Nuclear Spectra of Rb^{82} and Rb^{84}†

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The nuclear spectra of Rb^{82} (6.3 hr) and Rb^{84} (34 days) have been measured with a magnetic lens spectrometer. Rb^{82} emits two positron groups of energies 0.775 and 0.175 Mev. It also decays by orbital electron capture. A large number of gamma-rays accompanies the disintegration (Table I). Reasonable agreement with the gamma-rays emitted by Br^{82} has been obtained. Rb^{84} emits three groups of positrons having end-point energies of 1.629, 0.822, and 0.373 Mev. One gamma-ray whose energy is 0.890 Mev has been found. Level diagrams for these disintegrations are discussed.

1. INTRODUCTION

THE radioactive nuclei Rb^{82} and Rb^{84} have been studied by a number of authors. Bombardment of bromine by high energy α-particles produces Rb^{81} (4.7 hr), Rb^{82} (6.3 hr), Rb^{83} (107 days), and Rb^{84} (34 days). The mass assignment and periods of these activities were studied carefully by Reynolds, Karraker, and Templeton[1] and by Karraker and Templeton.[2] The mass assignments were made with the help of a mass-spectrograph and the half-lives were measured with a counter. They found that, for lower energy α-particles (<20 Mev), the α-$2n$ reaction was weak compared to the α-n, so that activities were characteristic of Rb^{82} and Rb^{84}. Both Rb^{82} and Rb^{84} are positron emitters, and there is some orbital electron capture. They state that the end point of the positron spectrum of Rb^{82} is 0.670 ± 0.05 Mev and that of Rb^{84} is 1.5 Mev, with a lower energy group about 0.37 Mev.

Beckham and Pool[3] bombarded krypton with α-particles and deuterons. The rubidium activity showed a half-life of 38 days. They found that both positrons and electrons were emitted, the positrons having an end-point energy of 1.3 Mev, as measured by aluminum absorption. This activity is ascribed to Rb^{84}.

TABLE I. Gamma-rays of Rb^{82}. Energies are in kev.

Present work			Confirmation	
Pb radiator	U radiator	Internal conv.	Siegbahn *et al.*	Hubert *et al.*
		188 K		
		248 K & L		
		322 K & L		
388 K	390 K	390 K		
423 K	423 K			
465 K	468 K	464 K		
545 K	550 K	558 K	550	547
610 K	610 K & L		610	615
690 K	690 K		692	682
768 K	770 K & L		769	752
	818 K & L		824	823
	1020 K	1018 K	1036	1026
		1314 K	1321	1306
	1464 K & L	1464 K & L		1453

It is clear that Rb^{82} decays to Kr^{82} and that Rb^{84} decays to Kr^{84} with some possibility of decay to Sr^{84}. The energy levels of both Kr^{82} and Kr^{84} have been at least partially investigated from a study of the decay of Br^{82} and Br^{84}.

Siegbahn, Hedgran, and Deutsch,[4] and Hubert and Laberrigue-Frolow,[5] have studied the radiations from Br^{82}. The former studied the gamma-rays by means of photoelectrons and internal conversion electrons, while the latter measured only the photoelectrons. In all, some eight gamma-rays were observed. Their energies are shown in Table I. Work on the beta-ray spectrum has not been published, but Siegbahn[6] has found at least three groups. The decay scheme appears to be quite complicated.

The beta-rays of Br^{84} have been investigated by Duffield and Langer[7] who found four groups of beta-rays having end-point energies of 4.679, 3.45, 2.53, 1.72 Mev. The gamma-rays were not measured.

In order to obtain additional information on the levels of Kr^{82} and Kr^{84} an investigation of the radiations from Rb^{82} and Rb^{84} has been undertaken.

2. PREPARATION OF SOURCES

The sources were prepared by bombarding ammonium bromide with alpha-particles in the Indiana University cyclotron. The material was covered with a 1-mil copper foil to reduce the energy of the alpha-particles, originally 23 Mev, below the threshold for the α,$2n$ reactions. The current to the target had to be kept low, around 5 microamperes, in order not to vaporize the NH_4Br.

