field for measurement of backward scattering cross-sections.

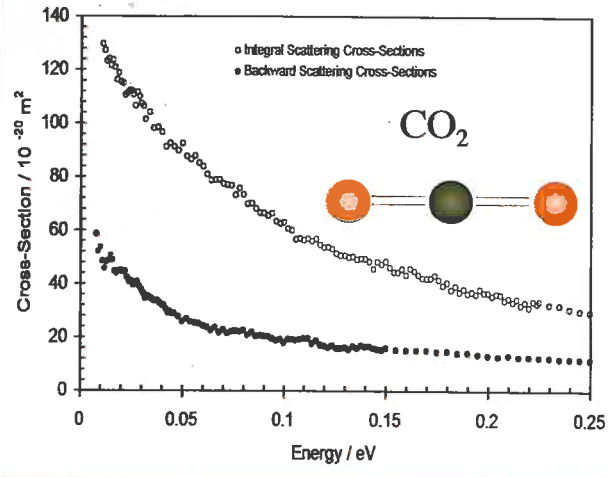
Understanding the data

How does the incoming electron appear to the target molecule, and how does the molecule appear to the electron? Because of the wave nature of the cold electron, it is spread out in space and the incoming wave explores a superposition of paths, rather than a well-defined classical path. Each path within this superposition may be accorded a collisional angular momentum, which is quantized with respect to the molecular target at the "scattering centre". Moreover on the time-scale of encounters, even at meV energies, the target molecule has no time to rotate and presents a single face to the incoming electron. The "head-on" component of the electron trajectory is called the "s-wave", with angular momentum zero, with "p-waves" for angular momentum of unity and so on. Let us say for example that only the s-wave is scattered: the steady state angular distribution of scattered electrons will then be spherically symmetrical about the target. If a p_z-wave is scattered, then the electron will by contrast show backward-forward scattering asymmetry.

The beauty of cold collision studies is that only very few of these so-called "partial waves" are involved in scattering, in fact only s- and p-. As these waves are scattered, they undergo energy dependent phase shifts, which quantum theory shows may be simply related to scattering cross-sections. Expressions for cross-sections include the coherent superposition of scattered s- and p-waves, for example for backward-scattering. Predictions about the relative amount of backward and forward scattering, for example, may be compared with experiment and this style of analysis gives considerable insight into the nature of cold collisions.

The point of view of the electron

How does the molecular target appear to the electron beam? Imagine yourself sitting on the electron wave as you accelerate towards the molecule. In order to understand your fate, you can think of yourself as refracted through the target with a refractive index of more than or less than unity. The former case corresponds to a weak interaction and the target appears closer than it truly is. The system is said to possess a "positive scattering length". If for a different target the



▲ **Fig. 2:** Scattering of electrons by carbon dioxide: scattering cross-sections versus electron kinetic energy.

field is stronger, the target may appear further away, equivalent to a refractive index of less than unity, and the system possesses a negative scattering length. If the field is very strong, there may be a bound state within the electron-molecule potential well, and the scattering length becomes positive again. The latter can lead to dissociative attachment.

As the electron energy tends to zero, so the cross-section tends to the surface area of a sphere of radius the scattering length, A, that is, $4\pi A^2$. The sign of the scattering length is however crucial to understanding the nature of the collision. You may be deflected with low cross-section (small positive A), be projected into a virtual state (large negative A) or you may attach and perhaps dissociate the molecule (large positive A).

The response of the target: symmetry

A further powerful concept, in addition to that of partial waves, involves the symmetry of the molecular target. Both DA and virtual state scattering involve an initial step of attachment, however fleeting, of the electron to the target molecule. A low energy electron will attempt to attach into the "lowest unoccupied molecular orbital" or LUMO, whose symmetry is dictated by that of the host molecule, such as a hexagon for benzene or a football for C_{60}. The impinging electron is also subject to this symmetry, and the incoming wave must be able to fit into the LUMO. For example, spherical s-waves fit snugly into the spherical LUMO of CCl_4, whereas the water-wings form of a p-wave does not.

In Figure 2, we show data for CO_2, which shows strong scattering at low energy [9]. However, weak scattering is expected; for example, the cross-section for N_2 at 10 meV is only ~$3\times10^{-20}m^2$, nearly 50 times lower than CO_2. The strange behaviour of CO_2, which we have found in a number of other molecules, is due to virtual state scattering. This process may be understood in terms of lifetimes of scattering states.

Lifetimes in scattering

How sticky are electron-molecule collisions? That is, if you were to time the passage of an electron over some distance, what difference in travel time would result if the electron experienced a scattering process or if it moved unimpeded?

Theory shows that the lifetime of a collision complex is equal to twice to the rate of change of the phase of the electron wave with collision energy, in atomic units. This rate of change may be obtained by suitable fitting of the data in figure 2, resulting in a lifetime of CO_2^- at 10 meV impact energy of $8.48\pm0.1\times10^{-15}$ seconds. But how can this be? An s-wave is attempting to attach to CO_2. The LUMO of CO_2 is however of p-like symmetry: the overlap is zero. But let us say that the molecule borrows some time from the classically inaccessible quantum world, in a manner restricted by the Heisenberg relationship $\Delta E.\Delta t \geq h/2\pi$. In this borrowed time, the system may explore paths in which the molecule is "virtually bent", where virtual implies something happening in borrowed time. As the molecule virtually bends, the p-like orbital splits into two components, one of which is of spherical symmetry and can happily accommodate an s-wave. When the interaction is over, the borrowed time is returned—but not all. The lifetime of $\sim8.5\times10^{-15}$ seconds may be seem as a remnant of the borrowed time.

Molecules may also be transparent to electrons, rather than present a large cross-section. For example, at 90 meV impact energy, electrons pass almost unimpeded through CF_4, in the so-called Ramsauer-Townsend effect. It is as if the molecule were not present and you might very reasonably conclude: no scattering, no phase shift of the electron matter wave, no effect at all. However, this is not so. The scattering state is found rather to have a *negative* lifetime of $900\pm60\times10^{-18}$ seconds. Thus the electron spends less than no time in the vicinity of the scattering centre. This "hole in quantum space" may be thought of as representing the destructive interference of the incoming and scattered outgoing s-waves, a quantum hop of matter from one position to another, the matter disappearing from one side of the scattering centre and reappearing at the other in a process of nanoscopic matter-wave teleportation.

Conclusion

We set out by suggesting that the study of cold collisions may help us to understand the nature of quantum dynamics. Perhaps understanding may best be described as appreciation. The study of cold collisions makes quantum events more familiar and allows us, if not to understand as we claim to understand classical mechanics, at least to come to terms with the strange phenomena of quantum collisions.

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Atom Chips

C.J. Vale, B.V. Hall, D.C. Lau, M.P.A. Jones, J.A. Retter and E.A. Hinds
SCOAP, University of Sussex, Brighton, United Kingdom

In the last decade atomic physics has undergone a renaissance. Nobel Prizes in Physics were awarded to Cohen-Tannoudji, Chu, and Phillips in 1997 for laser cooling and trapping of atoms and to Ketterle, Cornell, and Wieman in 2001 for Bose-Einstein condensation (BEC) in dilute alkali gases. New experimental methods unlocked through this research have resulted in an explosive growth in the field of cold and ultra-cold atoms. At μK temperatures atoms have sufficiently low energy that their de Broglie wave nature becomes evident. Such atoms can be controlled by atom optical elements (lenses, mirrors, diffraction gratings, waveguides and interferometers) in analogy with light.

One area that has been particularly exciting recently is the development of integrated atom optical devices for the storage, manipulation and controlled interaction of atoms onboard a micro-fabricated structure, the "Atom Chip" [1, 2]. Miniature current-carrying wire structures or permanent magnet structures can be used to create microscopic magnetic potentials that control atoms. Experimenters are currently trying to realise beam splitters and interferometers for BEC on board atom chips. Such devices offer new levels of measurement sensitivity and have been suggested as a possible way to implement quantum information processing [3]. In this article, we give a brief review of important developments in the field atom chips and describe some of the atom chip experiments performed in our group at Sussex.

Atoms with a magnetic moment μ experience an interaction potential, $-\mu \cdot B$, in the presence of a magnetic field B. Those atoms with their magnetic moment aligned antiparallel to the direction of the field are known as weak field seekers because their interaction energy is lowest in areas of low field. Such atoms can be trapped or guided by a local minimum of the magnetic field, which offers a convenient means of controlling them. However, the energy scale associated with this interaction is low compared to the thermal energy of room temperature atoms, so only very cold atoms ($T \leq 1$ mK) can be manipulated this way.

With the recent advent of laser cooling and the magneto-optical trap (MOT) it has become routine to create samples of $\approx 10^8$ atoms at temperatures of around 50 μK or lower. This provides an invaluable source of ultra-cold atoms which can be magnetically trapped using modest fields. The first demonstration of the possibilities for atom guides were the guiding of atoms released from a MOT source. A review of this earlier work can be found in [1].

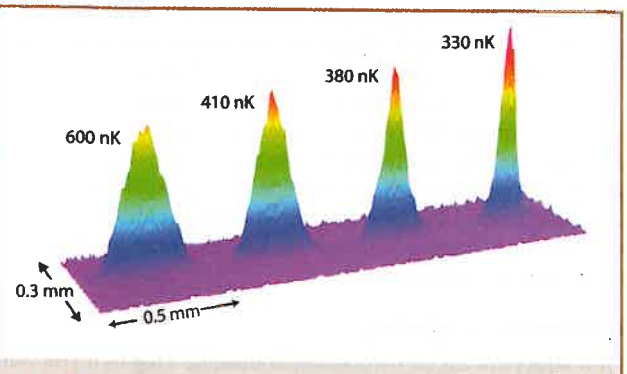
An important development for atom chips was the invention of the mirror MOT [4] which provides easy preparation and loading of cold atom clouds directly onto a surface. A mirror MOT uses the same laser and quadrupole magnetic field configuration as a standard six-beam MOT, except that two of the laser beams are formed by reflection from a mirror surface. Atoms are trapped close to the surface in the region where the incident and reflected beams overlap. The mirror is typically a gold layer on a substrate which also incorporates a pattern of current-carrying wires that can be activated to create magnetic micro-traps. A picture of our BEC atom chip is shown in figure 1 below. One can see the gold surface of the chip, the MOT coils oriented at 45 to the mirror and the guide wire running across the centre of the chip. Four transverse wires located just underneath the surface (not visible) provide confinement of magnetically trapped clouds along the length of the guide.

▶ Fig. 1: The Sussex BEC atom chip.

A major breakthrough for atom chips came in 2001 with the realisation of BEC on board a chip demonstrated almost simultaneously in the groups of Claus Zimmerman in Tübingen [5] and Ted Hänsch [6] in Munich. There are now several groups, including ours, who have created [2] or loaded [7] BEC on a chip and the number is growing rapidly.

In our experiments, 1×10^8 ^{87}Rb atoms are collected and cooled to 60 μK in a mirror MOT 4 mm above the gold surface. Approximately 2×10^7 atoms are loaded into a magnetic micro-trap formed by the wires embedded in and under the surface. The atoms are then adiabatically compressed by ramping up the trap frequencies to $2\pi \times 840$ s^{-1} in the radial direction and and $2\pi \times 26$ s^{-1} axially. This increases the atom density and raises the elastic collision rate to $\gtrsim 30$ s^{-1}, high enough for efficient evaporative cooling to take place. We use forced rf evaporation to cool the atoms down to below 415 nK at which point the cloud Bose condenses. The rf frequency is swept logarithmically from 13 MHz to a final frequency of around 600 kHz over 12.5 s. The trap is 200 μm above the surface when the condensate forms and the number of condensed atoms is typically 22000. We view the condensate using absorption imaging, after first turning off the axial confinement and letting the atoms expand along the guide for 8 ms. Figure 2 shows the atom cloud changing from a thermal cloud above 415 nK to a BEC at lower temperatures.

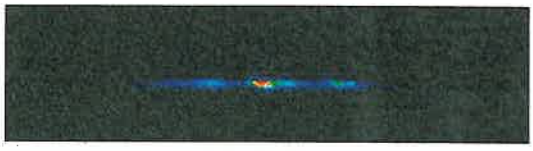
One advantage of atom chips is that the elements producing the magnetic field are very close to the atoms. This means that the traps can have very steep potential gradients where the quantum mechanical (vibrational) modes are widely spaced, with intervals similar to the thermal energy of the atoms. For the special case of BEC, all of the atoms collect in the ground state of the trap and their behaviour is described by a single quantum mechanical wavefunction. Single mode operation is important for realising coherent quantum devices. As an example we have previously considered the case of a two-wire guide [8]. This versatile scheme consists of two wires carrying parallel currents in the presence of a transverse bias field. Simply by varying the strength of the bias field it becomes possible to split and recombine atom



▲ Fig. 2: Density plots for four different atom clouds. Each cloud is cooled to a different temperature before being released, expanded, and imaged. The BEC starts to form at approximately 415 nK. The right-hand peak is almost entirely condensate.

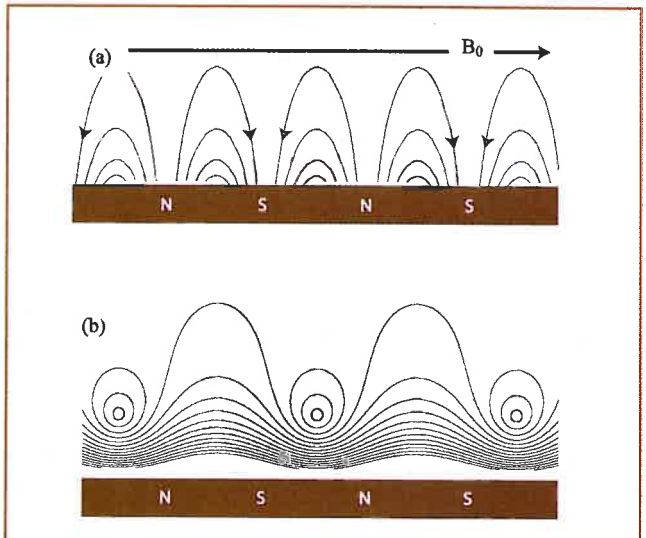
clouds, opening the possibility of making an exceedingly sensitive atom interferometer [8]. Several groups, in addition to ours, who have loaded a BEC onto an atom chip [2, 5, 6, 7] are actively pursuing quantum interferometers.

Some very recent studies in our group and others [7, 9] have looked at the interaction of cold atom clouds and BECs with the surface of the chip. When a very cold atom cloud or BEC is brought close to the surface, the cloud is seen to break up into fragments. These appear to be due to a small modulation of the confining potential whose origin is not yet understood. Figure 3 shows a cloud of atoms ($T = 4\mu K$) released into a guide 10 μm above the conductor surface. Rather than expanding freely along the guide the atoms instead gather in the potential wells that arise near the surface. We have observed atoms trapped in these surface induced wells for times greater than 200 ms.



▲ **Fig. 3:** Images of a fragmented 4 μK atom cloud 15 μm above the guide wire.

The rapid development of atom chips based on current carrying wires is due in part to the advances made within the microcircuit fabrication industry. In our laboratory we are also pursuing atom chips where the microscopic potentials are made using commercially available magnetic storage media, most recently videotape. Permanent magnetic materials have potential advantages over current-carrying conductors as they can produce large field gradients without dissipating any energy and are without Johnson noise or temporal fluctuations. In the past we have shown that a periodically patterned magnetic surface can be used as an effective atom mirror and that such mirrors can be modulated through the addition of small external magnetic fields [1]. Figure 4(a) shows a uniform magnetic field B_0 added to the field of a sinusoidally magnetized videotape. At a constant height above the surface the applied field periodically cancels the field produced by the videotape. A plot of the trapping equipotentials created by this combination of fields reveals a periodic array of magnetic minima, shown in 4(b).



▲ **Fig. 4:** Fields and interaction potentials above a sinusoidally magnetised videotape. (a) A field B_0 is added to the field of the videotape itself. (b) The resulting equipotentials of the atom's interaction with the field. The circles indicate an array of tubular minima where atoms can be trapped or guided.

Atoms can be radially confined and propagated along these 2D magnetic guides. In our experiments two wires perpendicular to these guides make fields that confine the atoms axially. The radial gradient of the field strength in these magnetic micro-traps is $b = 2\pi B_0/\lambda$, where λ is the wavelength of the magnetised recording. Even with a modest applied field, large gradients can be achieved since wavelengths as short as 10-100 μm can readily be recorded (e.g. $B_0 = 1$ mT, $\lambda = 10$ μm, $b = 600$ Tm^{-1}). In recent experiments with atoms in videotape micro-traps we observed three-body recombination, a loss process that requires high atom density, 10^{15} cm^{-3}. Moreover, we observed that in the limit of low density, the lifetime of the trapped atoms was independent of distance from the magnetic surface and was independent of trap gradient. These results are in contrast to the height dependent lifetimes measured in micro-traps made by current carrying patterned wires [9].

