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Author
Wiegand, Clyde E.

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Clyde E. Wiegand

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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

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MEASUREMENT OF K^--MESONIC X-RAY SPECTRA OF MEDIUM AND HEAVY ELEMENTS

Clyde E. Wiegand

Lawrence Radiation Laboratory
University of California
Berkeley, California

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Lines of the kaonic x-ray spectra of 24 elements ranging from Z = 17 to Z = 92 have been measured. Kaons are absorbed at the nuclear surface from circular orbits. The sudden cutoff of transitions to successively lower principal quantum numbers at certain values of Z indicates that nuclear matter (probably neutrons) extends above the conventional nuclear surfaces. A peak in one of the spectra corresponds to x rays from Σ^--hyperonic atoms.

Negative kaons are sensitive probes of the nuclear surface because they are absorbed on the surface by overlap from circular orbits.[1] In 24 elements ranging from Z = 17 through Z = 92 we have measured x rays emitted by the hydrogenic system, K^- + nucleus. The data indicate that kaons are absorbed at larger distances from the nuclei than would be expected from conventional nuclear dimensions. An attractive, although not unique, explanation of the experiment is to assume a nuclear skin of neutrons as has been suggested by many authors.[2]

Using the same K^- beam of the Bevatron but with larger Ge(Li) detectors[3] we have extended the previous K^--mesic x-ray experiment[4] to medium and heavy elements. Figure 1 shows some examples of the spectra as they are obtained from the data-acquisition system. No backgrounds have been

subtracted and no corrections have been applied for detector efficiency or target absorption of the x rays.

Table I gives Z, the transition, energy, and intensity of the observed lines with the above corrections applied. The listed energies are the Klein-Gordon equation[5] values with the proper reduced mass and without further corrections. The experimental data agree with them except where deviations are indicated by putting the K-G value in parenthesis. The vacuum polarization and the small nuclear size correction account for most of the deviations. Present accuracy is insufficient to establish a residual difference, if any, due to nuclear or other effects. Intensities are given in x rays per stopped kaon. The values are approximate and are in fair agreement with Eisenberg and Kessler[6] except where nuclear capture predominates.

If we observe the intensity of a particular transition $n \rightarrow n-1$ as a function of the atomic number Z, we find that this transition becomes unobservable at a certain Z. See Table II. For example, as Z increases, the last transition from $n = 7 \rightarrow 6$ occurs in $_{64}$Gd (or $_{65}$Tb). We interpret this cutoff to indicate that the nuclear capture probability is greater than the radiative transition probability at $n = 7$, $Z = 64$.

We believe that the kaons are captured from circular orbits $(n,\ n-1 \rightarrow n-1,\ n-2)$ because of the very existence of a series of lines such as those in the Pb spectrum. Also the intensities are in agreement with the calculations of Eisenberg and Kessler. With the hydrogenic system in circular orbits, its radiative transition rate is given by

$$P_{rad} = 0.535 \times 10^{10} \frac{M_K Z^4}{M_e} \frac{2^{4n}\, n^{2n-4} (n-1)^{2n-2}}{(2n-1)^{4n-1}} \ \text{sec}^{-1}. \qquad (1)$$

The capture rate can be estimated by taking

$$P_{cap} = \frac{W}{\hbar} \int \frac{\rho(0)}{1 + \exp[(r-C)/z]} R_n^2 r^2 \, dr \ \text{sec}^{-1}, \qquad (2)$$

where $\rho(0)$ is the nuclear matter density at the center of the nucleus in units of particles per F^3, R_n is the hydrogenic wave function for K^-, and W is the imaginary part of the kaon-nucleus potential. Wilkinson[7] quoted the calculated values in Table II based on the Saxon-Woods form for the density of nuclear matter with $C = 1.07 A^{1/3} F$, $z = 0.55F$, and $W = 30$ MeV. The calculated values do not agree with our results except possibly at $Z = 16$, but there are many ways to establish agreement. One method is to assign different distributions to the proton density ρ_p and the neutron density ρ_n and to increase W. For example, the density distribution could be

$$\rho(r) = \frac{\rho(0)_p}{1 + \exp[(r-C_p)/z_p]} + \frac{\rho(0)_n}{1 + \exp[(r-C_n)/z_n]}, \qquad (3)$$

