## 1993 EGAS

# Lasers and Highly Charged Ions Feature

While most of the contributions made at the 25th annual meeting of the European Group for Atomic Spectroscopy (EGAS) held in Caen on 13-16 July 1993 dealing with the theory of atomic spectra, term analysis, isotope shifts, hyperfine structures, and so on may appear as routine work, many were very interesting from the conceptual point of view... and also from the applied one. In his invited talk, N. Grevesse (Liège) emphasized the astrophysicists' urgent need for all data in all these areas in order to perform a thorough analysis of the spectra of the Sun and other stars, and to better understand their internal physical condition and relative abundances of elements.

Perhaps owing to the proximity of GANIL (a heavy ion accelerator in Caen), there was considerable interest in the atomic physics of highly charged ions. A large number of contributed papers dealt with this topic, including two invited talks. P.H. Mokler (GSI, Darmstadt) spoke about x-ray transitions in hydrogen- and helium-like very heavy ions, such as $U^{91+}$ and $U^{90+}$ (see insert) while N. Stolterfoht (Caen and Berlin) reviewed high-resolution spectroscopy of Auger electrons produced in collisions of multicharged ions with atoms. He gave special attention to the often underestimated role of dielectronic Coulomb processes.

The conference was also interested in the technical progress which allows spectroscopists to perform experiments that would hardly have been dreamt of a few years ago, and two invited papers belonged to this category. L.A. Shmaenok (St. Petersburg) reported on progress in multilayer-based high reflectivity mirrors for the soft x-ray domain. He discussed, in particular, the interesting properties of the association of such a reflecting multilayer with a traditional optical element of high spectral selectivity. G. Tino (Naples) showed how the tremendous progress in semiconductor diode lasers and their use in an extended cavity configuration allow them to be used more and more widely in atomic and molecular spectroscopy.

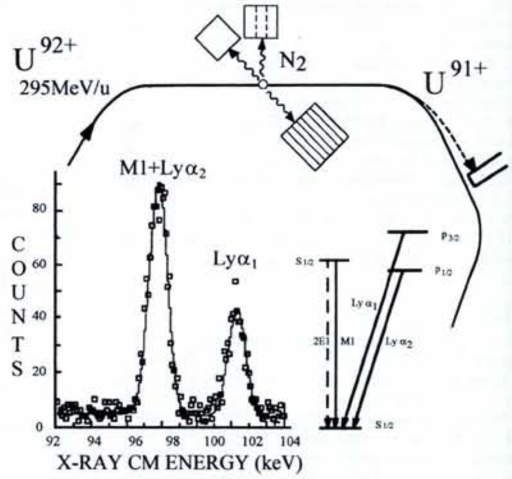
The six remaining invited lectures as well as many contributed papers dealt with the various very fascinating domains which would have remained either completely excluded, or at least very difficult to explore, without the recent progress in laser-based techniques. A. Brillet (Orsay) described the Italo-French VIRGO interferometer which will be built to detect gravitational waves. Apart from the conceptual interest of testing an important prediction of general relativity, the audience was much impressed by the tremendous technical challenge (one must detect relative variations of length of the order of $10^{-21}$) and, of course, it was greatly interested by the laser aspects of the project. P. Camus (Orsay) showed how one can fabricate fairly exotic atoms using suitable laser excitations. For example, double Rydberg alkaline-earth atoms may be created with their two excited electrons orbiting at markedly different distances from the core. This allows observation of interesting correlation effects between the two electrons.

G. Rempe (Constance) spoke on cavity quantum electrodynamics and how the radiative properties of an atom inside a optical cavity with a high finesse differ radically from those of the same atom in free space. P. Grangier (Orsay) reviewed quantum non-demolition (QND) measurements in optics: the aim is to make a quantum measurement without adding noise to the quantity under study. The trick is to get rid of the unavoidable excess quantum noise due to the measurement by feeding it entirely into a complementary observable. Two successful experimental demonstrations have shown this attractive scheme to be possible in practice. The conference was also very interested in experiments with laser-cooled atoms or ions, sometimes free, often trapped. Atom temperatures of the order of tens of μK allow many exciting and new experiments which were the subject of a number of contributed papers (see, for example, the insert by W.

