Measurement of K x rays from muonic helium formed in a low-density target in an intense pulsed muon beam

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An experiment was constructed to measure the contribution of vacuum polarization [in quantum electrodynamics (QED)] to the $3d$-$3p$ energy difference in muonic helium. Major features of the experimental apparatus included design and construction of a pulsed beam of stopping muons with the highest instantaneous intensity available, a laser system producing multijoule pulses from doubly isotopic CO_2 gas, a cavity to trap the laser light in 3 atm of helium, and Si(Li) detectors to measure the helium x rays. The number of stimulated x rays accumulated was not sufficient to permit a statistically significant QED measurement, but the results demonstrate the feasibility of laser spectroscopy in a pulsed muon beam. The intensities of separate K x-ray lines in muonic helium were measured at 1 and 3 atm for comparison with recent theories of pressure effects on the muon cascade.

I. INTRODUCTION

In the course of setting up a new experiment[1,2] to measure the effects of vacuum polarization in the muonic helium ion,[3] we have built a pulsed, low-momentum negative muon beam at the Brookhaven alternating-gradient synchrotron (AGS). This new beam, which has been developed in collaboration with the AGS staff,[4] provides 10 000 25-MeV/c negative muons in 50-ns bursts. In this bunched beam we used the following procedure.

(i) We first studied the prompt background and reduced it with appropriate shielding.

(ii) In order to observe prompt muonic x rays in the presence of this background, we then had to provide sufficient segmentation of the Si(Li) detectors by reducing the solid angle of each detector to about 12 msr. (The background still blocks our ability to detect the desired x rays in about one out of every two bursts.)

(iii) Under these conditions, we have measured the relative rates of the muonic x rays from He at 1 and 3 atm.

The vacuum-polarization experiment is described in Sec. II, the beam in Sec. III, and the results and interpretation of the x-ray measurements in Secs. IV and V.

II. VACUUM-POLARIZATION EXPERIMENT

The beam and measurements described in this article come from the initial phase of our vacuum-polarization experiment, which is designed to measure the energy difference between the $3d$ and $3p$ levels in the muonic helium ion. By measuring transitions between these levels rather than between the metastable $2s$ state and the $2p$ state,[3] the dependence on the nuclear-charge radius and consequent uncertainties in interpretation are avoided. However, the short lifetime of the $3d$ state in the initial cascade of the muon requires a pulsed experiment. A 4-J pulse of resonant infrared radiation of 9.85 μm wavelength from a $^{13}C^{18}O_2$ transversely excited atmospheric (TEA) laser is trapped for tens of nanoseconds by reflection between copper mirrors. This illuminates a 2-in.-diameter, 8-in.-wide transverse region, where the negative muons stop in He gas, as shown in Fig. 1. The signal for the induced transition is the 9.7-keV $K\beta$ x ray from the prompt $3p$-to-$1s$ deexcitation. The induced transition rate is low; therefore, a pulsed muon beam, of much higher instantaneous intensity than is available elsewhere, was needed to match the short duration time ($\sim$80 ns) and slow repetition rate ($\sim$0.5 Hz) of the laser bursts.

The relative intensities of the muonic helium x rays were measured (at 1 and 3 atm) for two reasons. (1) The yield of $K\beta$ x rays from the normal cascade represents the main physical background and thus determines the amount of running time needed to detect the induced transitions. (2) There is independent interest in this region of target density, where the formation of complex molecules $[(\mu^-\mathrm{He})^+\mathrm{He}_n]^+$, $n=1,2,\ldots$[5,6] begins to become relatively important.

