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RADIOACTIVITY OF NEUTRON-DEFICIENT RUBIDIUM ISOTOPES
Wesley Osborne Doggett
(Thesis)
June 12, 1956

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ABSTRACT

Conversion electrons of three γ rays associated with the Rb$_{81}$ decay (4.7 hours, β$^+$, electron capture) have been observed. The β$^+$ spectrum has three allowed components of maximum energies 1050, 575, 325 kev. The multipole order of the 190-kev transition in Kr$_{81m}$ (13 seconds) has been determined to be E3. A tentative decay scheme is proposed.

A 31.5-minute activity produced by 16-Mev alpha particles on BaBr$_2$ has been assigned to Rb$_{81m}$ on the basis of the growth of the 190-kev transition in the decay of Rb$_{81}$. Rb$_{81m}$ decays with approximately 1.4-Mev positrons and conversion electrons corresponding to an 85-kev transition to Rb$_{81}$.

Energy determinations for three γ rays in the decay of Rb$_{84m}$ (20.5 minutes) have been made from the internal conversion spectrum and coincidence measurements using scintillation-crystal pulse-height analyzers.

Rb$_{84}$ is found to decay by a β$^+$ group of maximum energy 1635 kev, by a β$^-$ group of maximum energy 908 kev (both groups having the first-forbidden unique shape), and by first-forbidden allowed shape β$^+$ and β$^-$ transitions of maximum energies 785 kev and 490 kev respectively. β-γ coincidences show the 785-kev β$^+$ spectrum to be in coincidence with a 0.89-Mev γ ray.

Involved in the decay of Rb$_{83}$ is a 522-kev γ ray and the radiations from Kr$_{83m}$.

Three γ rays and three β$^+$ components previously assigned to Rb$_{82}$ were placed in the decay scheme of Rb$_{81}$. The positron spectrum of Rb$_{82}$ is shown to be simple, with end-point energy 785 kev.
Tentative decay schemes are suggested for Rb$^{82,83,84}$, and $84m$, and are briefly discussed in relationship to the shell model.
Radioactivity of Rb$^{81}$

The radioactivity of Rb$^{81}$ (4.7 hours, $\beta^+$, K) has been established by Reynolds, Karraker, and Templeton$^1$ with a mass spectrographic technique. Later Karraker and Templeton$^2$ measured the $\beta^+$ spectrum (0.99 Mev) and determined a $\gamma$-ray energy (0.95 Mev) from absorption data. More recently the properties of Rb$^{81}$ have been investigated by Hobson, Hubbs, Nierenberg, and Silsbee,$^3$ who measured its spin (3/2), magnetic moment (1.99 nuclear magnetons) and hyperfine splitting (4980 Mc) with a zero-moment atomic beam apparatus. The investigation reported herein was undertaken in order to determine the decay scheme for Rb$^{81}$ and to measure the multipolarity of the Kr$^{81m}$ transition reported in Reference 2 as a product of the Rb$^{81}$ decay. The $\beta^+$ spectrum is found to be complex, and three additional $\gamma$ rays are observed. Kr$^{81m}$ deexcites with E3 radiation as predicted by the shell model.$^4$

Rb$^{81}$ is produced by the reactions Br$^{79}$ (a, 2n) Rb$^{81}$ and Br$^{81}$ (a, 4n) Rb$^{81}$, which occur with 48-Mev a-particle bombardment of BaBr$_2$ powder. Excitation functions for the Br(a, kn) Rb, k=1, 2, 3, 4 reactions are calculated in Appendix I from the liquid-drop model of the nucleus and are shown in Fig. 1. The chemical separation for Rb is similar to that used in Reference 3. After BaBr$_2$ has been dissolved in $H_2O$ containing RbBr carrier, a saturated solution of (NH$_4$)$_2$CO$_3$ is added to precipitate Ba as a carbonate, which is removed by filtration. The excess (NH$_4$)$_2$CO$_3$, NH$_4$Br, and Kr daughters are driven off by heating. Sources from the water-soluble RbBr residue are mounted on ~150-$\mu$ g/cm$^2$ Tygon films for observation in a thick-lens type $\beta$ spectrometer.$^5$ The $\beta$ spectrometer normally has a momentum resolution of 5%, which is reduced to 8% when it is operated with a helical baffle to select positrons or electrons. However, in order to study Kr$^{81m}$, it was necessary to design a ring baffle (cf. Appendix II), which improved the resolution to 1.5% and 2.2%, respectively, without and with the helical baffle.
The internal conversion spectrum—observed 10 hours after the bombardment so as to allow the decay of any short Rb activities, e.g., Rb$^{84m}$ (20.5 min.)—is shown in Fig. 2. Because the upper and lower ends of the spectrum were taken with different baffle arrangements, it is difficult to normalize the curves properly. The very intense transition at 190 kev was studied after a subsequent bombardment, and is shown in more detail in Fig. 3. No conversion peaks were observed for γ rays between 25 and 190 kev. As indicated in Fig. 1, the overlap of the excitation functions makes it impossible to produce Rb$^{81}$ without Rb$^{82}$ contamination. Before making line assignments one must either follow the decay of the individual components or observe the variation of their relative intensity with alpha energy. The half life of the 190-kev line, followed over seven half lives in the β spectrometer, is shown in Fig. 4 to be 4.7 ± .1 hours. The seven pronounced lines above 500 kev decay with a 6.3-hour half life and are assigned to Rb$^{82}$. The peaks due to the 253-kev and 450-kev transitions have ~4.5-hour half lives and are assigned to Rb$^{81}$. γ-γ coincidences indicate that a 1.1-Mev γ ray is in coincidence (<5 x 10$^{-6}$ sec) with the 253-kev γ transition (cf. Fig. 5). Shown in Fig. 7 is the photoelectron spectrum of Rb$^{81}$ and Rb$^{82}$ produced with a 1/4-mil Au foil. It is believed that the previous erroneous assignment$^{7,8}$ of the three lines below 500 kev to Rb$^{82}$ resulted from the relatively large particle background due to the several high-energy gammas involved in the Rb$^{82}$ decay (6.3 hours) in the case in Reference 7, and, in addition, to the β$^+$ spectrum in the case in Reference 8.