After bombardment the source was dissolved and any extraneous copper removed by precipitation with H_2S. The material was then made $0.1N$ in HCl and run through an ion column, measuring the activity of aliquots as a function of time. The rubidium which came through the column was essentially carrier free.

Beta-ray sources were prepared by evaporating a drop of the concentrated material onto a thin zapon film. Gamma-ray sources were prepared by soaking up

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[2] D. G. Karraker and D. H. Templeton, Phys. Rev. **80**, 646 (1950).
[3] C. Beckham and M. L. Pool, Phys. Rev. **80**, 125 (1950).
[4] Siegbahn, Hedgran, and Deutsch, Phys. Rev. **76**, 1263 (1949).
[5] P. Hubert and J. Laberrigue-Frolow, Compt. rend. **232**, 2420 (1951).
[6] K. Siegbahn (private communication).
[7] R. B. Duffield and L. M. Langer, Phys. Rev. **81**, 203 (1950).

a few drops of the concentrated material on cotton and placing this in a copper capsule.

3. MEASUREMENT OF THE SPECTRA

Measurements of the spectra were made in a magnetic lens spectrometer. Two different types of counters were used, one having a 4-mg/cm^2 mica window and one having a thin Zapon window capable of transmitting electrons down to 10 kev. Measurements of the beta-spectrum of both Rb^{82} and Rb^{84} were made. In measuring the spectrum of Rb^{82}, short bombardments of about 1 hour were made, the spectrum was measured, and the source was allowed to sit in the spectrometer until the 6.3-hour Rb^{82} had died away. The spectrum of the residual activity of Rb^{84} was then measured, and corrections were made to the Rb^{82} spectrum. In investigating Rb^{84}, 5-hour bombardments were used, and the Rb^{82} was allowed to die out before measuring the spectrum. The energies of the gamma-rays from Rb^{82} were determined by measuring the energies of the

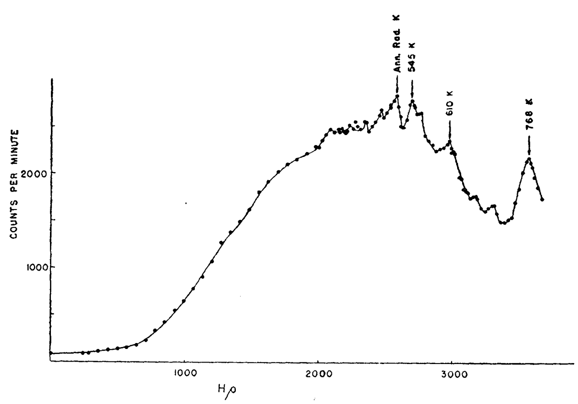


FIG. 1. Spectrum of photoelectrons ejected from Pb by gamma-rays of Rb^{82}. Energies are in kev.

photoelectrons ejected from both lead and uranium radiators. The sources of Rb^{84} were not strong enough to permit measuring the gamma-rays in the magnetic lens.

4. RESULTS ON Rb^{82}

The distribution in energy of the photoelectrons ejected from lead and uranium radiators are shown in Figs. 1 and 2, respectively. It will be seen at once that a large number of gamma-rays are present, some of them of quite low intensity. The energies of these gamma-rays as determined from the measurements of the photoelectrons ejected from lead and uranium radiators as well as the values determined from internal conversion lines are given in Table I. Some of the very weak lines did not appear in more than one run and are left out of the table. Only those lines which appeared in at least two runs are given. Since the half-lives of Rb^{82} and Rb^{81} are not too different, it would be impossible to rule out Rb^{81} impurities on the basis of period measure-

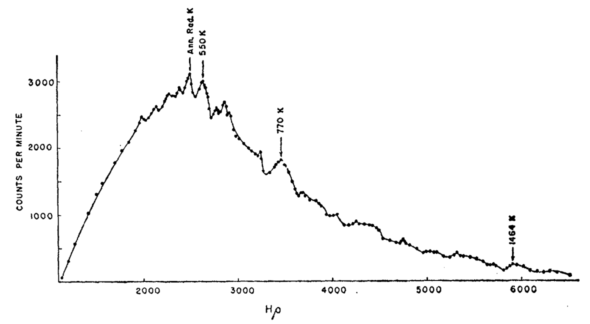


FIG. 2. Spectrum of photoelectrons ejected from U by gamma-rays of Rb^{82}. Energies are in kev.

ments. It is felt, however, that the method of preparation excludes the possibility of any Rb^{81}. It is interesting to note that all of the lines found by Siegbahn, Hedgran and Deutsch, or Hubert and Laberrigue-Frolow in their measurements on Br^{82} have been found in Rb^{82} and all are internally converted. It was not possible to make relative intensity measurements on the lines. However, it is clear that the strongest line is that at 0.768 Mev.

