Studies in the Decay of 4.7-h Rb^{81}†

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4.7-h Rb^{81} was produced from the $Br^{79}(\alpha,2n)Rb^{81}$ and from the $Br^{79}(He^3,n)Rb^{81}$ reactions. The decay of this isotope was studied using Ge(Li) and standard NaI(Tl) counters. γ rays of the following energies have been identified: 190.4, 357.6, 388.2, 446.0, 456.7, 476.6, 537.7, 547.7, 568.8, 729.7, 803.6, 835.4, and 978.0 keV. Information from singles and coincidence measurements has been incorporated into a decay scheme. The proposed levels in Kr^{81} are at 190, 457, 636, 994, and 1025 keV.

I. INTRODUCTION

THE decay of the 4.7-h ground state of Rb^{81} has previously been studied by three groups of investigators.[1–3] Their findings have been summarized in the *Nuclear Data Sheets*.[4] Upon examining the information in Ref. 4, however, it is immediately evident that further study is required. There are so many inconsistencies among the three reports that they almost seem not to be referring to the same radioactivity at all. Furthermore, very few of the reported γ rays have been fitted into a decay scheme. The present study was undertaken in an attempt to clarify the situation.

II. SOURCE PREPARATION

One of the more troublesome aspects of this decay scheme study is the problem of producing a pure source of 4.7-h Rb^{81}. From a cursory inspection of the γ-ray spectrum, it is evident that only two transitions have any appreciable intensity. In order to obtain more information, it is necessary to have a source of high purity so that weak transitions may also be studied. In particular, the amount of the neighboring 6.4-h Rb^{82} must be kept very small. The 6.4-h Rb^{82} is an isomeric 5− state whose decay to the 0+ ground state of Kr^{82} is through a cascade of γ rays with energies between 0.5 and 1.0 MeV. These γ rays constitute a serious source of interference even if Rb^{82} is present in the sample only to the extent of a few percent. In order to produce samples with as little Rb^{82} as possible, several different reactions were tried using He^4 and He^3 ion from the heavy-ion accelerator at Yale University. Following is a brief discussion of the three samples which were subsequently used in our experiments.

Sample I: 24-MeV He^4 on natural Br. Rb^{81} was produced in the $Br^{79}(\alpha,2n)Rb^{81}$ reaction. The target material was in the form of NaBr. The α-beam energy was kept below the $(\alpha,3n)$ threshold so that Rb^{82} would not be produced from Br^{81}. However, some Rb^{82} production from the reaction $Br^{79}(\alpha,n)Rb^{82}$ was unavoidable. Although it was evident that the source consisted mainly of Rb^{81}, in the γ-ray spectrum one saw little other than Rb^{82} above 0.5 MeV.

Sample II: 14-MeV He^3 on 99.9% Br^{79}. NaBr enriched to 99.9% in Br^{79} was used as target. With a He^3 beam of 14 MeV, a very pure source of Rb^{81} was made from the (He^3,n) reaction. However, the source intensity was too low to be useful in coincidence experiments.

Sample III: 20-MeV He^3 on 99.9% Br^{79}. Sample III was produced in the same way as sample II, except that the beam energy was raised to 20 MeV. A much stronger source was produced, but also one with proportionately more of the 6.4-h Rb^{82} in it.

Since each of the above described samples was made from He bombardment of NaBr, the chemical procedure for separating out the Rb was the same for all of them. The chemical separation performed was as follows: The irradiated target of NaBr was dissolved in HCl. 20 mg Rb (carrier solution 20 mg/ml) and 5 ml concentrated perchloric acid were added to the above solution. The solution was evaporated to dryness, cooled to room temperature, and transferred with 15 ml absolute alcohol (ethanol) to a centrifuge tube. This solution

TABLE I. Energies and relative intensities of γ rays from the decay of 4.7-h Rb^{81}. Assuming the 190-keV transition to be $E3$, its γ-ray intensity is given as 64.5% so that the total Rb^{81} decay would be 100%.

