Radiative Yields of the K Series in π-Mesonic Atoms*

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The total radiative yields of the K-series lines from π-mesonic atoms have been measured for the elements Li through F, inclusive, and Na. The yield is a maximum at Be, 21%, and falls to about 3% at Na. The yields of N, O, and F are roughly comparable. This anomaly may be due to a magic-number effect at $Z=8$.

THE formation of short-lived π-mesonic atoms as a preliminary step in the absorption of π mesons by nuclei is a well-established fact. K, L, and M emission lines from these atoms have been studied in varying detail by several groups.[1,2] An important motivation for these investigations is to study the specific pion-nucleus interaction. The effect of this interaction on the energy shift of the $2p\rightarrow 1s$ (K_α) lines has been discussed in an earlier paper[3] (henceforth referred to as I). Of equal interest is the effect of this interaction on the nuclear absorption of mesons directly from their excited states. As will be shown, this absorption process increases very strongly with increasing Z, and, since it competes with radiative transitions, it is strikingly exhibited by a decrease in the mesonic x-ray yield. Because of this direct competition, its strength can be measured in terms of the well-known radiative-transition probabilities. In this paper we discuss some recent measurements of the absolute radiative yields and relative intensities of the K series ($2p\rightarrow 1s$, $3p\rightarrow 1s$, etc.). Some preliminary measurements of the relative yields have been reported earlier.[1] These have been repeated more carefully with improved technique. The elements investigated were Li through F, inclusive, and Na. The K yield was unobservable (<3%) for elements heavier than Na. For these heavier elements the mesons are predominantly absorbed directly from the p states and hence cannot radiate to the ground state.

EXPERIMENTAL PROCEDURE

The experimental apparatus and procedure is similar to that described in a previous paper on μ-mesonic atoms[4] (henceforth referred to as II). As discussed in II, the raw experimental data must be corrected for the following: (1) absorption and scattering of the x-rays in the meson target, the anticoincidence counter, and the aluminum window of the NaI detector; (2) escape x-rays from the NaI detector; (3) carbon x-rays originating in the third counter of the meson telescope: (4) x-rays from undesired elements (in the case of compounds) and contaminants; (5) the variation with energy of the NaI detection efficiency. Most of these corrections can be taken directly from the μ-meson work, with only slight modifications due to the different mass of the π meson and hence the energy of the characteristic x-rays.

A $\frac{1}{16}$-in. thick NaI crystal was used as the x-ray detector for lithium and beryllium and their matching carbon targets. A $\frac{1}{2}$-in. thick NaI crystal was used for Be, B, C, and N and a 2-in. crystal for C, N, O, F, and Na. The efficiencies of the crystals were calculated and measured in the manner described in II. The meson targets were the same as those used in the μ-meson work.

RESULTS

Some typical K-series spectra are shown in Fig. 1. For some of the elements the backgrounds are rather large compared to the peaks because of the small radiative yields of the K x-rays. In order to estimate the backgrounds reliably considerable care was taken in examining each spectrum well above and below the K line. Since the 24-channel pulse-height selector used in the experiment did not have a sufficient number of channels to observe the detail desired, it was set, in successive runs, to scan overlapping energy regions, usually three or four. These were then combined to give the complete spectrum. The curves of Fig. 1 are these composite curves. In addition to the predominant $2p\rightarrow 1s$ (K_α) peak one sees contributions from higher transitions (K_β to K_∞), escape x-rays, and the contaminant carbon x-rays originating in the third counter of the meson telescope. The K_α line is not clearly resolved from the higher transitions. This is due to the inherent limited resolution of the NaI detectors at these energies (~40% at 22 kev to about 20% at 90 kev for the $\frac{1}{16}$-in. and $\frac{1}{2}$-in. crystals) and to the close spacing of the K lines [$E(K_\beta)/E(K_\alpha)\approx 1.18$]. The widths of the peaks are purely instrumental and are discussed in I.

Table I gives the energies of the K_α lines, the absolute total K-radiative yields (per stopped meson), and the fractional yield of higher transitions for the elements Li through Na. The energies of the K_α lines are taken from I. In all cases the measured values, which are listed in the table, are less than the calculated values.

At this point it should be emphasized that the absolute radiative K yields measured in this experiment are the number of K x-rays emitted per meson stopped in the target. For comparison with theory the more pertinent quantity, but at present unattainable, is the

