

Measurement of Kaonic X Rays from  ${}^4\text{He}^\dagger$ 

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Three spectral lines corresponding to Bohr orbit transitions  $n=3 \rightarrow 2$ ,  $n=4 \rightarrow 2$ , and  $n=5 \rightarrow 2$  in liquid  ${}^4\text{He}$  have been measured with a resolution of 340 eV. Intensities per stopped kaon were 0.09, 0.05, and 0.02, respectively. No evidence was seen for transitions to  $n=1$  (intensity  $< 0.004$ ).

Kaonic x rays are emitted from excited states of  $K^-$  mesons bound to nuclei by Coulomb forces. When negative kaons stop in matter they are captured into Bohr orbits of large principal quantum number,  $n$ , and form hydrogen-like atoms that undergo de-excitation by the Auger effect and the emission of x rays. Several experiments<sup>1</sup> have studied the kaonic x rays of many elements from  $Z=2$  through 92. Helium is particularly interesting because the  $K^-$ - $\alpha$  interaction is amenable to calculation and has been extensively studied in He bubble chambers. An understanding of the  $K^-$ - $\alpha$  system is useful for determining the combined parity of kaons and hyperons. For example, are kaons absorbed by the nucleus from  $s$  states or  $p$  states? The present experiment indicates that at least 16% are absorbed from  $p$  states.

Two previous attempts to observe the kaonic x rays of  ${}^4\text{He}$  gave contradictory results. The most recent experiment by Berezin, Burlson, Eartly, Roberts, and White<sup>2</sup> disclosed *no* identifiable x-ray lines from He with yield limits of  $K\alpha(2p \rightarrow 1s) = 0.06 \pm 0.05$  and  $L\alpha(3d \rightarrow 2p) = 0.03 \pm 0.07$ , although the first experiment reported by Burlson, Cohen, Lamb, Michael, and Schluter<sup>3</sup> claimed to have definitely observed a  $6.7 \pm 0.2$ -

keV line with an apparently large absolute yield. Also reported in the earlier work was evidence for a  $34.7 \pm 0.3$ -keV line whose intensity compared with the intensity of the 6.7-keV line was  $0.21 \pm 0.12$ .

In a recently completed experiment at the Bevatron of the Lawrence Berkeley Laboratory, we obtained the spectrum shown in Fig. 1. The spectrum is from a Si(Li) detector and is presented exactly as it came from the spectrometer. For comparison, see Michael, Fig. 4.<sup>3</sup> Three x-ray lines from  ${}^4\text{He}$  are seen with peak-to-background ratios of about 5:1 for two of the lines and 2:1 for the third line. In Fig. 1 an arrow at 35.0 keV indicates the region of the spectrum where x rays from transitions  $n=2 \rightarrow 1$  would be expected if there were no energy shift due to strong interactions. Clearly no line is observed. An ultrahigh-purity Ge detector also verified the absence of x rays at 35.0 keV. Along with the  ${}^4\text{He}$  spectrum there are weak x-ray lines from kaons that stopped in the graphite energy degrader and the massive aluminum structure of the He target. There is also a weak line at 18.36 keV that corresponds to pionic-atom x rays from carbon.