requiring $\int \rho_p dV = Z$, $\int \rho_n dV = A-Z$, and increasing W to 100 MeV. For the above formulas to be in agreement with the experiment at $Z = 64$, we can maintain the conventional charge distributions, $C_p = 1.07 A^{1/3} F$ and $z_p = 0.55 F$ but increase the radius of the neutron distribution to $1.2 \times 1.07 A^{1/3} F$ and the thickness parameter to $2 \times 0.55F$. At this writing we do not know the correct value to use for W, but it is difficult to believe that W could be increased to such a high value as to account for the observed kaon absorption. This is evident when we consider that at $Z = 64$, $n = 7$, the radiation rate given by Eq. 1 is 1.2×10^{16} sec^{-1} whereas the absorption rate given by Eq. 2, using the conventional dimensions and $W = 100$ MeV, is 2.5×10^{14} sec^{-1}. To make the capture rate equal to the radiation rate, W would have to be increased 50-fold. However, when the distribution of Eq. 3 is used in Eq. 2 and C_n is made 20 percent larger than C_p, z_n twice z_p, and W is 100 MeV, the capture

rate becomes 1.1×10^{16} sec^{-1}. Obviously the overlap integral can be made to agree with the experiment by any number of suitable variations of the three parameters. The above changes appear to be more correction than is needed in the region of Z = 29. Bethe[2] suggested that the neutrons outside a nucleus ($r \gtrsim C$) should be distributed by

$$\rho_n(r) = (1/4)\,\rho_n(0)\,\exp[-(8M\epsilon)^{1/2}(r - C)/\hbar],$$

where M is the neutron mass and ϵ is the neutron binding energy.

In the next phase of the experiment we will determine the atomic numbers at which the $n = 6 \rightarrow 5$ and $n = 7 \rightarrow 6$ transitions are cut off.

The ultimate ability of kaonic x rays to yield information on the nuclear size parameters requires the accurate determination of the kaon-nucleus potential W.

$CaCl_2$ targets were used to test for an isotopic effect between ^{40}Ca and ^{44}Ca. (The isotopes were not available in metallic form.) There was no obvious difference between the two spectra. This is not surprising because one would expect an influence of added neutrons to be observable as a change of the intensity of the lowest transition only for the values of Z at which the transition disappears. For example, the intensity of the $n = 5 \rightarrow 4$ transition in $_{28}Ni$ might be different for different Ni isotopes. In Ca the n = 5 level is not dominated by nuclear absorption.

Σ^--hyperons are formed in the targets through the reactions $K^- + p \rightarrow \Sigma^- + \pi^+$ and $K^- + n \rightarrow \Sigma^- + \pi^0$, and upon capture by target nuclei make hyperonic atoms. We looked for the x rays corresponding to emissions from Σ^--hyperonic atoms and found one such line in the spectrum taken with a $_{19}K$ target. The peak at 136 keV corresponds to the hyperonic tran-

sition $n = 6 \rightarrow 5$. Its intensity is about 0.015 x rays per stopped kaon whereas the prominent kaonic line of $_{19}K$ is 40 times more intense. In photographic emulsion 0.08 K^- result in the formation of Σ^--hyperons.[8] Thus the observed intensity is consistent with the interpretation. However, the hyperonic x rays from the transition $n = 7 \rightarrow 6$ would be at 82.2 keV but are not seen. Nuclear absorption probably eliminates the transition $n = 5 \rightarrow 4$. In $CaCl_2$ the Ca hyperonic transition $n = 7 \rightarrow 6$ comes at the same energy as the Cl kaonic $8h \rightarrow 5g$ line. There is an indication of a Σ^--hyperonic peak from Cl $n = 6 \rightarrow 5$ at 109 keV, but it is not beyond statistical fluctuations. In the next experiment a more intense exposure should verify the formation of Σ^--hyperonic atoms. As detectors improve and more intense K^- beams become available it will be possible to observe Σ^--hyperonic x-ray lines of the heavy elements. These lines should show a fine structure due to the magnetic moment of Σ^-. For example, in Pb the splitting of the $n = 11 \rightarrow 10$ Σ^--hyperonic transition at 370.7 keV would amount to 0.85 keV per nuclear magneton.

