PIONIC AND MUONIC X RAYS IN LIQUID HELIUM*

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Although muonic and pionic x rays from targets of $Z=3$ or greater have frequently been studied, the corresponding x rays from helium have not heretofore been accessible experimentally.[1] We report here the first observation of the K-series lines from both muons and pions being captured into atomic states in liquid helium.

The experimental arrangement is shown in Fig. 1. A 200-MeV/c pion-muon beam from the Space Radiation Effects Laboratory (SREL) 600-MeV cyclotron entered a 3-liter liquid-helium scintillation counter.[2] Stopping particles were signaled by $123\bar{C}\,\mathrm{He}\,\bar{4}$. Differing amounts of polyethylene absorber between counters 2 and 3 provided separation between clearly defined pion and muon peaks in the range curve. Prompt coincidences ($\tau \simeq 175$ nsec) between the particle stop signal and pulses from an 80-mm$^2\times$3-mm thick Si(Li) detector were used as a gate for a 1600-channel analyzer in which the linear signal from the Si(Li) detector was displayed.[3] The energy scale chosen (80.2 eV/channel) allowed simultaneous display of all energy losses in this detector from below the chosen threshold of $\simeq$4 to 120 keV. The resolution of the Si(Li) detector preamplifier was $\simeq$590 eV (full width at half-maximum) at 14.37 keV during the 10-h period of data accumulation.

Figure 2 shows muonic and pionic spectra obtained from liquid helium, together with arrows marking Bohr energy positions and Co^{57} calibration points. There is clear separation of K_α and K_β peaks for both pions and muons, and evidence for K_γ and perhaps higher transitions on the upper sides of the K_β lines. In addition, evidence of muonic contamination of the pion spectrum appears at x-ray energies below the helium π-K_α position. The portions of both spectra from 15 to 100 keV (not shown in Fig. 2) exhibit no well-defined peaks, with only slight irregularities in the background to indicate the possible presence of x rays from elements other than helium. For example, the 50-mil beryllium exit window produced a total of 0 ± 33 counts at the position of the pionic 42.1-keV Be K_α line, thus indicating small contamination by the L lines of Be in the 8- to 11-keV region.

A least-squares analysis, assuming multiple Gaussian peaks plus sloping background, fixed the energies and widths of the observed lines, energies being calculated with reference to the 6.40-keV and 14.37-keV peaks from Co^{57}.[4] The results of the analysis are listed in Table I. Errors in this table were compounded from statistical, system-drift, and system-nonlinearity effects. Calculated energies include corrections to the Klein-Gordon and Dirac energy levels for a point nucleus arising from vacuum polarization and finite-size effects.[5] The latter correction (0.019 keV for the pionic 1s state) was calculated taking the He^4 radius to be $R=2.07$ F.

We conclude from Table I that the observed π-K_α and π-K_β energies are lower than the calculated values by 0.07 ± 0.06 keV. Both the direction and magnitude of this shift are consistent with the nuclear force effect predicted by Deser et al.[6] (0.102 keV) and by Bethe and de Hoffmann[7] (0.10 keV, using the value of Jenkins et al.[8] for the local nuclear potential V_0).

The natural width Γ_n of the π-K_α line was computed from the results in Table I, using the μ-K_α line as a measure of instrumental width. The result is $\Gamma_n = 0\pm 86$ eV, to be compared with the prediction by Eckstein of 351 eV,[9] and by Brueckner of 54 eV.[10]

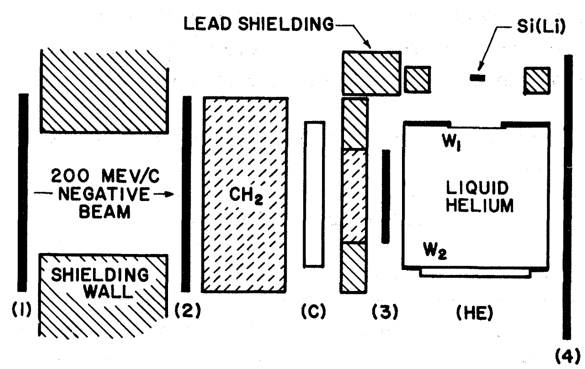

FIG. 1. Plan view of experimental arrangement. W_1 is a 50-mil Be exit window for the x rays. W_2 is a sapphire window through which the scintillation light from the 6-in diameter cylindrical helium counter is viewed. C is a Cherenkov counter used to discriminate against electrons in the beam.