The experimental arrangement to obtain and

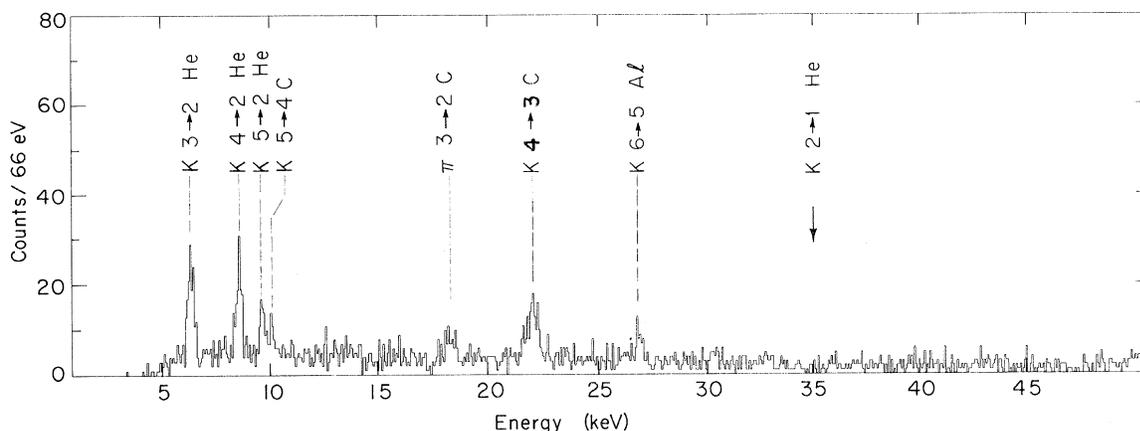


FIG. 1. Kaonic x-ray spectrum of  ${}^4\text{He}$  with energy resolution 340 eV. Lines from C and Al came from particles stopped in the graphite energy degrader and the Al structure of the target.

register stopped negative kaons was the same, except for the He target, as that employed by Wiegand and Mack<sup>1</sup> and Wiegand<sup>1</sup> in previously reported kaonic x-ray experiments. Helium at 2.5° K was contained in a flask 10 cm in diam with a total Mylar window thickness of 0.06 g cm<sup>-2</sup>.

Detector systems were the essence of this experiment and were the latest in a series developed by Goulding, Hansen, Landis, and Pehl.<sup>4</sup> The Si(Li) detector was 1.8 cm in diam by 0.4 cm thick. The Ge detector was the same size but of such high-purity material that Li compensation was unnecessary. The detectors were placed 10 cm from the center line of the kaon beam.

Table I shows the estimated intensities of the x-ray lines per stopped kaon, defined by

$$I = N_x [K_s T \eta (\Delta\Omega/4\pi)]^{-1}, \quad (1)$$

where  $N_x$  is the number of x rays in a spectral line,  $K_s$  is the number of kaons stopped in the target,  $T$  is the x-ray transmission of the target,  $\eta$  is the detector efficiency, and  $\Delta\Omega/4\pi$  is the solid angle subtended by the detector. Errors in the intensity include statistics and an estimate of the uncertainty in the true number of stopped kaons. Detector efficiency and target-window transmissions were determined by using calibrated radioactive sources and a mock-up target. Photoelectric absorption in the He itself was based on data from McMaster *et al.*<sup>5</sup>

The relative intensities are more accurate than the absolute values because it is difficult to determine the number of kaons stopped in the He and the effective solid angle subtended by the detectors. As an aid in estimating the number of stopped kaons, we constructed an "artificial" He target (actually made of carbon dust) that had the same geometric configuration and electron density as the real He. We assumed that the same fraction of beam kaons stopped in the real He and the "artificial" He and that the effective solid angle was the same in the two cases. Then the

following relation applies:

$$\frac{K_s(\text{He})}{K_b(\text{He})} = \frac{K_s(\text{artificial He})}{K_b(\text{artificial He})}, \quad (2)$$

where  $K_s$  is the true number of stopped kaons in He (or artificial He) and  $K_b$  is the number of kaons in the beam incident on the targets. The  $K_s$  (artificial He) was calculated from the intensity of the  $n = 4 \rightarrow 3$  transition in C as measured in a simpler geometry.

If we sum the intensities of the three lines of Table I, we note that about 16% of the stopped kaons arrived at  $n = 2$  and less than 0.4% made transitions from  $2p$  to the ground state. The transitions we measured were  $n = 3 \rightarrow 2$ ,  $n = 4 \rightarrow 2$ ,  $n = 5 \rightarrow 2$ —most likely  $3d \rightarrow 2p$ ,  $4d \rightarrow 2p$ , and  $5d \rightarrow 2p$ —and nuclear absorption took place from the  $2p$  state at a rate at least  $0.16/0.004 = 40$  times the radiation rate. From the  $2p$  state of kaonic He the radiation rate is  $P_{\text{abs}} \geq 0.85 \times 10^{13} \text{ sec}^{-1}$ , and therefore  $P_{\text{abs}} \geq 3 \times 10^{14} \text{ sec}^{-1}$ . Block, Kopelman, and Sun<sup>6</sup> (in their Table II), using Day's theory,<sup>7</sup> predict  $P_{\text{abs}}(2p) = 5 \times 10^{14} \text{ sec}^{-1}$  in agreement with the lower limit of the present experiment. It seems that additional absorption due to a Stark mixing is not necessary to account for the observations. An absorption rate of  $5 \times 10^{17} \text{ sec}^{-1}$  would be needed to broaden a line to that of our resolution, 340 eV. Therefore, we did not miss x rays due to broadened linewidth unless there were transitions to  $s$  states that were broadened to more than about 1 keV.