Energy (keV)	Relative intensity (% of Rb^{81} decays)
190.4±0.3	64.5
357.6±0.5	0.7
388.2±0.5	0.5
446.0±0.5	22.0
456.7±0.5	3.0
476.6±0.8	0.5
537.7±0.5	2.4
547.7±1.2	0.4
568.8±0.8	0.6
729.7±1.0	0.4
803.6±0.5	0.8
835.4±1.0	0.7
978.0±0.8	0.6
511	64.0

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[2] W. O. Doggett, University of California Radiation Laboratory Report No. UCRL-3438, 1956 (unpublished).
[3] W. H. Kelly and D. J. Horen (private communication); see *Nuclear Data Sheets*, compiled by K. Way *et al.* (Academic Press Inc., New York, 1966), B1-4-97.
[4] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Academic Press Inc., New York, 1966), B1-4-86, 87, 96, 97.

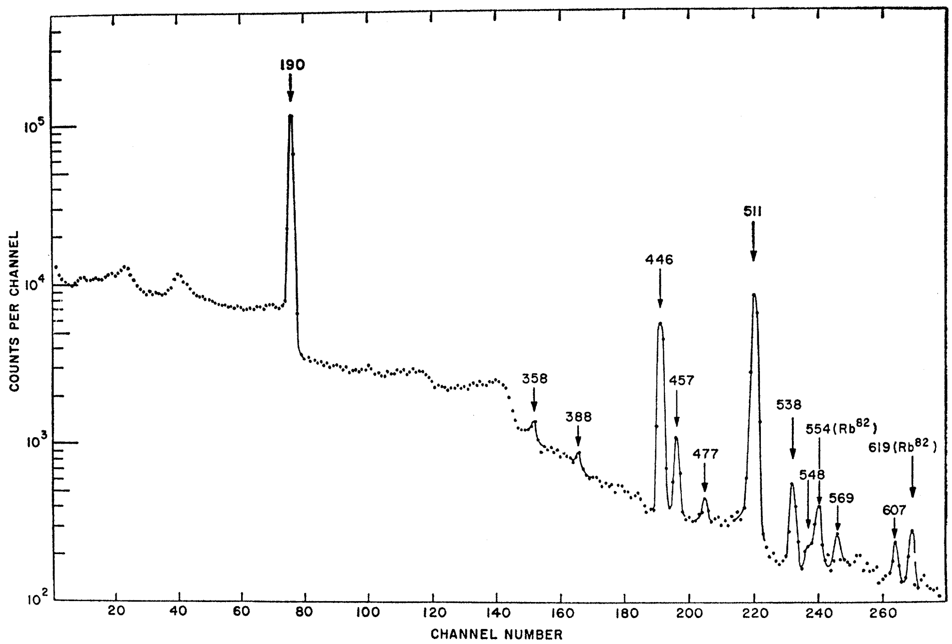

FIG. 1. Low-energy γ-ray spectrum as seen in Ge(Li) detector, taken with sample II.

was further cooled in an ice bath for 10 min with continuous stirring. The precipitate ($RbClO_4$) obtained was centrifuged, washed with absolute alcohol, and again dissolved in water. The above solution was evaporated to near dryness and a solution of H_2PtCl_6 (in alcohol) was added to precipitate the rubidium. The precipitate so obtained was filtered, washed with alcohol, and dried. These sources were used for our γ-ray measurements.