Recording on videotape is a convenient way to achieve microscopic magnetisation patterns along one direction. However, a more versatile approach may be to use magneto-optical films. To write trapping structures onto these films a focused laser beam heats the magnetic layer, raising the temperature locally towards the Curie point. A small applied magnetic field then changes the orientation of the magnetic domains in the heated region. Scanning the laser allows an arbitrary magnetic pattern to be written, with feature sizes that can be substantially smaller than 1 μm. It is possible to make some parts of the surface non-magnetic by etching away the film. Atom optics based on the patterning of permanent magnetic materials is also being pursued at the Swinburne University of Technology, Australia [10].

Atom chips offer the possibility of creating new types of quantum measurement devices and many experimental groups are now working towards realising such devices. In the near future we can expect that a wide range of atom-optical elements will be integrated onto a single chip. An important next step will be to integrate optical fibres and microcavities into atom chips [11]. These will make it possible to prepare and detect individual atoms in specific quantum states so that they can form the basis of quantum logic gates.

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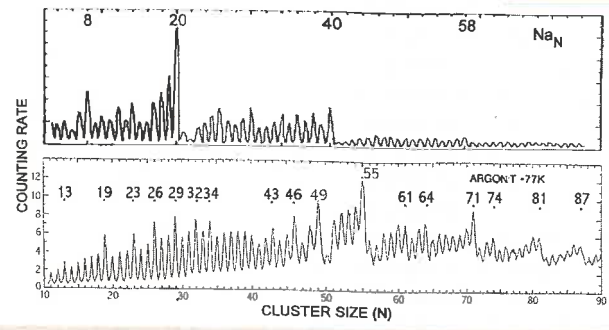
The science of clusters: An emerging field

Jean-Patrick Connerade[1], Andrey V. Solov'yov and Walter Greiner[2]
[1] The Blackett Laboratory, Imperial College, London, UK
[2] Institüt für Theoretische Physik der Universität Frankfurt am Main, Frankfurt, Germany

A group of atoms bound together by interatomic forces is called an atomic cluster (AC). There is no qualitative distinction between small ACs and molecules. However, as the number of atoms in the system increases, ACs acquire more and more specific properties making them unique physical objects different from both single molecules and from the solid state. In nature, there are many different types of AC: van der Waals ACs, metallic ACs, fullerenes, molecular, semiconductor, mixed ACs, and their shapes can depart considerably from the common spherical form: arborescent, linear, spirals, etc. Usually, one can distinguish between different types of ACs by the nature of the forces between the atoms, or by the principles of spatial organization within the ACs. ACs can exist in all forms of matter: solid state, liquid, gases and plasmas.

The novelty of AC physics arises mostly from the fact that AC properties explain the transition from single atoms or molecules to the solid state. Modern experimental techniques have made it possible to study this transition. By increasing the AC size, one can observe the emergence of the physical features in the system, such as plasmon excitations, electron conduction band formation, superconductivity and superfluidity, phase transitions, fission and many more. Most of these many-body phenomena exist in solid state but are absent for single atoms. Below we briefly summarize various aspects of AC physics, which to our mind make it an attractive field of research: (i) ACs provide a small, self-contained 'laboratory' in which the major interactions and many-body effects present also in solids can be analysed and studied as a function of their size; (ii) ACs straddle the limit between microscopic and quasi-classical systems, so they can be used to probe the boundary between quantum mechanics and semi-classical systems; (iii) ACs are the appropriate physical objects for studying statistical and thermodynamic laws in nanoscale systems, both classical and quantum; (iv) Small ACs are tractable computationally by *ab initio* methods; (v) ACs can be made and observed in the laboratory by using modern beam or deposition techniques; (vi) ACs provide new examples of many-body forces in a regime which is different from those of atomic, nuclear or solid-state physics, but is related to all of them; (vii) ACs can serve as building blocks for new forms of matter, the formation of AC-based molecules and new materials; (vii) ACs are of similar size to nanoscale devices, and so their physics is closely related to the physics of very small devices, in which quantum effects begin to appear, such as must occur when one wishes to make smaller and smaller chips for microcomputers.

The science of ACs is a highly interdisciplinary field. ACs concern astrophysicists, atomic and molecular physicists, chemists, molecular biologists, solid-state physicists, nuclear physicists, plasma physicists, technologists all of whom see them as a branch of their subjects but AC physics is a new subject in its own right. This becomes clear after a brief study of the problems which



▲ **Fig. 1:** Mass spectra measured for *Ar* and *Na* ACs (see [1]. The intense peaks indicate enhanced stability.

atomic AC physics addresses today: (i) The problem of collective excitations in ACs has obvious links in atomic and nuclear physics; (ii) The same is true for the confined atoms problem, and for various collision processes involving ACs; (iii) Fission of charged metal ACs is a process analogous to nuclear fission; (iv) Plasmon excitations, conduction bands, elasticity, superconductivity and superfluidity came to AC physics from solid state physics; (v) Studies of the AC heat capacities and phase transitions have obvious thermodynamic roots; (vi) Studies of AC reactions and AC potential energy surfaces establish links with chemistry and chemical physics; (vii) Studies of electronic and ionic structure and properties of ACs together form a bridge to the molecular biology research of proteins, nuclear acids and other complex biological molecules; (viii) Connections of AC physics to nanotechnology are apparent via quantum dots, quantum wires, nano-tubes and other nano-structures; (ix) ACs are formed in collisions in plasmas and interstellar media. This fact links AC physics to astrophysics, plasma physics and physical kinetics.

Significant progress achieved in the field over the past two decades brought the understanding of ACs as new physical objects with their own distinctive properties. This became clear after such experimental successes as the discovery of the fullerene C_{60}, of the electronic shell structure in metal ACs, the observation of plasmon resonances in metal ACs and fullerenes, the observation of magic numbers for various other types of ACs, the formation of singly and doubly charged negative AC ions and many more. A complete review of this field can be found e.g. in [1].

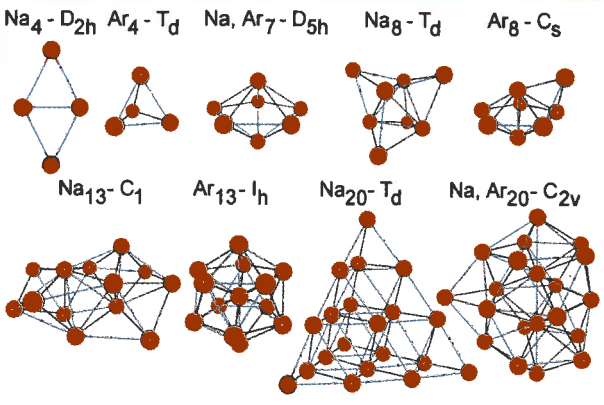
Distinctive properties of ACs

ACs, as new physical objects, possess some properties, which are distinctive characteristics of these systems. The AC geometry turns out to be an important feature, influencing the AC stability and vice-versa. The determination of the most stable AC forms is not a trivial task and the solution of this problem is different for various types of AC. The stability of ACs and the their transformations is a theme which does not exist at the atomic level and is not of great significance for solid state but is of crucial importance for AC systems. This problem is closely connected to the problem of AC magic numbers.

One can introduce very many different characteristic and properties relevant for ACs, which carry important and specific information about these systems as well as the principles of their organization and formation. In our brief review we are not able even to mention all these characteristics. Thus, we limit ourselves to only a few examples.

AC magic numbers

The sequence of AC magic numbers carries essential information about ACs electronic and ionic structure [1]. Understanding the magic numbers of an AC is pretty well equivalent to understanding its electronic and ionic structure. A good example of this kind occurs for sodium ACs. In this case, the magic numbers arise from the formation of closed shells of delocalised electrons, one from each atom. Another example is the the discovery of fullerenes, and in particular the C_{60} molecule [2], by means mass spectroscopy.



▲ **Fig. 2:** Geometries and the point symmetry groups of some *Na* and *Ar* ACs calculated in [3, 4].

The formation of a sequence of magic numbers is closely connected to mechanisms of AC formation and growth. It is natural to expect that one can explain the magic numbers sequence to find the most stable AC isomers by modelling mechanisms of cluster assembly and growth [3].

In Fig. 1, we present the mass spectra measured for *Ar* and *Na* ACs (see [1]), which clearly demonstrate the emergence of magic numbers. The forces binding atoms in these two different types of ACs are different. The argon (noble gas) ACs are formed by van der Waals forces, while atoms in the sodium (alkali) ACs are bound by the delocalized valence electrons moving in the entire AC volume. The differences in the inter-atomic potentials and pairing forces lead to the significant differences in structure between *Na* and *Ar* ACs, their mass spectra and their magic numbers.

In Fig. 2, we present and compare the geometries of a few small *Na* and *Ar* ACs of the same size. It is clear from Fig. 2 that the principles of AC organization are different for the alkali and noble gas families. Such differences can easily be explained. The van der Waals forces lead to enhanced stability of AC geometries based on the most dense icosahedral packing. The the most prominent peaks in mass spectra of argon ACs correspond to completed icosahedral shells of 13, 55, 147, 309 etc. atoms. The origin of the sodium AC magic numbers is different. In this case the AC magic numbers 8, 20, 34, 40, 58, 92 etc. correspond to the completed shells of the delocalised electrons: $1s^2\ 1p^6\ 1d^{10}\ 2s^2\ 1f^{14}\ 2p^6$ etc.. This feature of small metal ACs make them qualitatively similar to atomic nuclei for which quantum shell effects play the crucial role in determining their properties [5].

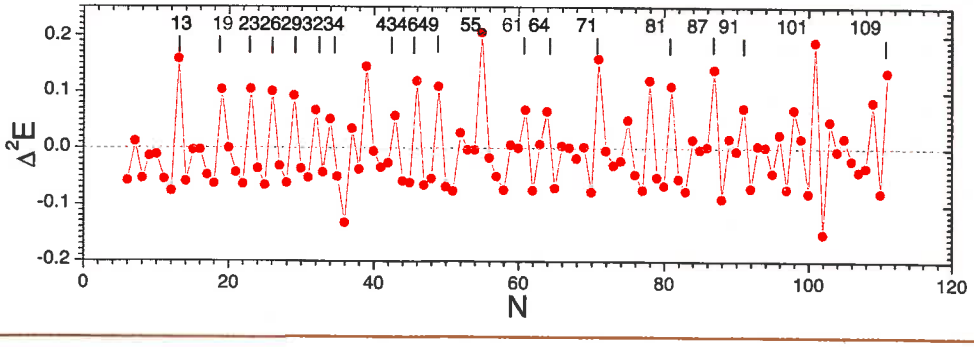
The enhanced stability of AC systems can be characterized by computing the second differences in AC binding energies. In Fig. 3, we present the second differences in *Ar* ACs binding energies calculated in [3]. The correspondence of the peaks in Fig. to those in the *Ar* ACs mass spectrum shown in Fig. 1 is readily established.

Plasmon excitations

Electron excitations in metal AC systems have a profoundly collective nature. They can be pictured as oscillations of electron density against ions, the so-called plasmon oscillations. This name is carried over from solid state physics where a similar phenomenon occurs. Collective electron excitations have also been studied for single atoms and molecules [6]. In this case the effect is known under the name of the shape or the giant resonance. The name giant resonance came to atomic physics from nuclear physics, where the collective oscillations of neutrons against protons have been investigated [5]. The interest of plasmon excitations in small metal ACs is connected with the fact that the plasmon resonances carry a lot of useful information about AC electronic and ionic structure. By observing plasmon excitations in small metal ACs one can study, for example, the transition from the pure classical Mie picture of the plasmon oscillations to its quantum limit or to detect AC deformations by the value of splitting of the plasmon resonance frequencies. The plasmon resonances can be seen in the cross sections of various collision processes: photabsorption and photoionization, electron inelastic scattering, electron attachment, bremstrahlung [1]. Both surface and volume plasmons can be excited. In electron collisions and in the multiphoton absorption regime, plasmons with large angular momenta play an important role in the formation the cross sections of these processes [7].

Fission process

Multicharged ACs become unstable towards fission. The process of multicharged metal ACs fission is qualitatively analogous to nuclear fission. The fission instability of charged liquid droplets was first described by Lord Rayleigh in 1882 [8] within the framework of classical electrodynamics. For review of recent work on metallic AC fission see [1]. The fission process is a complex process in which the evolution of AC shape, AC deformations, many-electron correlation and shell effects play the important role. For more details, we refer here to the recent work [9].



▲ **Fig. 3:** Second differences in binding energies calculated for for *Ar* ACs in [3].

Atoms and ions trapped in ACs: confined atoms

Another problem closely related to AC physics is the *confined atom* (see [10]). This name is given to an atom surrounded by a symmetrical cage of other atoms, and to the modification of its quantum properties which result when it is trapped in this way. The first studies of confined atoms go back nearly as far as the origins of quantum mechanics, and interested such great pioneers as Arnold Sommerfeld, who co-authored a paper on the subject. Recently, there has been a revival, stimulated in part by the observation of the so-called metallofullerenes, in which a metal atom is trapped inside the hollow cage of a C_{60} or larger fullerene. Other forms of confinement also exist. For example, a metallic ion can also be inserted into a noble gas AC, which usually causes a rearrangement, modifying the magic numbers.

Conclusion

In recent years, AC physics has made very significant progress, but a large number of problems in the field are still open. The transition of matter from the atomic to the solid state implies changes of organization which turn out to be a good deal more subtle and complex than was originally supposed. Different type of ACs, composite ACs, various size ranges, AC geometries, complex molecules (including biological), ACs on a surface and in plasmas, all provide additional themes which make this field of science very rich and varied. Collisions involving ACs, mass spectroscopy and laser techniques provide tools for experimental studies of the AC structure and properties. However, what are the experimental limitations? Where should the theory go next? Where does the future lie? Could ACs one day become the smallest devices or be used to make the smallest devices? Could one manipulate AC isomers for the production new materials and nano-structures? What is the difference between a AC and a virus? What are the principles of the matter self-organization, self-assembling and functioning on the nanoscale? We merely mention such intriguing questions in this paper, but we hope that at least some of them will be resolved during the future development of the new science of AC.

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Fullerenes

Eleanor E.B. Campbell, Dept. of Experimental Physics, School of Physics and Engineering Physics, Göteborg University and Chalmers, Göteborg, Sweden

Fullerenes have been the subject of many fascinating fundamental dynamical studies within the field of atomic and molecular physics since their discovery in 1985, a discovery that was awarded with the Nobel Prize for Chemistry in 1996. They are an allotrope of pure carbon where the carbon atoms form a closed, hollow cage. The most famous example of the family of fullerenes is Buckminsterfullerene, C_{60}. The molecule has the geometrical form of a truncated dodecahedron with a carbon atom sitting at each corner of the polyhedron. This is the same geometrical structure as a European football and, in fact, the fullerene has roughly the same relationship in size to a football as a football has to the Earth, Fig. 1. A breakthrough in 1990 led to the development of a very simple method for producing bulk quantities of C_{60}. The molecule's high stability, due both to the geometrical form as well as to its closed electronic shell, means that it can be handled very easily. This has made it an attractive subject of study in many areas of physics and it has been shown to have a wealth of interesting properties. One of the most important properties from the point of view of atomic and molecular physicists is that it can be easily sublimed to produce a molecular beam of isolated molecules in the gas phase. This has opened up a whole new area by providing a convenient and attractive model system for studying the behaviour of complex molecular systems with a large number of degrees of freedom. One very nice example of this is a fullerene beam diffraction experiment, carried out by the group of Anton Zeilinger in Vienna, showing quantum interference behaviour from C_{60} [1].

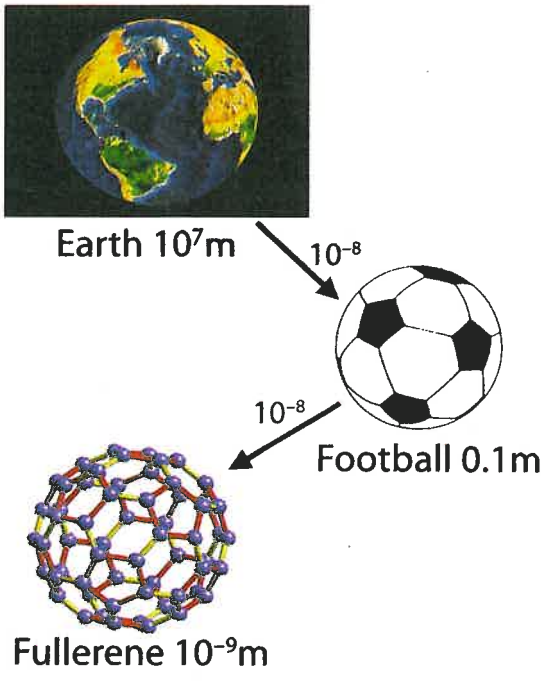
Many of the techniques employed traditionally by atomic physicists have been applied to the study of fullerenes and have greatly increased our insight into the dynamical behaviour of large molecules. In many cases, the experience gained by atomic physicists from experiments with fullerenes is now being applied to obtain insight into the behaviour of even more complex biomolecules. In this article I will try to convey the fascination of studying the fundamental properties of fullerenes in the gas phase and give the reader a flavour of the wide range of activities in this area.