The results of the measurements of the particle spectrum are shown in Fig. 3. These experiments were performed using a magnetic lens spectrometer without any device to separate particles of different sign. Both positrons and internal conversion electrons are recorded. It will be seen that many of the lines previously investigated in the gamma-ray experiments are internally converted. In addition, four other internal conversion lines, together with an Auger line, were found. The most intense internal conversion line is that whose gamma-ray energy is 0.188 Mev.

Figure 4 shows a Fermi plot of the positron spectrum. It will be seen that there are two groups whose end-point energies are 0.775 and 0.175 Mev. The energies, relative abundances, and values of logft are given in Table II.

All of the gamma-ray lines, the two beta-ray groups, together with the three known beta-ray groups from Br^{82}—0.447, 0.323, and 0.181 Mev—can be fitted

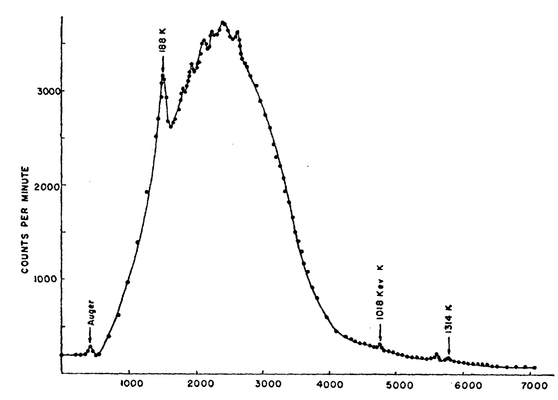


FIG. 3. Particle spectrum of Rb^{82}. Energies are in kev.

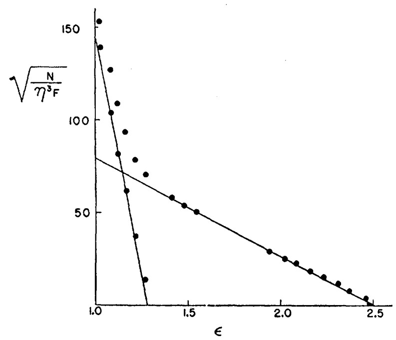


FIG. 4. Fermi plot of positrons from Rb^{82}.

reasonably well into a disintegration scheme. However, since the scheme is very complicated and the information on the intensity of the gamma-ray lines is meager, the scheme may not be unique. A possible tentative scheme, which omits only a line at 1.260 Mev, is shown in Fig. 5. The strongest line is the one at 0.768 Mev, and this would appear to be at the bottom of the

TABLE II. Positrons from Rb^{82}.

E(Mev)	Abundance (percent)	$\log ft$
0.775	76	4.93
0.175	24	4.88

scheme. No other line is of comparable intensity. The two positron groups feed the first excited level and the second excited level, respectively. The gamma-ray of 0.610 Mev corresponds to the difference in energy of these two states. The higher levels, fed by orbital electron capture, are less certain.