### HYDROGEN-LIKE URANIUM

## Ground-State Transitions Validate High-Order QED Corrections

*The x-ray spectrum (at the centre of mass) for L to K transitions (mainly the Lyman-α transitions but including the $M_1$ transition) for H-like $U^{91+}$ ions: the measured transition energies correspond to a Lamb shift of 429 ± 63 eV. The upper part illustrates the experimental arrangement at the ESR, where the $U^{92+}$ coasting beam interacts with the internal gas target and emitted x-rays are detected in coincidence with down-charged H-like $U^{91+}$ ions.*




The heavy-ion synchrotron (SIS) and electron storage ring (ESR) facility at GSI, Darmstadt, provides intense beams of cooled, highly charged heavy ions up to bare uranium $U^{92+}$. Excited atomic states are populated by electron capture during ion-atom collisions in the ESR's gas-jet target, or by recombination processes in the ESR's "electron cooler".

The various reaction mechanisms - in particular, radiative electron capture (REC), radiative and dielectronic recombination (RR and DR) — as well as the detailed atomic structure of very heavy, one- to four-electron ions (H-, He-, Li-, Be-sequences) are investigated, mainly in order to determine the influence of relativistics and quantum electrodynamics (QED) at very high central potentials. Ground-state transitions in hydrogen-like heavy ions — the simplest systems — give the most direct access to these effects. Using high-precision spectroscopy of the transition energies, the ground-state Lamb shift (the difference between the correct relativistic Dirac-Coulomb energy and the real one) can be determined at high atomic number *Z*.

As an example, the figure shows the spectral region for L to K transitions — mainly the Lyman-α transitions including the $M_1$ transition which at this high atomic number is already prompt — for H-like $U^{91+}$ ions, together with the experimental arrangement at the ESR. A cooled beam of 295 Me*V/u* bare U ions ($U^{92+}$) interacts with the $N_2$ molecules of the gas jet. The prompt x-rays emitted from the target region are measured in coincidence with the down-charged hydrogen-like ions ($U^{91+}$) which are monitored using a particle detector after magnetic separation from the coasting $U^{92+}$. The emitted x-rays are detected by segmented intrinsic Ge detectors allowing an almost event-by-event Doppler correction of the photons to give the corresponding centre-of-mass (CM) spectrum shown in the figure [Stöhlker Th. *et al., Phys. Rev. Lett.* **71** (1993) 2184]. A ground-state Lamb shift of 429 ± 63 eV is deduced from the measured transition energies (around 100 keV in the CM system), a value which agrees nicely with the theoretically predicted 458 eV. The dominant term originates from the self-energy contribution (60%) where most of the corrections are due to higher order-terms which cannot be measured for low-*Z* species.

The present accuracy of about 10% for the Lamb shift will certainly be improved by applying additional x-ray dispersive detection techniques. On the other hand, using dielectronic recombination resonances for spectroscopy, the structure in more electron systems (Li/Be-like sequences) have already been probed at the ESR on a sub-eV level for the L-shell structure of very heavy ions up to U. Moreover, the hyperfine ground-state splitting in H-like $^{209}Bi^{82+}$ has been measured using laser-assisted resonance fluorescence spectroscopy to access even higher-order QED terms.

**P.H. Mokler**, GSI, Darmstadt

## LASER TRAPPED Mg ATOMS

# Optical Ramsey Interferences Demonstrated

Laser-cooled and trapped free atoms provide powerful tools for high-resolution spectroscopy and quantum optics. The density of trapped atoms of low velocities that can be achieved allows considerable improvements in the resolved line $Q$ and dramatic reductions in frequency shifts and line broadenings, *e.g.*, in the second-order Doppler shift and in transit-time broadening. A novel trap configuration has been developed that represents a further step towards improved optical frequency standards based on laser-cooled neutral particles, and for new experiments in the fields of atom interferometry and quantum optics.

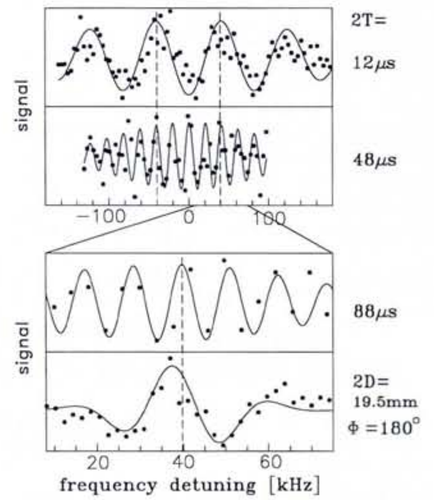
Magnesium is a well suited for combining trapping and cooling techniques with high-resolution spectroscopy. The intercombination transition $^1S_0$-$^3P_1$ ($\lambda$ = 457 nm) offers resolutions in the Hz regime ($\tau$ = 5.1 ms; $\nu/\delta\nu$ = 2 x $10^{-13}$) while the fast transition $^1S_0$-$^1P_1$ at 285 nm ($\tau$ = 2 ns) can be used for the manipulation and trapping of atoms in a magneto-optical trap.