Several investigators$^{2,9}$ have observed electrons from Kr$^{81m}$ (13 sec, 193 kev) following the decay of Rb$^{81}$. The presence of Kr$^{81m}$ was confirmed by observing the rapid growth in the activity after Kr was driven off by heating. Since the shell model predicts an E3 transition for Kr$^{81m}$, it is of interest to verify this assignment experimentally. Table I gives the results of the measurements for the K/(L+M) ratio and the total conversion coefficient α to be compared with the K/(L+M) ratio from the empirical curves by Goldhaber and Sunyar$^{10}$. 
and the theoretical values of $\alpha$ from Rose's tables. The $K/(L+M)$ ratio for the 190-kev transition involved in the decay of Rb$^{81}$ is computed from Fig. 3, which has been corrected for Geiger tube dead time, decay, background (equal to 0.25% of K peak), and the fact that we have $\Delta p \cdot \Delta t$ for the $\beta$ spectrometer. The ratio of the areas under the K and L+M peaks is equal to the ratio of the peak heights to within 1%. The value quoted in Table I has been corrected for the relative absorption (factor of 1.013), by the 0.66 mg/cm$^2$ Mylar Geiger tube window, of electrons with energies 176 kev and 188 kev.

Table I

<p>| Multipole order determination for $^{36}\text{Kr}^{81}m$ |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |</p>
<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>E1</th>
<th>M2</th>
<th>E2</th>
<th>M3</th>
<th>E3</th>
<th>M4</th>
<th>E4</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.024</td>
<td>0.014</td>
<td>0.15</td>
<td>0.093</td>
<td>0.83</td>
<td>0.49</td>
<td>4.5</td>
<td>2.5</td>
<td>0.54 $\pm$ 0.07</td>
</tr>
<tr>
<td>K/L</td>
<td>8.0</td>
<td>--</td>
<td>8.6</td>
<td>7.2</td>
<td>7.4</td>
<td>4.5</td>
<td>5</td>
<td>2.9</td>
<td>K/(L+M) 5.16 $\pm$ 0.30</td>
</tr>
<tr>
<td>T 1/2</td>
<td>3x10$^{-12}$</td>
<td>3x10$^{-14}$</td>
<td>3x10$^{-6}$</td>
<td>3x10$^{-8}$</td>
<td>4</td>
<td>0.04</td>
<td>4x10$^{7}$</td>
<td>4x10$^{5}$</td>
<td>13 sec $^{24}$</td>
</tr>
</tbody>
</table>

The total conversion coefficient is measured by comparing the number of internal conversion electrons from the K and L+M peaks with the number of gammas emitted, as inferred from the photoelectrons ejected from a 0.25-mil Au converter. The photoconverter was calibrated with the known 173- and 247-kev lines in In$^{111}$. Normally two sources are required for determining $\alpha$: one for the conversion electrons, and a stronger one for the photoelectrons because of the low photoconversion efficiency. However, when the activity is decaying with a complex half life—e.g., Rb$^{81}$ (4.7 hours) +Rb$^{82}$ (6.3 hours)—it is difficult to determine the relative source strengths of one of the
component activities (Rb$^{81}$). In this experiment a single source was used with a converter arrangement indicated in Fig. 33. The conversion spectrum of the line was taken several half lives after the photoconversion spectrum shown in Fig. 6, and the ratio of the source strengths for the two spectra is simply the half-life correction.

The assignment of E3, based on a., is considered reasonably certain in view of the agreement within the experimental error with the theoretical conversion coefficient. The observed K/(L+M) value is somewhat higher than that expected from the empirical curve for an E3 transition. However, this deviation might be expected, since it has been pointed out that the low-Z isotopes commonly have higher K/(L+M) ratios than the higher-Z isotopes for the same $Z^2/E$ value. The previous assignment of this transition to Rb$^{82}$ resulted in its erroneous designation as E2 based on a measurement of a utilizing the two-source technique discussed above. The error in the determination probably lies in the measurement of the relative source strengths and in the decay correction.

