Energy Levels in ^{85}Rb and ^{87}Rb from the $(n, n'\gamma)$ Reaction*

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High-resolution measurements of the γ rays following neutron inelastic scattering in ^{85}Rb and ^{87}Rb have been made for neutron energies between 0.3 and 2.2 MeV. An enriched ^{85}Rb scatterer was used for isotopic identification. Eight new levels were assigned in ^{85}Rb below 1445 keV excitation and two new levels below 1739 keV were observed in ^{87}Rb. Branching ratios and differential γ-ray production cross sections at 95° were also determined.

I. INTRODUCTION

The level structures of the stable isotopes of rubidium are important because of their proximity to the "good" core nucleus ^{88}Sr which has 50 neutrons and 38 protons. The isotope ^{87}Rb has been studied primarily from the β decay of ^{87}Kr by several investigators.[1-3] Most recently, Shihab-Eldin *et al.*[4] have presented a very complete study of the β decay of ^{87}Kr. Their results agree qualitatively with a simple coupling of a single particle or hole state of the 37 protons in ^{87}Rb with a ^{88}Sr core. A similar analysis of ^{85}Rb in terms of a ^{86}Sr core should be applicable. However, experimental information of the structure of ^{85}Rb is very sparse. Only three excited states have been previously observed, mainly from the β decay of ^{85}Sr and ^{85}Kr.[5] In this work, the level structures of the naturally occurring rubidium isotopes were studied by the observation of γ rays from the $(n, n'\gamma)$ reaction. Eight new levels below 1445 keV were observed in ^{85}Rb. The level structure of ^{87}Rb was found to agree with previous work with the addition of two new levels below 1739 keV.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURE

Our experimental arrangement has been described previously.[6] A beam of protons from the Tulane 3-MeV Van de Graaff accelerator was directed to a tritium-titanium target where neutrons were produced through the $T(p, n)^3He$ reaction. The neutrons were allowed to strike a ring scatterer which was placed coaxially around the crystal housing of a 32-cm^3 Ge(Li) detector. The front of the detector was shielded from the direct neutron beam by an iron shadow cone suspended along the beam axis. The γ rays originating from the scatterer were incident upon the detector at approximately 95° with respect to the neutron direction. Neutrons were monitored with a BF_3 long counter placed at 90° to the tritium target.

Measurements were taken in 100-keV steps for neutron energies (E_n) of 300 keV–2.2 MeV. Background peaks were identified by a series of runs using a carbon ring scatterer. Absolute cross sections were determined in the following way. The neutron flux was measured at 0° and 90° for each bombarding energy studied. These quantities were then compared to the differential cross sections measured by Jarmie and Seagrave[7] for the $T(p, n)^3He$ reaction and the relative efficiency of the neutron monitor was calculated. The γ-ray yields were then corrected for attentuation in the scatterer and the efficiency of the detector. The corrected γ-ray yields normalized to the neutron monitor count were then compared with the yield of the 847-keV line from the ^{56}Fe$(n, n'\gamma)$ reaction which was obtained with an iron ring scatterer. The value of 32.6 ± 6.5 mb/sr for the differential cross section at 90° and $E_n = 1.5$ MeV obtained by Benjamin *et al.*[8] was used to compute the cross sections. Details of this procedure and the uncertainties in the measurements are given in Ref. 6.

It was decided initially to use a natural rubidium scatterer, containing 72% ^{85}Rb and 28% ^{87}Rb, since a comparison with the well-studied levels of ^{87}Rb should allow a proper isotopic assignment of the γ rays. Because of its favorable background characteristics, the chemical form Rb_2CO_3 was used to obtain most of the preliminary data. However, due to ambiguities in the isotopic assignment of some of the γ rays, a scatterer of 99.9% enriched ^{85}RbCl was obtained.[9] Identical Lucite rings, filled with 180 g each of ^{nat}RbCl and ^{85}RbCl, were exposed to the neutron beam for equal times. Comparison of the resulting spectra allowed unambiguous isotopic assignment of the γ rays originating in ^{85}Rb and ^{87}Rb.

III. DATA

Figure 1 is a γ-ray spectrum obtained from a $^{nat}Rb_2CO_3$ scatterer with $E_n = 2.2$ MeV. The spectrum was accumulated for about 1 h with a beam current of 2 μA. Over-all resolution was 4.5 keV for γ rays of 1-MeV energy. The origins of the predominant background γ rays are indicated. They arise mainly from the detector-cryostat apparatus. Since they were difficult to distinguish from the background, γ rays above 1800 keV in energy were not analyzed.