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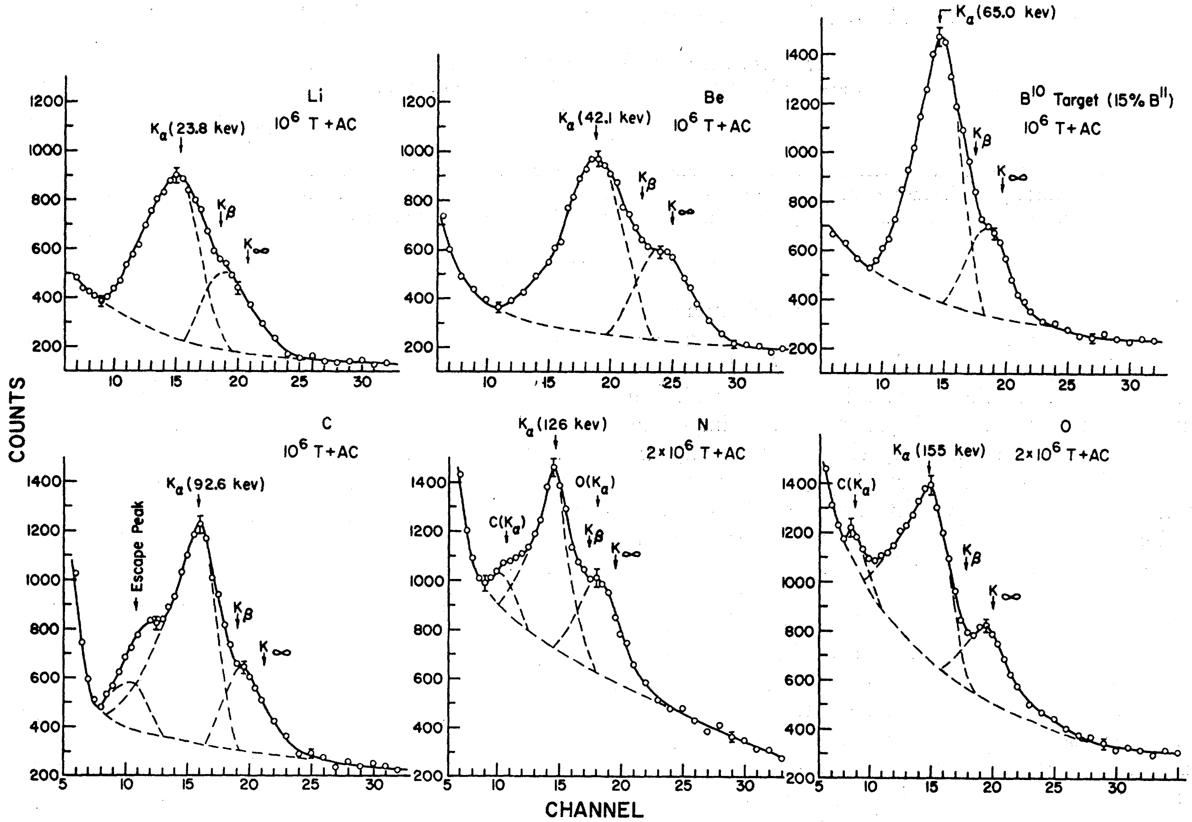

FIG. 1. Typical $\pi-K$ spectra. $T+AC$ (triples plus anticoincidence) indicate the number of mesons stopped in the target. The $\pi-C(K)$ contamination arises from mesons stopping in the third counter of the meson telescope. The higher transitions are not clearly resolved because of the limited resolution of the NaI detector and the close spacing of the K lines ($K_\beta \approx 1.18 K_\alpha$).

number of x-rays emitted per mesonic atom. These two entities are not, in general, equivalent. Some π mesons may be absorbed directly from the continuum without the intermediate formation of a mesonic atom.[5] It is difficult to estimate this effect accurately since little is known about the behavior of π mesons near zero energy. For this reason we have found it convenient to use the term "absolute radiative yield" for the number of x-rays emitted per *stopped* meson. Strictly speaking, of course, these measured values are only *lower* limits to the true absolute yields.

TABLE I. Energies and yields of π-K series.

Element	Energy of $2p\rightarrow 1s$ (kev)	Total radiative yield (x-rays per stopped meson)	Ratio of higher transitions to total
Li	23.8	0.135 ± 0.02	0.26
Be	42.1	$0.21\ \pm0.02$	0.26
B	63.8 (B^{11}) 65.0 (B^{10})	$0.18\ \pm0.015$	0.23
C	92.6	$0.15_{-0.02}^{+0.01}$	0.22
N	126.0	$0.045_{-0.004}^{+0.008}$	0.25
O	155.2	0.046 ± 0.006	0.26
F	196.3	0.051 ± 0.009	0.20
Na	~290	<0.032	

[5] This difficulty is not important for μ mesons since their interaction with nuclei is small.

The absolute π-K yields were determined by comparing them with known π-L yields. This is simpler experimentally than a direct measurement since π-L yields are much larger than π-K, and data can be accumulated more swiftly and accurately. The π-Al(L) yield was chosen as the absolute standard. Its measurement will be described in a subsequent paper (IV) on π-L yields. K and L lines of comparable energy were intercompared. The K yields of C, B, Be, and Li were measured relative to the L yields of Al(87 kev), F(42 kev), and N(25 kev), respectively. The errors listed in Table I include both the errors incurred in the measurements of relative yields (shown in Fig. 2) and those arising from the absolute yield determination. The main sources of error in the relative yields are due to uncertainties in the subtraction of backgrounds and contaminant lines and to the detection-efficiency corrections. Generous estimates of these uncertainties were made for each run. The errors in Fig. 2 are the rms errors of several runs. They indicate, in general, the reproducibility of the data. (Drifts in the electronic equipment and possible nonlinearities in the pulse-height selector will not contribute errors since, to a first approximation, they alter the shape of the curves but do not affect the yields.) The error in the absolute yield includes uncertainties in the measurements of the π-Al(*L*) absolute-yield standard and the cross comparisons of the *K* and *L* yields.