The present article will also demonstrate the feasibility of counting x rays emitted from a low-density target during the intense accelerator burst of 10^{12} protons striking the external production target, when the x-ray signal and most of the background are compressed into 50 ns. However, with each of the 2-cm^2 x-ray detectors at the ap-

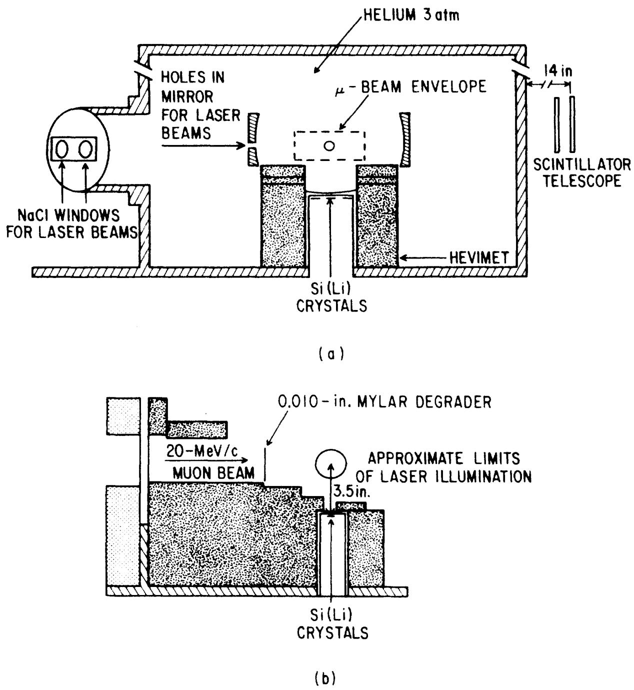

FIG. 1. (a) Front view of the region where muons stop in the helium gas, with indications of the shielding, detector placement, and arrangement of windows and mirrors for trapping the laser light. (b) Side view of the same area.

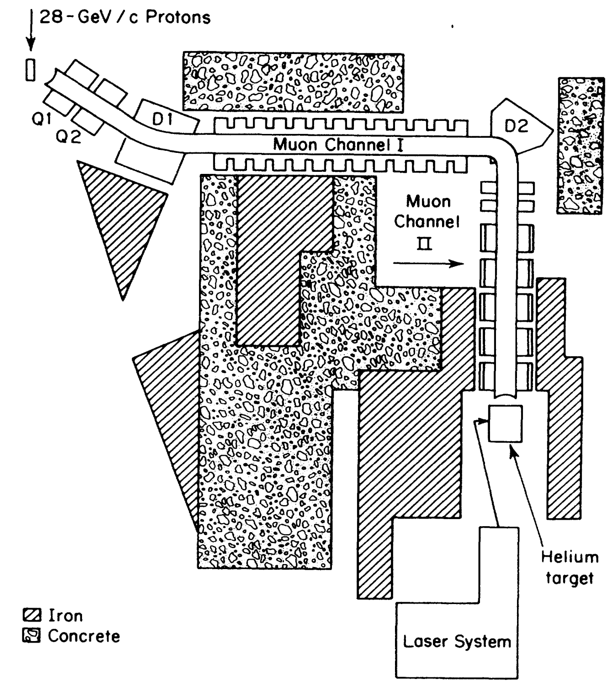

FIG. 2. Layout of muon-beam line and shielding.

propriate distance of 13 cm from the stopping region, the total amount of data taken with the laser during the run at the AGS has not been statistically sufficient to detect the induced resonance.

III. PULSED NEGATIVE MUON BEAM

The very-low-momentum negative muon beam line, which was required in order to stop the muons in a 2-in. depth of 3 atm of helium gas, was installed at the *D* line of the Brookhaven alternating gradient synchrotron. The internal beam at the AGS normally consists of 12 bunches, each of 10^{12} protons. The bunches are ~ 40 ns long and are separated from each other by 224 ns. For neutrino experiments, the 12 bunches are usually fast extracted every 1.4 s to the "*U* line" at the full energy of 28 GeV. For our experiment, the AGS staff developed a new single-bunch-extraction (SBE) system.[4] SBE extracts a bunch (10^{12} protons) from the ring through a switchyard to the "*D* line" at 24 GeV during the acceleration cycle. One hundred milliseconds later, the remaining 11 bunches, accelerated to full energy, are extracted to the *U*-line neutrino experiments. Figure 2 gives a layout of the muon-beam line, which consists of 24 quadrupole and dipole magnets, previously used in the external beams of the Space Radiation Effects Laboratory (SREL) and Nevis synchrocyclotrons. A quadrupole doublet, Q1-Q2, collects pions produced in the 7.6-cm-long platinum target of the *D* line. The dipole magnet D1 bends the pions through 35° and selects the momentum of those entering the 5-m-long quadrupole channel I. A 90° bend in dipole magnet D2 selects the momentum of muons which come from the backward (c.m.) decays of the pions in channel I. Higher-momentum muons and remaining pions are absorbed in a "pion-beam stop" after bending through smaller angles in D2. A 3-m-long channel II, with larger-aperture quadrupoles, transports the low-momentum muons to the final target, which is thus well separated from channel I and the pion-beam stop.

