

PHYSICAL REVIEW LETTERS

VOLUME 22

9 JUNE 1969

NUMBER 23

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

Clyde E. Wiegand

Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

(Received 14 April 1969)

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) detectors³ we have extended the previous K^- -mesonic x-ray experiment⁴ 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 following comments concern Table I:

(a) The natural isotopic abundances of the ele-

ments were used except as noted for Ca.

(b) 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 .

(c) The listed energies are the Klein-Gordon equation⁵ values with the proper reduced mass and without further corrections. The experimental data agree with them except where deviations are indicated by putting the Klein-Gordon value in parentheses. 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. 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.

(d) Intensities are given in x rays per stopped kaon. The values are approximate and are in fair agreement with Eisenberg and Kessler⁶ except where nuclear capture predominates. 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 applica-

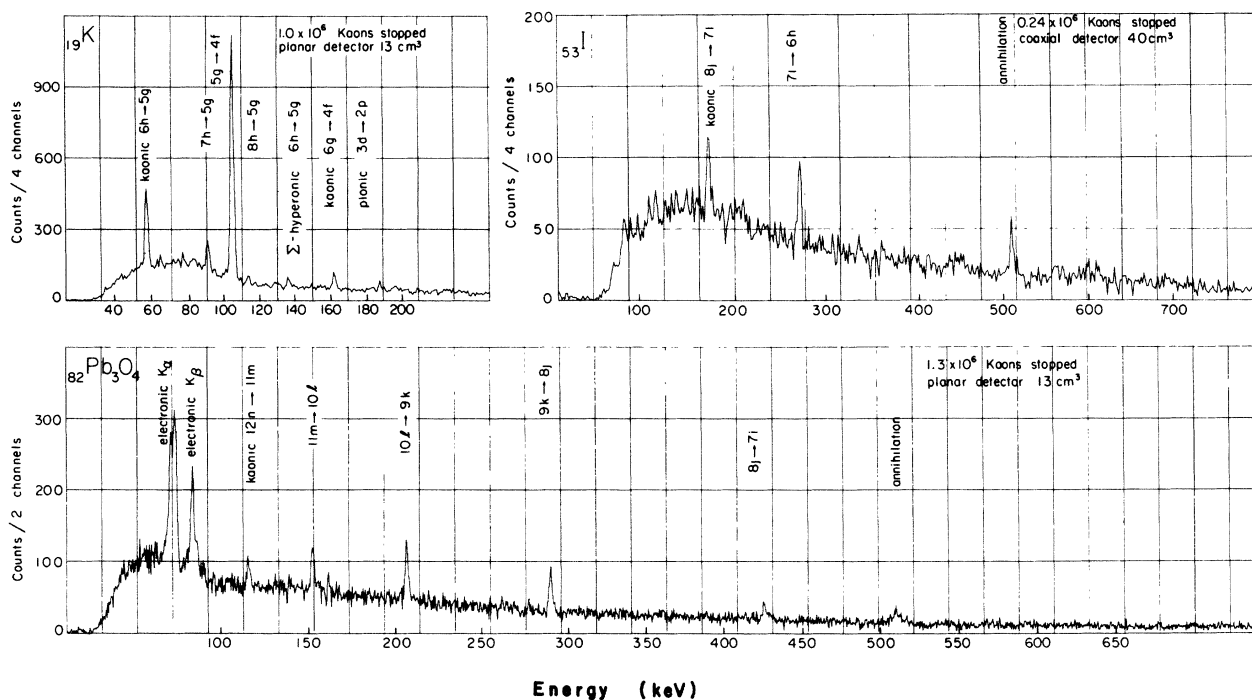


FIG. 1. Examples of kaonic x-ray spectra.

ble. 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.

If we observe the intensity of a particular transition $n-n-1$ as a function of the atomic number Z , we find that this transition becomes unobservable at a certain Z . See Table I. For example, as Z increases, the last transition from $n=7-6$ occurs in $_{84}\text{Gd}$ (or $_{85}\text{Tb}$). We interpret this cutoff to indicate that the nuclear-capture probability is greater than the radiative-transition probability at $n=7$ and $Z=64$. Likewise the $n=5-4$ lines cut off at $_{28}\text{Ni}$.

We believe that the kaons are captured from circular orbits ($n, n-1-n-1, n-2$) 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

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

The capture rate can be estimated by taking

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

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. Wilkinson⁷ quoted calculations that predicted the series $n=4-3$, $5-4$, $6-5$, and $7-6$ would cut off at $Z=16$, 33 , 56 , and 83 , respectively. We find, instead, that the series terminate at $Z=17$, 28 , $42 \leq Z \leq 53$, and 64 (or 65). The calculations were based on the Saxon-Woods form for the density of nuclear matter with $C=1.07A^{1/3} F$, $z=0.55 F$, and $W=30 \text{ MeV}$. 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

