of the delay between the advanced and retarded parts of the atom's wave function.

Measuring the atom's final state thus provides information about the cavity-induced delay, and hence about the photon number in the cavity. State-selective detection of the atoms is performed by ionizing them in two small detectors and counting the resulting electrons. Each detector consists of plates with a small electric field across them: the first detector operates at a low field to ionize atoms in the upper level, and the second one at a higher field to ionize the lower level.

The radiation field fed into the cavity by a weak radiation source usually presents relatively large photon number fluctuations of an inherently quantum nature. Prior to measurement, the cavity thus contains a field described by a quantum photon number "wave function". The squared modulus of each wave function's component is the probability that the cavity stores a given photon number. Computer simulations show that this wave function progressively collapses into a pure photon number state, known as a Fock state, as successive atoms cross the cavity and are detected. If the experiment is resumed, each time with the same initial field in the cavity, the statistical distribution of photon numbers will be retrieved by the histogram of individual measurements. In any given run, however, the photon number will remain constant after it has been pinned down.

A Quantum Non-Demolition Method

The above method, which relies on atom-cavity force effects using a slightly detuned cavity, will realise a feat of observation known as quantum non-demolition (QND). The photons are indeed counted without being destroyed, as opposed to conventional photodetection methods based on photon to electron conversion. The atoms are strongly coupled to the cavity field while they are inside the resonator, but they decouple adiabatically as they exit the cavity, leaving the field energy unaffected. The atom-cavity "collision" is an "elastic" process and the atom carries away information about the photon number, which is not destructive for the field intensity. After the field has been reduced into a Fock state, it remains unperturbed by further measurements, which will all yield the same result. This is completely at variance with conventional photon counting, which continuously deplete photons from the measured field. The method has the potential to measure extremely weak fields down to the single photon or even cavity vacuum level. Spurious photon counts will be essentially due to the low noise level of the state-selective atomic ionization counters and should be unlikely. Such QND measurements would have a sensitivity unattainable by conventional detection methods in the microwave region.

Atom-cavity QND methods should allow one to monitor events impossible to observe otherwise. For example, if a single photon disappears in the cavity walls due to small losses, this quantum jump event would register as a change of the atomic states detection probabilities. In this way, the death of photons could be witnessed, so to speak, in real-time without affecting its natural rate by the measurement process itself. The creation of a single photon in the cavity could be monitored as well. Such exquisitely sensitive measurements, performed at the quantum level, may one day be used to detect tiny forces which slightly deform the cavity boundaries, inducing discrete changes to photon numbers. QND processes were first mentioned in the context of gravity wave detection experiments [12], which imply the monitoring of exceedingly small length changes of a gravitational antenna. It remains to be seen whether the QND methods described here, or some variations based on them, can be of help in these very challenging experiments.

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High-Energy C_{60} Beams Available

S. Della-Negra and Y. Le Beyec of the Institut de Physique Nucléaire, Orsay, outline progress in upgrading facilities for producing high-energy beams of cluster ions including fullerenes.

The interactions of ions with surfaces and solid material have been investigated using a large variety of projectiles, ranging from the commonly used monoatomic ions up to dust particles. Recent work in several laboratories has demonstrated enhancement, relative to the rate for individual ions, of secondary ion emission (SIE) from various targets under the impact of clusters of atoms. The bombardment of organic and inorganic materials by keV ion clusters has also shown that cluster projectiles eject complex secondary ions from the surfaces more efficiently than single ions (Fig. 1 from [1]).

The energies of the beams used to perform these experiments are in the keV to a few tens of keV range; the yield of secondary electrons is rising sharply with the energy of impact so it is interesting to increase the kinetic energy using clusters with high masses. There are today no facilities available capable of producing suitably heavy and fast projectiles.

The availability of high energy, heavy projectile beams will also open up new domains owing to the large amount of energy deposited in a small volume of solid. For example, the linear energy loss easily reaches 5 keV/Å which is larger than the maximum values obtained with atomic projectiles such as uranium at a few MeV per nucleon. Secondly, the simultaneous impact of several atoms on a small surface (100 Å^2) can induce coherent effects: phenomena which must be studied include energy loss and fragmentation of the projectile, the charge density of the solid, pressure pulses and shock waves, defect production in insulators, and physical modification of the surface.