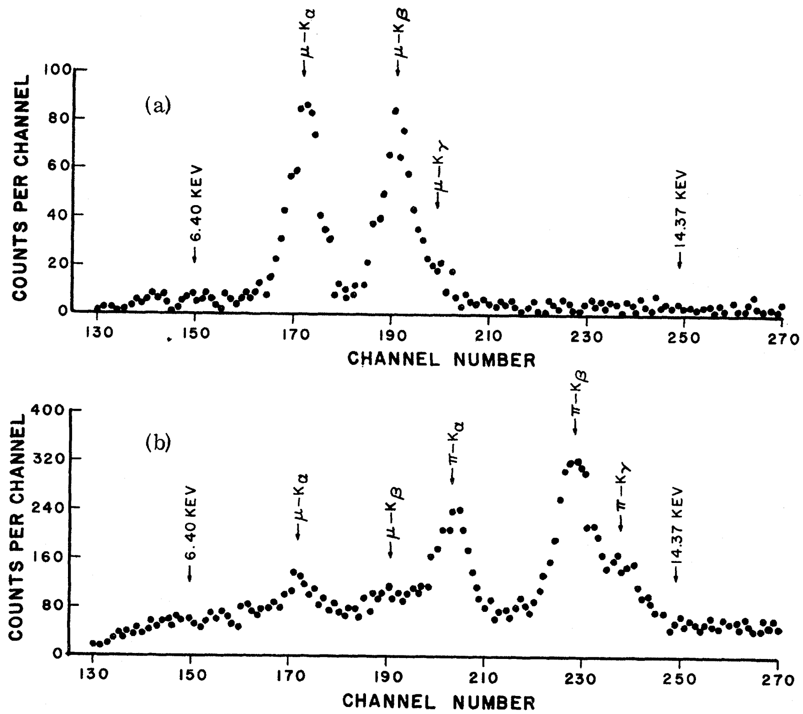

FIG. 2. Pulse-height spectra from Si(Li) detector viewing x rays from (a) muons and (b) pions stopping in He counter. Channel positions corresponding to the calibration energies of Co^{57} are indicated by arrows, together with the energies for the Bohr K series in helium.

The relative yield of $K_\alpha/(\text{all } K)$ was observed to be 0.54 ± 0.05 for muons, which is considerably smaller than for any other light nucleus.[11] The corresponding ratio for pions was 0.31 ± 0.05. At these energies there is substantial self-absorption of the x rays in the liquid helium and in the Be windows. These absorption corrections have been calculated on the assumption that all particles stopped in the center of the helium counter, so that a systematic error may still be present in the yields quoted above. Nevertheless, these data suggest strongly that the $3p$ state is populated comparably to the $2p$ state, in marked disagreement with the usual models[12] in which the captured meson is supposed to pass almost exclusively through circular orbits when it reaches states of low principal quantum number.

Table I. Energies and widths for pionic and muonic K x-rays in helium.

Transition	Calculated energy[a] (keV)	Measured energy (keV)	Measured width (eV)
π-K_α	10.763	10.69 ± 0.06	582 ± 38
π-K_β	12.753	12.68 ± 0.06	633 ± 32
π-K_γ [b]	13.450	13.46 ± 0.08	736 ± 113
μ-K_α	8.218	8.18 ± 0.04	580 ± 25
μ-K_β	9.738	9.70 ± 0.04	580 ± 38
μ-K_γ [b]	10.270	10.34 ± 0.11	480 ± 113

[a]See text.
[b]May also include higher unresolved transitions.

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RELATIVE INTENSITIES OF K AND L SERIES OF MUONIC X RAYS*

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Relative intensities of muonic x rays have been measured for the K series of Ca, S, Si, and Mg and L series of Ca. K_α yields of all the elements are about 80% of the total K lines. The relative intensities of Ca K_γ, K_δ, K_ϵ, and K_ζ x rays are almost constant and are about 2% of the total K lines. A statistical initial distribution of muons in a high-n state might be sufficient to explain the data if electron stripping effects are included in the calculations.

The capture processes of negative muons have been discussed by many authors.[1] The muons are first bound to a nucleus in a high quantum state by the process of Auger capture, then proceed to cascade toward an atomic 1s state by Auger and radiative transitions. The Auger-to-radiative transition branching ratio varies rapidly with the principal quantum number, n, so that the Auger transitions occur when n is larger than some value. If the relative intensities of the radiative transitions are measured some information about the initial capture states, cascade processes, and anomalous intensities of the x-ray yields[2] may be obtained. The ratio of the higher transitions to the total transitions for various elements have been measured.[3]

The negative muon beam from the Carnegie-Mellon University synchrocyclotron mu channel[4] was momentum analyzed by a bending magnet, slowed down by a graphite modulator, and brought to rest in a target. A muon stop in the target was identified by a counter telescope in the usual way. The rate of the stopping muons was about 10 000 per second. The x-ray detector, a lithium-drifted germanium crystal with a volume of about 3.5 cc, was placed right behind an anti counter in order to optimize the counting rate. The signals from the Ge(Li) crystal were registered in a 3200-channel pulse-height analyzer. The gain of the system was stabilized by a digital stabilizer with the Co^{60} 1332.48-keV γ ray as a reference source. The resolution of the system was 3.8 keV full width at half-maximum at 783.8 keV, the K_α x ray of calcium.

The targets were chemically pure powdered magnesium (5.72 g/cm^2), silicon (6.80 g/cm^2), and calcium (5.62 g/cm^2). The sulfur target was a cast block (9.78 g/cm^2) and the iron target[5] consisted of pure iron plates with a total thickness of 9.92 g/cm^2. All the targets were of equal dimensions so that the correction for the effect of the geometrical solid angle on the detector response calibration was negligible.

A typical observed spectrum is shown in Fig. 1. The data correspond to Ca L and K series muonic x rays. The low-energy side of the background under a peak is higher than the high-energy side of the background because of x rays which are Compton scattered by a target element and the materials around the detector. This was taken into account by subtracting background in the following manner. A straight-line background was subtracted from the data counts and the mean channel was found. Both the low- and high-energy sides of the background were then fitted individually by straight lines and the two lines were connected by an integral function of the peak line shape. This new background was then subtracted from the data and a new mean channel was found. This process was repeated until the difference between two successive mean channels was less than some