The positron spectrum of Rb$^{81}$ is distorted by the presence of Rb$^{82}$, which has a simple spectrum with end-point energy 783 kev. The Fermi-Kurie analysis of the spectrum (Fig. 8) is somewhat complicated, owing to the different component half lives. The upper end (1.05 ± .03 Mev) of the observed positron spectrum decays with a 4.7-hour half life and is clearly due to Rb$^{81}$. Further decomposition results in three additional $\beta^+$ components, of energies 810 ± 30 kev, 575 ± 35 kev, and 325 ± 40 kev. In order to determine the half lives of the individual positron groups, the spectrum was scanned three times over a period of 15 hours. A time plot of the intensities determined by integrating the N(p)-vs-p curves obtained from extrapolating the Fermi-Kurie analysis shows the 1050-kev and 810-kev components to have half lives of 4.7 hours (Rb$^{81}$) and 6.3 hours (Rb$^{82}$) respectively. The results for the weaker components were inconclusive, owing to their lower intensity and the errors associated with the decomposition of the F-K plot. The 575-kev and 325-kev $\beta^+$ groups can be assigned to Rb$^{81}$ in view of their absence in recent experiments on Rb$^{82}$.
We have the following values for the Rb$^{81}$ $\beta^+$ components.

<table>
<thead>
<tr>
<th>energy (kev)</th>
<th>relative intensity (%)</th>
<th>log ft value$^{17}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050 ± 30</td>
<td>74</td>
<td>5.6</td>
</tr>
<tr>
<td>575 ± 35</td>
<td>16</td>
<td>5.2</td>
</tr>
<tr>
<td>325 ± 40</td>
<td>10</td>
<td>4.3</td>
</tr>
</tbody>
</table>

These values characterize these transitions as allowed,$^{18}$ with $\Delta I = 0, 1$, and with no parity change. These $\beta^+$ groups were previously observed by Easterday$^7$ in a study of Rb$^{82}$ and assigned to this isotope because 14-Mev alpha particle bombardment of CuBr was not believed to produce the Br$^{79}$(a, 2n)Rb$^{81}$ reaction. However, it was pointed out$^{19}$ to Easterday that the threshold for the (a, 2n) reaction is below 14 Mev; consequently, his sources were contaminated with appreciable amounts of Rb$^{81}$. Moreover, the (a, n) cross section for the production of Rb$^{82}$ is suppressed because of the competitive (a, n) reactions (cf. Appendix I) that lead to Rb$^{82m}$, which decays directly to the ground state of Kr$^{82}$ and does not feed the ground state of Rb$^{82}$.\footnote{20}

A tentative decay scheme for Rb$^{81}$ is shown in Fig. 9. According to the shell model the ground state of Rb$^{81}$ has either spin $3/2$ or $5/2$. The assignment $3/2$ is based on the measured spin and magnetic moment.$^3$ In order to estimate the mass differences between ground states of the Rb and Kr isotopes, the recent mass measurements and energy differences of known decay schemes have been plotted in Fig. 10$^{44}$ according to Reference 21. The measured points have their errors indicated. The energy difference between Kr$^{81}$ and Rb$^{81}$ (~2.1 Mev) is obtained from an extrapolation of the mass parabola and is in agreement with that expected from $\beta$-decay systematics (~2.2 Mev).\footnote{22}

The most intense transition in the decay of Rb$^{81}$ is the 190-kev E3 line due to Kr$^{81m}$. Spin and parity assignments$^4$ for the levels involved in the Kr$^{81m}$ decay have been made on the basis of the shell model. The higher levels fed by positron emission have odd parity and
spin 1/2, 3/2, or 5/2 because of the allowed nature of the positron components. Cross-over transitions are expected from the higher levels; however, the several cascade γ rays in the Rb\(^{82}\) contamination prevented observation of these transitions. Rb\(^{81}\) can be produced without Rb\(^{82}\) contamination with the reaction Rb\(^{85}\) (p, 5n)Sr\(^{81}\)\(^{29}\)min → Rb\(^{81}\), since the Sr\(^{82}\) resulting from the (p, 4n) reaction does not decay to the ground state of Rb\(^{82}\).\(^{20,23}\)
Experimental Evidence for Rb$^{81m}$

During the investigation of Rb$^{81}$, conversion electrons from a 31.5-min activity corresponding to an 85-kev $\gamma$ ray were observed in the $\beta$ spectrometer. Chemical procedure established that the half life is due to a Rb isotope. The known Rb activities$^{24}$ that are produced by $(a, kn) k = 1, 2, 3, 4$ $(a, \gamma)$ reactions$^{25}$ with 48-Mev alpha particles, are Rb$^{81}$ (4.7 h), Rb$^{82}$ (6.3 h), Rb$^{82m}$ (1.25 m), Rb$^{83}$ (83 d), Rb$^{84}$ (33 d), Rb$^{84m}$ (20.5 m), and Rb$^{85m}$ (0.9 $\mu$s). The radiations of Rb$^{84m}$ are reported in Section III, and simultaneous observations of the two activities clearly show two distinct half lives (cf. Figs. 11 and 15). Subsequent bombardments at lower energies show that the threshold for the production of the 31.5-min activity is between 12 and 16 Mev, an energy which indicates its formation with an $(a, 2n)$ reaction (cf. Fig. 1). The ratio of the 31.5-min activity and 20.5-min Rb$^{84m}$ (produced with an $(a, n)$ reaction) decreased with alpha energy, and at 11 Mev Rb$^{84m}$ was still produced but the 31.5-min activity was no longer present.

