OBSERVATION OF K-MESONIC X RAYS IN HELIUM*

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We are reporting the observation of x rays from bound atomic states of K^- mesons and He^4 nuclei. Although μ-mesonic and π-mesonic x rays are well known experimentally,[1,2] there have been no previously reported observations of K-mesonic x rays. Definitely observed in this work is a 6.7 ± 0.2-keV x ray assumed to be an $n = 3$ to $n = 2$ transition (L_α). There is also evidence for an $n = 2$ to $n = 1$ transition (K_α) of 34.7 ± 0.3 keV with an intensity about 20% relative to the L_α line. The corresponding Klein-Gordon values for these transitions, corrected for nuclear size and vacuum polarization, are 6.5 and 34.9 keV.

The experimental arrangement is shown in Fig. 1. The beam consisted of unseparated negative particles of momentum 840 MeV/c from an internal target of the Argonne zero gradient synchrotron. A pair of inverse-threshold Čerenkov counters $\check{C}_1$ and $\check{C}_2$ selected K mesons. For an internal beam of 3×10^{11} protons/pulse, approximately 5×10^6 π's and 3×10^3 K's passed through $\check{C}_2$ during a spill time of about 100 msec. The K's were slowed by a Cu absorber and came to rest in a liquid-helium target. Approximately 15 K's per pulse were stopped in the helium. Further electronic selection was provided by a scintillation counter D with a threshold set to respond to K's, which were four times minimum ionizing, but to exclude pions, which were near minimum ionizing. The complete stopping K signal was $\check{C}_1\check{C}_2D$.

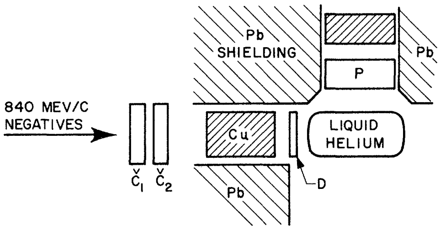

FIG. 1. The experimental arrangement. The K^- mesons in the beam were selected by the Čerenkov counters $\check{C}_1$ and $\check{C}_2$ and the scintillation counter D, degraded by the Cu absorber, and brought to rest in the liquid-helium target. The x rays were detected in the proportional counter P.

The liquid-helium target was a 6-liter vessel of beam depth 4.0 g/cm^2. The target walls were constructed to be transparent to low-energy x rays,[3] so that the x-ray transmission was principally limited by self-absorption in the helium. The x rays were detected by counter P in Fig. 1, a gas-proportional counter filled with argon (10% methane). The counter was 10.5 cm thick, with an effective surface area of 300 cm^2, and its energy resolution at 22 keV was 12.5%. Pulses from P were amplified and recorded by a 200-channel pulse-height analyzer (TMC 401) gated by the stopping-K signal.

The data were taken in a set of six runs, lasting for a period of about eight hours. This was followed by a background run taken with the target in place but empty, and another set of runs in which the target was replaced by a block of natural lithium of thickness 14.9 g/cm^2 along the beam. The system was calibrated during runs with the 22.2-keV line of Cd^{109} and the 5.9-keV line of Fe^{55}.

The target-empty background spectrum was normalized to the total helium spectrum by making the areas of the two curves equal in the region where they are congruent within statistics (channels 40-120). A direct subtraction of the normalized background yields the distribution shown in Fig. 2.

A clear peak is seen around channel 20, and a smaller peak around channel 155. All other regions of the distribution are statistically compatible with a difference of zero counts when summed over a number of adjacent channels corresponding to the resolution width. The number of counts in each peak was found by summing in a region of 20 channels around each peak. For the lower peak, this eliminated the shoulder below channel 10. This gave 3631

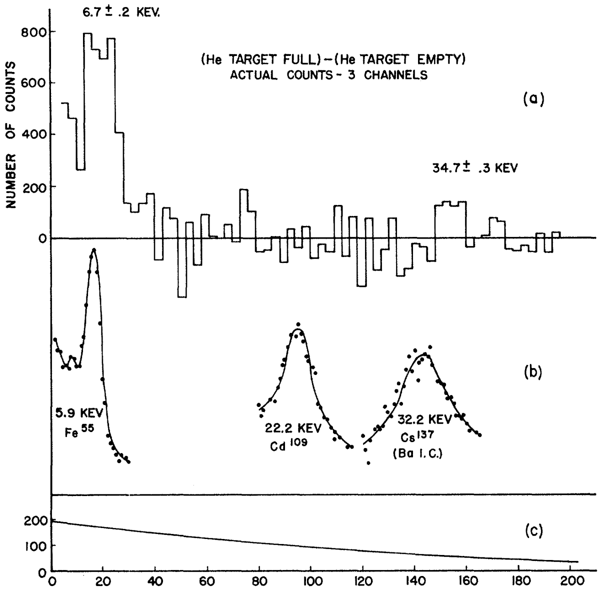

FIG. 2. (a) Pulse-height spectrum of counts detected in the proportional counter, with target-empty background subtracted. (For clarity, the sum of counts in three adjacent channels are plotted.) (b) Pulse-height spectra of three x-ray lines as detected in the same proportional counter. (c) Curve indicating the magnitude of the statistical errors associated with the spectrum in (a). (For example, around channel 90 the error is ±100 counts.)