To take advantage of the high $Q$ value of the intercombination line, the four-zone optical Ramsey method, known from many atomic beam experiments, was transformed into a pulsed excitation scheme on trapped and cooled atoms. The trap volume was irradiated from opposite directions by two pairs of co-propagating 457 nm laser pulses (2 μs pulse width; separation time $T$ within one pair of up to 88 μs) while the 285 nm trap light was switched off for a short time (typically 200 μs). This four-pulse Ramsey cycle excites a few of the trapped atoms (about 5%) to the $^3P_1$ level.

Owing to the long lifetime of the metastable $^3P_1$ state, these atoms have left the trapping volume when the trap laser light is switched on again so they are lost from the trap. This "electron shelving" effect is combined with an efficient detection of the strong fluorescence on the fast, trap transition of the remaining atoms. The excitation signal is therefore "quantum amplified" and generates a high signal-to-noise ratio, even with only a few thousand trapped atoms.

In first experiments, the resolution reached 4 kHz ($\delta\nu/\nu$ = 8 x $10^{-12}$) and the accuracy approached the 1 Hz level ($\delta\nu/\nu$ = 2 x $10^{-15}$). Data from these measurements are compared in the figure with a parallel set of measurements made using a conventional thermal beam apparatus. It can be seen that the optical Ramsey fringes for the laser-trapped magnesium atoms have been observed for the first time with a resolution of a few kHz [Sengstock K. *et al.*, *Opt. Comm.* (1993), in press].

Besides spectroscopic applications, the trap setup offers many opportunities for atom interferometry. The four-pulse excitation generates a matter wave interferometer ideally suited for studying Berry's phases and phase shifts due to time-dependent interactions such as the scalar Aharonov-Bohm effect [Müller J.H. and Ertmer W., to be published]. The physical mechanisms (additional electric, magnetic and/or laser fields) can easily be introduced during one of the dark periods between the Ramsey pulses.




*Ramsey fringes of trapped atoms (upper three curves) for different pulse separations T in comparison with a signal from a thermal beam apparatus (lowest curve). The points correspond to measured data; the solid lines are the results of numerical calculations.*

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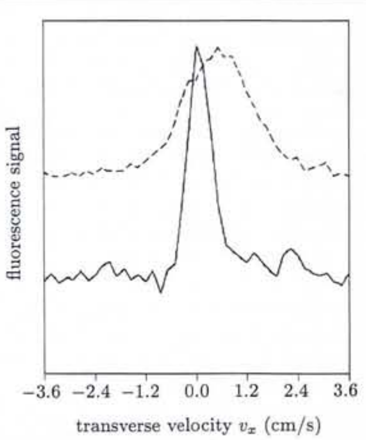
## Cs ATOMIC FOUNTAIN CLOCK

# Raman Velocity Selection Improves the Precision

An atomic clock based on a fountain of cold caesium atoms offers a potential improvement of a factor of 100 in stability over current primary standard caesium atomic-beam clocks [Clairon A. *et al.*, *Europhys. Lett.* **16** (1991) 165; Gibble K. & Chu S., *Metrologia* **29** (1992) 201]. In our fountain clock [Clairon A. *et al.*, *SPIE Proc.* **1837** (1992) 306], the atoms are first trapped and cooled in the upper ground-state hyperfine level to a temperature of 5 μK, before being launched upwards at a velocity of up to 5 m $s^{-1}$. In the course of their ballistic flight, the atoms pass twice through a microwave cavity. The time between the two microwave interactions can be up to 1 s, giving a narrow Ramsey resonance and enabling the hyperfine (clock) frequency to be determined to high precision.