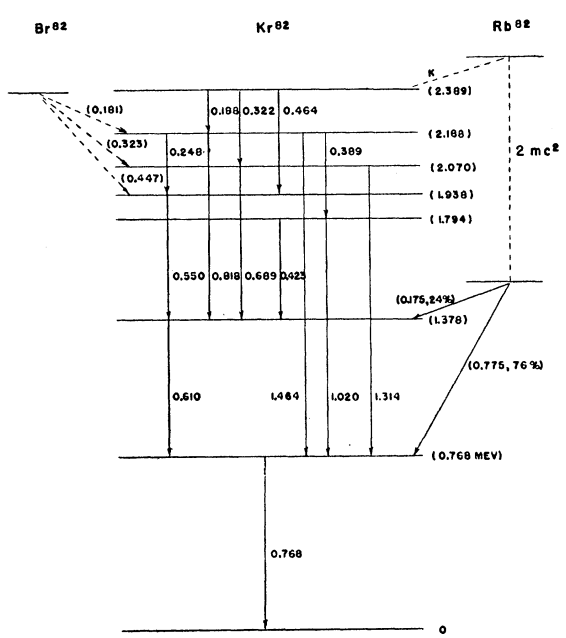


FIG. 5. Tentative energy level diagram of Kr^{82}. Energies are in Mev.

The values of $\log ft$ for the two positron groups indicate that each is an allowed transition. The shell model would give several possibilities for the configurations of ${}_{37}Rb_{45}{}^{82}$ and ${}_{35}Br_{47}{}^{82}$. If one chooses the configuration $(f_{5/2}, p_{1/2})$ for Rb^{82}, this state will have even parity and a spin of 3. Thus the transition to the ground state of Kr^{82} (0, even) would be forbidden and the transitions to the first two excited states would be allowed if the spins and parities of the ground and first two excited states of Kr^{82} are 0, 2, 4 and even. For Br^{82}, on the other hand, the most likely configuration is $(p_{3/2}, g_{9/2})$ which would give a high spin and odd parity, explaining why no transitions to the lower excited states of Kr^{82} occur. The above configurations are in agreement with Nordheim's Rule.

5. EXPERIMENTS ON Rb^{84}

The beta-ray spectrum of Rb^{84} was measured both in a 180° spectrometer and in a magnetic lens spectrometer. The results in the two cases are essentially in agreement. The experiments using the 180° spectrometer assured, of course, that positrons were being

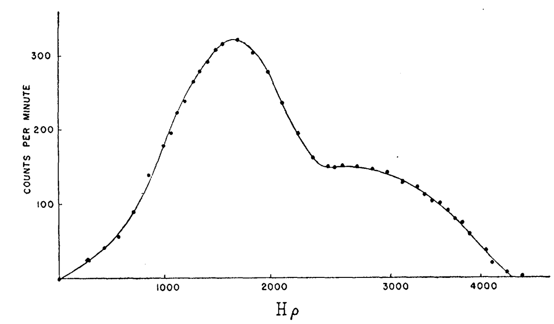


FIG. 6. Positron spectrum of Rb^{84}.

measured. The magnetic lens was used without a separating baffle.

The spectrum obtained using the lens spectrometer is shown in Fig. 6. A Fermi plot of the data is shown in Fig. 7. It will be seen at once that the high energy group of positrons has a forbidden shape. Applying the shape corrections for a transition of the type $\Delta j = \pm 2$ yes, a straight line Fermi plot was obtained. The spectrum could then be analyzed into three groups as shown in Table III. The lowest energy group is quite weak and may not be real. It is to be noted that the value of $\log(W_0{}^2-1)ft$ for the highest energy group is in accord with the usual values obtained for transitions of the type $\Delta j = \pm 2$, yes.

Since the sources used were too weak to allow one to measure gamma-rays in a magnetic spectrograph, internal conversion electrons were sought in the 180° spectrometer and a gamma-ray was also found using a scintillation spectrometer. The electron spectrum as measured in the 180° spectrometer showed a weak internal conversion line corresponding to a gamma-ray of energy 0.890 Mev.

A careful search was made using a scintillation counter with a NaI(Tl) crystal. A gamma-ray, whose energy is 0.890 Mev, was found. No other gamma-rays, except a line at 0.510 Mev corresponding to annihilation radiation, were found.

