Making muonium in vacuum

from C.J. Batty and G. Marshall

MUONIUM is the name given to the simple atomic state consisting of a positively charged muon and an electron. For atomic and chemical purposes it is aptly described as a light isotope of hydrogen with only about one-ninth the hydrogen mass. However the properties of its 'nucleus' make muonium both interesting and useful in physics and chemistry. Two recent papers describe a novel way of forming muonium which will extend its use to measurements in vacuum.

The muon, identified in 1936 in cosmic ray studies, was one of the earliest of the elementary particles to be discovered. But despite an enormous amount of study and a considerable knowledge of its properties, its existence remains an enigma. Like the electron and the positron, negative and positive muons are weakly interacting point-like leptons and are not influenced by the strong interaction felt by hadrons. The muon differs from the electron essentially only in its mass, which is 207 times that of the electron.

It is relatively simple to produce intense, high-quality muon beams from the decay of pions obtained at some particle accelerators. So it has been possible to make a thorough study of the properties of the muon, and then with this knowledge, to use the muon as a tool for measurements in other fields. Thus the spin and magnetic moment of the muon, together with the fact that its weak decay (with a mean lifetime of 2.2 μs) into an electron plus two neutrinos is asymmetric or parity violating, have been used to give information on the magnetic fields inside a variety of materials. This technique of muon spin rotation, or μSR in analogy with NMR and ESR, is a subject of intense interest at several laboratories throughout the world. Another application involves the formation of muonic atoms, in which a negative muon is captured in an atomic orbital, effectively replacing one of the electrons. Measurements of the radiation emitted in the subsequent atomic cascade can determine the distribution of charge in the nucleus.

The formation of muonium is fundamental to experiments with muons in fields as diverse as quantum electrodynamics, particle physics, solid-state and surface physics, and chemistry. For most applications muonium can be formed by arresting a beam of energetic positive muons in a suitable solid, liquid, or gas target, in the same way that hydrogen atoms can be formed by stopping proton beams. Near the end of its range, the positive particle loses energy by ionization, and in the low-velocity regime (corresponding to less than about 20 keV for muons) there is a high probability that it will form a neutral muonium atom. In general the muon will capture and lose an electron many times before it reaches thermal energies, and if the likelihood for the capture process is large compared with that for electron loss as thermalization becomes complete, muonium will be formed. In most chemical and solid-state applications the interaction of muonium with the target material is studied, but this interaction can be a hindrance when studying certain other phenomena. It is therefore of interest to develop an alternative method of muonium production so that measurements can be made on the atom in vacuum.

A group working at the LAMPF accelerator facility in New Mexico has recently reported the observation of fast (~10 keV) muonium in vacuum (P.R. Bolton *et al. Phys. Rev. Lett.* **47**, 1441; 1981). The authors allowed an intense low-energy (4 MeV) muon beam to slow down in a polyethylene degrader before it passed through a thin foil target in vacuum. It is predicted, on the basis of proton measurements, that a significant fraction of the muons emerging with energies less than 20 keV will be in the form of muonium.

In order to separate the small neutral muonium component from the charged remainder of the beam, a 5 kG magnetic sweeping field is used immediately after the target foil. The neutral particles travel 160 cm from the target through the magnetic field to a beam stop. The positrons expected from the decay of the muon are detected in an array of scintillation counters and a NaI detector. If the e^+ are from the decay of μ^+ then they should have a characteristic energy spectrum with an endpoint energy of 53 MeV.

This characteristic energy spectrum, superimposed on a flat background of events due to cosmic rays and dominated at energies below 30 MeV by counts due to the electron contamination in the incident beam, has been observed in the experiment reported. The introduction of a few Torr of helium gas into the normally evacuated ($< 5 \times 10^{-5}$ Torr) apparatus causes the muonium signal to disappear due to the ionizing collisions $\mu^+e^- + \mathrm{He} \rightarrow \mu^+ + e^- + \mathrm{He}$; the μ^+ are then swept away by the magnet, and the background spectrum can be measured. The results show that, for the particular muon beam used, the production rate for muonium is about 3×10^{-4} per incident μ^+ regardless of which of several target foils is used. The conclusions are consistent with proton beam data and with models of the neutralization process. Estimates of the energies of the muonium atoms indicate that 50 per cent have energies of less than 5 keV and 95 per cent of less than 20 keV.

There are two measurements in particular which would benefit from copious quantities of muonium in vacuum. One is a sensitive search for the conversion of muonium to antimuonium (μ^-e^+) which can be accommodated in some versions of the electroweak theory. The interaction of muonium with matter drastically reduces the expected conversion rate, so that current limits on the process are not particularly restrictive. The other is the Lamb shift in muonium, the energy difference between the 2s½ and 2p½ states of the $n = 2$ atomic level. Since both the muon and the electron are leptons and thus have no structure, quantum electrodynamics can predict the Lamb shift very accurately, in contrast to the case for atomic hydrogen. The fast muonium emerging from the foil in the LAMPF experiment should contain a 2s component of about one-eighth the total muonium intensity.

This component was also shown to exist in another recent experiment performed by a group from the TRIUMF meson facility in Vancouver, Canada (C.J. Oram *et al. J. Phys.* **B14**, L789; 1981) using a similar muon beam and thin foil target. Muonium produced in the skin of the foil emerged to pass through two successive sets of parallel plates, used to produce high electric fields at right angles to the direction of motion of the atoms. The electric fields will introduce through the Stark effect a 2p component to any 2s state which may be present. Decay can then proceed from the 2p to the 1s state by emission of UV light with a lifetime of about 3 ns. The light can be detected by a wavelength shifter and photomultiplier system mounted close to the second set of plates. A clock is started when a muon is incident on the thin foil and is stopped when an event is recorded by the UV detection system.

If voltage is applied only to the second set of plates the time spectrum should show three muon components: an exponential decay due to muon-decay positrons incident on the photomultiplier system; a flat background due to uncorrelated events; and a foreground peak, about 150 ns wide, due to muonium in the 2s state decaying in the region of high electric field. The foreground peak should largely disappear when an electric field is applied to the first set of plates, as this would cause the 2s state muonium atoms emerging from the foil to decay rapidly to the 1s ground state before they reach the second set of plates and photon detector system.

Further experiments are planned to improve the production of muonium in vacuum. In this way, the goals of an accurate determination of the Lamb shift and a sensitive search for the conversion of muonium to antimuonium should be achieved. ☐

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0028-0836/82/060457-01$01.00