For example, it is necessary to validate theoretical work at Orsay [2] showing that a

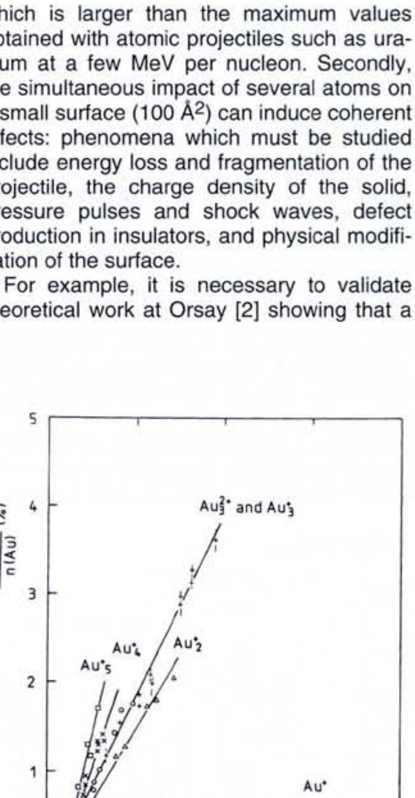

Fig. 1 — The yield of molecular ions from a phenylalanine target bombarded with Au^+ and Au cluster projectiles [1]. Data are plotted as a function of the projectile energy per unit mass (E/A), equivalent to the square of the projectile velocity, so that the desorption yields obtained with different gold cluster projectiles can be compared at the same velocity. The molecular ion yield increases by a factor 30 on going from Au^{3+} to Au^{5+}, implying that a non-linear effect arises during cluster impact in the keV range. Other complex projectiles lead to the same yield enhancement.

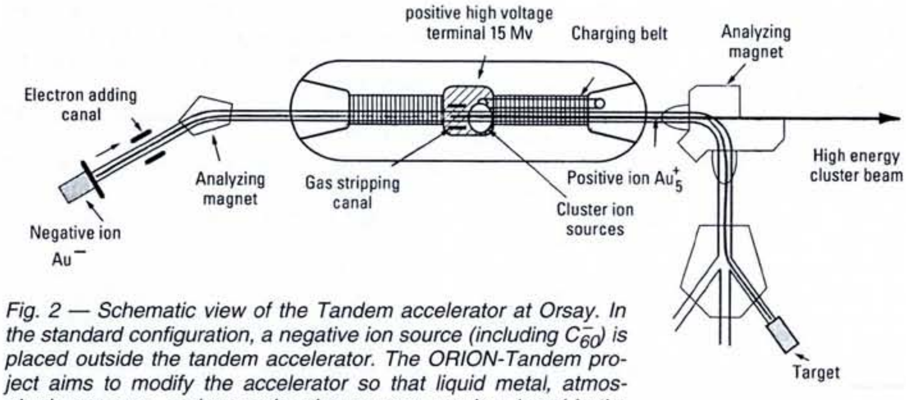

Fig. 2 — Schematic view of the Tandem accelerator at Orsay. In the standard configuration, a negative ion source (including C_{60}^-) is placed outside the tandem accelerator. The ORION-Tandem project aims to modify the accelerator so that liquid metal, atmospheric pressure, and secondary ion sources can be placed in the positive high-voltage terminal.

pronounced deceleration is expected in a gaseous, liquid or solid target owing to electrostatic correlation between ionized fragments produced during the breakup of a cluster. The correlation effects between fragments determine the stopping power for a charged cluster because at the high velocities encountered, Coulomb repulsion between fragments induces a separation velocity which is much smaller than the centre-of-mass velocity.

Another example involves heavy-ion inertial fusion: conventional scenarios envisage high-intensity particle beams of several kiloamperes, where the physics associated with the modes of interaction between the particles can be simulated, in a first step, using showers of ions resulting from the Coulomb explosions of massive clusters.

Accelerator Upgrades

The MUMMA project at Uppsala aims to accelerate multiply charged and very large molecular ions with an acceleration voltage of 200 kV. A special high-voltage system has been built and a molecular beam of several MeV will be delivered. Appropriate modifications are also being made to the MP9 Tandem accelerator at Orsay, where the ORION project will allow the acceleration of clusters from a positive ion source in the terminal of the tandem up to an energy of 15 MeV per charge (Fig. 2). Developments are also underway in Erlangen.

The first type of terminal source will be of the liquid metal type to produce metallic clusters based on tin, gold or bismuth with up to ten or more constituents. It emits monoatomic ions and mono- and multi-charged cluster ions; ionic intensities of few tens of pA to nA are expected, depending on the type of cluster. The lifetime of the source is more than a few hundred hours. The project started in 1990 and the first metallic cluster beams are expected this year. Meanwhile, other high-energy cluster ion beams based on metals such as silicon, silver and gold, but using the standard tandem mode (the source is placed outside the tandem), are being developed in collaboration with a group from Erlangen.

A second step involves an atmospheric pressure ion source to allow the injection of multiply charged biomolecular ions: the mass range expected is 10^4-10^5 mass units, with charge states of 10^+ to 100^+ and an energy of up to 1 GeV.

The use of an ion source in the terminal requires modifications of the tandem accelerator. These modifications will be compatible with the acceleration of cluster ions sputtered from a thin target, located in the terminal, by heavy ion bombardment or by laser irradiation. Cluster beams of 5 to 15 MeV will be available for several hours depending on the lifetime of the target.