Our results have a bearing on the question of metastable orbits of heavy mesons in liquid He. Two measurements<sup>6,8</sup> of the average cascade time  $T_c = \tau(N_d/N_t)$  have been made in liquid-He bubble chambers by counting the number of kaon decays at rest,  $N_d$ , and the total number of stopped kaons,  $N_t$ . The mean kaon lifetime  $\tau$  is  $1.24 \times 10^{-8} \text{ sec}$ . The value obtained was about  $(2.8 \pm 0.3) \times 10^{-10} \text{ sec}$ . The calculation by Day<sup>7</sup> predicted a shorter cascade time than that observed. To account for the long cascade time, Condo<sup>9</sup> conjec-

TABLE I. Summary of <sup>4</sup>He kaonic x-ray data. Calculated energies are Klein-Gordon plus corrections for vacuum polarization. The numbers of x rays were corrected for detector efficiency and target absorption.

Transition	$E_{\text{calc}}$ (keV)	$E_{\text{obs}}$ (keV)	$E_{\text{obs}} - E_{\text{calc}}$ (keV)	Observed	Corrected	Intensity per stopped kaon
$3d \rightarrow 2p$	6.47	$6.47 \pm 0.05$	0	$115 \pm 13$	$250 \pm 28$	$0.092 \pm 0.02$
$4d \rightarrow 2p$	8.73	$8.65 \pm 0.05$	-0.08	$101 \pm 13$	$140 \pm 18$	$0.052 \pm 0.01$
$5d \rightarrow 2p$	9.78	$9.73 \pm 0.10$	-0.05	$51 \pm 9$	$65 \pm 11$	$0.024 \pm 0.006$
$2p \rightarrow 1s$	35.0	• • •	• • •	$-6 \pm 5$	$-6 \pm 5$	$-0.004 \pm 0.004$

tured that a small fraction of the kaons might be detained in metastable orbits of high  $n$ . Condo's notion was discussed by Russell<sup>10</sup> who extended the idea to antiprotonic He atoms. A recent calculation by Fetkovich, Riley, and Wang<sup>11</sup> further supported the trapping of kaons in metastable orbits from which a few percent decay. However, we found that 16% of the kaons made radiative transitions to  $n=2$ , and adding the 2% that have been seen to decay in bubble chambers shows that at least 18% did not get forced into nuclear absorption by Auger, Stark, or other processes. The appearance of radiation from kaons in low-lying  $d$  states could mean that they had spent sufficient time in orbits of  $n \sim 10$  to allow for the observed decays and thus obviate trapping in metastable orbits.

Berezin *et al.*<sup>2</sup> made a calculation of atomic-state populations in the de-excitation of muonic and pionic He and found that, to achieve agreement with experiment, it was necessary to include weak collisional (Stark) mixing in the form of "sliding transitions." They used their pionic results to predict that in kaonic He the  $3d$  state population would be 16%. This is in fair agreement with our observation of 9%.

Observed transition energies listed in Table I were determined by comparing the pulse heights of He kaonic x-ray signals with those of standard sources by means of a 4096-channel pulse-height analyzer. Center channels of all the lines were defined by fitting modified Gaussian curves to the pulse-height distributions. The energies of the kaonic lines were then determined by linear interpolation between lines of known energy. Calibrations were made before, during, and after collection of the data and included Mn x rays (5.895 keV) and Np x rays (11.89 and 13.94 keV) from sources of <sup>55</sup>Fe and <sup>241</sup>Am. The error in the energies of the  $3d \rightarrow 2p$  and  $4d \rightarrow 2p$  lines is estimated to be  $\pm 50$  eV, but, because of the interference of the kaonic C line with the He  $5d \rightarrow 2p$ , we estimate its error to be  $\pm 100$  eV.

The calculated energies were provided by God-

frey<sup>12</sup> who computed the Klein-Gordon energies and vacuum polarization for both the noncircular and circular orbits of kaonic He. Energies of the states with the same  $n$  but different  $l$  were equal within 1 eV. Vacuum polarization of the  $2p$  level was the only significant correction and amounted to 15 eV. We assumed that corrections for finite nuclear size and screening effects were negligible.

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