3d-3p Transitions in ($\mu^+\text{He}^4$)$^{++}$

M. May
Brookhaven National Laboratory, Upton, New York, 11973

An experiment¹ to measure the energy of 3d-3p transitions in the ($\mu^+\text{He}^4$)$^{++}$ ion is now in progress. The experiment, which is being performed at the Brookhaven National Laboratory Alternating Gradient Synchrotron, will use an infrared CO$_2$ laser to stimulate the transitions. These transitions are of interest because their energy is due almost entirely to the polarization of the vacuum. In a pure Coulomb field, states with the same principal quantum number, $n$, and total angular momentum, $J$, are degenerate. Vacuum polarization, because of its nonlinear dependence on electric field strength, results in departure from an inverse square Coulomb field, causing a splitting which depends on the orbital angular momentum, removing the degeneracy. The dominance of vacuum polarization in giving rise to these splittings in the muonic ion is in contrast to the situation in electronic atoms where vacuum polarization makes a very minor contribution to the Lamb shift.

This experiment may be regarded as a test of vacuum polarization terms in quantum electrodynamics, or as a search for an anomalous muon nucleus interaction. QED calculations of the effect are reviewed in Ref. 2.

The measurement of a transition energy, which is almost entirely due to vacuum polarization, directly in terms of a laser frequency gives this experiment the potential of going beyond the accuracy of previous experiments. Experiments which are sensitive to vacuum polarization include $\mu-2$ of the electron, $\mu-2$ of the muon, the Lamb shift in hydrogen, and the 2p-2s transition in muonic helium³. The most precise test to date is the measurement using x-rays from high Z muonic atoms⁴ reported at this conference.

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These experiments are less direct than the present experiment in that either vacuum polarization gives only a small contribution to the effect measured or the interpretation of the experiment depends on the values of externally measured quantities whose values are imprecisely known (e.g., nuclear size corrections introduce uncertainty in the 2p-2s experiment).

Figure 1 shows the energy levels of ($\mu^{-}$He$^4$)$^+$ (not to scale).

In the majority of cases the muon proceeds through the 3d state to the 2p state and then to the ground state with the emission of a $K_\alpha$ x-ray of energy 8.226 keV. In the normal cascade in helium gas at 1 atmosphere, $K_\beta$ rays (9.748 keV) occur in about 15% of the cases, while $K_\alpha$ occur in 70%. Stimulation of 3d-3p transitions with a laser results in an increase in the number of $K_\beta$ transitions. The $K_\alpha$ and $K_\beta$ x-rays are easily resolved using lithium drifted silicon
Fig. 2. Line shape of the $3d_{5/2}^1-3p_{3/2}^1$ transition in ($\mu$He$^+$). Vertical bars indicate lines in a $^{13}C^{18}O_2$ isotopic gas laser.

detectors. A change in the ratio $K_\beta/K_\alpha$ signals the occurrence of a transition.

Of the three possible transitions, the $3d_{5/2}^1-3p_{3/2}^1$ transition rate is highest necessitating the use of $^{13}C^{18}O_2$ gas in the laser. The use of a rare isotopic gas entails recirculating the gas and recombining gas molecules disassociated during the laser discharge using a platinum catalyst.

The $3d_{5/2}^1-3p_{3/2}^1$ transition has a wavelength of 9.8 microns and is broadened to a width of 500 Å because of the short lifetime of the states. The individual lines in a rotational band of $^{13}C^{18}O_2$ are separated by about
Fig. 3. Top view of target box.

200 Å (fig. 2). The individual lines may be selected by a diffraction grating. By tuning through the laser lines which overlap the transition, the line shape can be mapped and the transition energy accurately determined.

The apparatus is shown schematically in fig. 3. The muon beam enters the target box which contains helium gas at a pressure of up to 3 atmospheres. The laser beam is split into two to avoid problems of breakdown. The beams enter the target box through a NaCl window and are captured by reflection between two copper mirrors of 20 meter curvature, one of which has two 7 mm diameter entrance holes. The laser beam traces out an ellipse on the mirrors and exits through the entrance hole after 38 bounces. The muons stop in a volume that is illuminated by the laser radiation. Three lithium drifted silicon detectors each 1.6 cm diameter are mounted below the stopping region to detect the X-rays. A tungsten shield and collimator surrounds the SiLi detector to protect it from the direct beam which has a large electron
component, from x-rays and decay electrons produced by muons stopping in helium outside of the volume illuminated by the laser, and from beam halo interacting in the mirrors.

The 24 MeV/c muon beam was constructed specifically for this experiment and has a pulsed mode of operation which is matched to the repetition rate of a high power CO₂ laser. Every 1.4 seconds $10^{12}$ protons at 28 GeV/c strike a platinum production target producing a beam of $10^4$ negative muons. The muons arrive at the target in a pulse of 30 nanoseconds duration and 200 muons per pulse stop in 3 atmospheres of helium gas in a volume 2"x2"x6". We must then detect the prompt K x-rays in the presence of all the prompt background associated with the pulse of high energy protons on the production target and with the pulse of muons entering the target box. Timing resolution due to the SiLi detector and the time width of the beam is about 50 ns full width and can be used to reject background. Sources of background include electrons in the beam which come early with respect to the muon pulse and slow neutrons or muon decays which come late. However all these sources contribute to the deadtime since the SiLi detector must be sensitive for one microsecond to achieve adequate energy resolution.

Extensive preparations for the experiment have been required to develop the pulsed low energy muon beam and to reduce the backgrounds to a level at which the K x-ray spectrum could be cleanly observed. Figure 4 shows the spectrum which was observed with one detector in one atmosphere of helium gas. In our anticipated running condition, with 3 detectors and 3 atmospheres of helium, an equivalent spectrum could be taken in 12 minutes. Further improvements in rate may be possible. The background level in the spectrum is very low, and there is no evidence of any structure in the background.
Fig. 4. Muonic x-ray spectrum for helium at 1 atmosphere pressure taken in the pulsed muon beam.

The laser system has been successfully operated, and a four joule laser pulse trapped in the target cavity containing 3 atmospheres of helium. In March 1986, all aspects of the experiment will be in place together for the first time. We expect to observe a resonant effect at one frequency during this phase of the experiment.

References