C_{60} Beams

Before the new terminal ion source is available, cluster beams accelerated to MeV energies in the standard tandem mode (Fig. 2) include a MeV C_{60} ion beam [3] which is now available for basic research and for studying ion-solid and ion-gas interactions. Sputtered C_{60} fullerene ions produced by a high-intensity Cs^+ beam bombarding a C_{60} sample are accelerated, and the intact molecules selected using a magnetic field. After a pre-acceleration to 200 keV, the beam is introduced into the tandem and accelerated to the energy qV, q being the charge on a particle and V the voltage applied of the terminal. The charge of the C_{60} cluster is changed from negative to positive by collision with nitrogen molecules in a gas cell at the terminal.

It is remarkable that the C_{60} clusters undergo multiple ionization whereby C_{60}^- becomes intact C_{60}^{n+} clusters of charge $n+$ which are accelerated in the second section of the tandem (the total energy of a cluster is given by the simple formula $E = [n+1]\ V + 0.2$ MeV). The positively charged ion clusters travel about 10 m after leaving the tandem and are deflected by a 90° analyzing magnet at the end of the beam line. Intact fullerene ions are deflected by few degrees at the maximum field (1.5 T), the ion fragments deflected to larger angles, and neutrals undeflected. To identify the accelerated molecular ions, the low-energy beam is pulsed and time-of-flight (TOF) measurements made between the deflection system and a micro-channel plate detector installed behind the magnet; the energies of the projectiles are measured using a silicon detector in coincidence with the TOF.

Examples of TOF measurements are given in Fig. 3. Fig. 3a for a terminal voltage of 10 MV shows three peaks corresponding to C_{60} neutrals, C_{60}^{1+} and C_{60}^{2+}. In Fig. 3b with a 4 MV terminal voltage, these TOF peaks are still present, but several fragment ions induced by the collisions in the gas cell are detected. The energy measurements indicate that the positively charged C_{60} cluster ions were accelerated intact through a total distance of 35 m.

The highest intensities of both singly charged and multiply charged, intact C_{60} molecules were obtained at the same pressure of nitrogen, indicating that multiple ionization is reached in one collision with C_{60}. A simple calculation shows that a single ionization of carbon atom by a carbon-nitrogen binary collision corresponds to a recoil energy of carbon in C_{60}, which is less than the bond energy of a carbon in the structure. Multiple ionization may be due to consecutive collisions of nitrogen atoms with 2 to 3 carbon atoms in the same molecule of C_{60}. Moreover, ionization probably takes place in the peripheral region of the fullerene cluster owing to its characteristic hollow structure.

Magnetic deflection is used after the accelerator's exit in order to select a given beam from among the various accelerated cluster ions. It has been shown recently that C_{60}^{1+} and C_{60}^{2+} can be obtained at a very precisely defined angle, and that these ions arrive intact at the detector (or target). Clusters of $(Au)_m$ at 10-20 MeV with $1<m<5$ have also been deflected at a precise angle and they are also intact. Experiments with these exotic beams are now in progress.

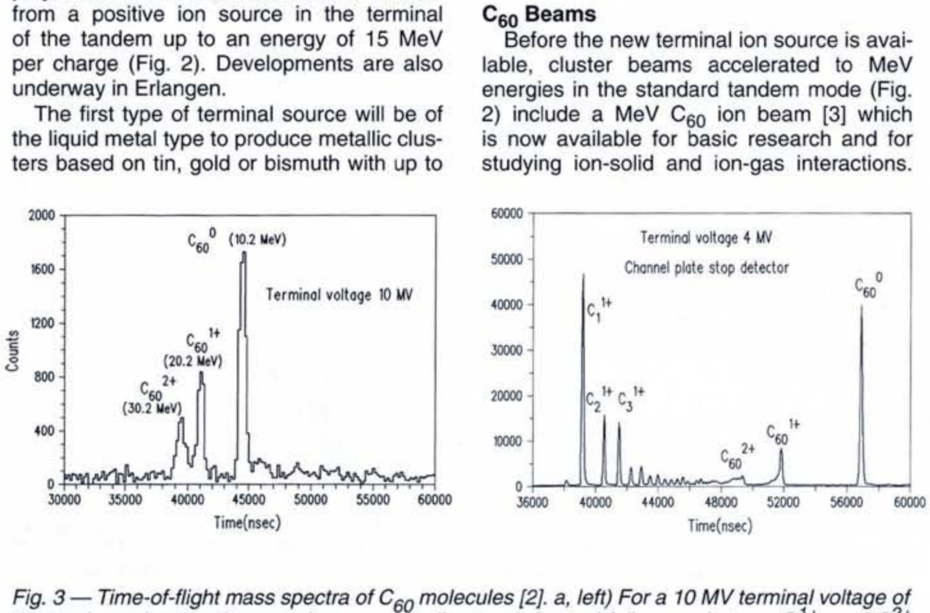

Fig. 3 — Time-of-flight mass spectra of C_{60} molecules [2]. a, left) For a 10 MV terminal voltage of the tandem, showing three peaks corresponding to uncharged fullerene clusters, C_{60}^{1+} and C_{60}^{2+} accelerated to 10.2, 20.2 and 30.2 MeV, respectively. b, right) For a 4 MV terminal voltage, showing that fragment ions are present in the accelerated beam.

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