III. γ-RAY SPECTROSCOPY

A. Singles Spectra Studies

The problem of identifying the γ rays from Rb^{81} is illustrated in Figs. 1 and 2. Figure 1 is a singles spectrum of γ rays from sample II, as seen in a Ge(Li) detector. Sample II is the "cleanest" of the samples, in the sense that it contains the smallest amount of the 6.4-h Rb^{82} in proportion to the 4.7-h Rb^{81}. One sees that just above 0.5 MeV, Rb^{82} γ rays are already very prominent compared to the neighboring γ rays from Rb^{81}. The situation rapidly deteriorates for samples I and III. Sample I has proportionately the largest amount of Rb^{82}. The γ-ray spectrum from sample I is as shown in Fig. 2(a), where most of the activity one sees is from Rb^{82}. Spectrum (b) in Fig. 2 is the γ-ray singles from sample III. By comparing the three spectra, it is possible in most instances to decide whether or not a particular γ ray is from the decay of Rb^{81}.

Table I lists all the γ rays which have been identified with the decay of Rb^{81}. The criteria for identification are as follows: The γ ray must decay with approximately a 4.7-h half-life, and its enhancement relative to known Rb^{82} γ rays must be greatest in sample II, less in sample III, and least in sample I. The 607-keV γ ray, for example, fails the second criterion; it is insufficiently enhanced in the spectrum from sample III. Except for the strongest transitions, the half-lives of the γ rays could not be determined precisely as 4.7 h. It could only be observed that they decayed faster than the 6.4-h Rb^{82} γ rays.

A search was made for γ rays of higher energy. Between 1 and 2 MeV, no γ ray from Rb^{81} was seen.

B. Coincidence Studies

From Figs. 1 and 2, it is evident that above 0.5 MeV, γ rays from Rb^{81} would be almost undetectable if nothing more than NaI(Tl) counters were used. On the other hand, in using Ge(Li) detectors limitations are imposed by the rapid drop in counter efficiency with increased γ-ray energy. In the present coincidence studies, a compromise solution was adopted in using one NaI(Tl) counter and one Ge(Li) detector. The sources were of the type of sample III.

Figure 3 shows the γ-ray singles spectrum obtained with a 3 in.×3-in. NaI(Tl) counter. Energy selection channels A and B were roughly centered about 446 and 511 keV, respectively. However, these channels did not select the 446- and 511-keV γ rays exclusively. Since the resolution of the NaI(Tl) counter is not better than ~8.5% at these energies, channel A certainly includes the 457-keV γ ray and channel B the 538-keV and perhaps the 548-keV γ ray. Figure 4 shows the γ-ray spectra as seen in the Ge(Li) counter. Spectra (a), (b), and (c) are, respectively, the singles spectrum, the spectrum in coincidence with channel A, and the spectrum in coincidence with channel B. Only the energy range between 300 and 600 keV is shown because

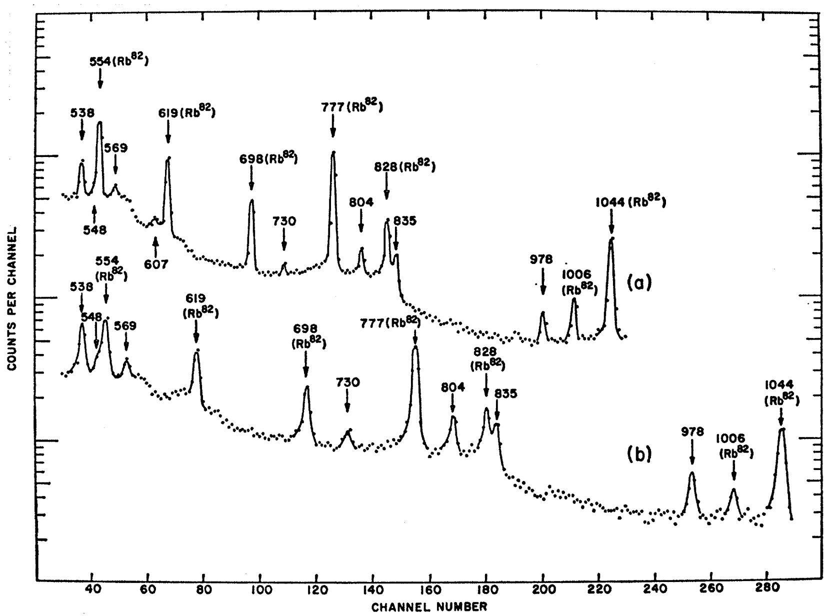

FIG. 2. High-energy γ-ray spectrum as seen in Ge(Li) detector. Spectrum (a) was taken with sample I and spectrum (b) was taken with sample III.