Table I. 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)
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 ₂ O 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 ₂ O	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
32	Ge	7i 6h	0.4 ±0.2	...			8j 7i	0.1 ±0.05	374.3 (373.3)
		6h 5g	0.4 ±0.2	...	80	HgCl	10l 9k	0.7 ±0.1	197.3
33	As	7i 6h	0.4 ±0.2	...			9k 8j	0.6 ±0.1	276.1
		6h 5g	0.4 ±0.2	...			8j 7i	0.4 ±0.1	406.3 (403.1)
34	Se	7i 6h	0.4 ±0.2	...	81	TlCl	11m 10l	0.7 ±0.1	149.6
		6h 5g	0.4 ±0.2	...			10l 9k	0.7 ±0.1	202.3
42	Mo	9k 8j	0.3 ±0.1	75.7			9k 8j	0.5 ±0.1	283.1
		8j 7i	0.25±0.1	110.5			8j 7i	0.4 ±0.1	416.6 (413.3)
		7i 6h	0.3 ±0.1	170.3	82	Pb ₃ O ₄	12n 11m	0.3 ±0.1	116.6
		6h 5g	0.15±0.05	283.3 (282.6)			11m 10l	0.5 ±0.1	153.3
53	I	10l 9k	0.6 ±0.1	86.4			10l 9k	0.5 ±0.1	207.4
		9k 8j	0.4 ±0.1	120.8			9k 8j	0.4 ±0.1	290.1
		8j 7i	0.5 ±0.1	176.2			8j 7i	0.1 ±0.05	426.7 (423.6)
		7i 6h	0.5 ±0.1	271.8 (271.7)	92	U	12m 11m	0.4 ±0.1	146.9
56	BaO	9k 8j	0.3 ±0.1	134.9			11m 10l	0.5 ±0.1	193.2
		8j 7i	0.3 ±0.1	196.9			10l 9k	0.4 ±0.1	261.3
		7i 6h	0.3 ±0.1	304 (303.6)			9k 8j	0.25±0.1	365.6
							8j 7i	0.1 ±0.05	539.0 (534.1)

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

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

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, $C_p = 1.07A^{1/3}$ F, and $z_p = 0.55$ F, but increase the radius of the neutron distribution to $1.2 \times 1.07A^{1/3}$ F and the thickness parameter to

2×0.55 F. 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 $Z = 64$ and $n = 7$, the radiation rate given by Eq. (1) is $1.2 \times 10^{16} \text{ sec}^{-1}$, whereas the absorption rate given by Eq. (2), using the conventional dimensions and $W = 100$ MeV, is $2.5 \times 10^{14} \text{ sec}^{-1}$. 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% larger than C_p , z_n twice z_p , and W is 100 MeV, the capture rate becomes $1.1 \times 10^{16} \text{ sec}^{-1}$. 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 correct than is needed in the region of $Z = 29$. Bethe² suggested that the neutrons outside a nu-

nucleus ($r \geq C$) should be distributed as

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

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 transition $n = 6 \rightarrow 5$. 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^- results 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 struc-

ture 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.

The author expresses his appreciation to the many persons who made the experiment possible, and especially to Dr. Richard Pehl for the detectors, Rory Van Tuyl and Jack Walton for the electronics, Carl Quong for the computer programs, the technicians for watching the apparatus, and the Bevatron crews for furnishing many hours of beam. Dr. Raymond Kunselman helped in the running of the experiment. He made numerous computer calculations, including the overlap integrals; his assistance is especially appreciated. Professor Emilio Segrè contributed many valuable ideas to the interpretation of the data.

¹D. H. Wilkinson, *Comments Nucl. Particle Phys.* **1**, 112 (1967).

²M. H. Johnson and E. Teller, *Phys. Rev.* **93**, 357 (1954); P. B. Jones, *Phil Mag.* **3**, 33 (1958); R. G. Seyler and C. H. Blanchard, *Phys. Rev.* **131**, 355 (1963); D. H. Davis, S. P. Lovell, M. Csejthey-Barth, J. Sacton, G. Schorochoff, and M. O'Reilly, *Nucl. Phys.* **B1**, 434 (1967); E. H. S. Burhop, *Nucl. Phys.* **B1**, 438 (1967); H. A. Bethe, *Phys. Rev.* **167**, 879 (1968); G. W. Greenlees, G. J. Pyle, and Y. C. Tang, *Phys. Rev.* **171**, 1115 (1968).

³F. S. Goulding, D. A. Landis, and R. H. Pehl, *University of California Lawrence Radiation Laboratory Report No. UCRL-17560*, 1967 (unpublished).

⁴C. E. Wiegand and D. A. Mack, *Phys. Rev. Letters* **18**, 685 (1967).

⁵H. A. Bethe, *Intermediate Quantum Mechanics* (W. A. Benjamin, Inc., New York, 1964), p. 186.

⁶Y. Eisenberg and D. Kessler, *Phys. Rev.* **130**, 2352 (1963).

⁷D. H. Wilkinson, in *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Birks (Heywood and Company, Ltd., London, England, 1962), p. 339.

⁸B. Bhowmik et al., *Nuovo Cimento* **14**, 315 (1959).