Ionisation Dynamics

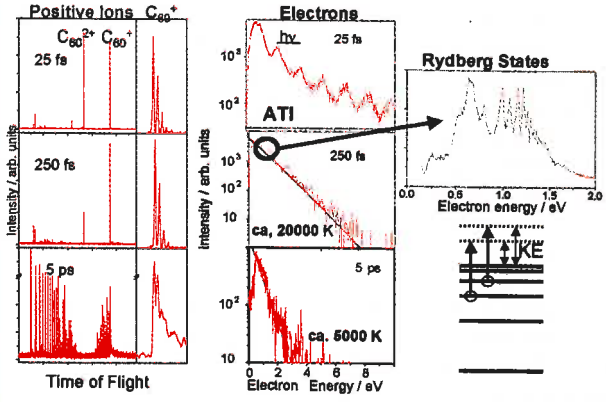
The ionisation mechanisms of fullerenes have been the subject of intense investigation since their first discovery. One of the early theoretical predictions was that a collective excitation of the electrons or "giant plasmon resonance" should occur at an excitation energy of approximately 20 eV. This was beautifully confirmed shortly afterwards in single-photon ionisation experiments carried out with synchrotron radiation. Rather different effects are seen when the fullerenes are excited with laser photons with energy less than the ionisation potential of the molecule. If nanosecond pulsed lasers are used for excitation then there is sufficient time available during the laser pulse for energy to be

redistributed within the molecule. This leads to a successive absorption of single photons with sufficient time between the absorbed photons for transfer of the electronic energy to vibrational degrees of freedom, thus producing a molecule with a very high vibrational temperature. One outcome of this is that the molecules can ionise thermally in a process akin to thermionic electron emission from hot metals. This is normally observed as a tail on the parent molecular ion peak in time-of-flight mass spectra extending many tens of microseconds to longer arrival times due to the delayed, statistical nature of the electron emission. There are relatively few isolated systems where this phenomenon can be observed so clearly. Normally in large molecules the dissociation energy of the molecule is considerably less than the ionisation potential so the most probable statistical decay channel of a vibrationally excited molecule will be neutral fragmentation. In C_{60}, the relatively low ionisation potential combined with the high dissociation energy means that thermionic electron emission competes with fragmentation. A third, competing decay channel is radiative cooling. Vibrationally excited fullerenes have been shown to emit black-body like radiation corresponding to their vibrational temperature. The understanding of the complex interplay of these different cooling processes and their fundamental mechanisms is presently the focus of experimental and theoretical activities within an EU financed Network ("Delayed Ionisation and Competing Cooling Mechanisms in Atomic Clusters").

The increasing availability of "user-friendly" ultrashort pulsed laser systems in recent years has opened up more opportunities for studying the real-time dynamics of energy flow in molecules. Fullerenes show quite different behaviour depending on the amount of time available to the molecule. This is illustrated in Fig. 2 where positive ion mass spectra and the corresponding electron kinetic energy distributions are shown for fullerenes interacting with laser pulses of different duration from 25 fs to 5 ps. One sees evidence of energy equilibration among the electronic degrees of freedom of the molecule for pulse durations higher than ca. 70 fs. This manifests itself in a clearly thermal electron kinetic energy distribution. On the order of a few hundred femtoseconds the electronic energy starts to couple to vibrational degrees of freedom. This is seen in a dramatic decrease in the electronic temperature (since the same total energy is now divided among electronic and vibrational degrees of freedom), the strong fragmentation observed in the mass spectrum and the delayed ionisation tail on the parent mass peak extending to longer times. The main observations can be explained qualitatively and, partially, quantitatively within the context of relatively simple statistical models. It might appear that C_{60} is behaving more like



▲ Fig. 1: A fullerene bears the same relation in size to a European football as the football does to the size of the Earth.



▲ Fig. 2: Positive ion mass spectra and corresponding electron kinetic energy distributions obtained from exciting C_{60} with 800 nm wavelength laser pulses with the same energy per pulse (3.5 J/cm²) but different pulse duration (Campbell et al., Phys. Rev. Lett. 84 (2000) 2128). Three different ionisation mechanisms can be clearly seen in the experiments depending upon the duration of the excitation pulse. For short laser pulses (< 70 fs) the ionisation is dominated by prompt, direct multi-photon ionisation. Singly and multiply charged parent molecular ion peaks are observed. The electron kinetic energy distribution shows peaks separated by an energy equivalent to the photon energy. This is known as "above threshold ionisation (ATI)" and is well known for atomic ionisation in strong laser fields. The parent ion peaks shows well-resolved structure corresponding to the naturally occurring ^{13}C isotope, indicating prompt ionisation on the time scale of the mass spectrometer (< 1 ns). For intermediate pulse durations (ca. 70fs – 500 fs) the ATI peaks disappear and the emitted electrons show a thermal distribution but the corresponding positive ions are vibrationally cold, are produced promptly and show no significant fragmentation. For longer pulse durations (> 1 ps) the electron temperature decreases but the positive ions are obviously highly vibrationally excited with massive fragmentation observed in the mass spectra and a tail to longer arrival times on the parent ion peak showing the presence of delayed, statistical ionisation. This behaviour can be nicely explained by considering the time scales for energy flow among the different degrees of freedom in the highly excited molecule.
Superimposed on the thermal electron distribution is a rich structure, clearly seen on the right-hand figure where the low electron energy data is plotted with a linear intensity scale. This has been shown to be due to the single photon ionisation of Rydberg states, produced and ionised within the same laser pulse (Boyle et al., Phys. Rev. Lett. 87 (2001) 273401).

features

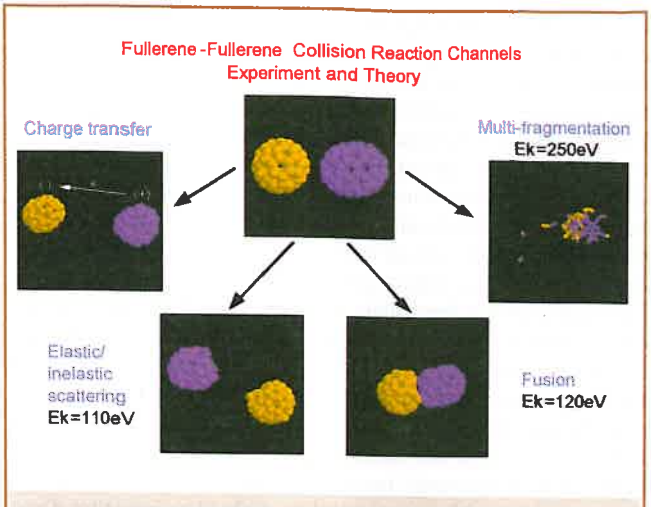
a little nano-sized piece of bulk matter rather than like a molecule, however, if one looks carefully at the electron kinetic energy distributions one sees a very nice indication of the molecular nature. Superimposed on the dominant thermal electron emission is a rich structure that turns out to be due to the multi-photon excitation and subsequent single-photon ionisation of Rydberg states. This is perhaps one of the most interesting aspects of working with fullerenes: the dynamical behaviour is truly intermediate between that of individual molecules and bulk matter with characteristics from both molecular physics and solid state physics.

Another interesting aspect of C_{60} ionisation is the ease with which electrons can be removed from the molecule. Very recently a group at the Steacie Insitute in Canada has shown that it is possible to remove up to 12 electrons from C_{60} without inducing significant fragmentation by using an intense ultrashort IR laser pulse. This has just exceeded, by one electron, the record set by the community studying highly-charged ion collisions with C_{60} and it will be interesting to see how far this limit can be pushed in the future. Highly-charged ion collisions with C_{60} is one of the most active research areas involving fullerenes within atomic and molecular physics. The projectile ion captures the transferred electrons initially into highly excited states, forming a so-called hollow ion with many vacancies in the inner shells. Similar processes are studied by colliding highly-charged ions with surfaces, however, the disadvantage in these collisions is that the hollow ion crashes into the surface soon after its formation. By studying collisions with gas phase fullerenes it is possible to follow the development of the hollow ion on a considerably longer time scale.

Collisions

Many different collisional processes have been and are continuing to be studied using fullerenes: from thermal reactions to MeV fullerene ion implantation. Charge transfer and collision induced fragmentation are the most studied reaction channels. The unique hollow structure with its relatively large diameter, the highly delocalised electronic system and the large number of vibrational degrees of freedom can all significantly affect the charge transfer dynamics and provide a challenging problem for theoretical treatment. In collision induced fragmentation studies, depending on the time scale of the collision and the transient potentials produced, one can induce predominantly vibrational excitation in the fullerene or, for very high energy ion collisions, can induce predominantly electronic excitation. The fragmentation behaviour in the former case is very similar to what is observed for nanosecond laser excitations whereas the products from very high energy collisions have a strong resemblance to the fragmentation spectra seen in electron collisions or for femtosecond laser excitation.

Apart from the more "traditional" reaction channels, some collision processes are sofar unique to fullerenes. It is e.g. possible to shoot atoms or ions inside the fullerene cage in gas phase collisions. This occurs for collision energies of a few tens of eV and provides a remarkably efficient way to produce endohedral fullerenes (fullerenes doped internally by having foreign atoms inside the cage). However, almost the entire centre-of-mass collision energy is transferred to the cage, in these collisions, which is then unstable and fragments on the microsecond time scale. A method has been developed to produce macroscopic amounts of such endohedral fullerenes by ion implantation into C_{60}, based on the gas phase collision experiments. The fullerenes are first deposited on a metal substrate before ion implantation that serves to conduct away the excess internal energy before the fullerene



▲ **Fig. 3:** Illustration of the different reaction channels that have been studied both theoretically and experimentally for fullerene-fullerene collisions. The stated collision energies are those used in the molecular dynamics simulations leading to the pictured products.

can undergo statistical unimolecular decay. It is then possible to dissolve the endohedral fullerenes and purify them by liquid chromatography. These molecules are interesting building blocks for nanoelectronics or even as q-bits for quantum computers and two EU-supported collaborative projects are presently exploring these possibilities.

Finally, I would like to mention the various reaction channels that occur in fullerene-fullerene collisions, Fig. 3. The availability of macroscopic amounts of purified fullerenes has made it possible to experimentally study single collisions between clusters and bridge the gap between studies of colliding atomic nuclei and macroscopic liquid droplets. The most interesting channel, from my point of view, is molecular fusion between the two colliding fullerenes to produce a metastable larger fullerene. We have been able to study this in detail over the years and could show that although there are some initial similarities with the dynamics of colliding atomic nuclei, there are also some significant differences that can be rationalised in terms of phase space arguments and competing reaction channels[‡].

Fullerenes have proved to be very fruitful and fascinating model systems for studying the dynamics of molecular systems with a large number of degrees of freedom. I am convinced that fullerenes will continue to surprise and delight us for many years to come and in the process teach us a great deal more about the behaviour of complex molecular systems.

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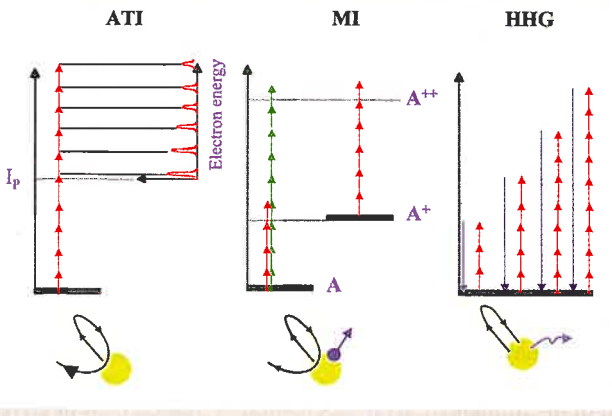
Atoms in strong laser fields

Anne L'Huillier, Lund University, Lund, Sweden

The field of research "atoms in strong laser fields" born a few years after the invention of the laser in 1960, has evolved considerably during the last two decades owing to the rapid technological development of high-power short-pulse lasers. When a high-power laser is focused into a gas of atoms, the electromagnetic field becomes of the same magnitude as the Coulomb field, which binds a 1s electron in a Hydrogen atom (5.1×10^9 V.m^{-1}). Three highly nonlinear phenomena, schematically pictured in Figure 1, can happen: Electrons initially in the ground state absorb a large number of photons, many more than the minimum number required for ionisation, thus being ionised with a high kinetic energy. This process, shown for the first time in 1979, is called Above Threshold Ionisation (ATI). Not only one, but many electrons can be emitted from atoms subject to strong laser fields. They can be emitted one at a time, in a sequential process, or simultaneously, a mechanism called direct, or non-sequential. Double ionisation of alkaline earth atoms was observed as early as in 1975 and the first evidence for non-sequential ionisation of rare gas atoms was first demonstrated in 1983. Finally, efficient photon emission in the extreme ultraviolet (XUV) range, in the form of high-order harmonics of the fundamental (linearly-polarised) laser field (HHG), shown for the first time in 1987, can occur.

This field of research remained rather small and exotic through the 1970's and part of the 1980's, restricted, for the experimental part, to a few well-founded research institutes, that could afford expensive laser systems. About fifteen years ago, a new laser material, titanium-sapphire, and a new amplification technique, chirped pulse amplification, made high-power lasers accessible to many university laboratories. This research has become one of the most exciting fields of research in atomic, molecular and optical (AMO) physics, attracting a large number of scientists all over the world, with a strong European contribution.



▲ **Fig. 1:** Schematic description of three phenomena occuring when atoms are exposed to strong laser fields: Above-Threshold-Ionisation (ATI); multiple ionisation (MI), sequential (red arrows) or non-sequential (green arrows); high-order harmonic generation (HHG). A simple interpretation of these phenomena is represented at the bottom.

Experiment

A typical and general experimental setup for studying atoms in strong laser fields is shown in Figure 2. The first element is a short pulse laser. The laser pulses used are often in the femtosecond range, the shortest being sub-10 fs. High repetition rates, today in the kHz range, allow experimentalists to get good statistics. Focused intensities needed to get into the strong field regime are of the order of 10^{14}–10^{15} W.cm^{-2}. In the last decade, the favourite tool has become the titanium sapphire laser, operating at 800 nm in the near-infrared, and providing very short pulse duration, high laser intensity at high repetition rate. A large part of the experimental activity is to make front-line lasers work, and it is no coincidence that many laboratories successful in this field of research also develop these laser systems and their diagnostics.
The second part of the experimental setup is a vacuum chamber where a gas of atoms (often rare gases) is being introduced, in a cell or pulsed jet. Ions and/or electrons are detected and analysed using time-of-flight techniques. In addition, angular distribution of the photoelectrons can be recorded. Lately, this field of research has benefited considerably from advances in coincidence and imaging techniques, developed in the AMO physics community working with synchrotron radiation. This has been particularly useful to unravel the mechanism responsible for non-sequential ionisation. In high-order harmonic generation experiments, the atomic density is much higher than in ionisation experiments, up to a few hundreds mbar. The radiation emitted on axis can be detected and analysed using a standard XUV spectrometer, including a grating and a photon detector.

Theory

The theoretical problem consists in solving the time-dependent Schrödinger equation (TDSE) that describes the interaction of a many-electron atom with a laser field. During many years, theorists have concentrated their effort on solving the problem of a hydrogen atom, or more generally, a single-active electron atom in a strong laser field. A number of methods have been proposed to solve this problem. Two of them stand out: the numerical solution of the TDSE, pioneered by Kulander at the end of the 80's and the semiclassical strong field approximation (SFA) developed by Lewenstein and others in the 90's. A large effort is presently being devoted to go beyond the single-active electron approximation.
Many insights in the physical understanding of the interaction between atoms and strong laser fields have been provided by a very simple model, called the "simple man's theory", proposed first in 1987 by Van der Linden van der Heuvell and Muller in the context of ATI and later on extended by Corkum and others to the other phenomena shown in Figure 1. According to this model, the electron tunnels through the energy barrier formed by the Coulomb field in the presence of the relatively slowly-varying linearly polarised electric field of the laser. It then undergoes (classical) oscillations in the field, during which the influence of the Coulomb force from the nucleus is practically negligible. If the electron comes back to the vicinity of the nucleus, it may be rescattered one or several times by the nucleus, possibly acquiring a high kinetic energy, and in some cases, kicking out a second or third electron. It may also recombine back to the ground state, thus producing a high energy photon. These effects are illustrated at the bottom of Figure 1.

