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ATOMIC PHYSICS AT RELATIVISTIC ENERGY*

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When atoms, accelerated to a fraction of the speed of light collide, they can lose most, or even all of their electrons. In this way bare uranium nuclei (uranium atoms with all 92 electrons removed) are made by passing a beam of uranium ions, accelerated to 0.4 GeV/nucleon (70% the speed of light), through thin metal foils. Lower velocities produce beams of uranium with predominately one, two, or three electrons. The lower the velocity, the more electrons remain on the atom. Bare, and few-electron uranium and other heavy ions are used in experiments to study new effects that take place during ultra relativistic atomic collisions, and to test quantum electrodynamic (QED) calculations of few-electron atoms. Both involve the study of fundamental electromagnetic interactions in very strong electromagnetic fields.

Quantum Electrodynamic Effects

In elements with large numbers of protons (high atomic number, Z), such as Au, (Z=79), Pb (Z=82) or U (Z=92), the large nuclear charge produces a strong electromagnetic field near the nucleus that greatly enhances both the relativistic and QED effects on the binding energy of the inner electrons. Although relativistic and QED effects are well understood in hydrogen and in one-electron ions; only recently have techniques been developed for calculating the spectra of atoms and ions with more than one electron. Theoretical progress in calculating these effects in few electron ions has been stimulated by experiments that can measure QED effects in few electron very high-Z ions produced in tokamaks, electron beam ion traps, and especially in heavy-ion accelerators.

The measurement of the 281 eV transition energy between the $2^2S_{1/2}$ ground state and $2^2P_{1/2}$ first excited state of lithiumlike uranium (U^{89+}) is presently the most rigorous test of these calculations. The QED effects contribute about 43 eV to this transition energy, of which about 2 eV comes from QED effects involving more than one electron.

Lithiumlike uranium is excited to the $2^2P_{1/2}$ state by passing U^{89+} ions, traveling at β = v/c = 0.42 (where v is the velocity and c the speed of light in vacuum), through a thin aluminum foil. The energy of the 281 eV photon produced by its decay back to the ground state is measured using a Doppler-tuned spectrometer (Fig. 1). Because the photons are emitted from a moving source, their energy is seen Doppler shifted in the laboratory:

$$\omega_{ion} = \omega_{lab}\ (1-\beta \cos \theta_{lab})/(1-\beta^2)^{1/2} \qquad (1)$$

where ω_{ion} is the energy of the emitted photon, ω_{lab} is the energy of the emitted photon as seen in the laboratory, θ_{lab} is the viewing angle and β is the beam velocity. When viewed through a column of argon gas, the photons will pass through the gas as long as they can not efficiently excite the argon atoms. However at 244.39 (0.01) eV the photons can excite the 2p - 4s resonance transition. The photons are absorbed as the viewing angle is rotated to Doppler-shift the photon energy, ω_{lab}, through this energy. For $\beta = 0.42$ this occurs near $\theta_{lab} \approx 95$ degrees. Measuring the angle, θ_{lab} and the velocity β, determines the energy of the emitted photon.

Although the measured value of 280.56 (0.1) eV agrees with present calculations, a few small effects have not yet been included in the calculations. Although they are not expected to effect the agreement between experiment and theory, it is worth remembering that QED was invented in part to explain a small effect in the spectrum of atomic hydrogen.

New Type of Atomic Collision at Relativistic Energy

In atomic collisions, the nuclei pass close to each other, but do not touch. They do however pass through the cloud of atomic electrons and may transfer enough energy to remove one or more of these electrons. It is also possible for electrons to be added to an ion in such a collision and this forms a balance between electron capture and loss. Until recently, it was thought that all of the processes for electron capture had cross sections that decreased rapidly with increasing collision energy and at ultra relativistic energies, electron capture would be insignificant.

In relativistic, and especially ultra relativistic collisions ($\beta > 0.999$), however, time dilation greatly increases the already large electromagnetic fields of the passing heavy nuclei. The strong electromagnetic fields can spawn electron-positron pairs with the electron from the pair sometimes emerging from the collision bound to one of the ions (Fig 2). The process is known as electron capture from pair production and was first observed at done at the Lawrence Berkeley Laboratory's Bevalac. For 0.96 GeV/nucleon ($\beta = 0.85$) bare uranium ions colliding with a gold target, the electron from the electron-positron pair emerges from the collision bound to the uranium ion about 40% of the time.

This experiment, the first to observe capture from pair production, detectied uranium ions that changed charge state from U^{92+} to U^{91+} in coincidence with the positron from the electron-positron pair. The positron was confirmed by its subsequent annihilation (with an electron in the detector) into two 511 keV photons.

Other experiments, and calculations show that for heavy ions above about 20 GeV/nucleon ($v/c = 0.999$) capture from pair production will be the dominant electron capture mechanism. This is because the cross section for capture from pair production increases with energy due to increased numbers of electron-positron pairs that are produced by stronger electromagnetic fields at higher energies. The cross section for capture from pair production also increases with increasing atomic number. This is because the larger nuclear charge produces stronger fields, and the larger nuclear charge produces a larger electron binding energy, increasing the probability that the electron will bind.

Since the electron that is captured is produced in the collision, it is possible for two bare nuclei to pass by each other and for one or both of them to emerge from the collision with an electron attached. Exactly this situation will exist at the Relativistic Heavy Ion Collider

(RHIC) under construction at the Brookhaven National Laboratory, and when heavy ions are introduced, at the Large Hadron Collider (LHC) under construction at CERN. RHIC will collide opposing beams of 100 GeV/nucleon bare gold and other nuclei to search for a quark-gluon plasma. Because RHIC collides opposing beams, its 100 GeV/nucleon energy per beam is equivalent to a 20,000 GeV/nucleon beam passing through a fixed target.

Capture of an electron by one of the bare ions changes its orbit in the confining magnetic field and it is lost from the collider. Calculations show that this will be important but should not limit the effectiveness of RHIC. However until RHIC is operating the only accelerators that can test the calculations are fixed target accelerators with collision energies hundreds to thousands of times lower.

Future Prospects

At the ultra relativistic energies of RHIC and LHC, the electromagnetic fields produced by the atomic collision of two ions become strong enough to spawn particle-anti-particle pairs that are much heavier than electron-positron pairs. This includes taus (a short lived cousin of the electron with 3500 times the electron mass), mesons (a quark-anti-quark pair) containing a charm (c) quark and/or bottom (b) quark, and some have speculated, even Higgs Bosons. Some of the time, the negative particle of the pair will emerge bound to one of the ions (as an atom). Muons, and pi mesons (an anti-up and a down quark), K- mesons (anti-up and a strange quark), and of course electrons, have been studied in atoms. Much of what we know about the physics of these particles comes from these studies. But taus and c and b containing mesons (D- and B- mesons) have not been studied in atoms. Since the tau, D and B lifetimes are typically 1 ps or less, capture from pair production is likely to be the only way to form and study them.

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