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MEASUREMENT OF K^--MESONIC X RAYS FROM Li, Be, B, AND C†

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K^--mesonic x rays were first observed in He by Burleson et al.[1] We report here the measurements on several lines emitted by the light elements Li^7, Be^9, B^{nat}, and C^{12} and compare them with the predictions of Eisenberg and Kessler (EK).[2] The K-particle beam is described[3] as beam No. 5. Particles of momentum 500 ± 10 MeV/c full width at half-maximum were slowed down in an energy degrader equivalent to 47 g cm^{-2} C in the arrangement shown in Fig. 1. The targets in which the K^- mesons stopped were 5×5 cm^2 transverse to the beam and had the following lengths and thicknesses: LiH, 6.0 cm and 4.4 g cm^{-2}; Be, 6.2 cm and 11.4 g cm^{-2}; B, 6.0 cm and 3.2 g cm^{-2}; and CH_2, 6.0 cm and 5.5 g cm^{-2}.

Two separate systems were used to measure the x rays: (1) an array of four lithium-drifted silicon detectors 0.3 cm thick with a sensitive-area diameter of 1 cm each, and (2) a lithium-drifted germanium detector 2.1×1.5 cm^2 by 0.4 cm thick.

The detectors were placed as close as practicable to the targets as indicated in Fig. 1. Each detector element was connected directly to the gate of a field-effect transistor and they were operated in vacuum at temperatures prescribed by Bowman et al.[4]

Each Si(Li) detector had its own preamplifier and amplifier. The four channels connected to the Si detectors were electronically identical and their amplifier outputs were joined together by a mixer circuit of conducting transistors. The combined signals were fed to a pulse height analyzer (PHA) for accumulation of the data. The Ge(Li) detector channel was conventional and was connected to a separate PHA.

The electronic command to store data was generated by the K-particle counter telescope

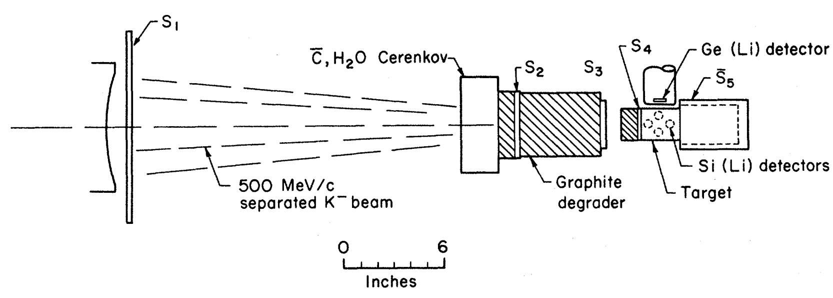

FIG. 1. Plan view schematic of the arrangement of the apparatus.

consisting of scintillation counters S_1, S_2, S_3, S_4, $\bar{S}_5$, and Cherenkov counter $\bar{C}$ ($\bar{S}_5$ and $\bar{C}$ were connected in anticoincidence). The sensitivity of thin counter S_4 was adjusted to respond only to particles of high specific ionization. A count in S_1, $\bar{C}$, S_2, S_3, S_4, and $\bar{S}_5$ indicated that a low-velocity particle had either stopped in or scattered out of the target. From a range curve of telescope counts versus degrader thickness, we estimate that about 0.9 of the events S_1, $\bar{C}$, S_2, S_3, S_4, $\bar{S}_5$ were caused by K mesons stopping in the target. Counter $\bar{S}_5$ actually had the shape of a five-sided box and was placed around the target when π^- mesons were stopped for calibration purposes. $\bar{S}_5$ could not be left around the target when K^- particles were stopped because the K^- reaction products would cause many events to be vetoed—for example, $K^- + p \rightarrow \Sigma^+ + \pi^-$, in which the pions would be counted by $\bar{S}_5$. The signals generated by stopping K^- particles were used to open gates at the entrance to the PHA's. No coincidence signals from the x-ray detectors were required to open the gates.