Above-threshold-ionisation

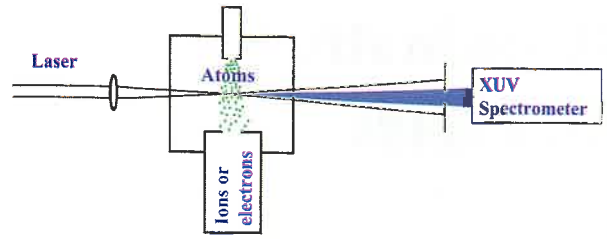
A typical ATI spectrum shows a number of electron peaks separated by the laser photon energy (see Figure 1). For short and intense laser pulses, the ionisation potential (I_p) is increased by the (time-dependent) ponderomotive potential, i.e. the mean kinetic energy acquired by an electron oscillating in the laser field $U_p = e^2 E^2/4mw^2$, where e is the electron charge, m is its mass, and E and w are the laser electric field and frequency, respectively. Most of the early work, performed in the 1980's, concentrated on the low-energy part of the spectrum, showing, for example, the influence of the ponderomotive potential, the role of AC-Stark shifted resonant excited states and the transition from the multiphoton to the tunneling regime. The experimental precision in detecting electron spectra increased significantly from the mid 90's owing essentially to higher laser repetition rates. Thus ATI spectra with many decades in number of counts could be recorded. Amazingly, the spectra were found to extend over many tens of eV, with a decrease for the first orders, up to ~$2U_p$, followed by a large plateau extending to ~$10\,U_p$. In general, with linear polarisation, electrons are generated along the polarisation's direction. It was found that angular distributions exhibit a much more complex (off-axis) structure at the edge of the plateau, called "scattering rings". The large plateau and the complex angular structure originate from the rescattering of the electron wavepacket on the parent ion.

Multiple ionisation

The simplest multiple ionisation mechanism for atoms in strong laser fields is the so-called sequential stripping mechanism, i.e. a sequence of single electron ionisation acts: ionisation of the atom, then of the singly charged ion, then of the doubly charged ion and so on. The main experimental effort during the 1980's was to test the limits of this mechanism with the available laser powers and to understand the process responsible for the ionisation of the different charge states (multiphoton or tunnelling). The existence of a "knee" in the ion signal variation as a function of intensity indicates, however, that sequential ionisation is not the only mechanism responsible for multiple ionisation. A lot of effort has been and is still devoted to the understanding of the nonsequential ionisation process. Several ideas have been proposed, one of them, illustrated in Fig. 1, being electron scattering on a parent ion, leading to ejection of a second electron. Up to a couple of years ago, the experimental method consisted in measuring the number of ions as a function of the laser intensity and in varying the laser pulse characteristics (for example, its polarisation). Progress in experimental techniques with, for example, recoil-ion momentum spectroscopy and electron-ion coincidence measurements allows now scientists to record the energies and angular distributions of the electrons emitted during a multiple ionisation process, thus providing better experimental insight.

High-order harmonic generation

A high-order harmonic spectrum consists in a sequence of peaks centered at frequency qw, where q is an odd integer. Only odd orders can be observed, owing to inversion symmetry in an atomic gas (In the time domain, this means that the process is periodical with a periodicity twice the laser period). A HHG spectrum has a characteristic behaviour: A fast decrease for the first few harmonics, followed by a long plateau of harmonics with approximately constant intensity. The plateau ends up by a sharp cut-off. Most of the early work on harmonic generation concentrated on the extension of the plateau, i.e. the generation of harmonics of shorter wavelength. Today, harmonic spectra produced with short and intense laser pulses extend to more than 500



▲ **Fig. 2:** Typical schematic experimental setup in the study of atoms in strong laser fields. An intense short pulse laser is focused into an interaction chamber, which contains a gas of atoms. Ions or electrons can be detected, e.g. with time-of-flight techniques. Alternatively, the radiation, which is emitted on axis, can be analysed with an extreme-ultraviolet spectrometer.

eV, down to the water window below the carbon K-edge at 4.4 nm. A large effort has been devoted to optimize and characterize the properties of this new source of XUV radiation. A milestone in the understanding of HHG processes was the finding by Kulander and coworkers in 1992 that the cut-off position in the harmonic spectrum follows the universal law $I_p + 3U_p$. This result was immediately interpreted in terms of the simple man's theory, and led to the formulation of the SFA. A realistic description of HHG involves, however, not only the calculation of the single atom response, but also the solution of propagation (Maxwell) equations for the emitted radiation.

Attosecond Pulses

Almost immediately after the first observation of the harmonic plateau at the end of the 1980's, it was realised that, if the harmonics were emitted in phase, i.e. phase-locked, the temporal structure of the radiation emitted from the medium would consist of a "train" of attosecond pulses separated by half the laser period. There is a clear analogy here with mode-locked lasers, where axial modes oscillating in a laser cavity are locked in phase, leading to the production of trains of short pulses. From a microscopic point of view, at each half-laser cycle, there is a short (attosecond) burst of light, as an electron recombines back to the ground state. Isolated attosecond pulses can be produced if one limits these returns to single events. The simplest idea is to use a very short (7 fs) and intense laser pulse. Such a laser source should allow one to generate single attosecond pulses, because harmonic generation occurs during a limited time interval, before the onset of ionisation. Attosecond pulses have remained, however, essentially a theoretical prediction, until last year. Two important experiments show evidence for trains of 250 as pulses (Agostini, Muller and coworkers), and for isolated 650 as pulses (Krausz and coworkers).

Outlook

In conclusion, "atoms in strong laser fields" is a fascinating field of AMO physics, that has progressed considerably during the last decade. At the start of the 21st century, we begin to understand a lot of the fundamental physics behind. A unified view of HHG, ATI and non-sequential ionisation, originating from the simple man's model and the strong field approximation, expressed in terms of electron trajectories or quantum paths is slowly emerging. The systematic study of multi-electron ionisation and electron correlation processes in strong laser fields, however, has only just begun and we may expect a lot of activities in this area in the near future.

This field of research, though quite fundamental, has led to a very interesting application: The harmonic radiation, with its unique properties of ultrashort pulse duration, high brightness and good spatial and temporal coherence, is being used in a growing number of applications ranging from atomic and molecular spectroscopy to solid-state and plasma physics. It has also been proposed as an alternative source for nanolithography, in particular for metrological purposes. It opens up two new fields of research: multiphoton processes in the XUV range, demonstrated for the first time three years ago, and attosecond physics, where processes in atoms and molecules can be studied at an unprecedented time scale. Attophysics is just born and there is already an active discussion on the possible applications of attosecond XUV pulses. The first step towards the use of attosecond pulses has been recently taken by Krausz and his collaborators who have been able to "steer" electron wavepackets, generated by attosecond XUV pulses, in the laser light.

This work has been supported by the Swedish Research Council.

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Probing biomolecules: Gas phase experiments and biological relevance

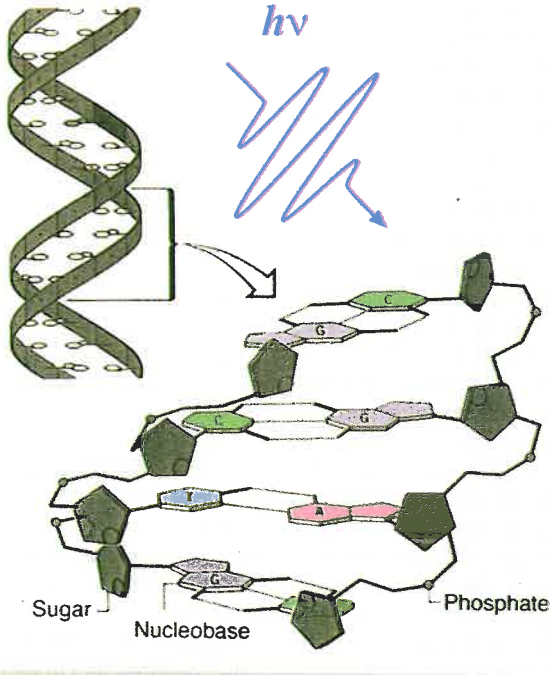
Sascha Gohlke and Eugen Illenberger
Institut für Chemie—Physikalische und Theoretische Chemie
Freie Universitär Berlin, Berlin, Germany

After the discovery of X-rays, radioactivity and ultimately nuclear fission—leading to the release of atomic bombs over Hiroshima and Nagasaki—it became clear that the exposure of living beings to high energy radiation (particles and photons) can result in fatal effects for the concerned individual. The result of such effects is subsumed under the all embracing term *radiation damage*. It includes damage of biological material on a short time scale, i.e. the immediate collapse of living cells eventually resulting in the death of the individual within hours or days but also describes effects appearing on much longer time scales since, instead of complete destruction of cells, radiation can also change the genetic expression of DNA. This may ultimately result in cancer and the appearance of tumours; but for prolonged periods after initial exposure the individual amy appear to have no obvious problems, however such dormant effects may appear as mutations in the individuals descendants (e.g the number of deformities in babies born in the Ukraine in the years after the Chernobyl accident).

> .. it became clear that he exposure of living eings to high energy adiation can result in atal effects

Radiation damage and radiosensitisers for tumour therapy

While high energy radiation can irreversibly damage biological material, radiation may also be successfully used in tumour therapy. The problem here is to only expose the cancerous material while keeping all other areas unirradiated. One method of treatment uses *radiosensitisers* with the effect that the sensitised cancerous cells will be destroyed with radiation dosages that leave the healthy material essentially unaffected. The necessary prerequisite for effective and controlled therapy strategies is the understanding of the molecular mechanisms of the underlying processes. In an effort to describe these effects on a molecular level, different laboratories have started programs to study the building blocks of biomolecules in the gas phase [1–4]. The advantage of gas phase studies is that experimental techniques like mass spectrometry or electron spectroscopy (eventually in combination with laser pump and probe techniques) can easily be applied. These techniques allow detailed information on the properties of molecules and the dynamics of reactions to be explored. The question then is to which degree these *intrinsic* properties



▲ Fig. 1: The DNA double helix and an extended view showing the base pairing through hydrogen bonding. The arrow represents a bunch of high energy photons in the MeV range interacting with DNA and its environment.

(as revealed by gas phase studies) can be transferred to their analogue in solution. This problem has been a longstanding issue in many areas of Physical Chemistry. One has to be aware that the solvent represents a dissipative environment and in the case of reactions where charged particles are involved, solvation can considerably modify the energy profile along the reaction coordinate.

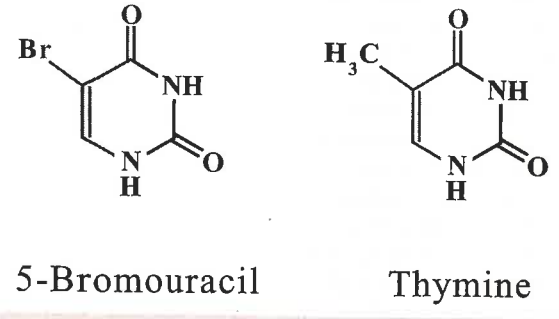
The most important component of the cell nuclei is DNA in which genetic information is stored. DNA is a biopolymer consisting of two chains (strands) containing the 4 heterocyclic bases thymine (T), adenine (A), cytosine (C) and guanine (G), each of them bound to the DNA backbone which itself is composed of phosphate and sugar units. Both strands are connected through reciprocal hydrogen bonding between pairs of bases in opposite positions in the two strands. The geometry is such that adenine pairs with thymine (AT) and guanine with cytosine (GC) resulting in the well recognised double helix form. The DNA itself is surrounded by other biomolecules (proteins) and, of course, water.

Primary and secondary processes in living cells

To understand the effect of high energy radiation on DNA and its environment one may follow this interaction in terms of its chronological sequence. As an example consider a bunch of photons at energies in the MeV range interacting with DNA and its environment. The *primary* photon interaction (absorption, scattering) removes electrons from essentially any occupied state, from valence orbitals to core levels. Depending on the energy of these ionised electrons they induce further ionisation events thereby losing energy and being slowed down. The estimated quantity is 10^4 *secondary* electrons per 1 MeV primary quantum [5]. These electrons are usually assigned as *secondary* although they are the result from primary, secondary, tertiary etc. interactions, including electrons from Auger processes during relaxation of the core holes. Taking a snapshot a few femtoseconds after the primary interaction we will see multiple charged sites within the complex molecular network (eventually undergoing Coulomb explosion), single ionised and electronically excited sites and, last but not least, an exceedingly large number of low energy secondary electrons. Although the double and single ionised sites as well as electronic excitation can result in the rupture of chemical bonds, the major effects are induced by the large number of secondary electrons. In the course of successive inelastic collisions within the medium these are thermalised within picoseconds before they reach some stage of solvation.

Direct damage concerns reactions directly in the DNA and its closely bound water molecules.

Damage of the genome in a living cell by ionising radiation is about one third a *direct* and two thirds an *indirect processes*. Direct damage concerns reactions directly in the DNA and its closely bound water molecules. Indirect damage results from energy deposition in water molecules and other biomolecules in the surrounding of the DNA. It is believed that almost all the indirect damage is due to the attack of the highly reactive hydroxyl radical OH^* on the DHA chain.



▲ **Fig. 2:** The nucleobases thymine (T) and bromouracil (BrU).

Electron initiated reactions in gas phase DNA bases

In order to reveal the mechanism of *direct* damage it appears straightforward to investigate the interaction of low energy electrons with single DNA bases representing the building blocks of the large polymer. Such experiments have been carried out in different laboratories [1–4] with crossed electron/molecular beam arrangements where a monochromatised electron beam interacts with an effusive molecular beam containing the DNA bases. The beam is generated by moderately heating the powder sample containing the DNA bases to 150 – 200°C and effusing the molecules through the collision region. The ions resulting from the electron – molecule collisions are extracted from the collision region and focused to a mass filter where they are mass analysed and detected. An alternative and partially complementary technique is to record the electron current transmitted through the gaseous target [2].

We shall consider here a prototype gas phase result to illustrate the effect on the DNA base thymine (T) and bromouracil (BrU). It has been known for many years that substitution of T by BrU in the genetic sequence of cellular DNA (Fig. 2) leads to a greater sensitivity to ionising radiation without changing the gene expression in unirradiated cells. Hence bromouracil potentially may be used as a tumour specific sensitiser in cancer therapy. On proceeding from higher energies to low energies the following features in electron impact to T and BrU become apparent:

A. The ionisation and excitation cross sections for both compounds behave in the manner usual for polyatomic molecules i. e. they rise gradually above the corresponding threshold with total values remaining below the geometrical cross section of the molecule. Ionisation and electronic excitation can also result in fragmentation but this area is still fairly unexplored.

B. However while T and BrU behave quite similarly at energies above electronic excitation there are remarkable differences in the subexcitation region. The common feature is that both molecules exhibit pronounced resonance features due to resonant electron attachment but such resonances have very different cross sections.

In thymine (T) the most abundant channel is identified as

$$e^- (\approx 2\ eV) + T \rightarrow T^{\#-} \rightarrow (T-H)^- + H^* \qquad (1)$$

with a resonance maximum near 2 eV and a threshold close to 0 eV [4]. $T^{\#-}$ represents the transient negative ion formed upon a Franck–Condon transition from the neutral molecule which decomposes into the closed shell fragment anion $(T-H)^-$ and a neutral hydrogen radical H^*. The absolute cross section for this dissociative electron attachment (DEA) cross section can be estimated as $\sigma_{DEA} \approx 2$ Å^2.

In contrast to that, the radiosensitiser bromouracil exhibits a very intense and narrow low energy resonances (Fig. 3) located close to 0 eV and associated with the processes

$$e^-(0\ eV) + BrU \rightarrow BrU^{\#-} \rightarrow (U\text{–}yl)^* + Br^- \quad (2a)$$

$$\rightarrow (U\text{–}yl)^- + Br^* \quad (2b)$$

which are complementary with respect to the negative charge. (U–yl) denotes the fragment formed by the loss of bromine. (2a) is the most abundant channel with an estimated cross section of 600 Å^2. Reaction (2b) is also open at zero eV (though at only 6% of the efficiency of (2a)). Due to the appreciable electron affinities of Br* and (U–yl)* exceeding 3 eV, reactions (2a) and (2b) have low energy thresholds. Figure 3 also shows that the undissociated anion weakly appears within the time scale of the experiment (ca. 50 μs).

It is interesting to note that both T and BrU are damaged at electron energies below 3 eV. The absolute cross sections, however, differ by more than two orders of magnitude. The conclusion then is that the initial mechanism for *direct* DNA damage is bond cleavage by low energy secondary electrons which is much more effective in the radiosensitisers.