Table I is a summary of γ-ray transitions observed in this and other work. A total of twenty-eight γ rays were observed from the ^{nat}Rb(n, $n'\gamma$) reaction. Of the twenty-three transitions which were assigned to ^{85}Rb, twenty have not been reported previously. In addition, two new γ rays were assigned to the decay of ^{87}Rb.

In Fig. 2 are plotted the production cross sections for the most intense γ rays resulting from the de-excitation of ^{85}Rb. The errors indicated are standard deviations in the *relative* cross sections only. The normalization to absolute cross section involves an additional uncertainty of about 30%.

IV. RESULTS AND ANALYSIS

Figure 3 is a summary of results obtained for ^{85}Rb. Also shown for comparison is the energy level diagram for ^{85}Rb based upon previous work.[5] The standard error in the γ-ray energies of this work is <1 keV in most cases. The quantities in parentheses are branching ratios. The dashed lines indicate transitions observed in other work only.

In ^{85}Rb, the production threshold (Fig. 2) for the 150-keV γ ray is consistent with a ground-state transition from the first excited state.

The 129-keV γ ray is of particular interest. Although the intensity of this γ ray is about 25% of that of the most intense γ ray at 150 keV (Table I), it has not been reported in previous ^{85}Rb studies. A weak γ ray at 129 keV had been observed by Shihab-Eldin *et al.*[4] in their studies of ^{87}Rb. However, its source was not determined. We interpret the 129-keV γ ray as a transition between a new level at 280 keV and the first excited state at 150 keV. This is based upon the production thresholds for the 129-keV γ ray and the 450-keV cascade transition from the 731-keV level to the 280-keV level. A 280-keV ground-state transition is not observed and the intensity of such a transition would necessarily be less than 0.5% of the 150-keV intensity. The tentative assignment of $J^{\pi}=\frac{1}{2}^-$ is

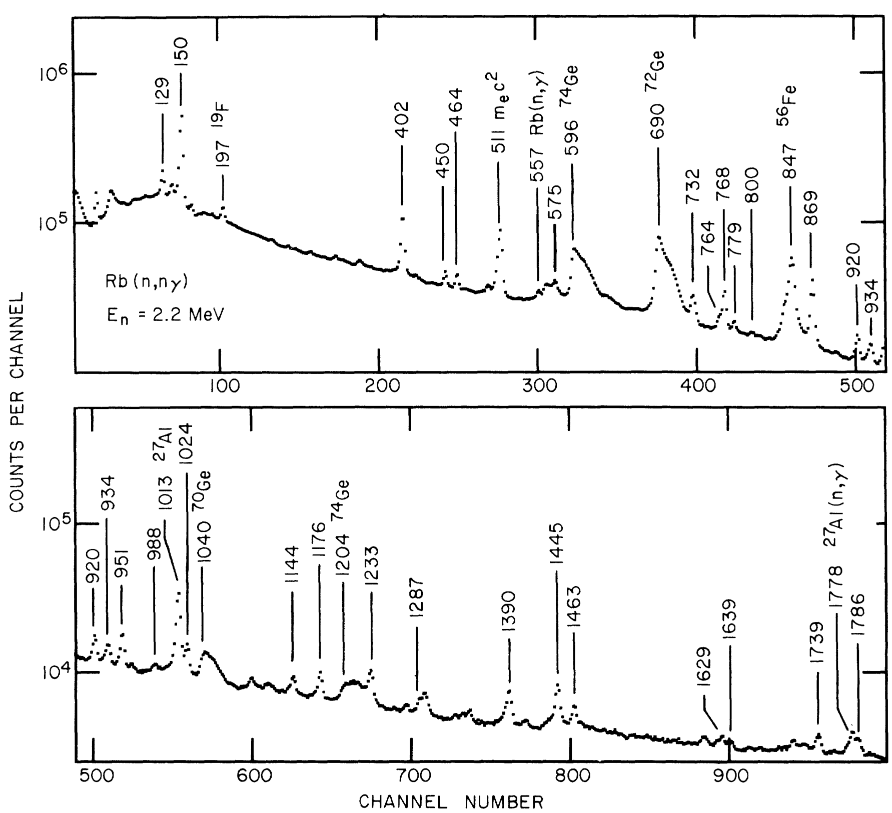

FIG. 1. A γ-ray spectrum produced by bombardment of a $^{nat}Rb_2CO_3$ with 2.2-MeV neutrons. The angle of observation is approximately 95°. The background has not been subtracted from this spectrum. The γ rays attributed to inelastic scattering in ^{85,87}Rb are labeled together with a few prominent background peaks.