The higher transitions constitute about 20–25% of the total yield. As can be seen from Table I, they are essentially independent of *Z*.

A LiF target was used in the measurement of the fluorine yield. No correction was made for the absorption of π mesons by the lithium in the compound. This is in accordance with the results of the μ-*K* and μ-*L* yields, discussed in II, and the π-*L* yields, to be described in IV. In all these cases, when corrections for the lithium were made, the fluorine yields become anomalously large. The best fits were always consistent with the assumption that the Li in LiF (like H in CH_2) is ineffective in absorbing mesons.

The total yields given in Table I can be compared with the yields of the Rochester group[2] for those elements measured by both groups. Within statistics there is agreement for Be, N, and O. The B and C yields, however, are not in agreement.

Figure 2 is a plot of the relative total π-*K* radiative yields *vs Z*. The solid curve is an attempt to fit the experimental points with the function, const $aZ^4/(c+aZ^4+bZ^n)$. The form of this function is suggested by the competition between radiative transitions, Auger transitions, and nuclear capture. The multiplying constant represents the population of the initial states which is assumed to be independent of *Z*. In Fig. 2 it has been set equal to 0.7. This value is not

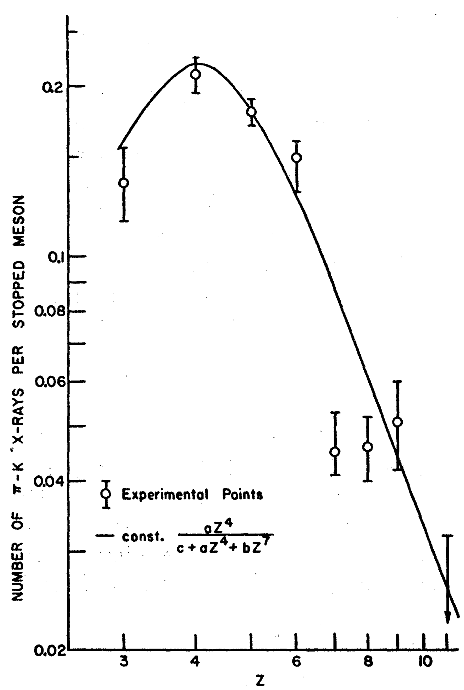

FIG. 2. Relative yields of π-*K* x-rays per stopped meson *vs Z*. The absolute yields are given in Table I. The formula for the solid curve is suggested by the competing processes of Auger transitions and nuclear absorption.

critical in determining the shape of the curve since the only effect of a variation in its magnitude is to translate the curve up or down on the log-log plot. The quantity aZ^4 is the well-known radiative transition probability, where $a=1.75\times10^{11}$ sec^{-1}. The nuclear capture probability is described by bZ^n, and *c* is the Auger transition probability. Since the experimental data do not include a sufficient number of elements in the "Auger region" to allow an independent determination of *c*, it has been assigned a value about 400 times larger than the calculated value. This assignment is consistent with the measured values of *c* derived from the μ-*K*, μ-*L*, and π-*L* data. (The μ-*K* and μ-*L* values are about 300 and 30 times their respective calculated values.[4] The π-*L* value is about 40 times greater.)

The values of *c*, *b*, and *n* used in fitting the curve in Fig. 2 are $c=4\times10^{13}$ sec^{-1}, $b=3.5\times10^9$ sec^{-1}, and $n=7$. It should be noted that *b*, the nuclear absorption probability for hydrogen, is about 50 times smaller than the corresponding radiative transition probability. This is of interest in the interpretation of experiments involving the capture of slow π mesons in hydrogen and deuterium. It confirms the conclusion of Brueckner *et al.*[6] that π mesons captured in deuterium are absorbed predominantly from the 1*s* state.

The seventh power of *Z* in the nuclear absorption probability is somewhat larger than anticipated. Simple theoretical considerations would indicate a Z^6 dependence. To a first approximation one expects the nuclear absorption rate to be the product of (1) the probability of the meson being at the nucleus and (2) the number of protons present to absorb the meson. For a meson of angular momentum *l* the meson probability density at the origin is $\sim Z^{2l+3}$. Hence the nuclear absorption rate might be expected to go as Z^{2l+4}, or Z^6 for *p* states. [To put it more accurately, the branching ratio might be expected to go as Z^{-2} since what is actually measured is the competition between radiation (Z^4) and nuclear capture from *p* states (Z^n).] The branching ratio is observed to go more nearly as Z^{-3}. However, the fluctuations in radiative yield near $Z=8$ make an accurate determination of *n* difficult.

The similarity of the yields of N, O, and F is thought to be due to a magic-number effect at $Z=8$. This anomaly is also observed in the π-*L* series near $Z=28$ and the π-*M* series at $Z=50$. Such magic-number effects have been suggested by Messiah and Marshak.[7]

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[7] A. M. L. Messiah and R. E. Marshak, Phys. Rev. **88**, 678 (1952).