Neutron background from the proton-beam target, which initially saturated the x-ray detectors, was reduced by placing large steel blocks between the target and the experimental area. In addition, a steel enclosure, 1–3 m thick and lined with borated wax and water, surrounded the helium-target area open only at the rear (see Fig. 2).

With the beam set for 75-MeV/*c* pions decaying into 25-MeV/*c* muons, 10 000 negative muons emerged from channel II into a 2×6-in.^{2} area for 10^{12} incident protons. Of these muons, 300 stopped in a 2-in. depth of 3 atm of He gas, the region illuminated by the laser beam in the vacuum-polarization experiment. (See Fig. 1.) At 1 atm, 100 stopped in the same region. For 90-MeV/*c* muons (from 180-MeV/*c* pions), the total flux was 2×10^5 muons into the same area, but only 75 of the muons stopped in the region for 1 atm of He gas. Muon rates were determined by counting decay electrons in scintillation counter telescopes located outside the He target. The total beam flux was determined by stopping muons in a thick foil. The differential range curve shown in Fig. 3 was taken by measuring the delayed electrons emitted in the decay of negative muons stopping in 1 atm of air. The central momentum of the beam is ~ 20 MeV/*c* after it passes through the window of the beam pipe. After unfolding the thickness of the air from which the electrons emerged, the full width of the range curve corresponds to ~ 70 mg/cm^2 of Mylar absorber compared to the 3-mg/cm^2 thickness of the illuminated region of He gas. A

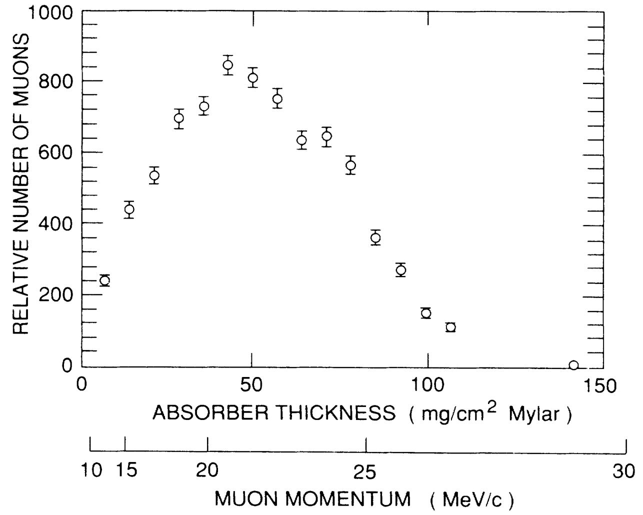

FIG. 3. Differential range curve of the "25-MeV/c" negative muon beam after the muons have passed through the exit window of the beam pipe. For each thickness of Mylar absorber, the relative number of muons stopping in 1 atm of air was determined by counting delayed decay electrons.