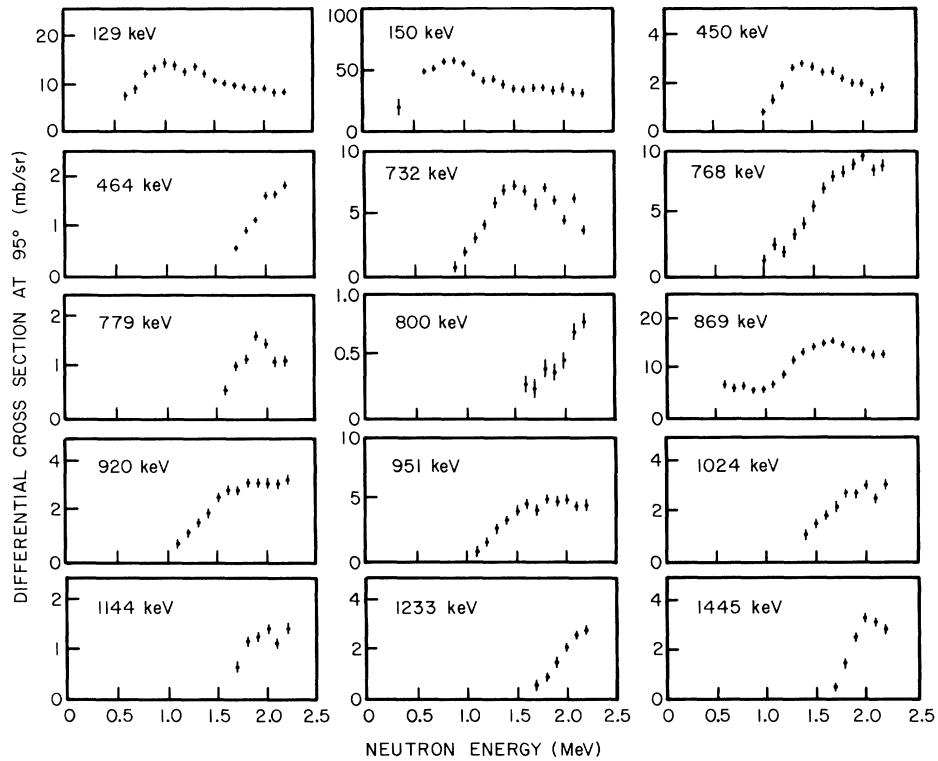

FIG. 2. Production differential cross sections at 95° for γ rays from the ^{85}Rb$(n, n'\gamma)$ reaction. Error bars indicate standard deviations in the relative cross sections. In the case of the 869-keV γ ray, the decreasing cross section below 1 MeV is probably due to interference with the 870-keV capture γ ray from ^{16}O.

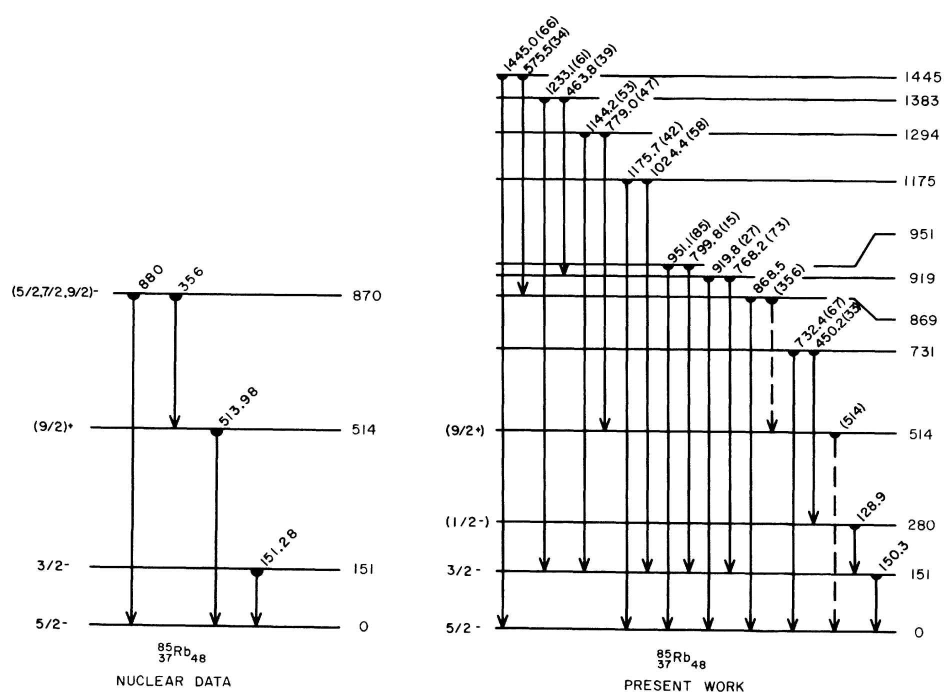

FIG. 3. Energy levels and γ-ray transitions in ^{85}Rb. Values in parentheses are branching ratios measured in percent of total decays from each level. The dashed lines indicate transitions not observed in this work. Shown for comparison is the level scheme of ^{85}Rb as presented in Ref. 5.