The number of K^- stopped per Bevatron pulse depended upon the intensity of the external proton beam and the thickness of the target. Most of the data were collected by stopping about 10 K^- per pulse although 50 per pulse were attainable at 10 pulses per minute.

In practice a period of operation was started and ended by calibrating the apparatus with an Am^{241} source of x rays. The individual channels of the Si(Li) detectors were adjusted separately to make their pulse height outputs equal for a selected spectral line. The fact that the resolution was practically the same with one or more detectors contributing to a stored spectrum shows that the channels were remarkably linear in output with respect to x-ray energy. All amplifier circuits had excellent stability. Spectrum peaks shifted no more than one channel out of 100 channels during any run of typically 12-h duration. K^--mesonic spectra were printed out at intervals of 2 to 4 h in order to safeguard the accumulated data in event of a power or equipment failure.

Figure 2 presents the accumulated spectra. The three lines of Am^{241} serve only to determine the energy scale of the LiH data and are not part of the efficiency calibration. The LiH spectrum was taken before the Ge(Li) detector was put into operation. For the LiH data only we used the second PHA to measure background.

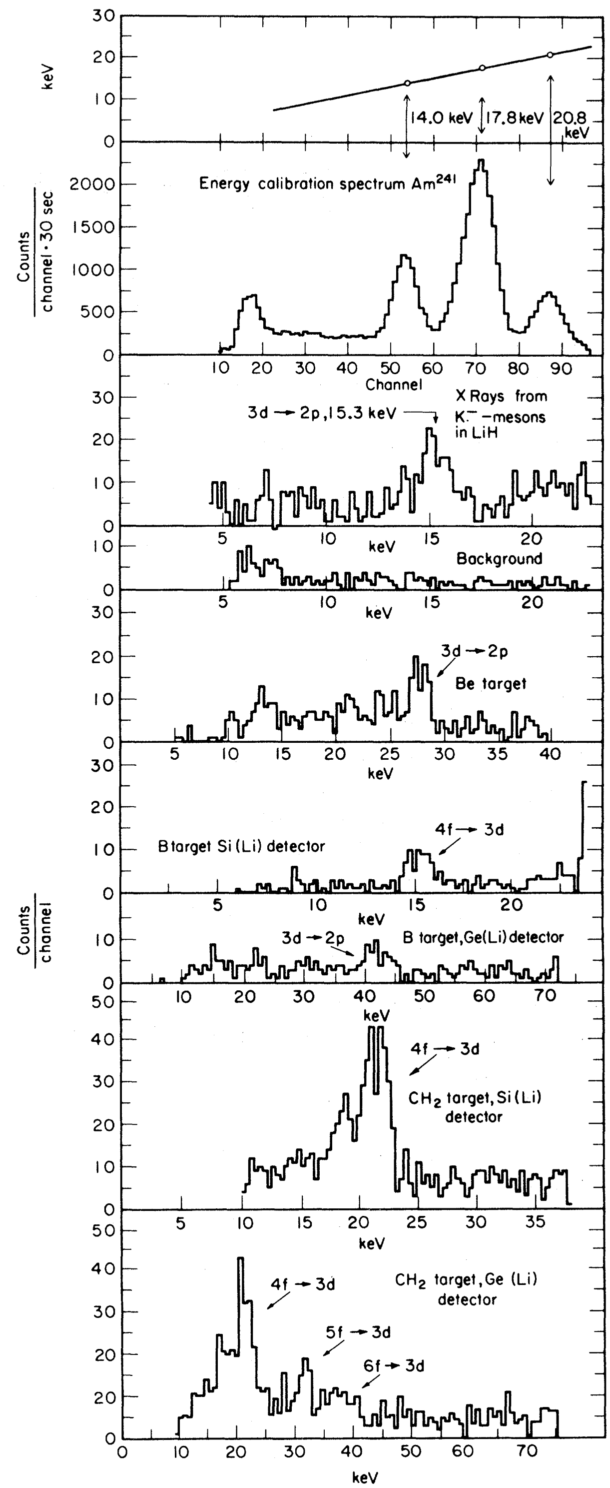

FIG. 2. Experimental x-ray spectra. The curves above the LiH spectrum show how the energy scales were established by means of an Am^{241} source. Only the LiH data had a background subtracted and this background is shown immediately beneath the LiH data.