Gas phase results and biological reality

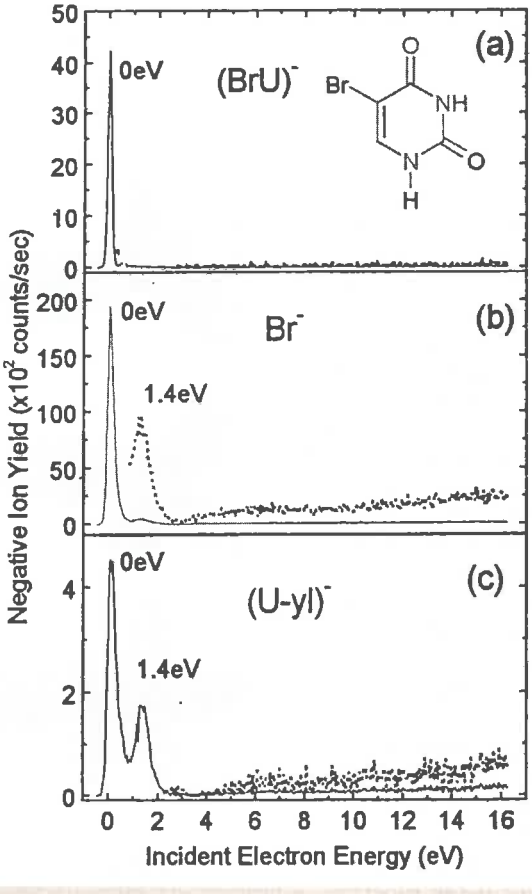
The general problem still remains on the question to which degree such gas phase results are relevant for a real (*in vivo*) biological system. DNA as a polymer is embedded in a medium while the present reactions are observed from isolated gas phase components. In the following we consider a few critical points that require further investigations:

1. Coupling of the nucleobases to the backbone and the opposite chain will certainly modify the energy of the involved molecular orbitals to some degree but can one assume the essential DEA features of the isolated bases will remain in the polymer?
2. In a condensed environment the reactivity (bond cleavage) is usually suppressed due to energy dissipation, but there are also situations where bond rupture via low energy attachment can be enhanced by the medium [6]. Irrespective of the phase condition, however, can one assume that BrU remains the more effective dissociative electron scavenger which respect to T which explains the mechanism by which BrU operates as radio sensitiser?
3. The reaction route from dissociative electron capture to single and double strand breaks is not directly obvious and has to be explored.

The importance of reactions of *presolvated* electrons with amino acids and nucleotides has already been pointed out more than 2 decades ago by time resolved pulse radiolysis experiments [7]. More recently, the ability of *free* ballistic electrons (3–20 eV) to efficiently induce single and double strand breaks in supercoiled DNA has clearly been shown [5]. In these studies it was demonstrated that the DNA strand breaks were initiated by the formation and decay of transient negative ion (TNI) states, localised on the various DNA components (phosphate, deoxyribose or hydration water). Unfortunately these experiments did not cover the energy region below 3 eV.

We finally mention that electrons in the solvated stage may not play any significant role. The binding energy of those electrons in water is above 3 eV and hence any dissociative electron transfer associated with reactions of the form (2a) and (2b) are associated with a large activation barrier and may not play any significant role.

To conclude it seems almost paradoxical that the damage of high energy radiation in the million eV range is actually the result of the interaction of secondary electrons at very low energies. Capture of electrons into antibonding molecular orbitals, however, is a very effective means to transfer energy of the light electron into motion of the heavy nuclei.



▲ **Fig. 3:** Negative ions observed in low energy electron impact to gas phase bromouracil.

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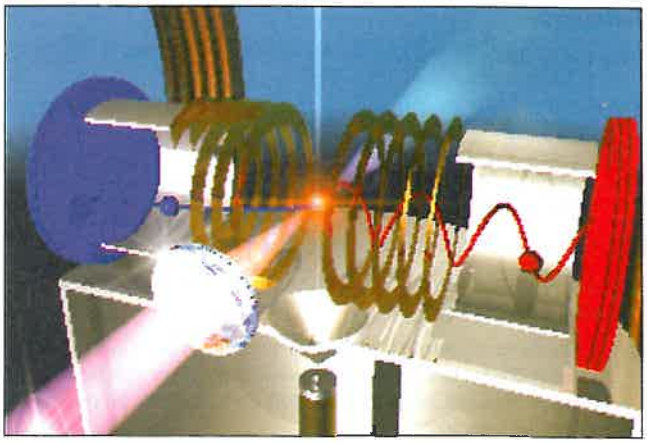
The bubble chamber technique for low energy fragmentation processes in atomic, molecular, and surface physics.

COLTRIMS

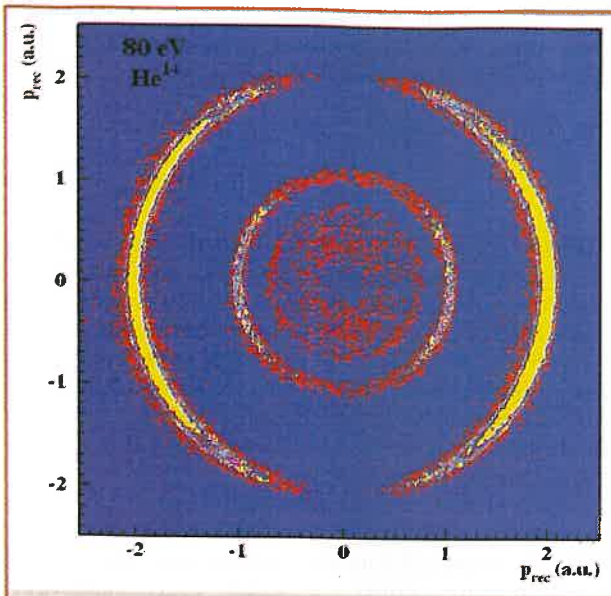
H.Schmidt-Böcking[1], R.Dörner[1] and J.Ullrich[2]
[1] Institut für Kernphysik, Universität Frankfurt,Frankfurt, FRG
[2] MPI für Kernphysik Heidelberg, Heidelberg, FRG

Correlated many-particle dynamics in Coulombic systems, which is one of the unsolved fundamental problems in physics, can now be experimentally approached with so far unprecedented completeness and precision. The recent development of the COLTRIMS technique (COLd Target Recoil Ion Momentum Spectroscopy) [1,2] provides a coincident multi-fragment imaging technique for eV and sub-eV fragment detection. In its completeness it is as powerful as the bubble chamber in high energy physics. Based on state-of-the-art cooling techniques (super sonic jets, MOT etc.) and nuclear physics imaging methods fragmentation processes of atoms, molecules, clusters, as well as of solid state surfaces induced by single photon or multi photon laser absorption, electron or ion impact can be explored completely in momentum space and, for ions, with micro-eV resolution. In recent benchmark experiments [1,2] quasi snapshots (duration as short an atto-sec) of the correlated dynamics between electrons and nuclei has been made for atomic and molecular objects. This new imaging technique has opened a powerful observation window into the hidden world of many-particle dynamics.

The principle of the method, namely measuring the momentum of the emitted charged particles from an atomic fragmentation process is as simple as determining the trajectory of a thrown stone. From knowing the position, from where the stone was slung and where it hits the target as well as measuring its time-of-flight, the trajectory of the stone and thus its initial velocity vector can precisely be determined. Furthermore, in order to achieve good precision we have to know whether the person, who throws the stone, was at rest in the frame of observation



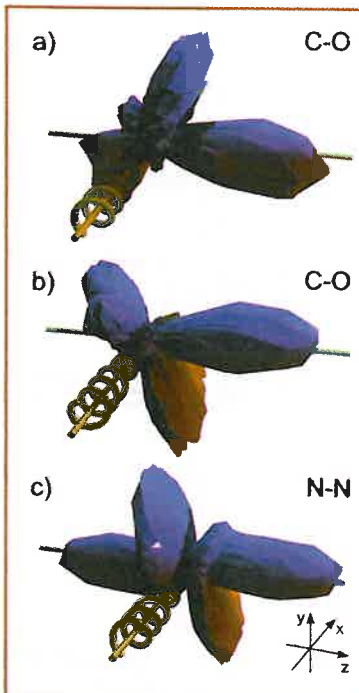
▲ **Fig. 1:** Artist view of the COLTRIMS imaging system [1,2].



▲ **Fig. 2:** Recoil-ion momentum distribution for single ionization of He induced by a single photon of 80eV [1,2].

or with which relative velocity this person was moving. Thus to obtain optimal momentum resolution for the exploding fragments one has to bring the fragmenting object to a complete rest in the frame of measurement before the reaction occurs, i.e. if the object is a gas atom or molecule one has to cool it down to sub-milli Kelvin temperatures.

In figure 1 the principle of the new reaction microscope (synonym: COLTRIMS) is presented. In a well designed electric field configuration (static or pulsed) the positively as well as the negatively charged fragments are projected (typically with 4π solid angle) on two position-sensitive detectors. Measuring the impact position on the detector (typically < 0,1mm resolution) and the time-of-flight of the fragment (TOF) between the moment of fragmentation till hitting the detector, the particle trajectory, and thus the particle momentum after fragmentation, can be determined. To improve its momentum resolution electrostatic lenses can be incorporated into the projection system, such that the influence of the unknown size of the target region, from where the fragments originate, can completely be eliminated [1-4]. To detect also the higher energetic electrons, magnetic fields, superimposed over the electric field [1-3]), as well as pulsed electric fields can be used. If



▲ **Fig. 3:** Angular distribution for K photo electron emission in diatomic molecules after K shell ionization by a circular polarized photon of 300eV [5].

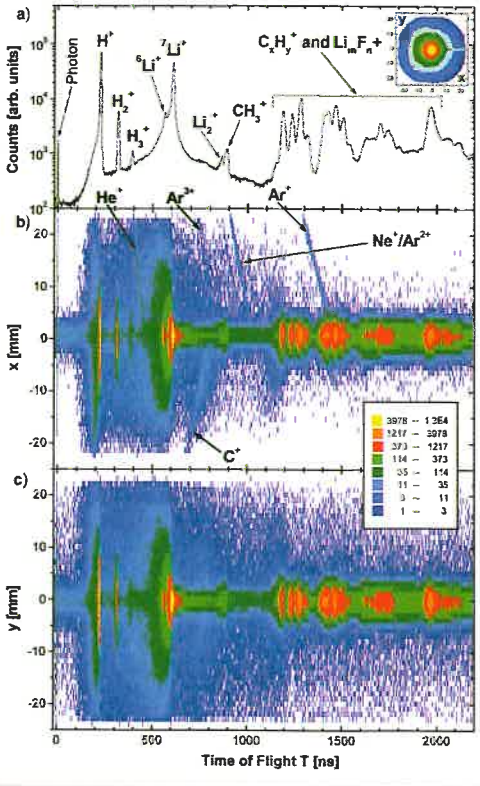
particle detectors based on fast delay-line position read-out are used multi-hit detection is possible. Even two particles hitting the detector at the "same" instant (Δt < 1nano-sec) can simultaneously be detected. The number of detected multi-hits is practically only limited by the electronics needed to store in event mode all information. In future even up to 100 particles per microsec might be detectable if fast transient recorder units with channel resolution of about 0,1 nano-sec become available. Thus, for low energy particles (micro-eV to hundreds of eV) the COLTRIMS method is indeed as powerful as advanced bubble chamber systems for high energetic (mega-eV) particles. It is even comparable with modern TPC systems used in high energy physics. Furthermore the rate of fragmentation processes per second can exceed several 100kHz.

As a typical example for COLTRIMS data, figure 2 shows the recoil-ion momentum distribution of He^+ ions from the photoelectric effect at a single atom (the electric field vector of the linear polarized photon is parallel to the horizontal direction). This data set is simultaneously obtained for all momenta. Using COLTRIMS, the typical duration of such measurements is less than one hour for data sets. The physics of these data is discussed in ref. [1, 2].

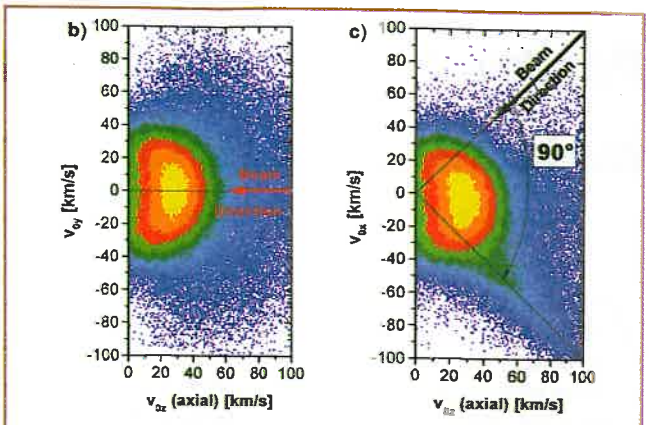
In figure 3 the angular distribution for K photo electron emission for the reaction

$$\gamma(\text{circular polarized}) + AB \Rightarrow A^+ + B^+ + e_\gamma + e_{K\text{-Auger}}$$

is shown. The molecular axis is oriented parallel to the electric field vector (z-axis). The circular polarization and the impact direction of the photon are indicated by the arrow. In this measurement both photo electron and recoil-ion momentum



▲ Fig. 4: Secondary ion distribution from a LiF+Al surface after 25keV/u Ar^{9+} impact (see text).



▲ Fig. 5: Secondary H^+ ion velocity distribution (see figure 4 and text).

distribution are detected in coincidence and the digitized data are stored in list-mode technique.

The COLTRIMS imaging method can be applied also to surface fragmentation processes. In figure 4a the time-of- flight (TOF) spectrum for ion emission from a surface after single ion impact (25keV/u Ar^{0+} on LiF+Al) is shown, the insert in figure 4a shows the ion position distribution on the detector.

In figures 4b and c the ion TOF distribution (perpendicular to the surface, z direction) as function of the x and y directions are presented. X and y direction are parallel to the surface, where the x axis is the projection of the incoming fast ion direction. In figure 5 for H^+ ions the velocity distributions are shown for the x, y, and z directions. In one measurement the whole momentum distribution of all emitted ions is detected with high momentum resolution. Details of the physical interpretation of these data are given in ref. [6].

Many new applications for COLTRIMS in different areas of AMOP physics are under way. Experiments of atomic and molecular fragmentation processes in strong femtosec laser pulses have recently been performed yielding precise information on sub femto-sec dynamics of the correlated motion of electrons and nuclei in strong laser pulses. The detection of fragmentation of BE condensates is in preparation. Last not least the fragmentation of biological species is an interesting application for the COLTRIMS imaging method.

Acknowledgement:

COLTRIMS was developed in a group effort during the last 17 years. Without the tremendous work and excellent ideas of C.L.Cocke, V.Mergel, O.Jagutzki, R.Moshammer, R.Ali, L.Schmidt, K.Ullmann and other friends and colleagues this new technique would not exist. We are thankful for the excellent support of the DFG and BMBF/GSI.

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features

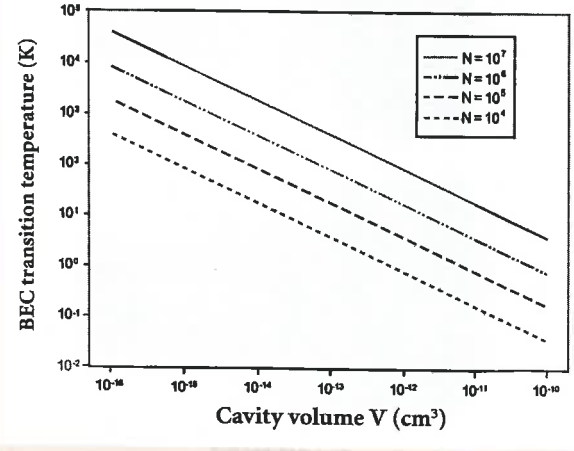
Positron and positronium physics in atomic and molecular gases: Challenges for the 21st century

F.A. Gianturco, Department of Chemistry, University of Rome "La Sapienza" and INFM, Rome, Italy

The subject of positron and positronium (Ps) physics with atoms and molecules is indeed one with a long history, but also a subject where a surprisingly large number of fundamental questions raised by a variety of recent observations still remain to be answered. Many of the problems in this area come up when discussing low-energy interaction of positrons and Ps with atomic and molecular aggregates and therefore provide the fundamental understanding for setting up a more quantitative approach to the chemistry of matter-antimatter processes.

To illustrate the status of modern research in positron physics and in the chemistry of positron/Ps processes, I have chosen to discuss only a few of the current issues which, hopefully, will convey to the reader the excitement coming from the resurgence of interest in this field and the current wave of experiments with their new findings. For a more extensive discussion that endeavours to better document the details of the topics which I shall only lightly touch on in this overview, I refer the interested reader to a recently published volume containing a broad range of articles on antimatter processes [1].