consistent with this intensity estimate and the known spins and parities of the ground and first excited states.

Although there is some evidence in this work for the ground-state transition from the 514-keV level, it is obscured by the annihilation γ ray at 511 keV.

The existence of a level at 731 keV was first indicated in the work of Sattler[10] who reported the tentative observation of a γ ray at 733 keV. However, this was interpreted as a transition between a level at 880 keV and the first excited state. The placement of the level at 731 keV is consistent with the observed γ-ray production thresholds.

The 880-keV γ ray, first observed in the decay of ^{85}Sr by Sattler[10], is the highest energy transition previously reported in ^{85}Rb. However, a recent study of Bubb *et al.*[11] indicates that this

TABLE I. Deexcitation γ rays from levels in ^{85}Rb and ^{87}Rb.

^{nat}Rb$(n, n'\gamma)$ – This work E_γ (keV) [c]	I_γ (rel) [d]	β decay of ^{85}Sr [a] E_γ (keV)	β decay of ^{87}Kr [b] E_γ (keV)
128.9 ± 0.6	25.4		
150.3 ± 0.5	100	151.28 ± 0.10	
		356 ± 15	
402.1 ± 0.6 [e]	39.2		402.7 ± 0.3
450.2 ± 0.6	5.7		
463.8 ± 0.4	5.6		
		513.98 ± 0.03	
575.5 ± 0.4	4.6		
732.1 ± 0.7	11.6	733 ± 20	
763.1 ± 0.7			
+768.2 ± 0.7	27.2 [f]		
779.0 ± 0.5	3.9		
799.8 ± 0.8	2.4		
			845.6 ± 0.3
868.5 ± 0.6	39.0	878 ± 12	
			894.2 ± 0.4
919.8 ± 0.7	10.1		
934.4 ± 0.5 [h]	8.8		
			947.0 ± 0.3
951.1 ± 0.8	13.8		
987.7 ± 0.4 [e]	1.8		
1024.4 ± 0.7	9.7		
1144.2 ± 0.5	4.5		
1175.7 ± 0.7 [g]	7.2		1175.5 ± 0.2
1233.2 ± 0.8	8.8		
1287.1 ± 0.5 [h]	2.2		
			1338.2 ± 0.2
1389.7 ± 0.9 [e]	11.2		1389.8 ± 0.2
1445.0 ± 1.0	8.9		
1463.5 ± 0.8 [e]	4.4		
			1578.3 ± 0.4
1628.8 ± 0.9 [h]	1.4		
1639.4 ± 0.8 [h]	1.2		
1739.3 ± 0.5 [e]	4.8		1740.4 ± 0.2
1785.6 ± 0.8 [h]	1.9		

[a] From Ref. 5.
[b] From Ref. 4.
[c] Assigned to ^{85}Rb unless otherwise noted.
[d] Intensities relative to I_γ (150) = 100 at E_n = 2.2 MeV.
[e] Assigned to ^{87}Rb.
[f] Intensity is due to composite peak. The 763-keV γ ray is not placed in the decay scheme.
[g] Observed in both ^{85}Rb and ^{87}Rb.
[h] Assigned to ^{85}Rb but not placed in decay scheme.