Since the Rb isotopes produced by $(a, 2n)$ reactions with Br$^{79,81}$ have mass numbers 81 and 83, this activity must be due to an isomeric level in one of the isotopes. In order to determine if the 85-kev transition represents the decay of the isomer to the ground state of the isotope rather than the decay of an excited level in the isomer's Kr daughter, the K and L conversion peaks were carefully scanned (cf. Fig. 12) in an attempt to measure the K-L energy difference. Even though the absolute energy calibration of the $\beta$ spectrometer is not accurate enough for the absolute determination of the K and L peaks to the precision required for this measurement, a sufficiently accurate relative determination of neighboring lines can be made. The measured K-L energy difference (13.5 ± .6 kev), when compared with the known K-L differences for Kr (12.4 kev), Rb (13.1 kev), and Sr (13.9 kev),$^{26}$ indicates that the transition involves states in Rb and not in a Kr daughter.
Assuming the 85-kev transition to be the dominant influence in the 31.5-min half life, we can estimate the type of transition from the Weisskopf formula. The partial γ half lives for \( A = 81, E = 85 \text{ kev} \) are \( E2 \left( 5 \times 10^{-6} \text{ sec} \right) \), \( M2 \left( 480 \times 10^{-6} \text{ sec} \right) \), \( E3 \left( 50 \text{ sec} \right) \), \( M3 \left( 4800 \text{ sec} \right) \), \( E4 \left( 10^9 \text{ sec} \right) \), and \( M4 \left( 90 \times 10^9 \text{ sec} \right) \). The actual half life is shortened by the internal conversion process and positron and electron capture events. The choice of an \( E3 \) or \( M3 \) assignment on the basis of half-life considerations is justified in view of the spread of observed half lives of such transitions.

The ground state of \( \text{Rb}^{83} \) is expected to be \( f \ 5/2 \) or \( p \ 3/2 \) according to the shell model, and recent work on the decay scheme suggests the \( f \ 5/2 \) assignment. Preliminary measurements with an atomic-beam magnetic-resonance apparatus in this department by Nierenberg, Silsbee, and Sunderland indicate a spin of 5/2. Since it is extremely unlikely that there exists a level with spin 11/2 only 86 kev above the ground state of \( \text{Rb}^{83} \), the isomer can hardly belong to the \( \text{Rb}^{83} \) isotope. Neither the 522-kev nor the 32.2-kev transition involved in the decay of \( \text{Rb}^{83} \) is observed to be associated with the 31.5-min activity.

\( \text{Rb}^{81} \), however, has its odd proton in a \( p \ 3/2 \) orbital (cf. Section I) in the ground state. Moreover, a \( g \ 9/2 \) state immediately above the ground state is not unlikely in view of the 360-kev energy difference between the \( +9/2 \) and \( -3/2 \) levels in \( \text{Rb}^{85} \). The energy relationship of the \( -5/2 \) and \( +9/2 \) levels relative to the \( -3/2 \) state for the odd-A \( \text{Rb} \) isotopes is shown in Fig. 13 in a manner originally suggested by Hill. The levels in \( \text{Rb}^{85} \) are well established. The lowest levels (ground states) of \( \text{Rb}^{81} \) and \( \text{Rb}^{87} \) have been determined to be \( p \ 3/2 \) and--as indicated earlier--\( \text{Rb}^{83} \) can be assigned a \( f \ 5/2 \) orbital. The level assignments for \( \text{Rb}^{87} \) are based on Thulin's tentative decay scheme. It should be pointed out that the one-particle shell model is inadequate to interpret the experimental data in both cases, \( \text{Rb}^{85} \) and \( \text{Rb}^{87} \). However, the theory of De Shalit and Goldhaber, who consider mixed configurations due to a "stabilization" effect of one configuration by another, can explain the observed data. Reference to Fig. 13 shows that the \( f \ 5/2 \) and \( p \ 3/2 \) states lie close together, a well-known fact.
If the general trend indicated by the g 9/2 points for Rb\(^{85,87}\) is continued, it is not unreasonable to expect a g 9/2 level in Rb\(^{81}\) lying between the p 3/2 and f 5/2 levels. It seems plausible, therefore, that this 85-kev transition can be assigned to Rb\(^{81m}\).

The existence of Rb\(^{81m}\) can be verified by observing the following properties. Rb\(^{81m}\) should partially decay by allowed \(\beta^+\) emission (1.33 Mev) to the ground state of Kr\(^{81}\) (+7/2), and the radiation from Rb\(^{81}\) should show an increase in activity immediately after the end of a bombardment owing to the decay of Rb\(^{81m}\) into Rb\(^{81}\). A search for positrons in the region above the end-point energy of Rb\(^{81}\) positrons (1.05 Mev) revealed a weak component with upper energy 1.4 \(\pm\) 2 Mev and half life 26 \(\pm\) 6 minutes, believed to be due to Rb\(^{81m}\) (although Rb\(^{84m}\) cannot be excluded in this observation). Furthermore, the build-up in the activity of Rb\(^{81}\) was confirmed by observing the conversion electrons from the 190-kev transition in the \(\beta\) spectrometer immediately following the bombardment. The actual build-up curve of the Rb\(^{81}\) activity is somewhat distorted owing to the 13-sec half life of the 190-kev transition (Kr\(^{81m}\)); however, the general trend is preserved. To insure that the observed growth of the line was not associated with the physical properties of krypton gas, identical sources were made several hours after the bombardment and introduced into the spectrometer. In this case the activity immediately began to decay with a 4.7-hour half life, with no evidence of growth. Figure 14 shows a typical growth curve taken with a sample of bombarded BaBr\(_2\) powder before chemical separation. It is worth noting that the build-up in the 190-kev transition indicates that there is hardly any decay from Rb\(^{81m}\) to Kr\(^{81}\) levels feeding Kr\(^{81m}\).