The increase in the interest of the scientific community on positrons as a research tool follows the development of low-energy positron beams, particularly over the last 15 years or so. It was realised early on, in fact, that to have such sources available might offer additional tests on the polarisation forces and scattering states probed by the counterpart studies with low energy electron beams of atomic and molecular gases. Furthermore, such studies indicated that correlation forces between the impinging positron and the bound electrons, either atomic or molecular, are much more important than the same effects in electron collisions, a consideration with profound implications in the sense that the virtual positronium (Ps) formation channels (that can be viewed as transient bound state complexes moving in the field of the atomic or the molecular ion) now make the treatment of positron-atom/molecule collision events a much more complicated situation to handle with theoretical modellings. Thus, to have removed the non-locality of the exchange interaction that affects electron scattering processes turned out to be a simplification outweighted by the more complicated features of the electron-positron correlation effects which play a more explicit role, together with the one coming from the Ps formation channel. The latter is certainly one of the most fundamental examples of a charge exchange reaction that definitely requires for its description a quantum mechanical formulation of target-projectile interactions and dynamics. To this end, the new experimental techniques which exploit positron accumulators [2, 3] have markedly increased our capabilities for investigating positron and Ps interactions with matter at very low energies: they work already in the meV range and with possible developments which could bring us down to the μeV region. The elastic channels and the annihilation channels are always open as the kinetic energy of the probe approaches zero. Ps formation could also be energetically allowed whenever the target ionization energy is below 6.8 eV, the binding energy of the ground state Ps. Experiments could therefore be able to tell us what happens in that region of interaction where scattering states become close to the weakly bound states of the interacting species, if they exist at all. Both the annihilation process and the Ps formation cross section are expected, from general theoretical estimates, to increase proportionally to 1/v, v being the relative velocity of the partners, as the energy tends to zero. One of the puzzling questions pertaining to such very low-energy scenario is provided by the possibility to find experimental evidence and theoretical confirmation on the existence of bound states or of metastable resonant states associated to cold positrons and Ps that are made to interact with fairly cold atomic and molecular gases. This is an aspect of the physics of antiparticles that has made very impressive progress, in the last 4–5 years, on the theoretical and computational predictions of such states while still rather absent at the experimental level. The definition of a stable antimatter compound could be had, in its simplest form, by changing a bound proton of a known stable compound with a positron. Thus PsH (positronium hydride) and Ps_2 become real chemical species that are related to the stable molecule of H_2. Naturally, all such systems invariably annihilate and their lifetimes are of the order of ~ 100 picoseconds. Hence, an operational definition of a stable antimatter species could be had whenever the latter has at least one bound state that does not dissociate or autoionize before the inevitable annihilation occurs. Several of the properties of such apparently strange compounds are of direct interest at the fundamental level, besides being useful in many areas of applied, engineering studies [4]. Their binding energies, their annihilation rates and the momentum distributions of the emitted annihilation photons are amenable to calculations which have made tremendous progress in the last few years, thereby hopefull spurring future experimental attempts at producing comparable measurements: it may not



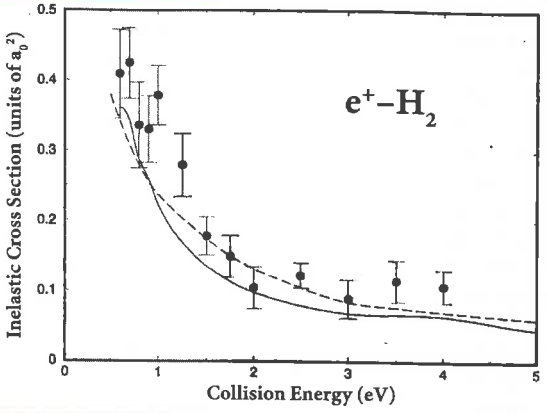
▲ **Fig. 1:** The variation of the BEC transition temperature as a function of cavity sizes and for different, possible Ps densities in the cavity (adapted from ref. [14]).

be long, therefore, before these will become available and will test the quality of the calculations.

Since the coupling between the quasi-discrete states and the continuum can be taken to be fairly weak [5], the calculations could then treat the latter states as conventional bound states and perform calculations of the pre-annihilation compounds using the quantum mechanical tools refined over the years to treat many-body bound structures [6, 7]. Thus, the evaluation of correlation forces becomes an essential feature for establishing the likelyhood of producing positronic compounds which can be defined as stable. In the case of the Ps system, the formation of the neutral compounds like PsX, with X being either an atomic or molecular partner, depends on its stability with respect to its main dissociation channel: PsX → Ps+X, hence one may qualitatively consider the source of binding to be due to simultaneous attraction of an electron to the positron and to the X complex. Theory therefore needs to provide a balanced evaluation of correlation forces versus annihilation rates before binding [6, 7]. The most advanced efforts in this area have established that the presence of 'virtual' positronium formation during the interaction is one of the crucial ingredients for reliable values of binding energies vs annihilation rates [8]. In spite of the computational difficulties, in fact, more than 50 different antimatter compounds have been identified from theoretical studies, a truly explosive growth of the last four or five years [9].

It should have become already clear from the above examples that the renewed efforts in analysing low-energy behaviour of antimatter particles with ordinary matter compounds is providing one of the most exciting arenas in positron physics. It is therefore not surprising to discover that a large group of experimentalists, with strong theoretical support, is currently working on a cooperative effort named the ATHENA experiment [10]. The acronym describes an ApparaTus for High precision Experiments on Neutral Antimatter. It takes place at the Geneva CERN laboratory, carrying out experiments on antihydrogen ($\bar{H}$) that are expected to test the CPT Invariance of Quantum Field Theory as well as Einstein's Equivalence Principle. The idea behind it is to trap H at very low temperatures of less than 1K using an inhomogeneous magnetic field. The collaboration involves 7 different countries and more than fifty scientists. The above effort also tells us that our fundamental understanding of the mechanism by which the antiparticle will be kept in the trap and will avoid evaporative cooling via collisions with H, H_2 and He that are present in it, is an important requirement for choosing the best conditions which maximise the lifetime of $\bar{H}$ [11, 12].

With the current resurgence of studies at ultra-low temperatures and ultra-low energies, antiparticles have also been considered as possible candidates for the production of Bose Einstein condensates (BEC) of bosonic Ps by studying the possibility of creating a dense gas of Ps particles in a microcavity within some solid state material which will then allow the possible phase transition to a BEC state of the ensemble [13]. We know already that such a transition occurs when an ensemble of low-T bosons undergoes the transition and collapse into a single, low-lying ground state of the global system. Because of the intrinsic instability of a matter-antimatter system (as is the one we are considering) and given the experimental difficulties for getting hold of low-energy positrons in sufficiently large quantities, such a possibility has so far received only limited attention and therefore we know very little on the properties of dense interacting Ps gases. The variation of the expected BEC transition temperatures as a function of the cavity volume, and for different required Ps densities, is shown in figure 1 and should give an idea of the hard



▲ **Fig. 2:** Computed and measured partial integral cross Sections for the vibrational excitation of the (0 → 1) transition in the H_2 molecule by positron collisions. The solid circles are the experiments from ref. [18] while the solid line reports recent theoretical calculations [23]. Both data are on an absolute scale without any adjustment (adapted from ref. [23]).

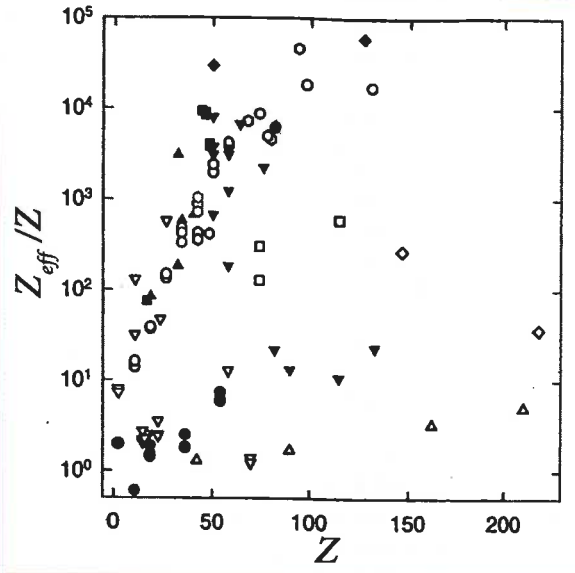
requirements for such exciting experiments to be successful [14]. They have been recently proposed to confine the Ps particles within microscopic cavities of solid sapphire that are located very near its surface, so that a highly focussed pulsed beam of energetic positrons can be made to impinge on the surface and be transported by injection into the cavity. After the Ps is formed there, and following the decay of its short-lived component, only the long-lived triplet state is expected to remain, thereby allowing the condensate to form during the cooling kinetics within the injected cavity [14, 15]. Our further understanding of BEC physics means that issues like establishing some correlation between the BEC lifetime and the Ps own lifetime, the effect of impurities and of the confining waves on the condensate existence and behaviour, the Ps scattering length at ultra-low energies, the cross sections for elastic and reactive (Ps_2 formation) collisions will all be very important factors that will play a significant role in the experiments which will provide the above information for the first time. The creation, storage and manipulation of such special material under very extreme conditions as those proposed for the BEC experiments, will also require the combination of different expertise in the experimental and theoretical studies of atomic, molecular and solid state physics of the antimatter and will necessarily need the creation of a new generation of positron facilities.

The impact of new experimental facilities and of new sources of low-energy positrons has been particularly evident in the case of molecular gases and of the chemical processes which positron and positronium can activate within such gases [16–18]. Thus, absolute differential scattering cross sections and state-resolved inelastic scattering cross sections has become a reality with the recent development of high resolution (~20 meV), high brightness beam of positrons [19], produced by using a Penning trap to form a reservoir of cold positrons to be released in a controlled fashion [16]. One can therefore nowadays collect much more accurate data on inelastic processes in molecular gases, e.g. vibrational excitations of specific molecular modes and variations of the corresponding angular distributions of the scattered positrons as different modes are being excited, ionization cross sections for positron impact on atomic and molecular gases, both as a direct ionization process and as ionization with Ps formation [20, 21]. In the latter cases, features related to a new

process that has become known as electron capture to the continuum (ECC) have been identified [22], providing new challenges for the theoretical interpretation of such events even in simple atomic gases. An interesting example of how the new class of experiments could be met by theoretical comparison is shown in figure 2. We report there the integral, partial inelastic cross section fort the excitation of the $(0 \rightarrow 1)$ vibrational mode of the H_2 molecule by positron impact. The experimental data are on an absolute scale [18] and the solid line calculations [23] are clearly reproducing experiments very closely and without any adjusted scaling.

Perhaps one of the most interesting molecular effects that has been uncovered by the recent experiments involving slow positrons interacting with polyatomic gases has been the behaviour of their annihilation rates in such gases [24]. The measured annihilation rates are found to be a linear function of the test gas pressure and the slope linearity yields the value of the rate, termed Z_{eff}. The extremely broad range of observed Z_{eff} values over the set of molecular gases which have been experimentally studied [25] indeed provides one of the challenges of positron physics that calls on the development of powerful computational models for cases where fairly complicated polyatomic gases are involved [25].
To make this point more evident, we report in figure 3 the behaviour of the Z_{eff}/Z ratios for a wide variety of molecular species and as a function of Z. One clearly sees that the ratios are very far from unit when more complicated molecules are considered [26] and vary over several orders of magnitude.

The microscopic nature of $e^+ - e^-$ interactions with atoms and molecules is studied by measuring the Doppler-broadening of the 511-keV annihilation gamma-ray line [24]. The Doppler line width is determined by the momentum distribution of the electrons which take part in the annihilation. The usual interpretation of this feature is that the positron has a relatively long de Broglie wavelength in the vicinity of the target, due to its net repulsive interaction with the electronuclear network of bound particles which make up the molecule. Consequently, the positron interacts with roughly the same probability with any of the valence electrons. However, the observation of Z_{eff} values which range from ~ 20 up to 10^7–10^8 depending on the molecular gas points instead to the existence of qualitative differences between the mechanisms which are responsible for the annihilation in the atomic gases and in molecules of increasing complexity. To date, there has been no satisfactory explanation for such dramatic changes in molecular gases, beyond speculating on the formation of positron-molecule complexes with the existence of bound states depending on the molecular vibrational structure and with the occurrence of resonant mechanisms to enhance annihilation efficiency [27]. Such interesting conjecture has indeed made a number of predictions which are in qualitative agreement with the experiments and has therefore triggered both a flurry of more rigorous theoretical treatments and the gathering of additional experimental data. Both aspects of the problem are very hard to study: the experiments on the molecular gases require resolving the vibrational energy loss spectra for several modes of the molecule and to measure at those energy values the behaviour of the annihilation rates [28]. The theoretical models, on the other hand, need to treat as realistically as possible the dynamical couplings which take place between the impinging positron and the molecular vibrational modes during the annihilation process [29] and to do so for the large polyatomic species of the data in fig. 3. However, the puzzle constitutes a very interesting test of our understanding of molecular processes at the nanoscopic level and extends the use of our computational tools into the area of antimatter-matter processes.



▲ **Fig. 3:** Experimental values of Z_{eff}/Z plotted against Z, illustrating the fact that this quantity varies by orders of magnitude for modest changes in chemical species: (●) noble gases, (▽) simple molecules, (○) alkanes, (△) perfluorinated alkanes, (□) perchlorinated alkanes, (◇) perbrominated and periodated alkanes, (■) alkenes, (▲) oxygen-containing hydrocarbons, (○) ring hydrocarbons, (▼) substituted benzenes, and (◆) large organic molecules (adapted from ref. [26]).

In conclusion, what I have tried to outline above should prove to the reader that the field of positron and positronium research is undergoing a remarkable revival: while the use of positrons in chemistry and physics, especially in the applied areas related to the above subjects like, for example, polymer studies, material analysis and surface studies, has been in existence for decades, it is fair to say that the use of low-energy positron sources under high-resolution conditions is a much less mature field. The results gathered thus far are certainly promising and the response of the theoretical community has also been very encouraging in the sense that new quantum formulations and new computational models are being set up and refined to answer the experimental challenges both of the present and of the future observations. It is also not too far-fetched to expect that we could become capable of harnessing the annihilation photon energy produced by positron-matter interaction and put it to good use in many areas of our daily life. Such developments do point to the fact that antimatter will indeed matter a great deal for the science of the 21st century.

Acknowledgements

The authors acknowledges the numerous fruitful and illuminating discussions on the subject of positron/Ps physics with molecular systems that have taken place over the years with several colleagues: T. Nishimura, T. Mukherjee, A. Occhigrossi, R.R. Lucchese, R. Curik, C.M. Surko, D.M. Schrader, A.S. Gosh, G. Gribakin, M.A.P. Lima, M. Kimura and I. Shimamura.

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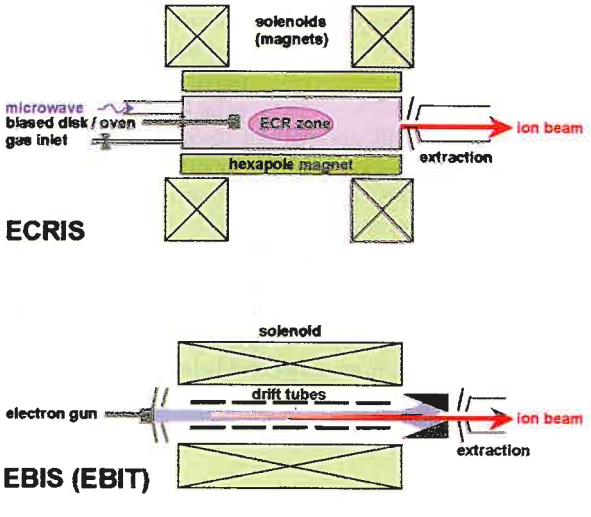


▲ **Fig. 1:** Sources for producing slow multiply charged ion beams. (top): ECRIS (electron cyclotron resonance ion source). Microwave radiation (2.45–28 GHz) fed into a magnetical plasma trap causes resonant heating of the plasma electrons while the also confined ions remain comparably cold. Fairly high ion charge states can be produced via step-by-step ionization, and relatively large ion currents may be extracted. (bottom): EBIS (electron beam ion source). Ions are confined in the space charge potential of a magnetically compressed electron beam (energy from keV up to 100 keV). Step-by-step ionization proceeds until the axial electric field barrier on the right hand side is lowered for ion extraction. In pulsed operation, up to fully stripped ions of any species can be produced but extractable ion currents are lower than for ECRIS. A closely related version (EBIT – electron beam ion trap) has been developed for studying highly charged ion spectra but can also be modified for MCI extraction.