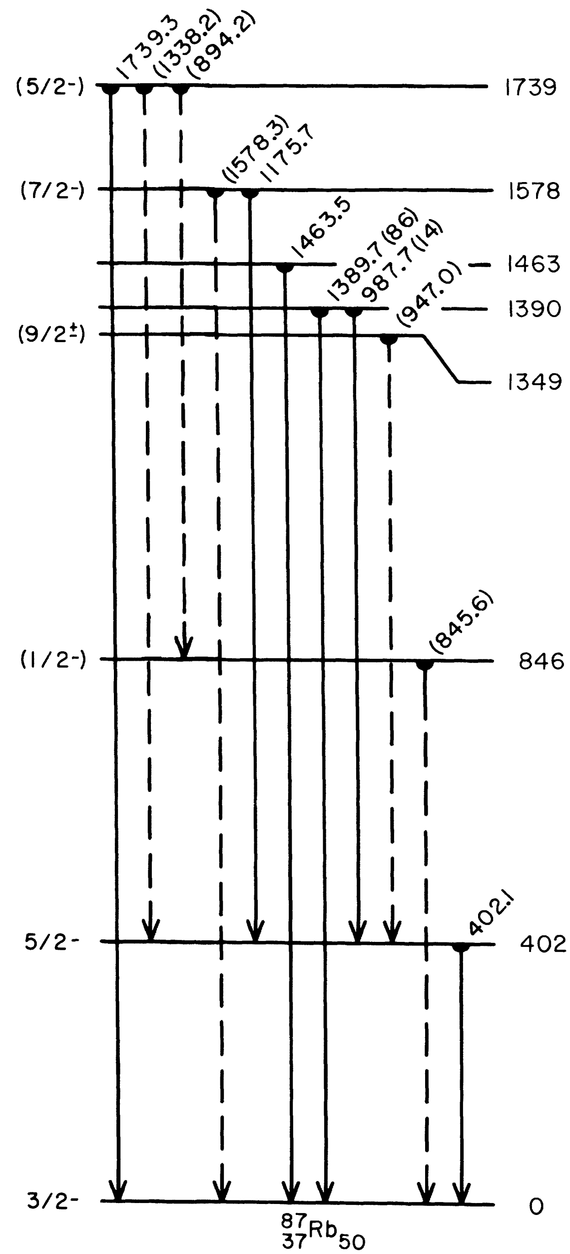

FIG. 4. Energy levels and γ-ray transitions in ^{87}Rb. Values in parentheses are branching ratios measured in percent of total decays from each level. The dashed lines indicate transitions not observed in this work.

transition does not participate in the decay of ^{85}Sr.

The J^{π} values assigned to the level at 869 keV in Fig. 3 are based upon the work of Andreev *et al.*,[12] who observed a γ ray of 870 keV in energy in the Coulomb excitation of ^{85}Rb. In Fig. 2 the production cross section for this transition can be seen to *decrease* with increasing energy until approximately 1 MeV where it exhibits behavior typical of a threshold curve. This is probably due to interference with the 870-keV ^{16}O capture γ ray. The energy value of the transition in ^{85}Rb was based upon spectra with $E_n > 1.5$ MeV.

With the exception of the level at 1175 keV, the placement of levels from 919 to 1445 keV was based upon γ-ray threshold determinations. A comparison of the spectra obtained from the naturally occurring and enriched rubidium scatterers indicates that the 1176 ± 1-keV γ ray originated from transitions in both ^{85}Rb and ^{87}Rb. The γ ray at 1176 keV is a composite peak and a threshold measurement was uncertain. However, the production threshold of the 1024-keV γ ray is consistent with a level at 1175 keV.

Figure 4 shows the energy level diagram for ^{87}Rb. With the exceptions of the transitions indicated by dashed lines, the γ rays observed in ^{87}Rb are in good agreement with the work of Shihab-Eldin *et al.*[4] The 846-keV γ ray was obscured by the strong transition in ^{56}Fe at 847 keV. The 947-keV γ ray may have been masked by the presence of the 951-keV transition in ^{85}Rb. There is little evidence for the presence of the 894-, 1338-, and 1578-keV γ rays. Their intensity would necessarily be less than 1% of that of the 402-keV ground-state transition.

Two new γ rays were observed in ^{87}Rb. Based upon its γ-ray production threshold the 1463-keV transition was assigned to a level at 1463 keV. A γ ray of energy 1461 keV was observed by Shihab-Eldin *et al.*[4] but assigned to the decay of a level at 2811 keV. If the 1461- and 1463-keV transitions do not comprise a doublet in the ^{87}Kr decay, the γ ray observed at this energy by Shihab-Eldin *et al.*[4] may arise from the level at 1463 keV. This would correct an intensity imbalance at the 1349-keV level in their work.

The γ ray at 988 keV was found to originate from the transition between a level at 1390 and the first excited state at 402 keV. A relatively weak transition in ^{87}Rb at 1390 keV was observed by Shihab-Eldin *et al.*[4] However, it was not included in their level scheme. Their failure to observe the 988-keV γ ray may be due to interference of an escape peak at 989.8 keV.

Thus, the level scheme of ^{87}Rb determined in this work is consistent with previous work[4] with the addition of the levels at 1390 and 1463 keV.

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