Goldhaber and Hill predict\(^4\) that a g 9/2 level in Kr\(^{81}\) lies \(\sim\) 0.2 Mev above the p 1/2 level. A transition from Rb\(^{81m}\) (g 9/2) to this level would be allowed. The g 9/2 level (Kr\(^{81}\)) would depopulate with transitions to the +7/2 ground state of Kr\(^{81}\) with a \(\gamma\) ray of \(\sim\) 0.4 Mev energy. A search for conversion electrons from such a transition yielded negative results. However, this transition cannot be excluded on these results, for less than 1% of the transitions\(^11\) would be converted. A tentative decay scheme is indicated in Fig. 15.
SECTION III

Radioactivity of Rb$^{84m}$

The radioactivity of Rb$^{84m}$ (20.5 min, EC, γ) has been studied by several investigators.\textsuperscript{6,30} Gamma rays of energies 463 keV, 239 keV, and 890 keV have been observed in the decay. Coincidence measurements\textsuperscript{6} indicate that two γ rays of ~239 keV are in cascade and are not coincident with the 463-keV transition. It became necessary to investigate the radiations from Rb$^{84m}$ (20.5 min) in the study of Rb$^{81m}$ (31.5 min) because of the similarity of half lives.

The half life of Rb$^{84m}$ (20.5 ± 2.0 min) was determined by following the decay of the ~239-keV γ transitions with a crystal spectrometer\textsuperscript{7} over seven half lives (cf. Fig. 16). The internal-conversion electron spectrum of the activity produced by 11-Mev α particles is shown in Fig. 17. Both peaks, corresponding to 217-keV and 466-keV γ-ray energies, decay with the 20.5-min half life and are due to Rb$^{84m}$. The absence of the 85-keV (Rb$^{81m}$) and 190-keV (Kr$^{81m}$) lines indicates that 11-Mev α-particle energy is below the (α, 2n) threshold. No conversion electron peaks were observed between 217 keV and 466 keV (limit 6% of 217-keV peak). A study of the γ rays in coincidence with the 217-keV γ (Fig. 18) shows that the 217-keV transition is in cascade with a γ ray of similar energy. Assuming these two γ rays to form a decay branch in parallel with the 466-keV γ transition, we obtain 249 keV as the energy of the coincident γ ray.

A tentative decay scheme\textsuperscript{6} is suggested in Fig. 19. The ground state of Rb$^{84}$ has spin -2, as inferred from the unique shapes of the first-forbidden $\beta^+$ and $\beta^-$ transitions (cf. Section IV) to the ground states of Kr$^{84}$ and Sr$^{84}$. A spin assignment of -3 and +6 to the excited states is partially based on lifetime-spin relationships. The -2 level is interpreted as an f 5/2 proton orbital coupling according to Nordheim's second rule with a g 9/2 neutron orbital to give a resultant spin which is the difference of the individual spins. A possible identification of the +6 excited level involves the elevation of the odd proton to the...
g 9/2 state. As suggested by Fig. 12, p 3/2 is the next lower proton level. However, a g 9/2 neutron and p 3/2 proton cannot couple to give a -3 resultant without violating Nordheim's third rule.\textsuperscript{31} It does not seem possible to explain the excited states in terms of the extreme one-particle shell model.
Particle Spectra - Rb$^{84}$

The decay of Rb$^{84}$ has been studied by numerous investigators. The later investigators fully review the previous work and are concerned chiefly with establishing the branching ratios for the first-forbidden K-capture positron transition and the relative probabilities of L and K capture. The weak $\beta^-$ transition to Sr$^{84}$, however, has not been well established, owing to its relatively low intensity. The upper energy for this transition has been reported as 440 kev by Welker and Perlman, who later indicate (in a footnote added in proof) an endpoint energy of 910 kev according to recent measurements by C. S. Wu and N. Benczer. It is the object of this investigation to measure the particle spectra of Rb$^{84}$ and determine the relative intensities of the positron and electron groups. The $\beta^-$ spectrum is found to be complex, having a first-forbidden unique-shape component with upper energy 908 ± 15 kev and a normal-shape component with end-point energy 490 ± 30 kev.

The $\beta^-$ spectrum is shown in Fig. 20, and the Fermi-Kuri analyses of the $\beta^-$- and $\beta^+$-spectra are presented in Figs. 21 and 22. The upper energy components are seen to have the unique shape indicating $\Delta I = 2$, change of parity, transitions. Correcting Figs. 21 and 22 with the shape factor, $\left[p^2 + q^2 \right]^{-1/2}$, $p = \beta^\pm$, neutrino momentum, results in the F-K plots shown in Figs. 23 and 24, which are further decomposed into normal-shape $\beta^-$ and $\beta^+$ components having energies 490 ± 30 kev and 785 ± 30 kev respectively. The upper section of the corrected $\beta^-$ spectrum is shown in more detail in Fig. 25. Energies, branching percentages, and log ft values are given in Table II.
Table II

Characteristics of \( \beta \) decays in \( \text{Rb}^{84} \)