This was accomplished by delaying one of the PHA gates to open 5 μsec after each K^- stop. The net number of counts in each channel is plotted along with the background that was subtracted. This particular kind of background amounted to 23% of the total number of counts. In the early stages of the experiment, several spectra were taken of K^- stopped in LiH under various beam conditions and amplifier settings. The main peak always came at 15.3 keV.

The spectrum taken with the Ge(Li) detector of K^- stopped in CH_2 is composed of two runs taken at different amplifier gain settings. The energy scale of one spectrum was adjusted to coincide with the other. All the other spectra are plotted from PHA printouts without any kind of manipulation of the data. Energy scales were determined by Am^{241} calibrations.

Table I presents a summary of the results. Explicit transitions are listed along with their Klein-Gordon (KG) energies even though states with the same principal quantum number have nearly the same energies. If Stark mixing is important, other transitions may occur including those to $l=0$ and consequent absorption by the nucleus. Within the limits of our detector resolution, all the observed lines are consistent with KG energies. We tried especially to find a line from C^{12} in the region of 63 keV ($3d \to 2p$) because the energy was predicted by EK to be 1.15 keV higher than the KG energy. Unfortunately the yield of x rays from transitions to $n=2$ was too low to detect in our experiment.

The yield is defined as the number of x rays in a given spectral line per stopped K^- meson. To find the yield we must determine three quantities: (1) the number of x rays in the line under investigation, (2) the number of K^- stopped in the target, and (3) the efficiency to detect the x rays. The number of x rays were determined by estimating the counts in the peaks of the spectra. Although the Am^{241} spectra give an idea of the resolution, the true resolution might be compromised because of extraneous pions passing through the target and general ambient backgrounds. The background must be estimated from the performance in channels adjacent to the peaks. Finally, the limited number of events sets a statistical limit on the accuracy.

The number of stopped K^- was estimated from a range curve to be 90% of the trigger rate.

The detector efficiencies given in Table I stem from a calibrated source of Am^{241} procured from the Vienna office of the International Atomic Energy Agency. The standard source is said to emit 1.60×10^5 sec^{-1} x rays at 59.54 keV. However, we are interested in the emissions at 26.4, 20.8, 17.8, and 14.0 keV, and have used the work of Magnusson,[5] who gave the relative intensities of the above lines as: 100, 7.0, 13.8, 51.2, and 37.5, respectively. In practice the standard source was placed at several positions within the Be and CH_2 targets, which were made up of slabs. Then the average counting rates of each line were determined with the detectors in their regular positions. It was impractical to put the source inside the LiH and B targets so extrapolations from external positions were made. The average over the target volumes was justified because the K^- particles stopped with an almost uniform distribution throughout the target. Having determined the efficiencies (counting rate/source rate) at the energies of the Am^{241} lines, we could interpolate to the efficiencies at other x-ray energies. The yields predicted by EK were based on initial distribution of K^- mesons

Table I. Summary of data.