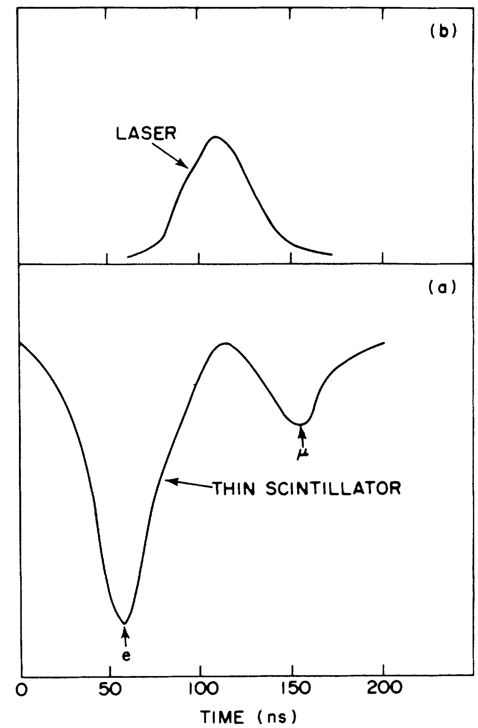

FIG. 4. (a) Representation of the oscilloscope trace of the integrated signal from the thin scintillator, indicating the times of arrival of the electrons and muons in the beam. (b) The output of a photon-drag detector, indicating the relative timing of the laser pulse.

Monte Carlo program, simulating the entire beam line, gave results consistent with the measured values.

The vertical profile of the stopping muon beam at the target position was measured in two ways: (a) by counting the muonic carbon $L\alpha$ x rays emitted from a 0.002-in.-thick Mylar foil, 2.8 in. high and 6 in. wide, which was held at 45° to cover the 2-in. height of the illuminated region and then just above and just below that region; and (b) by counting the decay electrons from muons stopping in a thicker foil strip that was moved through a series of vertical positions. Both sets of measurements gave the result that a total of less than one-third of the muons stopped above and below the central 2-in.-high region.

Figure 4 gives a time spectrum of the integrated light from a very thin (0.005-in.) scintillator situated after the last quadrupole magnet, at the entrance to the helium target. The initial burst of light comes from the electrons in the beam; the second burst, approximately 100 ns later, comes from the slow muons. Adjusted for the dE/dx of the particles, this indicates an electron-to-muon ratio of approximately eight. The thin scintillator signal is also used to adjust the timing of the lasers, so that the light enters the multireflective mirror cavity at an appropriate time before the arrival of the muons.

A detailed analysis was made of the sources of background in the x-ray detectors, based on the timing data and on a series of test runs designed to isolate the various components of the beam in different sections of the magnet line. Of the total counts (which caused dead time in the detectors), approximately 10% came from neutrons from the production target, 20% came indirectly from electrons in the beam, and the remainder came from muons stopping in the gas and heavy parts of the target box.

IV. MEASUREMENT OF K X RAYS

K x rays in the initial cascade from muonic helium were counted in three Si(Li) detectors, 1.6 cm in diameter and 5 mm thick, located ~ 13 cm below the stopping muons (see Fig. 1); the total detecting surface was thus about 6 cm^2. The x rays pass through a 0.010-in.-thick Mylar window in the gas-tight target box and 0.003-in.-thick Be windows in the top plate of the well-shielded detector enclosure. The detectors have a resolution [full width at half maximum (FWHM)] of ~ 700 eV for an integration time of 1 μs or ~ 450 eV for an integration time of 6 μs. The latter is sufficient to separate cleanly the 9.75-keV $K\beta$ x rays from the 8.23-keV $K\alpha$ x rays, with only a small overlap between the $K\beta$ and 10.28-keV $K\gamma$ pulse-height distributions.

Since the pulse of muons is essentially instantaneous compared to the integrating time of the x-ray detectors, only one count can be accepted by each detector during a single AGS burst. The selection of an optimum integration time is therefore a compromise between the improvement in resolution gained by integrating for a long time and the possible reduction in background interference by integrating for a shorter time. In order to permit a later off-line analysis, pulses from each detector were fed simultaneously to two amplifiers with 1- and 6-μs integrating times, as well as to a timing filter amplifier with a 0.5-μs integrating time. The rise of each of the timing pulses, after discrimination, was used to stop a time-to-height converter, which was initiated by a pulse from the AGS.

For each AGS burst, digitized signals were stored on magnetic tape from (a) the two gated pulse heights and the timing from each x-ray detector, (b) the real and accidental rates of delayed counts in the decay electron telescopes, and (c) the light in the thin scintillator, integrated during the muon arrival time, as well as from monitors of the intensities of the proton beam and the lasers.