<table>
<thead>
<tr>
<th>Energy (kev)</th>
<th>Branching Percentage</th>
<th>( \log f_{0t} )</th>
<th>( \log f_{1t} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta^+ )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1635 ± 40</td>
<td>44</td>
<td>8.8</td>
<td>8.7</td>
</tr>
<tr>
<td>785 ± 30</td>
<td>56</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta^- )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>908 ± 15</td>
<td>59</td>
<td>9.2</td>
<td>8.7</td>
</tr>
<tr>
<td>490 ± 30</td>
<td>41</td>
<td>8.5</td>
<td>( \beta^+/\beta^- = 5.6 )</td>
</tr>
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\( \beta^- \gamma \) coincidences taken with scintillation-crystal pulse-height analysis equipment\(^7\) show the 785-kev component to be coincident with a 0.89-Mev \( \gamma \) ray. The absence of coincidences above 800 kev (\( \beta \) energy) indicates that the higher energy \( \beta^+ \) and \( \beta^- \) transitions go to the \((0^+)\) ground states of \( \text{Kr}^{84} \) and \( \text{Sr}^{84} \) respectively, in agreement with earlier investigators.\(^{1,33}\) A tentative decay scheme is shown in Fig. 26, with electron capture branching percentages taken from Reference 33. In Fig. 26 the gamma transition to the ground state of \( \text{Sr}^{84} \) is indicated, but it was not observed because of its low intensity. The \( \text{Kr}^{84} - \text{Sr}^{84} \) mass difference calculated from the decay scheme (1.75 Mev) is in agreement with the difference calculated from mass spectroscopic data\(^{21}\) (1.6 Mev) (cf. Fig. 10).

The ground state of \( \text{Rb}^{84} \) can be assigned odd parity and spin 2 on the basis of the unique shape of the \( \beta^+ \) and \( \beta^- \) transitions. The probable nucleon configurations are indicated in Fig. 26. The level indicated in \( \text{Sr}^{84} \) is assigned a spin and parity \((+2)\) in view of the general occurrence of such levels\(^{36}\) in even-even nuclei. This transition fits into the general trend\(^{37}\) of the first excited states, as seen in Fig. 27.\(^{44}\)
SECTION V

Rb 83

The radioactivity of Rb\(^{83}\) has been studied by Karraker and Templeton,\(^2\) by Castner,\(^23\) and more recently by Welker and Perlman,\(^27\) who observed the decay to proceed by electron capture through a 525-kev \(\gamma\) ray to Kr\(^{83m}\), as indicated in Fig. 28. During the investigation of Rb\(^{84}\), the radiations from Rb\(^{83}\) were observed; they are presented here.

The internal-conversion electrons from two transitions are shown in Fig. 29. The 31.9-kev transition is identified with Kr\(^{83m}\) (2 hours) because of its growth in the \(\beta\)-spectrometer after heating. The higher-energy line corresponds to a 522-kev \(\gamma\) ray and is seen to be in coincidence with \(x\)-rays. Perlman and Welker\(^27\) were able to show that the number of \(x\)-rays emitted in the decay of the Rb\(^{83}\) is equal to the number of 525-kev \(\gamma\) rays to within 10\%, by combining their results with the growth curves of Kr\(^{83m}\) reported by Castner\(^23\) in the decay of Rb\(^{83}\).

From this analysis they made the spin assignments \(p\ 3/2\) for the upper level in Kr\(^{83}\) and \(f\ 5/2\) for Rb\(^{83}\) (cf. Fig. 28), which is in agreement with tentative results of the spin measurements of Rb\(^{83}\) by Nierenberg, Silsbee, and Sunderland in this laboratory.

Recently reported\(^38\) in the decay of Br\(^{83}\) is a 51-kev level (K/L-8) immediately above the Kr\(^{83m}\) level, which also has a spin assignment of \(p\ 3/2\). One would expect transitions between the two \(p\ 3/2\) levels; however, the agreement in energy between the \(\gamma\) transition reported by Perlman (observed with a scintillation crystal) and the internal-conversion electrons observed in this report, and the absence of two internal-conversion peaks in the region 475 to 525 kev, indicate that such transitions, if present, are very weak.\(^43\) The absence of this transition could perhaps be explained by assuming that the two \(p\ 3/2\)'s levels have much different nucleon configurations.
SECTION VI

Radiations of Rb$^{82}$

The decay of Rb$^{82}$ (6.3 hr, $\beta^+$, EC) has been reported by several workers. More recently Benczer and Wu have studied Rb$^{82}$ in connection with their investigation of the levels in Kr$^{82}$ reached by Br$^{82}$ decay. The $\beta^+$ spectrum was found to be simple and the $\gamma$ spectrum was found to consist of eight $\gamma$ rays with energies greater than 0.5 Mev. Three of the six previously reported $\gamma$ rays below 0.5 Mev were not found, and the other three were seen to decay with a half life less than 6.3 hr. The radiations of Rb$^{82}$ were observed during the Rb$^{81}$ experiments and are included in this report. The results are in agreement with those presented by Benczer and Wu.