Isotope	Transition	KG (keV)	Number K^- stopped	Number x rays	Detector type	Detection efficiency	Yield experimental
Li^7	$3d \to 2p$	15.3	215 000	225	Si(Li)	5×10^{-3}	0.21 ± 0.07
Be^9	$3d \to 2p$	27.6	99 000	60	Si(Li)	4×10^{-3}	0.15 ± 0.06
B^{nat}	$3d \to 2p$	43.6	81 000	40	Ge(Li)	7×10^{-3}	0.07 ± 0.03
B^{nat}	$4f \to 3d$	15.2	81 000	50	Si(Li)	2×10^{-3}	0.3 ± 0.15
C^{12}	$3d \to 2p$	63.0	186 000	...	Ge(Li)	7×10^{-3}	<0.04
C^{12}	$4f \to 3d$	22.0	190 000	220	Si(Li)	5×10^{-3}	0.23 ± 0.07
C^{12}	$4f \to 3d$	22.0	186 000	150	Ge(Li)	4×10^{-3}	0.20 ± 0.07
C^{12}	$5f \to 3d$	32.2	186 000	45	Ge(Li)	6×10^{-3}	0.04 ± 0.02
C^{12}	$6f \to 3d$	37.8	186 000	45	Ge(Li)	6×10^{-3}	0.04 ± 0.02

in the $n = 14$ level of the type $(2l+1)\exp(0.2l)$. The cascading process was presumed to be governed by conventional radiative- and Auger-transition probabilities. Finally, it was necessary to assume a parameter that characterized the strength of absorption of K^- by the nucleus.

Eisenberg and Kessler predicted the total yields of the x-ray series L, M, N, etc. for three values of a nuclear capture parameter; $\tau_K = \hbar/2W$, where τ_K is the mean life of K^- in nuclear matter and W is the imaginary part of the optical potential. They also list the ratios $L_\alpha/L_{\text{total}} \simeq 0.7$ for $Z = 3$ to 7. We measured the L_α yields for Li, Be, and B, and can compare them with the predicted values of EK (Fig. 1 of Ref. 2) by dividing the experimental values by $\simeq 0.7$. Our values are consistently lower than the theoretical curves implying that the nuclear absorption is stronger than anticipated. We also measured yields for M_α, M_β, and M_γ from C^{12} and find agreement with the predicted value of the ratio $M_\alpha/M_{\text{total}} \simeq 0.7$ for $Z = 5$ and 6. By dividing our M_α yields for B and C by 0.7, we can compare the experimental total M yields with the predicted values. Here we find somewhat better agreement. At the $n = 3$ level for $Z = 5$ and 6, the yields are not affected by nucleon capture but depend upon the initial meson distribution and the cascade mechanism.

Von Hippel and Douglas[6] and Uretsky[7] have attempted to fit to a satisfactory theory the results of Burleson et al.[1] on K^--mesonic x rays from He. The results of our work point to the need of further theoretical studies. In the meantime we hope to extend and improve the present experiment.

We wish to express our appreciation for the work of Terry Ricketts on the electronics. We gratefully acknowledge the contributions of our colleagues for making the detectors and the loan of their equipment. We wish to thank the Bevatron crew for their cooperation. Our appreciation is expressed to Professor E. Segrè for his suggestion that we search for the K^--mesonic x rays and his continued interest.

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DIRECT OBSERVATION OF COLLISION BROADENING AND EFFECT OF RESONANT INTERACTIONS ON GAS-LASER TRANSITIONS*

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Recently, the Lamb theory of a gas laser[1] has been modified by several authors[2-7] to allow for collision effects on the single-mode, power-tuning characteristics. At low pressures, this modification may be made by substituting the total phase-interruption rate including collisions for the spontaneous decay rate for each state. In that limit, the interaction probability of an excited atom with running waves at the optical frequency may be solved exactly.[8] The response about the Doppler-shifted resonance frequency is Lorentzian, with a width which increases linearly with gas density at low fields. Since the third-order theory of Lamb in effect ignores power broadening of these Lorentz widths,[9,10] the simple addition of a pressure-dependent term to the natural width appears consistent with the other approximations in this theory. The collision rates in fact reduce the importance of power broadening at low intensities. (Without collisions, power broadening would be extremely important in typical He-Ne lasers.) However, the power-broadening terms can also result in a satura-