In order to see whether or not the most energetic group of positrons goes to the ground state, the usual type of coincidence experiment was performed. A source was set up between two counters, one to measure gamma-rays and the other, an end-window counter, to measure positrons. With enough aluminum between both counters to stop all positrons, a gamma-gamma coincidence background was obtained. This, of course, included coincidences due to annihilation radiation. The positron-gamma coincidence rate was then measured as a function of the thickness of aluminum absorber. These measurements were corrected for chance,

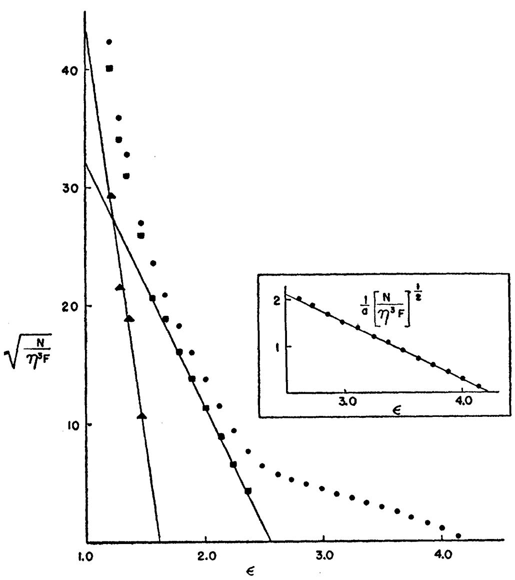


FIG. 7. Fermi plot for positrons from Rb^{84}.

cosmic-ray, and gamma-gamma coincidences. The results are shown in Fig. 8, in which the number of positron-gamma coincidences per recorded positron ($N_{\beta\gamma}/N_\beta \times 10^3$) is plotted against absorber thickness. There are no coincidences beyond 0.1 cm Al absorber (0.750 Mev), indicating that the highest energy group goes to the ground state. Coincidences are found for positrons of energies less than approximately 0.750 Mev, showing that the second group of positrons is followed by the emission of a gamma-ray.

Since Rb^{84} lies between two stable nuclides—Kr^{84} and Sr^{84}—it is possible that Rb^{84} also decays by electron emission. The experiments with the 180° spectrometer showed that there was a small background of electrons, which was only a few counts per minute above the background. If there is a group of electrons its intensity must be extremely small.

These experiments on Rb^{84} show that it disintegrates with the emission of three groups of positrons. The

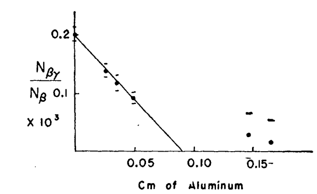
TABLE III. Positron spectrum of Rb^{84}.

E_{Mev}	Abundance percent	$\log ft$	$\log(W_0^2-1)ft$
1.629±0.005	39	9.24	10.44
0.822±0.05	58	8.15	—
0.373±0.05	3	8.87	—

highest energy group goes to the ground state and has a forbidden shape characteristic of a once forbidden spectrum with $\Delta j = \pm 2$. The second group goes to a state at 0.890 Mev above the ground state and is followed by the emission of a gamma-ray. The third group is extremely weak and no gamma-ray corresponding to transitions to the ground state has been found.

The results of this investigation are embodied in the decay scheme shown in Fig. 9, and it is of interest to discuss this scheme in the light of theoretical predictions. The shell model would predict the configuration

FIG. 8. Positron-gamma coincidences in Rb^{84}.



$(f_{5/2}, p_{1/2})$ or $(f_{5/2}, g_{9/2})$ for the ground state of ${}_{37}Rb_{47}{}^{84}$. Since the ground state of Kr^{84} has zero spin and even parity and since the positron transition from Rb^{84} to this state corresponds to $\Delta j = 2$ and a change of parity, it follows that the ground state of Rb^{84} has spin 2 and odd parity. This suggests the configuration $(f_{5/2}, g_{9/2})$ for the ground state of Rb^{84}. The second positron transition has an allowed shape and a value of $\log ft = 8.2$. This suggests that the transition is $\Delta j = 0$, yes, which would make the first excited state have spin 2