The internal-conversion spectrum of Rb$^{82}$ is shown in Fig. 2 along with the three $\gamma$ rays assigned to Rb$^{81}$. A Fermi-Kurie plot of the $\beta^+$ spectrum (log $t$ = 5.4) is shown in Fig. 8. The inaccuracy in the energy determination is due to the complexity of the $\beta^+$ spectrum involving different half lives. In order to study the spectrum without Rb$^{81}$ one can reduce the beam energy below the ($\alpha$, 2n) threshold, or, if Rb$^{81}$ (4.7 hr) is produced, allow it to decay to a negligible fraction of Rb$^{82}$ (6.3 hr) activity. Shown in Fig. 30 is the $\beta^+$ spectrum of Rb$^{82}$ observed, 67 hours after the 46-Mev $\alpha$-particle bombardment, with a plastic-crystal photomultiplier combination. The ratio of Rb$^{81}$ to Rb$^{82}$ activity has decreased by a factor of 1/12 because of the relative decay. To insure that the residual activity did not contain a significant amount of Rb$^{84}$ positrons, a thin target was used so that the exit energy (32 Mev) of the $\alpha$ beam was above the region where the ($\alpha$, n) reaction is dominant (cf. Fig. 1). The data in Fig. 30 have been corrected for Compton electrons produced in the crystal by the Rb$^{82}$ $\gamma$ rays, as determined after the particles from the source were stopped with an Al absorber.

An estimate of the Rb$^{82}$-Kr$^{82}$ mass difference can be made from Fig. 10. The energy difference must be greater than ~3.2 Mev to maintain the Rb odd-odd curve less stable than the odd-even curve.
The upper limit (4.0 Mev) for the energy difference is given by the 3.0 Mev allowed $\beta^+$ spectrum of Rb$^{82m}$ (+1), which goes to the ground state of Kr$^{82}$ (+0) (1.25 min). The absence of transitions$^{20}$ from Rb$^{82m}$ to Rb$^{82}$ (limit 0.1%) indicates a high spin change and (or) a small energy difference between these levels. Recent measurements by Nierenberg, Silsbee, and Sunderland in this department indicate a spin of 5 for Rb$^{82}$. An estimate of the maximum energy difference between Rb$^{82m}$ and Rb$^{82}$ compatible with these considerations (assuming odd parity for Rb$^{82}$) gives $\sim 0.35$ Mev, and the corresponding Rb$^{82}$-Kr$^{82}$ difference must be greater than $\sim 3.65$ Mev. The Kr$^{82}$ level arrangement proposed by Lu et al.$^{40}$ for the decay of Br$^{82}$ is in agreement with this energy difference, and is shown in Fig. 31.$^{24}$

The neighboring Rb even-A isotopes have spin -2, which suggests that the odd proton and neutron are in $f\ 5/2$ and $g\ 9/2$ states, respectively. However, Rb$^{82}$ is in the region of Rb isotopes in which the p $3/2$ and f $5/2$ exchange lower positions (cf. Fig. 13). The interpretation of the -5 level is probably similar to the case of Br$^{80m}$, which differs from Rb$^{82}$ by 2 protons. Goldhaber and Hill$^4$ indicate that the proton and neutron configurations are possibly p $3/2$, ($g\ 9/2$)$^{7/2}$, which couple to give a resultant of -5. Probable proton and neutron orbitals for Rb$^{82m}$ are p $3/2$ and p $1/2$. 
Acknowledgments

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APPENDIX

1. Cross-Section Calculation

In order to estimate cyclotron bombardment times, energies, and currents, it is necessary to determine the cross section of the reaction used for the production of the isotope under investigation. The cross section \( \sigma(\alpha, kn) \) \( k = 1, 2, 3, 4 \) for the capture of an \( \alpha \) particle and subsequent emission of \( k \) neutrons as a function of \( \alpha \) energy \( E \) (c.m.) can be approximated by the product of two factors:

\[
\sigma \left[ \sigma(\alpha(E), kn) \right] = \sigma_c \left[ \sigma_c(\alpha(E)) \right] \left\{ \begin{array}{ll}
0 & E \leq E_k \\
\left[ 1 - r_k(E) \right] \left[ 1 - r_{k-1}(E) \right] & E_k \leq E \leq E_{k+1} \\
\left[ 1 - r_{k}(E) \right] r_{k+1}(E), & E \geq E_{k+1}
\end{array} \right. \\
\left[ \frac{1 + \frac{E - E_k}{\theta k}}{} \right] \exp \left( \frac{E - E_k}{\theta k} \right), & k \neq 0, 1 \\
0 & k = 0, 1
\]

where \( E_k \) is c.m. threshold energy for \((\alpha, kn)\) reaction,

\( \theta k \) is nuclear temperature.

The first factor \( \sigma_c(\alpha(E)) \) represents the cross section for the formation of a compound nucleus by bombardment of \( \alpha \) particles. This cross section, which includes the Coulomb penetration factor, has been calculated by continuum theory and tabulated in Reference 41, Table 4.1.

The second factor describes the decay of the compound nucleus as the competitive evaporation of neutrons. The compound nucleus is considered statistically as a highly degenerate Fermi-Dirac nuclear gas sufficiently excited to allow such evaporation. The emission of \( k \) neutrons by a nucleus with excitation energy \( E - E_1 > E_k \) is described as the successive evaporation of neutrons, each neutron leaving the nucleus excited with energy \( > E_1 \) until \( k \) neutrons are emitted. For a particular excitation energy \( E - E_1 > E_{k-1} \), the compound nucleus may...
(depending on the energy carried away by the first neutron) emit $k, k-1, \ldots, 1$ neutron(s) with the relative probabilities approximated by the second factor in Eqs. (1).