± 440 counts in the lower peak and 431 ± 164 in the upper one.

The spectra from each of the six runs were analyzed in this manner, and each was consistent with this result. In particular, for each run the number of counts in the region of the upper peak was always positive and different from zero by more than one standard deviation. The spectrum taken with the lithium target was compared to the helium target-empty spectrum. The resulting difference showed no peaks and was statistically compatible with zero over the entire range of channels. This indicated that the presence of matter in the region of the target (such as liquid helium inside the target) does not lead to additional scattering of charged particles into the counter in such a way as to produce apparent peaks.

The energy values given in Fig. 2 were determined by assuming that the peak center is located at the median of the distribution in the 20-channel region around each peak. This located the lower peak at channel 20.5 ± 0.8 and the upper peak at channel 154.8 ± 1.2, corresponding to energies of 6.7 ± 0.2 and 34.7 ± 0.3 keV, respectively. The errors are statistical.

After correction for detection efficiency, we find the ratio of the intensity of the 34.7-keV line to that of the 6.7-keV line to be 0.21 ± 0.12, where the error includes systematic as well as statistical uncertainty. The x-ray detection efficiency includes corrections for absorption, solid angle, and proportional counter efficiency averaged over the target volume. The total efficiency per stopped K^- was 0.0205 for 6.7 keV and 0.0114 for 34.7 keV, with an estimated uncertainty of 5%. At this time it is not possible to give an accurate value for the absolute yield; however, it appears to be large (consistent with 100%, but not with 10%). Further analysis is in progress.

Atomic cascade.—The problem of the atomic cascade process of K^- mesons in helium is discussed by Day.[4] Besides the usual mechanisms for de-excitation (radiation and the Auger effect), he considers collisional mechanisms, such as Stark mixing, which can facilitate nuclear capture by producing transitions to S states within a principal level. Our result shows that most K mesons escape nuclear capture until they reach low-lying levels ($n = 3$, 2, and 1), so that the collisional-state mixing effects[4] do not dominate the cascade process. This conclusion agrees with the recent observations of π^- and K^- cascade times in helium,[5-7] which find an average cascade time roughly consistent with Auger and radiative transitions alone. The radiative cascade process favors the arrival of K mesons in low-lying states with the largest possible value of angular momentum. Therefore, about 80% of those reaching the $n = 2$ level are captured from the $2P$ state, and about 20% radiate to the $1S$ state and are captured.

Nuclear P-wave capture.—The radiative transition probability from the $2P$ to the $1S$ state is calculable.[8] The perturbation due to strong interactions should be small, since the meson Bohr radius is 31 F, which is much larger than the helium nucleus. The competition between radiation and capture serves to measure the capture rate from the $2P$ state. Using the experimental ratio of the line intensities and the calculated $2P$ to $1S$ transition rate, we find

$$\Gamma_{\text{capture}}(n=2) = 3.3^{+3.4}_{-1.2} \times 10^{13}\ \text{sec}^{-1}.$$

A previous estimate of this rate, $\Gamma_{\text{cap}}(2p) \approx 5 \times 10^{14}\ \text{sec}^{-1}$, was given by Day,[4] using experimental S-wave K^--proton results and assuming that the K-single-nucleon S-wave absorption amplitude is proportional to the overlap of the atomic P wave with the helium nucleus. Day's estimate is greater than our observed value by an order of magnitude. The capture rate in helium can be related to the K-nucleon P-wave interaction by assuming additivity of the isotopic spin amplitudes in the K-α system. Following Jackson, Ravenhall, and Wyld, Jr.,[9] we can write $\Gamma_{\text{cap}} = (12\pi\hbar/\mu)(3b_1^{\,p} + b_0^{\,p})|\nabla\psi(0)|^2$, where $b_{1,0}^{\,p}$ determine the absorption in an effective range approximation for K-nucleon P waves. Using this, our result gives

$$3b_1^{\,p} + b_0^{\,p} \approx 0.018 \text{ F}^{+3}.$$

Level shift.—The strong interaction of K^- with the helium nucleus may produce a level shift[10-13] of the atomic $n = 1$, 2, and 3 levels involved in the observed x-ray transitions. Under the assumption that any observed deviation of the transition energies from Klein-Gordon values for the K^--α system is due to shift of the 1S ground state, our observation gives a maximum shift of $\Delta E_{1S} \leq 0.4$ keV. This can be related to the K^--α scattering length A. In the approximation[12] that $A/B \ll 1$, where B is the K mesonic Bohr radius in helium, $\Delta E/E = -4A/B$, and our result is $|A| \leq 0.07$ F. In π-mesonic atoms qualitative agreement with experiment[13] is obtained by assuming that the effects of the nucleons are simply additive.[10] The same assumption[14] here gives $|3a_1^{\,S} + a_0^{\,S}| \leq 0.07$ F, where $a_{0,1}^{\,S}$ are the real parts of the $\bar{K}$-nucleon S-wave scattering lengths in the isospin channels 0 and 1. This condition is not satisfied by sets of scattering lengths published so far.[15-18]

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