Slow multicharged ions hitting a solid surface: From hollow atoms to novel applications

Hannspeter Winter and Friedrich Aumayr
Institut für Allgemeine Physik, TU Wien, A-1040 Vienna, Austria

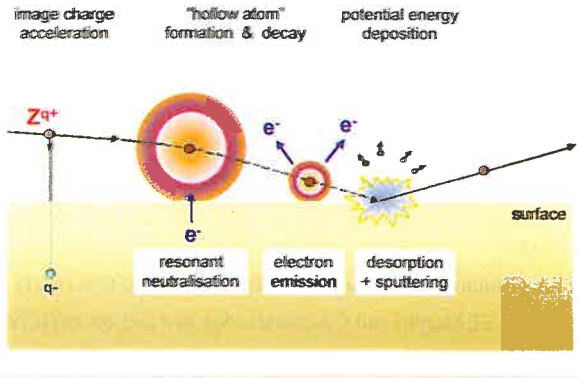
features

Impact of slow heavy particles (atoms, molecules, ions; impact velocity ≤ 1 a.u. = 25 keV/amu) on solid surfaces is of genuine interest in plasma- and surface physics and related applications (plasma technology, gaseous electronics, micro-electronics, surface analytics and -spectroscopy). Nature and intensity of the resulting interactions depend both on the kinetic and the potential energy which is carried by the projectile toward the surface. This can result in, e.g., sputtering, electron- and secondary ion emission, and elastic and inelastic projectile scattering (for details see [1, 2]).

In the last two decades a new branch of particle-surface interaction has evolved, comprising the surface-impact of slow multicharged ions (MCI) [3]. This branch was strongly promoted by the successful development of efficient, affordable MCI sources (cf. figs. 1a, b).

Basic processes

Fig. 2 illustrates various phenomena, which occur during the approach of a slow MCI in initial charge state q towards a clean metal surface with work function W. A classical over-the-barrier model developed by J. Burgdörfer [4] predicts for $q \gg 1$ first quasi-resonant electronic transitions from the surface to arise at a



▲ **Fig. 2:** MCI – surface interaction scenario (cf. text)

"critical distance" $d_c \approx (2q)^{1/2}/W$ into excited projectile states with hydrogenic principal quantum numbers $n_c \approx q^{3/4}/W^{1/2}$ (atomic units). E.g., for fully stripped argon (Z = q = 18; Z: projectile nuclear charge) on Al(111) (W = 0.16 au) the classical over-the-barrier model predicts $d_c \approx 2$ nm and $n_c \approx 22$.

The particle becomes rapidly neutralized and eventually a so-called "hollow atom" is formed. This hollow atom, an exotic creation during atomic collisions, is a short-lived multiply excited neutral atom which carries the larger part of its Z electrons in high-n levels while some inner shells remain transiently empty. This extreme population inversion can last for typically hundred femtoseconds during the approach of a slow MCI toward the surface.

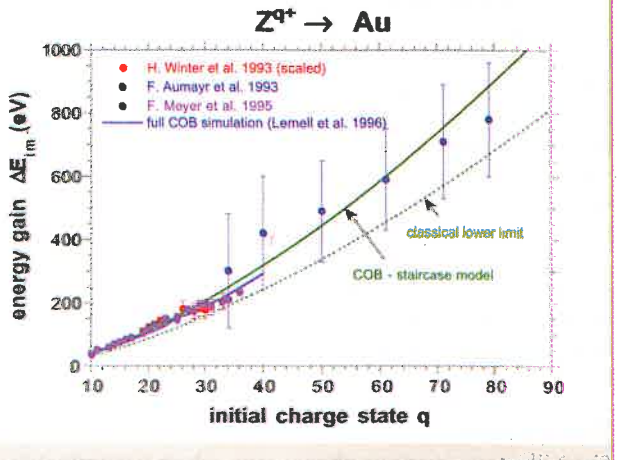
Despite its short lifetime the formation and decay of hollow atoms may be conveniently studied through their ejected electrons and characteristic soft X-rays (see below), and the trajectories, energy loss and final charge state distribution of surface-scattered projectiles [3]. Hollow atoms decay primarily via autoionisation by ejection of slow (≤ 10 eV) electrons. Subsequent re-neutralisation and electron emission continues until the hollow atom collapses upon close surface contact. Until its first full neutralisation the projectile will be accelerated toward the surface by its rapidly decreasing mirror charge, which provides an additional "vertical kinetic energy" $\Delta E_{q,im} \approx 1/4.q^{3/2}.W$ [3, 4]. For our above example, $\Delta E_{q,im}$ amounts to more than 80 eV.

This image charge acceleration could be experimentally demonstrated in different ways (cf. fig. 3), in excellent agreement with classical over-the-barrier model predictions. On the one hand, the slow electron emission proceeds until close surface impact and the corresponding electron yield increases with decreasing perpendicular impact energy, for which $DE_{q,im}$ is setting the lower limit [6]. On the other hand, for grazing incident MCI on a very flat (monocrystalline) target surface the outgoing trajectory of the neutralized projectile becomes steeper than its incoming one due to image charge acceleration which acts until the close surface contact and subsequent specular reflection [7].

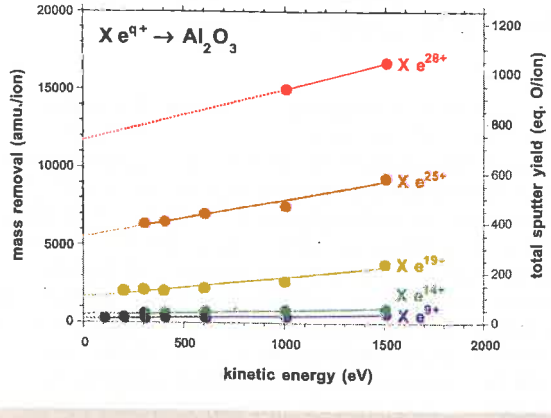
Above-surface electron emission and projectile image charge acceleration have also been observed for insulator surfaces and can be explained by the classical over-the-barrier model in a similar way as for metals, if the different electronic structure and time-dependent response of the target surface is properly taken into account.

> Applications have been envisioned for a broad spectrum ranging from information storage... to biotechnology.

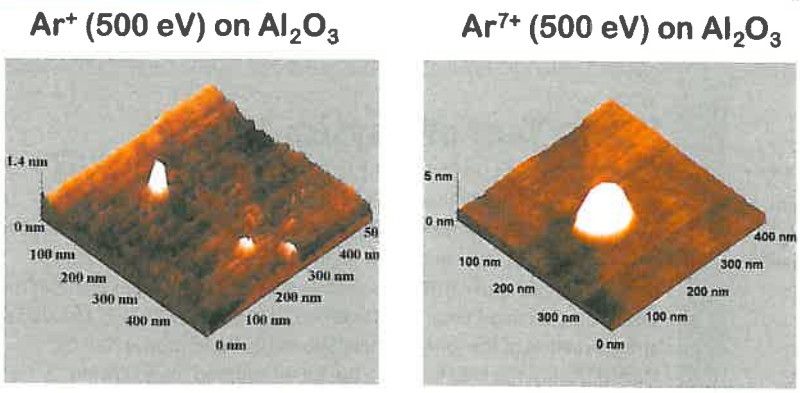
Fig. 2 indicates that upon and after close surface contact a considerable excitation energy remains stored in the hollow atom which can give rise to further electron emission at and below the surface. In particular, fast Auger electrons can result from filling of projectile inner shells, alternatively to emission of projectile-characteristic soft X-rays [3]. On the other hand, the rapid electron capture by a MCI during its approach to and contact with the surface causes a strong excitation of the latter, which in case of metal- and semiconductor targets can be effectively dissipated among the target quasi-free electron gas, but for an insulator surface may cause desorption of target constituents ("potential sputtering – PS", see below). With grazing incident MCI on flat surfaces contributions from above and below the surface can be



▲ **Fig. 3:** Test for MCI neutralization scenario: Comparison of measured image-charge energy gains (symbols) with predictions from the classical over-the-barrier model, for impact of MCI on clean gold surfaces [5].



▲ **Fig. 4:** Absolute mass (in atomic mass units) and number of oxygen atoms sputtered per primary ion vs. impact energy, for bombardment of clean polycrystalline Al_2O_3 by slow Xe^{q+} ions [12].



◀ Fig. 5: Al_2O_3 (0001) single crystal surface bombarded with 500 eV Ar^+ (left) and Ar^{7+} ions (right) as seen in UHV AFM contact mode. The observed defect size (both height and lateral dimension) increases with projectile charge state (from [13]).

separated [8]. Moreover, such a collision geometry is useful for elucidation of effects caused by the kinetic projectile energy [9].

Potential sputtering and its possible applications

To what extent the electronic relaxation of hollow atoms takes place above or below the surface is closely related to the way how this hollow atom dissipates its large potential energy. Emission of electrons and X-ray photons carries away only a fraction of the total potential energy originally stored in the MCI. The remaining part will be dumped into the solid and cause electronic excitation of a very small surface region. For metal surfaces even rather sudden perturbations of the electronic structure can be accommodated by the excitation energy being rapidly dissipated in the target material without inducing any structural modification. However, in recent studies on slow MCI impact on certain insulator surfaces a quite dramatic increase of the yields for total sputtering and secondary ion emission with increasing q has been observed (c.f. fig. 4).

> ... potential sputtering by MCI promises a much more gentle nanostructuring tool

This effect has been termed potential sputtering [10, 11], as compared to the more conventional kinetic sputtering by momentum transfer between impinging ion and recoiling target atoms in a collision cascade.

The possibility of exploiting the huge amount of potential energy stored in MCI for nano-fabrication, e.g. "writing" on a surface, has for some time captured the imagination of researchers. Applications have been envisioned for a broad spectrum ranging from information storage via materials processing to biotechnology.

While nanostructures produced by kinetic sputtering with and implantation of *fast* ions are subject to unwanted radiation damage, potential sputtering (PS) by MCI promises a much more gentle nanostructuring tool since,

a. their kinetic energy is small, so they only interact with the first few surface layers without penetrating into the target bulk;
b. they interact with the surface mainly through their potential energy, which can be tuned by varying the ion charge;
c. the potential energy causes primarily electronic excitation which leads to bond breaking and lattice defect production via electron-phonon coupling rather than violent momentum transfer in kinetic collision cascades;
d. the interaction of slow MCI with surfaces is highly material-selective, i.e. large differences between (semi-) conducting and insulating target materials are observed.

Beams of slow multicharged ions have so far been used to produce nanometer sized surface modifications [11, 13] on various substrates (fig. 5) as well as to form ultra-thin silicon oxyd layers or SiO_2 nanodots on Si surfaces [14].

Such nano-defects can be more conveniently studied by using (non-contact) atomic force- and scanning tunneling microscopy. They have already shown unusual excitonic features in their photoluminescence spectra [15].

The field of MCI–surface interaction has started out as a playground for exotic albeit fundamental atomic phenomena. First promising applications of multicharged ions are now emerging which make use of the unique opportunities provided by slow MCIs for engineering the topmost layers of insulating surfaces.

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features

noticeboard

ECAMP 8

The eighth European Conference on Atomic and Molecular Physics (ECAMP 8) will be held in Rennes, France, July 6-10 2004. Rennes is the capital of Brittany situated 350 km west of Paris.

The conference topics include atomic and molecular spectroscopy, interactions and collisions between ions, atoms, molecules, electrons, positrons and photons and other related areas of atomic and molecular physics.

The programme consists of plenary sessions and reviews, progress and "hot topic" talks. Contributed papers represent an important aspect of the conference. They will be presented in oral and poster sessions.
Other meetings, such as EGAS, and symposia on special topics, such as Cold Atoms, Life Sciences, Astrophysics/astrochemistry will also be organized in conjunction with this conference.

Further details will be available on the conference web site: www.ecamp8.org

World Year of Physics 2005

The EPS, IUPAP, the IOP, the DPG and the APS are taking the lead in coordinating activities for the 2005 World Year of Physics. Contact has been made with UNESCO for broad based international support, and the declaration by the UN of 2005 as a UN endorsed International Year is in the works. The Steering Committee for WYP2005 met in Berlin (9-11 Oct. 2002) at the occasion of the IUPAP General Assembly. Upon proposition by Martial Ducloy, the EPS President, the IUPAP adopted the following resolution:

Whereas Physics has been the basis of a developing understanding of the physical world and nature as a whole,
Whereas Physics and its application are the basis of much of today's technology,
Whereas an education in Physics is essential for the nations of the developing world to develop their scientific infrastructure, and
Whereas the year 2005 marks the 100th anniversary of a series of great scientific advances of Albert Einstein.

Therefore, at the suggestion of the European Physical Society, the International Union of Pure and Applied Physics declares that 2005 should be the World Year of Physics and will seek support from appropriate national and international organisations.

Election NPD

The Board of the EPS Nuclear Physics Division is organising elections to replace outgoing members. Four vacancies are announced herewith. Nominations must contain a short c.v. and a statement from the candidate, and should be addressed to M. Lazar, Nador Utca 7, H 1051 Budapest, Hungary. The deadline for receipt of nominations is: 28 February 2003. The resulting list of candidates and ballot papers will be mailed to EPS NPD Members who will be invited to vote, if necessary by the deadline of 30 March 2003. Newly elected Members of the Board of the will be notified of the result of the election in writing by the end of April 2003. The Board would like to take this opportunity to thank the following outgoing members for their hard work over the past 6 years: S. Aberg, R. Kalpakchieva, C.C. Petitjean, A. Zenoni

Science TV Drama Festival

An exciting event was organised at the Piccolo Theater in Milan (5-6 October 2002), the first Science TV Drama Festival. Sponsored by many European Organisations, including the EPS, the ESF, and EuroPAWS, the STV Drama Festival presented 10 made for TV programmes screened over the years 1950 to 1999. Famous scientists such as B. Pascal, M. Curie and R. Oppenheimer came to life thanks to great actors, writers and directors. An awards ceremony for two most outstanding presentations will be held in London on 25 November 2002.

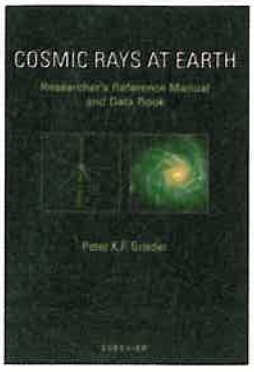
STM Conference

The 12th International Conference on Scanning Tunneling Microscopy/ Spectroscopy and Related Techniques (STM'03) will be held from July 21 to July 25, 2003 in Eindhoven, The Netherlands. For more information, see http://stm03.tue.nl.

Framework Programme 6

The Commission announced at the Framework Programme 6 launch conference that the first calls for financing of projects under the new Framework Programme will be published on 17 December at: www.cordis.lu/fp6/ .

BOOK REVIEWS



Cosmic Rays at Earth

Researcher's Reference Manual and Data Book

Peter K.F. Grieder
Elsevier, 2001
xx + 1093 pages

Perusing the history of astronomy and astrophysics, it is hard to avoid being fascinated by the great formative role played by the phenomenon of cosmic rays. Today, when we celebrate 90 years since the remarkable discovery of Victor Hess, we can look behind and see dozens of examples of phenomena related in one way or another to the ionising radiation infalling on Earth from outer space: from the Solar phenomena like sunspots and flares to supernovae to quasars, γ-ray bursts and other exotic extragalactic sources. Present day's important technologies, like the satellite communications, depend critically on our understanding of cosmic ray properties. In the nascent discipline of astrobiology, cosmic rays are tightly related to the question of existence and survival properties of life elsewhere in the universe. A book like this is, therefore, needed by scientists of very diverse interests.

And it performs its task splendidly enough. Several decades of the research experience of the author enabled him to give a wonderfully precise and detailed cross-section of almost all aspects of the modern cosmic ray physics. The book is written primarily as a reference manual, containing hundreds of plots and tables (well graphically produced), dealing with measured properties of various cosmic ray constituent particles (including neutrinos). In addition, there is a lot of background material, usually given at the beginning of each chapter, but often flowing smoothly parallel to the experimental and observational data. Thus, although explicitly avoiding conventional textbook approach, the book will be of interest to experts in many different areas, and to a large segment of physics and astronomy students.

The data presented cover cosmic radiation in immediate vicinity of Earth, in Earth's atmosphere, at sea level and underground. After the introductory Chapter, giving necessary definitions and basic properties of cosmic radiation, Chapter 2 deals with cosmic rays in the atmosphere. It is a good example of the methodical approach of the author, since it covers in separate sections charged hadrons, neutrons, γ-rays, both kinds of electrons, muons, heavy nuclei and their antimatter counterparts. The same taxonomy, with addition of neutrinos, is employed in Chapters 3 through 5, dealing with the sea level and underground radiation, as well as the primary cosmic ray spectrum. Chapter 6 deals with the heliospheric phenomena, but it includes a compact, but precise, summary of the solar neutrino problem with results of all major experiments to date (additionally interesting these days, one dare say, for the awarding of the 2002 Nobel prize in physics to Raymond Davies and Masatoshi Koshiba). Last Chapter (7) presents several miscellaneous topics (cosmogenic nuclides, galactic and intergalactic magnetic fields, etc.), and there is a wealth of data given in the appendices, like the list of all present cosmic rays experiments all over the world, and the like. Particular value of the manual lies in its extensive and detailed bibliography (organised on the levels of individual sections within each Chapter, thus enabling easier perusing). It enables rapid access to the wealth of original sources of the data presented, as well as to the more specific and expert literature in each subfield of the cosmic ray physics. The volume itself is robustly made, as well as aesthetically pleasing.