When negative kaons stop in the elements ordinary atomic K-shell x rays are emitted, as exemplified by the $_{82}Pb$ spectrum. The energies of the lines correspond to Pb x rays, so they do not come from the atoms in which the kaons stop, else they would have the energies of $_{81}Tl$ x rays. We believe these emissions are mainly fluorescent x rays stimulated by the kaonic x rays. The observed intensities are consistent with this explanation.

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FIGURE CAPTION

Fig. 1. Examples of kaonic x-ray spectra.

Table 1. Summary of x-ray spectral lines measured.

Z	K^- Target	Transition $n_1l_1 \rightarrow n_2l_2$		Intensity per K^-	Energy (keV)	Z	K^- Target	Transition $n_1l_1 \rightarrow n_2l_2$		Intensity per K^-	Energy (keV)
				KAONIC							
17	$CaCl_2$	5g	4f	0.6 ±0.1	84.3	62	Sm	10l	9k	0.4 ±0.1	118.3
		6g	4f	0.06±0.02	130.0			9k	8j	0.4 ±0.1	165.5
		4f	3d	0.05±0.02	182.2			8j	7i	0.5 ±0.1	241.5
19	K	6h	5g	0.55±0.1	57.3			7i	6h	0.3 ±0.1	373.9 (372.5)
		7h	5g	0.07±0.02	91.8	63	EuF_3	10l	9k	0.2 ±0.1	122.2
		8h	5g	0.02±0.01	114.2			9k	8j	0.3 ±0.1	170.9
		5g	4f	0.60±0.1	105.5			8j	7i	0.3 ±0.1	249.4
		6g	4f	0.04±0.02	162.7			7i	6h	0.15±0.1	385.7 (384.6)
20	$^{40}CaCl_2$	6h	5g	0.7 ±0.1	63.5	64	Gd_2O_3	10l	9k	0.3 ±0.1	126.1
		5g	4f	0.4 ±0.1	116.9			9k	8j	0.3 ±0.1	176.4
20	$^{44}CaCl_2$	6h	5g	0.6 ±0.1	63.5			8j	7i	0.3 ±0.1	257.4
		5g	4f	0.3 ±0.1	116.9			7i	6h	0.15±0.1	398.7 (397.0)
22	Ti	5g	4f	0.4 ±0.1	141.8	66	Dy	10l	9k	0.2 ±0.1	134.1
		6h	5g	0.4 ±0.1	77.0			9k	8j	0.2 ±0.1	187.6
		7h	5g	0.06±0.02	123.4			8j	7i	0.2 ±0.1	274.5 (273.8)
28	Ni	7i	6h	0.3 ±0.1	75.4	68	Er	10l	9k	0.4 ±0.1	142.4
		9i	6h	0.06±0.03	157.8			9k	8j	0.4 ±0.1	199.2
		6h	5g	0.2 ±0.1	125.0			8j	7i	0.2 ±0.1	291.6 (290.7)
		5g	4f	0.1 ±0.05	230.3	74	W	10l	9k	0.15±0.1	168.8
29	$CuCl_2 + 2H_2O$	7i	6h	0.1 ±0.05	80.9			9k	8j	0.15±0.1	236.1
		6h	5g	0.3 ±0.1	134.2			8j	7i	0.15±0.1	345.1 (344.6)
30	Zn	7i	6h	0.5 ±0.1	86.6	77	Ir	10l	9k	0.2 ±0.1	182.8
		6h	5g	0.6 ±0.1	143.6			9k	8j	0.2 ±0.1	255.7
								8j	7i	0.1 ±0.05	374.3 (373.3)
32	Ge	7i	6h	0.4 ±0.2	...	80	HgCl	10l	9k	0.7 ±0.1	197.3
		6h	5g	0.4 ±0.2	...			9k	8j	0.6 ±0.1	276.1
33	As	7i	6h	0.4 ±0.2	...			8j	7i	0.4 ±0.1	406.3 (403.1)
		6h	5g	0.4 ±0.2	...	81	TlCl	11m	10l	0.7 ±0.1	149.6
34	Se	7i	6h	0.4 ±0.2	...			10l	9k	0.7 ±0.1	202.3
		6h	5g	0.4 ±0.2	...			9k	8j	0.5 ±0.1	283.1
								8j	7i	0.4 ±0.1	416.6 (413.3)
42	Mo	9k	8j	0.3 ±0.1	75.7	82	Pb_3O_4	12n	11m	0.3 ±0.1	116.6
		8j	7i	0.25±0.1	110.5			11m	10l	0.5 ±0.1	153.3
		7i	6h	0.3 ±0.1	170.3			10l	9k	0.5 ±0.1	207.4
		6h	5g	0.15±0.05	283.3 (282.6)			9k	8j	0.4 ±0.1	290.1
53	I	10l	9k	0.6 ±0.1	86.4			8j	7i	0.1 ±0.05	426.7 (423.6)
		9k	8j	0.4 ±0.1	120.8	92	U	12m	11m	0.4 ±0.1	146.9
		8j	7i	0.5 ±0.1	176.2			11m	10l	0.5 ±0.1	193.2
		7i	6h	0.5 ±0.1	271.8 (271.7)			10l	9k	0.4 ±0.1	261.3
56	BaO	9k	8j	0.3 ±0.1	134.9			9k	8j	0.25±0.1	365.6
		8j	7i	0.3 ±0.1	196.9			8j	7i	0.1 ±0.05	539.0 (534.1)
		7i	6h	0.3 ±0.1	304 (303.6)						
				Σ^--HYPERONIC							
19	K	6h	5g	0.015±0.05	136.3						
				ELECTRONIC							
82	Pb_3O_4	$2P_{1/2}$	$1S_{1/2}$	1.3 ±0.3	72.8	92	U	$2P_{1/2}$	$1S_{1/2}$	0.8 ±0.2	94.7
		$2P_{3/2}$	$1S_{1/2}$	1.3 ±0.3	75.0			$2P_{3/2}$	$1S_{1/2}$	1.3 ±0.3	98.4
		3	1	0.5 ±0.2	84.8			3	1	0.7 ±0.2	111.
								4	1	0.4 ±0.2	114.5