nothing below or above this range was seen clearly in coincidence. It is expected that the 190-keV transition would not be in coincidence with anything since this is an isomeric transition from a 13-sec state to the ground state. At the high-energy side, failure to observe a coincidence may in some cases be due to the poor statistics or to the interference of the Rb^{82} γ rays. Hence in Table II we have left some blanks as indicating that a coincidence has not been either observed or ruled out. The 804- and 835-keV γ rays, however, were definitely found not to be in coincidence with channel A. This conclusion was reached through additional studies, using two NaI(Tl) counters.

Based upon the information in Tables I and II, a level scheme of Kr^{81} is proposed as shown in Fig. 5. This level scheme has incorporated all the γ rays in Table I except for the 729.7- and 978.0-keV transitions. Within the uncertainty of precisely how much of which γ ray is in each channel, the level scheme is consistent with Table II with one possible exception. The apparent

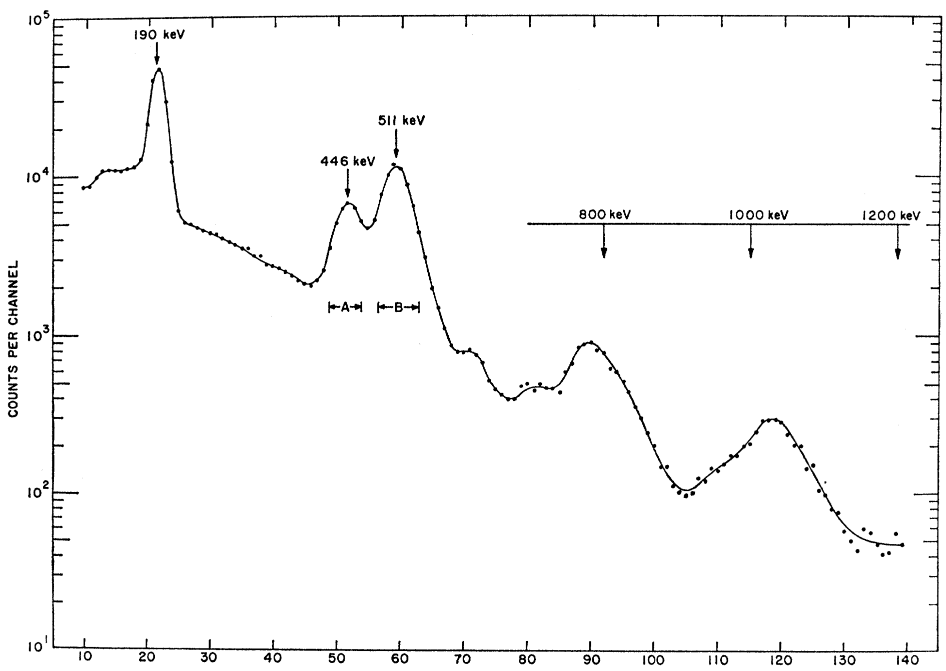

FIG. 3. γ-ray spectrum taken with a 3 in.$\times$3 in. NaI(Tl) counter. A and B were the energy-selection channel settings for coincidence experiments.

inconsistency is in connection with the 538-keV transition; this question will be discussed presently.