An *inevitable* weaknesses of a volume like this (apart from the normal fate of such compendia to be made obsolete after some time by novel experimental and theoretical data) lies in the choice of miscellaneous topics. As the author correctly admits, "a book like this can never be complete". Still, one cannot help missing several "hot" astrophysical topics important for one or more aspects of the cosmic ray physics, most notably γ-ray bursts (and their possible astrobiological implications), but also the searches for cold dark matter particles and anisotropies in the cosmic ray flux. All in all, "Cosmic Rays at Earth" is a very welcome contribution to the field, which should find place on the shelf of every serious student of high-energy physics, astrophysics and space science.

Milan M. Ćirković
Astronomical Observatory of Belgrade, Belgrade, Serbia

Books for review

Bad Astronomy
P. Plait, *Jon Wiley & Sons, Inc.*, 2002

Biophysics: An Introduction
R. Cotterill, *Jon Wiley & Sons, Inc.*, 2002

Computational Physics (Fortran version)
S. E. Koonin, D. C. Meredith, *Westview Press*, 2002

Design of High Frequency Integrated Analogue Filters
Y. Sun, *The Institution of Electrical Engineers (IEE)*, 2002

Evaluating the Measurement Uncertainty
I. Lira, *IoPP*, 2002

From Semiconductors to Proteins
S. J. L. Billinge & M. F. Thorpe, *Kluwer Academic/Plenum Publ.*, 2002

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Informataion and Measurement (Second Edition)
J.C.G. Lesurf, *IoPP*, 2002

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February 21, 2003

Instructions on how to prepare and submit proposals can be found on our web-site.

http://www.maxlab.lu.se

Proposals are selected on the basis of scientific merit by an independent peer review panel. Successful applicants will be allocated facility access free of charge, including logistical, technical and scientific support.
Travel and subsistence expenses for eligible users will be reimbursed. Information on the eligibility of research teams is found on
http://www.cordis.lu/improving/infrastructure/ari_eligi.htm

General description of the laboratory

The laboratory operates two storage rings for electrons, MAX I (550 MeV) and MAX II (1.5 GeV), which provide synchrotron radiation from the infrared spectral region to the x-ray (1Å) region. Research is carried out in physics, chemistry, biology, materials science and technology. Beamlines and experimental stations are available for experiments utilising various electron and photon spectroscopies, x-ray diffraction and lithography. More detailed information about the laboratory and the available experimental facilities are found at our web-site http://www.maxlab.lu.se

Address:
MAX-lab, Lund University
P.O. Box 118
SE-221 00 Lund
SWEDEN.
Fax +46-(0)46-222 47 10
http://www.maxlab.lu.se
Contact person:
Prof. Ralf Nyholm,
tel. +46-(0)46-222 44 52
e-mail ralf.nyholm@maxlab.lu.se
EU-Contract Manager:
Prof. Nils Mårtensson,
tel. +46-(0)46-222 96 95
e-mail: nils.martensson@maxlab.lu.se

AARHUS UNIVERSITET

Two Post-doctoral Positions

DEPARTMENT OF PHYSICS AND ASTRONOMY

Two Post-doctoral Positions in Condensed Matter Theory: Electronic Structure of f-electron Materials or Optical Properties of Solids.
Applications are invited for two post-doctoral positions funded by the European Research Training Networks, **Psi-k f-electron:** 'Ab-initio Computation of Electronic Properties of f-electron Materials' and EXCITING: 'First-Principles Approach to the Calculation of Optical Properties of Solids', respectively.

The positions are available for a period of 2 years starting first half of 2003. Extension is possible.

The applicants must comply with the RTN rules for network employment of young scientists: The applicants should hold a Ph.D. degree or equivalent in Physics or Chemistry, be aged 35 or younger, and should have some experience in computational Condensed Matter Theory. They must be of European Union nationality, or from one of the Associated Nations, or have resided in an EU country for the last five years or longer. Danish citizens are excluded, however.

The successful applicants shall participate in either of the above network projects. This implies applications of present computer codes to solid systems of high current interest as well as development of improved computer codes. The projects are collaborations in international teams and some travel activity between the research centers involved must be foreseen. More de tailed information concerning the project can be obtained upon request.

Salery as agreed between the Danish Ministry of Finance and the Confederation of Professional Unions.

Before applying for this position please read the full job description at http:// www.nat.au.dk/stilling
The job description is also obtainable from the Department of Physics and Astronomy, Phone no. (+45) 8942 3706.
Deadline: **December 16th, 2002, at 12,00 noon.** Please number the application: 212/5-27.

Laurentian University / Université Laurentienne

Postdoctoral Research Positions at Sudbury Neutrino Observatory

Laurentian University has immediate needs for two postdoctoral Research Associates to support SNO research efforts. The SNO detector studies fundamental properties of neutrinos from the Sun, the atmosphere, and supernovae. The recent first results from SNO have provided strong evidence of solar neutrino oscillation, a solution to the longstanding Solar Neutrino Problem.

Laurentian University's commitments to SNO include research into low energy background analysis and removal; the development of SNO's supernova trigger and participation in the Supernova Early Warning System (SNEWS); solar neutrino data analysis and near-line data processing. The Research Associates would take leading roles in one or more of these areas. The recently funded expansion of SNO into an International Facility for Underground Science will create other interesting opportunities for the Research Associates.

Candidates must have a PhD in experimental particle physics, nuclear physics or radiochemistry. For the low background work, experience with particle detectors and low rate counting is required, with radiochemistry experience an asset. For the other areas, experience with particle physics data analysis is required, with strong programming skills an asset.

Review of applications will begin no later than November 30th, 2002, until the positions are filled. Email Dr J. Farine (farine@surf.sno.laurentian.ca) or Dr C.J. Virtue (cjv@nu.phys.laurentian.ca), or see the SNO web site at www.sno.phy.queensu.ca for further information.

LIP

Laboratory for Instrumentation and Experimental Particle Physics

Applications are invited for a post-doctoral position at LIP-Lisbon (www.lip.pt). The position is funded by the European Research Training Network 'Physics Reconstruction and Selection at the Large Hadron Collider' (http://cern.ch/sphicas/PRSATLHC/). The main purpose of the proposed network is to study, design and implement the physics event selection of the CMS experiment in the LHC environment.

The position will be given for 2 to 3 years with a highly competitive salary determined according to qualification.

Qualifications required include a PhD or equivalent in High Energy Physics, and a clear demonstration of the ability to carry out a research program. Knowledge of modern programming techniques, Object-Oriented software and C++ will be an asset.

Applicants must satisfy the following eligibility criteria:

- Aged 35 or less at the time of their appointment to the network.
- Nationals of an EU Member State or Associated State or have resided in an EU Member State for at least five years immediately prior to their appointment in a network.
- International Mobility - they must not be Portuguese and must not have carried out their normal activities in Portugal for more than 12 of the 24 months prior to their appointment.

The position will remain open until suitable candidates are found.

Applications, including CV and reference letters, should be sent to:

Laboratory for Instrumentation and Experimental Particle Physics
Research Training Network-PRSATLHC
Av.Elias Garcia, nº 14 –1º , 1000-149 LISBON, PORTUGAL

EC-Human Potential Programme (HPP)
Transnational Access to Major Research Infrastructures
EU Contract No HPRI-CT-2001-00122

ISA

CALL FOR PROPOSALS

for the time period March 2003 to February 2004.

Researchers in the European Union and associated states are offered access to the research facilities at the Institute for Storage Ring Facilities (ISA) through the Human Potential Programme of the European Commission. Access is offered to the following installations:

The storage ring ASTRID operating with ions

The storage ring ELISA operating with ions

The synchrotron-radiation beamlines at ASTRID (2-1000 eV)

The extracted 580-MeV electron beam from ASTRID

For a detailed description of the facilities, please visit our web site.

Project proposals are evaluated on the basis of scientific merit by an independent panel.

Approved projects will receive access and support free of charge. Travel expenses and subsistence for eligible users will be reimbursed.

Application forms can be obtained from ISA at the address below, or from our web site. Forms must reach ISA no later than December 20, 2002.

For further information, please contact:

ISA, Aarhus University,
DK-8000 Aarhus C, Denmark.
Tel.: +45 8942 3778 Fax: +45 8612 0740
Email: fyssp@phys.au.dk
Web site: http://www.isa.au.dk

EU-Contract Manager: Søren Pape Møller

POSTDOCTORAL VACANCIES
European Research Training Network
COLD MOLECULES

Since September 1st 2002, a Research Training Network entitled

Cold Molecules: Formation, Trapping, and Dynamics

is funded by the European Commission (contract HPRN-CT-2002-00290).

The aim of the network is to take a major step forward in the emerging field of cold molecules. Experimental techniques (e.g. photoassociation of laser-cooled atoms, Stark deceleration and buffer gas cooling) are developed, first to create dense samples of various molecules at temperatures below milliKelvin, then to store and to detect them. Such samples will be used for high-precision measurements, making a molecular BEC and coherent control experiments. New theoretical tools are designed for interpretation.

The network is organizing an efficient and creative collaboration between leading experimental and theoretical groups from France (Orsay), the Netherlands (Utrecht), Germany (Hannover, Heidelberg, Düsseldorf, Konstanz), Italy (Pisa, Roma), Israel (Jerusalem), Austria (Innsbruck, Graz), United Kingdom (Brighton), associated with one group from Croatia (Zagreb), and one from the US (Storrs, CT).

Details on postdoctoral and PhD vacancies are posted on the network website:

http://www.lac.u-psud.fr/coldmolecules/network

together with links to the websites of the members, and on the vacancy searchtool of the CORDIS website :

http://www.cordis.lu/improving/networks/home.htm

LIMANS III: European Cluster of Large Scale Laser Installations

CUSBO
Centre for Ultrafast Science and Biomedical Optics
Milano, Italy

LCVU
Laser Centre Vrije Universiteit
Amsterdam, Netherlands

LENS
European Laboratory for Non-Linear Spectroscopy
Firenze, Italy

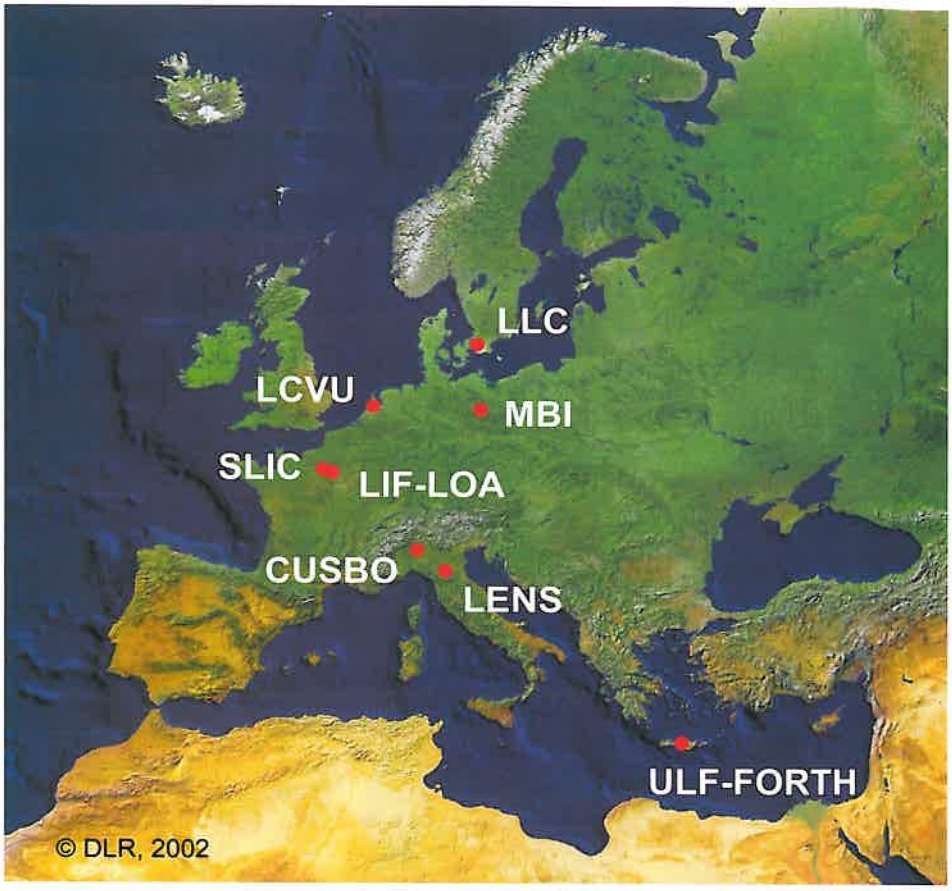
LIF-LOA
Laboratoire d'Optique Appliquée
Ecole Polytechnique
Palaiseau, France

LLC
Lund Laser Centre
Lund University
Lund, Sweden

MBI
Max-Born-Institut
for Nonlinear Optics and Short Pulse Spectroscopy
Berlin, Germany

SLIC
Saclay Laser-Matter Interaction Center
Saclay, France

ULF-FORTH
Ultraviolet Laser Facility
Foundation for Research and Technology - Hellas
Heraklion, Crete, Greece



Call for proposals

The LIMANS III institutions are funded under the current IHP Programme of the European Union to provide access to researchers or research teams of Member States and Associated States. Within the cluster they offer state-of-the-art scientific laser equipment and research environments with a wide range of research opportunities, allowing for today's most advanced light-matter interaction experiments in broad regimes of power, wavelengths, or pulse durations. Access is provided free of charge; travel and living expenses are covered by the host institution.

Interested researchers are invited to contact the LIMANS III website at **http://limans3.mbi-berlin.de**, from where they find all relevant information about the participating facilities and local contact points. Access is granted on the basis of proposals, which will be reviewed by an external panel of referees. Details about the submission procedure may be found on the LIMANS III website. Applicants are encouraged to contact any of the facilities directly to obtain additional information and assistance in preparing a proposal. Proposals are accepted at any time and from any eligible researcher or research team.

23-27 March Heriot-Watt University

The **Physics** Congress 2003

Physics at the heart of Congress

The Institute of Physics' landmark event for physicists world-wide

23-27 March

The Edinburgh Conference Centre, Heriot-Watt University, Edinburgh, UK

Congress provides a combination of scientific conferences, exhibitions, meetings on science policy, activities and social events for all ages and interests making it a unique opportunity for physicists to meet, discuss and collaborate. Conference fees, including special packages for some conferences and concessions for students can be found at congress.iop.org or in the registration pack.

Conferences

Electrostatics, Single Bio-molecule Interactions, Optics in Biosciences and Life Sciences, Preservation and Conservation Issues Related to Digital Printing and Photography, Dielectrics for Emerging Technologies, Waste Management, Industry Day- Physics and the Modern Economy, Structured Optical Materials, ITECC 2003, Worried about Nothing-Measurements and Safety in Vacuum Practice, and Novel Light Sources and Displays.

Industry Exhibition

An exhibition of physics-based industry and enterprise, focusing on Scottish business and including workshop sessions.

Plenary lectures

All participants are invited to plenary lectures addressing today's issues in physics and science policy. Speakers include Professor Tom Jones (University of Rochester, USA), Mr Tam Dalyell MP (Father of the House and MP for Linlithgow, Scotland) and Professor David Wallace (Institute President and Vice-Chancellor, Loughborough University).

Scottish Science Policy Meeting

Discuss policy issues affecting physics in Scotland. Talks will focus on the newly established Scottish Science Advisory Committee (SSAC) and the role of the Scottish Executive and the Scottish Higher Education Funding Council (SHEFC) in supporting physics higher education and research.

Activities for Physics Students and Recent Graduates

A social programme and opportunities for networking. Activities will be open to all Congress participants, but aimed towards students and young professionals.

Schools Programme for staff and pupils

Workshops for school staff will run alongside activities for pupils including an interactive hands-on programme, "Science in a Suitcase," Astrodomes, demonstrations and information about careers in science.

Public Programme

A Family Fun Day will include activities for toddlers and upwards with a programme of talks, theatre, demonstrations and hands-on activities.

The Institute of Physics, 76 Portland Place, London W1B 1NT
Tel: +44 (0)20 7470 4800 Fax: +44 (0)20 7470 4900 Email: congress@iop.org
Website: congress.iop.org