Notes:
1. The natural isotopic abundances of the elements were used except as noted for Ca.
2. Kaons were assumed to stop in the elements of compounds in the ratio of the charge of the elements to the molecular charge, e.g., 20/(20+34) stopped in the Ca of $CaCl_2$.
3. The intensity measurements are subject to many uncertainties. The errors were estimated by considering the peak-to-background ratio; the magnitude of the corrections for target self-absorption, and the agreement between two detectors where applicable.
4. The observed energies were indistinguishable from the Klein-Gordon energies listed except for lines of medium and heavy elements that were shifted mainly by vacuum polarization. For the shifted lines the observed energy is listed with the K-G energy in parenthesis beside the experimental value. The energies of the shifted lines are based upon the emissions of ^{133}Ba at 276, 302, 356, and 384 keV, and the errors are about ±1 keV. Electronic x-ray energies are from electron binding energy tables.
5. Some of the intensities of the lines that should not be subject to nuclear capture were unbelievably low, e.g., the 10l → 9k and 9k → 8j transitions in W and Ir. We could find no experimental reason for these apparently abnormal intensities.

Table II. Lowest orbital transitions and their atomic numbers.

Last $n \rightarrow n-1$ observed	$4 \rightarrow 3$	$5 \rightarrow 4$	$6 \rightarrow 5$	$7 \rightarrow 6$	$8 \rightarrow 7$
At. no. experimental	17	28	$42 \leq Z < 53$	$64 \leq Z \leq 66$	$92 \leq Z$
At. no. calculated	16	33	56	83	---