Figure 5(a) gives a timing distribution of all events recorded in one x-ray detector over the intervals of electron and muon arrival, including many pulses with saturated pulse heights. Figure 5(b) gives the distribution for only those pulse heights in the K x-ray region. The width of the distribution reflects the 40-ns beam spread and the resolution of the detector. A four-bin (60-ns) timing cut, with a small energy-dependent slewing correction, was thus used to reduce background and produce the energy spectrum of K x rays. The spectrum in one detector is shown in Fig. 6.

Fits to the spectrum have been made by varying the amplitudes of Gaussian curves for $K\alpha$, $K\beta$, $K\gamma$, and various combinations of higher K x rays. The centers of the Gaussian curves were fixed at the known energies, and the widths were fixed at the measured resolution of the detectors. This resolution is not sufficient to separate the higher x rays from each other. However, a variation in the fitting program of the relative intensities of the higher x rays makes a very small contribution to the error in the $K\beta$ and $K\gamma$ ratios. The background, which is a major source of error in the $K\beta$ and $K\gamma$ regions, is assumed to be constant over the relatively small range of K x-ray energies and is determined from the level of counts below and above the K x rays and between the $K\alpha$ and $K\beta$ peaks (averaged over the detectors).

A small gain in the energy resolution is obtained by taking a weighted average of the pulse heights from the 6- and 1-μs integration times for each event. Slightly more events are obtained in the 1-μs channel alone because of the lower blocking rate. Combining all of the data from the three detectors for 1 and 3 atm of helium, the results from the fitting program are given in Table I.

TABLE I. Measured ratios of the intensities of K x rays in muonic helium.

	3 atm of He	1 atm of He
$I(K\alpha)/I(K_{tot})$	0.572 ± 0.006	0.599 ± 0.016
$I(K\beta)/I(K_{tot})$	0.097 ± 0.003	0.114 ± 0.010
$I(K\gamma)/I(K_{tot})$	0.070 ± 0.004	0.041 ± 0.010

V. CONCLUSIONS AND DISCUSSION

In several previous experiments,[7,8] the ratios presented in Table I have been measured at pressures lower and higher than those used in the present experiment. A summary of existing measurements of $I(K\beta)/I(K_{tot})$ and $I(K\alpha)/I(K_{tot})$ as a function of pressure is given in Fig. 7.[9] Referring to Fig. 7, the following observations can be made. (i) At pressures higher than a few atmospheres, the $K\beta$ intensity begins to rise with density, signaling the onset of a new regime in which atomic collisions play a major role. (ii) For the purposes of the laser-resonance experiment, in which any $K\beta$ emission not induced by the laser is considered background, the most favorable region of density is just below the point

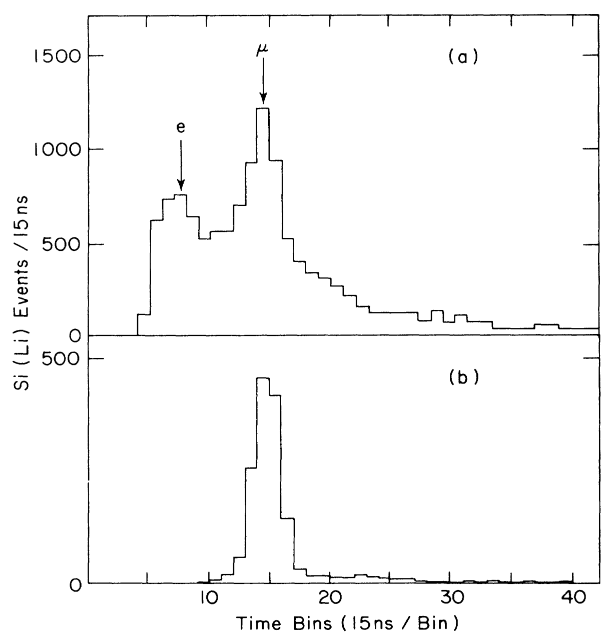

FIG. 5. (a) Timing distribution for all pulses recorded in a Si(Li) detector, indicating which pulses are associated with the electrons and which with the muons in the incident beam. (b) A similar timing distribution for only those pulses with heights which are in the region of the $K\alpha$ x rays from muonic helium.