Applying Eqs. (1) to the Br$^{79,81}$ (a, kn) Rb reactions results in the excitation functions shown in Fig. 1. The average threshold energies $E_k$ were determined from mass spectrographic data and known decay schemes (cf. Fig. 10). An average nuclear temperature $\bar{\theta} = 2.4$ Mev was chosen, corresponding to an average excitation energy of 20 Mev. The cross section $\sigma_c [a(E)]$ is based on the nuclear radius constant $r_0 = 1.3 \times 10^{-13}$ cm, and represents the total reaction cross section. It should be emphasized that Eqs. (1) should be considered only qualitatively correct because of the rough approximations involved in their determination; for example, the contribution to the decay of the compound nucleus by proton emission, $(a, p)$, $(a, pn)$ etc., has been assumed negligible, which is completely unacceptable in certain reactions, such as

$$\sigma \left[ \text{Ni}^{60} (a, pn) \text{ Cu}^{62} \right] \simeq 4 \sigma \left[ \text{Ni}^{60} (a, 2n) \text{ Zn}^{62} \right],$$

where the Coulomb barrier effect for the proton is overcompensated by the relative energy-level densities of the odd-odd and even-even product nuclei. However, this latter effect aids the Coulomb effect for the $a$ bombardment of Br$^{79,81}$, and further suppresses the cross section for proton emission.

Equations (1) give the cross sections of reactions leading to excited states of the product nuclei. In nonisomeric regions of the nuclear periodic table these excited levels promptly decay into the ground state, so that Eqs. (1) represent the cross sections for the ground-state production of the product nuclei. However, in reaction products that have isomeric levels, these excited states may decay either to the isomeric level or directly to the ground state. Therefore, a knowledge of the decay of the isomeric level and its production relative to that of the ground state is necessary in order to determine the ground-state cross section.
II. Equipment Modifications

The momentum resolution of the $\beta$ spectrometer was improved from 5% to 1.5% by means of a ring baffle designed jointly by the author and Michael Petroff. The dimensions of the baffle were determined from an analysis of the electron trajectories as indicated by x-ray film placed in the $\beta$ spectrometer. Twenty-four-hour exposures were made with a 10-µ curie Cs$^{137}$ source. The details of the final baffle design are given in Fig. 32.

The higher resolution of the $\beta$ spectrometer necessitated the construction of a better regulatory system for the current delivered by a 5-kw motor-generator combination. The earlier system, which employed a dc amplifier and controlled the current to 1 part in 1000, was replaced with a circuit that maintains short-term regulation to ± 1 part in 60,000. Utilized in the new closed-loop system (Fig. 34) is an ac type regulator designed by Kenneth Jenkins for current regulation in the 60-inch cyclotron of the Crocker Laboratory, with appropriate modifications for the present application. The current regulator compares the voltage developed across a standard resistance in the spectrometer coil circuit with a variable reference voltage, and chops the difference error signal into a 60-cycle square wave, which is then fed into a push-pull ac amplifier of maximum gain 200,000. The signal from the amplifier phase modulates two thyratrons which full-wave rectify the excitation current for the dc generator field so as to minimize the error signal. By means of a 15-turn helipot, the current is continuously adjustable over an equivalent electron energy from approximately 2 kev to 40 kev on the low-current range and from 15 kev to 2.5 Mev on the high-current range. As indicated in Fig. 3, the current can easily be adjusted to 1 part in 2000. The long-term drift (due primarily to the temperature dependence of the V-R tube used as the reference voltage) measured over a 24-hour period, was less than 0.04%. As shown in Fig. 34, an arrangement has been provided to permit demagnetization of the $\beta$ spectrometer by cycling the magnetization curve with a current-reversing switch while gradually reducing the voltage to the spectrometer coils to zero by means of a potentiometer.
switched across the generator output. After demagnetization, the momentum-current relationship with increasing field was observed to be linear down to 30 kev (Kr\textsuperscript{83m}), and is probably linear to considerably lower energies.
BIBLIOGRAPHY

11. Rose, Goertzel, and Perry, K-Shell Internal Conversion Coefficients; Revised Tables, ORNL-1023, June 25, 1951.
32. W. C. Barber, Phys. Rev. 72, 1156 (1947); C. Beckham and M. L. Pool, Phys. Rev. 80, 125 (1950); A.
42. E. Fermi, Nuclear Physics, University of Chicago Press, Chicago, 1950.
43. Heydenburg and Temmer, Bull. Am. Phys. Soc. Series II, 1, No. 4, 164 (1956), have observed a 457-kev γ ray corresponding to an excited state in Kr\(^{83}\) which was excited with 6.5-Mev α particles.
44. Waddell and Jensen, Phys. Rev. 102, 816 (1956), who have determined the relative intensities and internal conversion coefficients of the γ transitions in the decay of Br\(^{82}\), propose an energy-level diagram for Kr\(^{82}\) which is an inversion of the one proposed by Lu.
In this case the positron transition from Rb\(^{82}\) probably leads to the 2.62-Mev level of Kr\(^{82}\). The increased Rb\(^{82}\)-Kr\(^{82}\) mass difference will be reflected in Fig. 10 and the energy of the first excited state of Rb\(^{82}\) in Fig. 27 should be increased to 0.76 Mev.
FIGURE CAPTIONS

Fig. 1. Calculated excitation functions for Br(a, kn) Rb reactions.
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Fig. 30. $\beta^+$ spectrum, Rb$^{82}$, crystal spectrometer.
Fig. 31. Tentative decay scheme, Rb$^{82}$. 

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Fig. 32. Resolution baffle for $\beta$ spectrometer.
Fig. 33. Photoconverter.
**Fig. 34. Circuit diagram of β-spectrometer current regulator.**