Concerning the 190-keV level there is general agreement.[1–4] Since this is an isomeric level of 13 sec, obviously nothing would be seen in coincidence with the 190-keV transition. Next to the 190-keV transition, the 446-keV γ ray is the most intense transition observed. *A priori* one would not know whether this 446-keV transition is a ground-state transition or a transition to the 190-keV state. Data favoring the latter possibility are the following: Two positron branches differing in energy by $\sim$475 keV have been reported by Doggett.[2] The more energetic branch is presumably the decay branch to the 190-keV level, and the other is the branch to a level at 0.64 MeV. Assuming this to be correct, one can calculate the expected total positron intensity from γ-ray intensity balance and theoretical capture-to-positron ratios. The result of a such a calculation is reported in the *Nuclear Data Sheets*[4] as 33% of the total decay, whereas 34% was the measured value of Kelly and Horen.[3] While both the positron end-point energy and the positron intensity measurements indeed support the existence of a 0.64-MeV level, it should be noted that there are some problems in connection with each of these arguments. In addition to the two positron branches proceeding to the 0.19- and 0.64-MeV levels, Doggett[2] reported a third and quite strong branch. This branch supposedly feeds a level at 0.89 MeV, which in turn decays by the emission of a 253-keV γ ray to the 0.64-MeV state. This γ ray of 253 keV was not reported by Karraker and Templeton[1]; nor has it been observed in the present work. The 260-keV γ ray given by Kelly and Horen[3] is much too low in intensity to satisfy the requirements of Doggett's decay scheme. If one believes this third positron branch to be incorrect, then it would be inconsistent to place a great deal of weight on the other two branches. As for the agreement between the calculated and the measured total positron intensity, it should be recognized that the capture-to-positron ratios are very sensitive to the decay energies.

TABLE II. Coincidence of various transitions with γ rays in the channels A and B of Fig. 3. Y and N denote yes and no, respectively.

Transition (keV)	In coincidence with A	B
190	N	N
358	Y	N
388	Y	N
446	N	Y
457	N	Y
477	N	Y
538	Y	Y
548		
569	Y	N
730		
804	N	
835	N	
978		

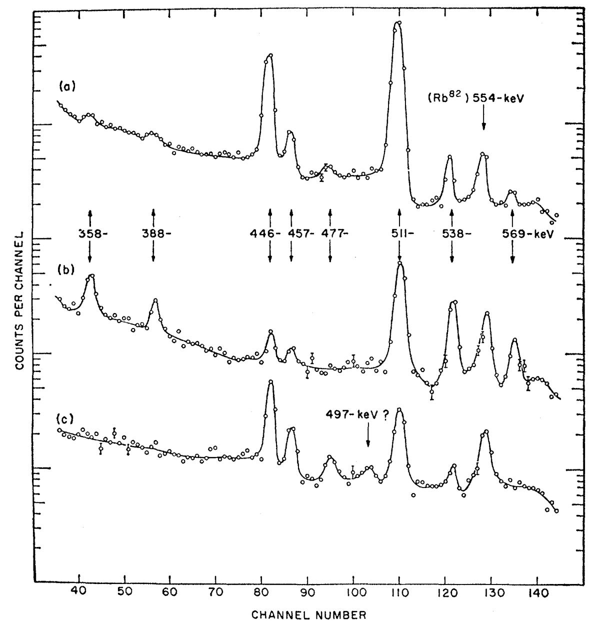

FIG. 4. Ge(Li) spectra (a), (b), and (c) are, respectively, the singles spectrum, the spectrum in coincidence with channel A, and the spectrum in coincidence with channel B. Channels A and B are the settings shown in Fig. 3.