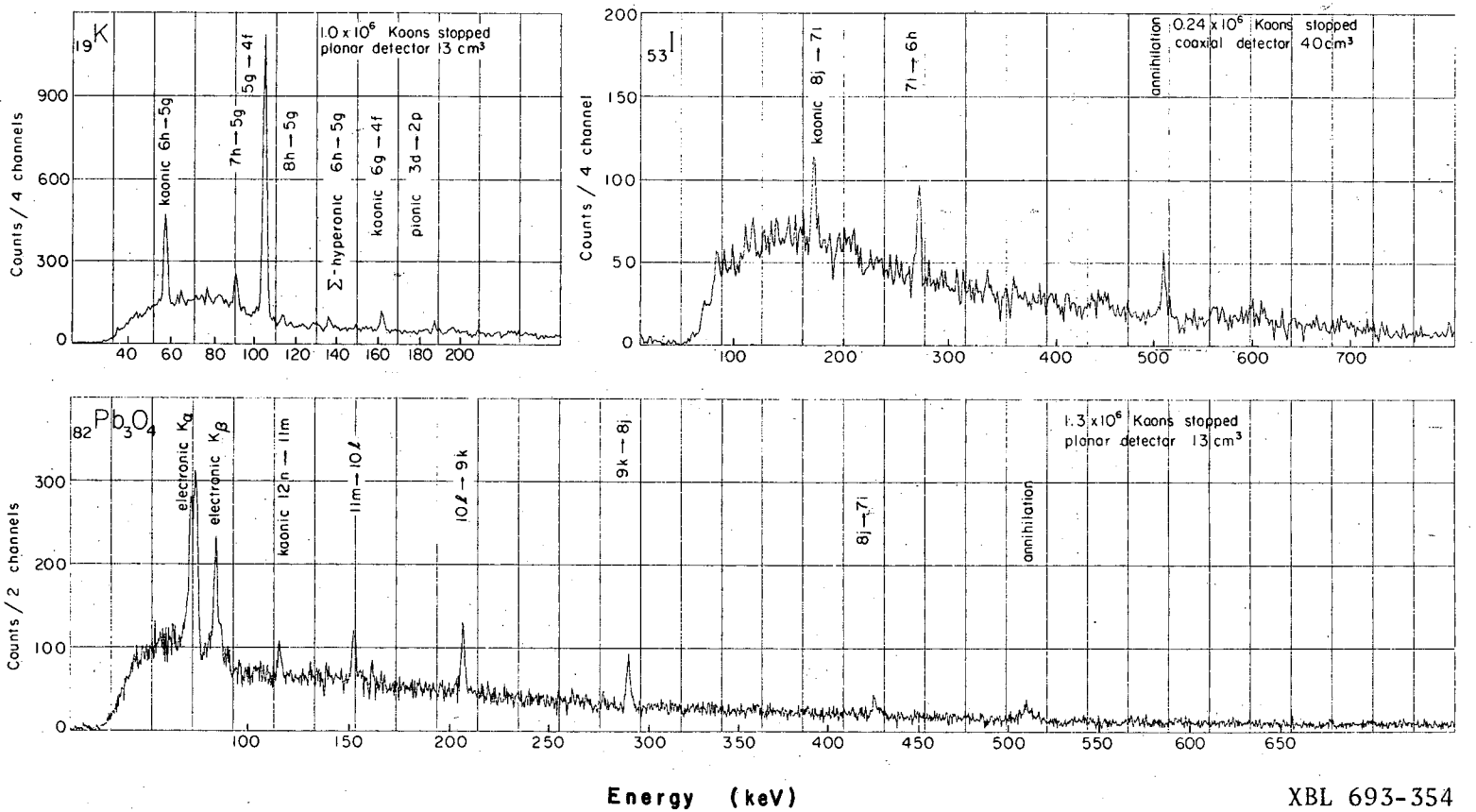
19K
1.0 x 10^6 Kaons stopped
planar detector 13 cm^3
kaonic 6h–5g
7h–5g
5g–4f
8h–5g
Σ⁻-hyperonic 6h–5g
kaonic 6g–4f
pionic 3d–2p
Counts / 4 channels
53I
0.24 x 10^6 Kaons stopped
coaxial detector 40 cm^3
kaonic 8j–7i
7i–6h
annihilation
Counts / 4 channel
82Pb3O4
1.3 x 10^6 Kaons stopped
planar detector 13 cm^3
electronic Kα
electronic Kβ
kaonic 12n–11m
11m–10l
10l–9k
9k–8j
8j–7i
annihilation
Counts / 2 channels
Energy (keV)
XBL 693-354

Fig. 1

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