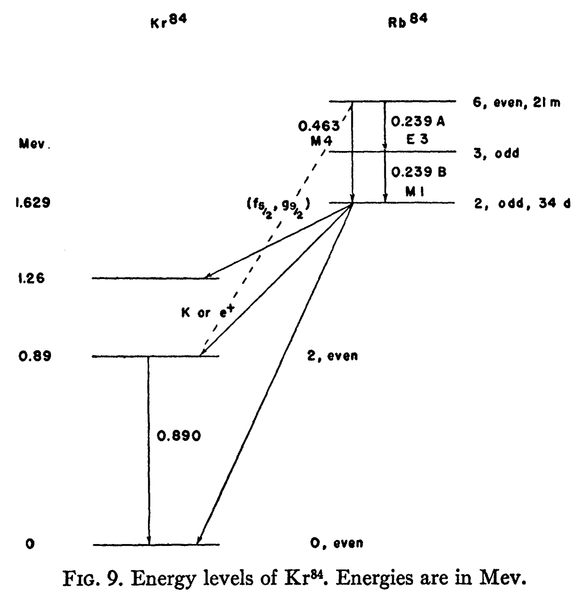


FIG. 9. Energy levels of Kr^{84}. Energies are in Mev.

and even parity. Flammersfeld[8] has shown that there is an excited state of Rb^{84} having a half-life of 23 min and emitting internal conversion electrons whose energy is approximately 0.320 Mev. Recent experiments in this laboratory[9] have delineated the excited states of Rb^{84} more exactly. The results of this investigation are shown for completeness in Fig. 9. The governing metastable state was found to have a half-life of 21 min.

It appeared difficult to reconcile the original decay scheme of Langer and Duffield[7] for Br^{84} with that proposed here for Rb^{84}. When the results of the present experiments became known, Dr. Langer and Dr. Duffield[10] measured the gamma-rays from Rb^{84} with the help of a scintillation spectrometer. Their results show a strong gamma-ray of energy 0.890 Mev and a weaker one of energy 1.89 Mev. It is now believed that the original decay scheme was incomplete and that the highest energy beta-ray group does not lead to the ground state, as originally supposed, but to an excited state from which the gamma-ray at 0.890 Mev is emitted.

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[10] The authors are indebted to Dr. L. M. Langer for communicating to them the results of their experiments.

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Total Neutron Cross Section of Sodium*

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The total neutron cross section of sodium has been measured over the energy range 120 to 1000 kev using resolutions of 2.5 to 5 kev. A number of resonances, corresponding to excited states in the compound nucleus Na^{24} were investigated. In some cases it is possible to assign J and l values and to compute the effective level spacings D_J^l. Evidence is given to show that the D_J^l, which are a measure of the complexity of a state, differ by a factor of 8 for two states of the same type and at approximately the same excitation energy (7.5 Mev) in the Na^{24} nucleus. An anomalous S-wave resonance at 300 kev suggests that the potential scattering may be spin dependent.

INTRODUCTION

THE recent good resolution work on the $Na^{23}(d,p)Na^{24}$ reaction by Sperduto *et al.*[1] gives a detailed picture of the level structure of the Na^{24} nucleus up to an excitation energy of 4.6 Mev. The level structure at somewhat higher excitation energies (7.0 Mev and above) can be studied by measuring the total neutron cross section of sodium. Adair *et al.*[2] measured this cross section from 40 to 1000 kev using a resolution of 20 kev. Although they found a number of maxima, they concluded that their resolution was not adequate for any detailed interpretation. To learn more concerning these virtual levels we have measured the cross section using resolutions of 2.5 to 5 kev.

EXPERIMENTAL METHOD

The experimental procedure for measuring the total neutron cross section was similar to that previously described.[3] Monoenergetic neutrons were produced by allowing protons of well-defined energy from the Rockefeller electrostatic generator to strike thin targets of lithium. The original proton-recoil counter was replaced by a new counter with an o.d. of 1 inch, effective length of 4 inches and 2-mil center wire, filled to 5 atmospheres of hydrogen gas and operated with 3.5 kev on the center wire. This counter was approximately twice as efficient and had a better signal-to-noise ratio. The ambiguity caused by the presence of the second group of neutrons from the $Li(p,n)$ reaction at energies above 640 kev was removed, as before, by adjusting the bias to make the counter insensitive to the lower energy group.

A metallic sodium scatterer, one inch in diameter and 0.186×10^{24} nuclei/cm^2 thick, was encased in a thin-walled (5 mil), air-tight steel cylinder. The scatterer and counter were placed at mean distances of 13 and 30 cm, respectively, from the target in the forward

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