In the present instance, the mass difference between Rb^{81} and Kr^{81} is not known very precisely. Furthermore, even though the other transitions are much weaker than the 190- and the 446-keV transitions, neglecting them in the calculation of the positron intensity may or may not be important, depending on how they fit into the decay scheme. The agreement between measured and calculated positron intensities may be fortuitous and

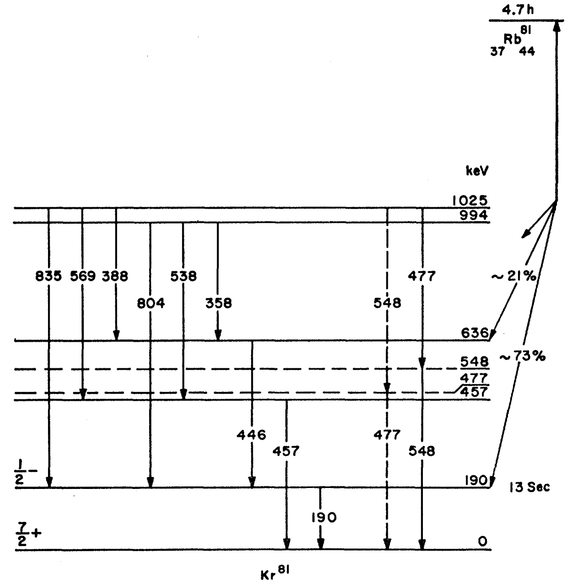

FIG. 5. Proposed decay scheme of Rb^{81}.

therefore does not necessarily prove that the 446-keV transition is from a 636-keV state.

Having taken notice of the weaknesses in the evidence for a level at 636 keV, we nevertheless propose this as a level in our decay scheme. The decay scheme is constructed to accommodate the largest number of transitions with the smallest number of levels, while satisfying the coincidence requirements. There is only one coincidence result which is not explained by the proposed decay scheme, namely, the coincidence of the 538-keV transition with channel B. To be in coincidence with B is to be in coincidence with a γ ray of roughly 511 keV. In the present case this would mean coincidence with annihilation radiation, or with the 538-, 548- and perhaps 569-keV γ rays. Since the 636-keV level is fed by positrons, the 446-keV transition is obviously in coincidence with annihilation radiation. The 457- and 477-keV transitions are in coincidence with 511 keV and/or with the several γ rays just above 511 keV. This is also satisfied by the present level scheme. What this level scheme leaves unexplained is the coincidence of the 538-keV transition with a γ ray of $\sim$500-keV. The decay to the 994-keV level is almost entirely by electron capture and 457 keV is too far from 511 keV to have been included in channel B. However, the following things should be recognized with respect to coincidence with channel B. Although there is a tremendous number of 511-keV γ rays in B as compared to other γ rays, very few of these annihilation quanta are in coincidence with anything. The capture-to-positron ratio changes from $\sim$1 for the 190-keV level to $\sim$100 for the 1-MeV level. Therefore, most of the positron decay is to the 190-keV level. In other words, even though most of the singles counts in channel B are from annihilation radiation, they contribute very little to true coincidences. On the other hand, because there are very many 511-keV singles, a weak transition close by may not be visible in singles, but may actually have an effect on the coincidence spectrum. For example, if the doubtful line at 496 keV in (c) of Fig. 4 is a true γ ray, and if it is in true coincidence with the 538-keV transition, this may explain the coincidence of 538 keV with channel B.

The 538- and 569-keV transitions are both in coincidence with channel A. By placing a level at 457 keV, these two transitions can be fitted into the decay scheme as the first transitions of cascades from the 994- and 1025-keV levels. Since 477 and 548 keV also add up to 1025 keV, these transitions may be interpreted as a cascade from the 1025-keV level. However, because these two transitions have approximately the same intensity, there is no basis for deciding which transition comes first. Hence there may be a level at 477 or at 548 keV. From our work, no evidence has been found for levels above 1025 keV.

IV. CONCLUSION

From the data we have shown, it is evident that good energy resolution is essential for the study of the decay scheme of Rb^{81}. The differences between our results and those of Kelly and Horen[3] can largely be explained by the fact that they used scintillation counters, whereas we used Ge(Li) detectors in addition. In our work, we have found that the most serious limitation is in the problem of source purity; we could not produce a source of Rb^{81} free of Rb^{82} contamination. Further studies of the decay of Rb^{81} should be undertaken using mass-separated sources.

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