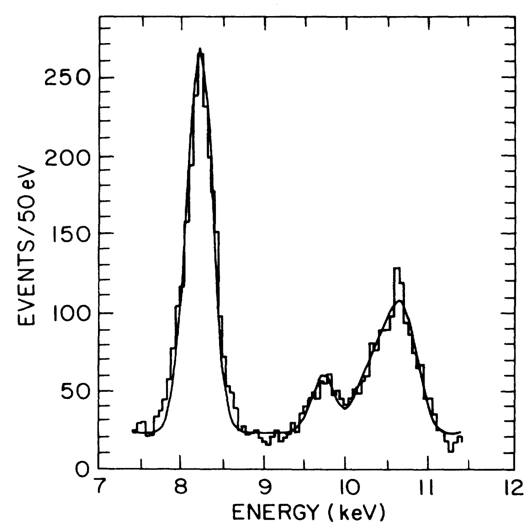

FIG. 6. The energy spectrum recorded in one Si(Li) detector of K x rays from negative muons stopping in 3 atm of helium gas. A timing cut has been made to include only those events with times in a 60-ns interval about the peak shown in Fig. 5(b). The smooth curve is a fit to the data, using Gaussian shapes with fixed centers and widths for the $K\alpha$, $K\beta$, $K\gamma$, and a combination of higher-K x rays, plus a flat background.

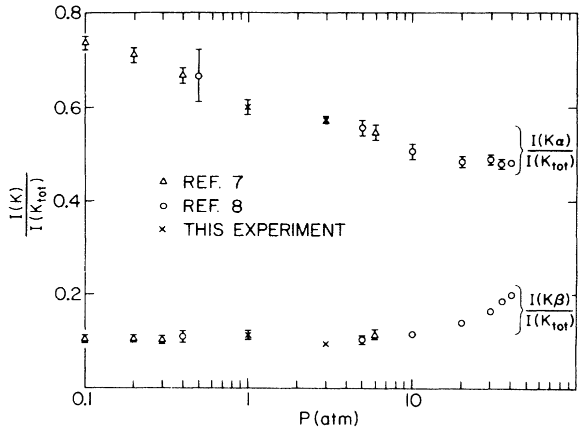

FIG. 7. (a) Measurements from experiments, including this one, of the ratio $I(K\beta)/I(K_{tot})$ for muonic x rays as a function of the pressure of the helium gas in which the muons stop. (b) Similar measurements for the ratio $I(K\alpha)/I(K_{tot})$.

where the $I(K\beta)/I(K_{tot})$ ratio begins to rise.

The K x-ray ratios are important for understanding the cascade of the muonic helium ion from its initial formation down to its ground state. The cascade, which in a dilute gas takes place through Auger and radiative transitions, is modified at higher pressures by atomic collisions. The Stark effect and external Auger effect become major features of the cascade, but they in turn may be influenced by the formation of bound complexes[5,6] between the muonic helium ion and one or more helium atoms, as pressure is further increased. The results of this experiment are in the region of pressure where muon molecular-ion formation begins to be significant.

Data in this experiment were also taken with and without the lasers firing at an appropriate wavelength for the $3d_{5/2}$-$3p_{3/2}$ transition. Following careful shielding from instrumental effects caused by laser discharges, sufficient data were collected to show that the measured ratios of $K\beta$ to $K\alpha$ x rays with and without the lasers firing were equal to an accuracy of 0.014. This is to be compared to a calculated change of 0.006 for induced transitions at the center of the resonance for the laser intensities used.

With the present beam and background conditions, in order to measure the $3d$-$3p$ energy-level difference with sufficient precision to improve upon previous vacuum-polarization tests, an x-ray detector with an area of about 60 cm^2 is required, assuming that the segmentation and energy resolution of the present detectors are maintained.

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