Currently, one of the effects limiting the accuracy of such a clock is a spin-exchange frequency shift due to collisions between the cold atoms — a shift which is particularly large for ultra-cold atoms [Tiesinga E. *et al.*, *Phys. Rev. A* **45** (1992) 2671; Gibble K. & Chu S., *Phys. Rev. Lett.* **70** (1993) 1771]. The cloud of launched atoms thermally expands as it performs its ballistic flight. Atoms in the wings of the transverse velocity distribution, which undergo the first microwave interaction, may not pass a second time through the cavity, the apertures of which (1 cm in diameter holes) are the limiting apertures of the system. These atoms do not contribute to the clock signal but do contribute to the collisional shift during the time between the microwave interactions. By rejecting these atoms from the fountain, the collisional shift, proportional to the atomic density, can be reduced without reducing the clock signal. This can be achieved by transverse velocity-selection using stimulated Raman transitions before the first microwave interaction [Kasevich M. *et al.*, *Phys. Rev. Lett.* **66** (1991) 2297].

Shortly after launching, the atoms pass through a pair of horizontal, counter-propagating laser beams, separated in frequency by about the clock frequency. Atoms for which this frequency offset is Doppler-shifted into resonance with the hyperfine splitting undergo Raman transitions to the lower hyperfine level. Atoms remaining in the upper level are subsequently removed by the radiation pressure of another laser pulse. The width of the selected velocity slice is determined by the atoms' transition time through the beams and may be tuned to optimize the atomic density. In our system, a 0.5 cm $s^{-1}$ wide velocity slice is selected, as illustrated in the figure giving results obtained in one dimension, for a fountain of 15 cm in height, at a laser power corresponding to a $\pi$-pulse. By extending the velocity selection to two dimensions, we can eliminate all atoms which do not contribute to the clock signal, thereby reducing the collisional shift by at least a factor of 10. We shall be able to measure the collisional shift, and extrapolate to the clock frequency at zero density, by determining the clock frequency over a range of densities.




*Caesium atoms in an atomic fountain: the transverse velocity distribution of atoms without velocity selection (dashed line) is reduced considerably after Raman velocity selection (the solid line gives the velocity distribution of the selected atoms).*

**S.N. Lea*, G. Santarelli, P. Laurent, C. Salomon*, A. Clairon**
Observatoire de Paris; *ENS, Paris

Ertmer on the optical Ramsey spectroscopy of trapped Mg atoms). There ware also two invited lectures covering similar topics. H. Walther (Garching) spoke on the spectroscopy of laser-cooled ions stored in radiofrequency traps, including collective effects which lead to regular structures (so-called ion crystals). C. Salomon (Paris) reviewed recent work dealing with the use of ultra-cold atoms to increase considerably the accuracy of atomic clocks (see insert by S.N. Lea *et al.*).

The 25th EGAS was organized in the usual style of EGAS conferences, with the aim of gathering the whole community of atomic spectroscopists from all European countries, including the community's younger members, essentially its graduate students and post-docs. These junior colleagues are thus given an opportunity to present personally the results of their first research work before an international audience and to discuss them freely and informally with young physicists from other countries, as well as with more senior scientists. The conference was therefore devised so as to minimize the cost for participants: on Caen University's campus they could find, within walking distance, the lecture rooms, the restaurant and the students' residence, in which everyone could be accommodated, whatever his or her status, and in which 60% effectively chose to lodge. Such a "half-closed" organization is observed to stimulate, more than anything, contacts between participants.

A number of grants had been obtained in order to help eastern Europe colleagues attend, the efficiency of which was increased by a chartered bus between Warsaw and Caen for 40 participants. The result was that from among a total of 264 physicists (from 25 different countries) who took part in the conference, 68 came from east and central Europe. The region therefore made a very important contribution to the conference: 80 communications (oral and posters) out of the scientific programme's total of 216 communications (36 oral and 180 posters) and 11 invited lectures. In addition, there were 4 oral papers and 44 posters which appeared in the abstracts book, but were finally cancelled because their authors could not attend.

One of the scientific sessions was dedicated to the memory of Professor Bengt Edlen (Lund) who died in February 1993. To open this session, his colleague B. Persson recalled the life and work of this great spectroscopist who contributed so much to our understanding of the spectra of multicharged ions. In another session, D.N. Stacey (Oxford) gave a twelfth invited paper, recalling with much humour the highlights of the first 25 years of EGAS history. The annual General Assembly was held at the conference and venues for future meetings were discussed.

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26 EGAS will be held in Barcelona on 11-16 July 1994. For further information, contact: R. Corbalán, Dept. de Física, Fac. des Ciencias, Univ. Autonoma de Barcelona, E-08193 Bellaterra (tel./fax: +34-3-581 16 53 / 581 21 55).

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