Inelastic Neutron Scattering from Rhodium and Niobium†

M. A. ROTHMAN, D. M. VAN PATTER, V. S. DUBEY,* W. C. PORTER, AND C. E. MANDEVILLE
Bartol Research Foundation of The Franklin Institute, Swarthmore, Pennsylvania
(Received March 12, 1957)

Inelastic scattering of neutrons has been used to study excited states in Rh^{103} and Nb^{93}. Gamma rays have been observed from the 300- and 365-kev levels in Rh. Gamma rays of 736- and 957-kev energy have been obtained from Nb. As a result of threshold measurements, these gamma rays are interpreted as representing transitions to the 29-kev metastable state from levels at 764- and 977-kev in Nb.

I. INTRODUCTION

INELASTIC neutron scattering is a useful tool for the determination of nuclear level schemes. Accurate measurements of the gamma-ray energies together with the thresholds for the production of these gamma rays enable one to obtain the level energies and decay schemes. For this method to be unambiguous, the levels in the compound nucleus must be closely spaced. This restricts the validity of this method to medium- and heavy-weight elements.

We have studied the elements Rh^{103} and Nb^{93}. Both of these are of 100% isotopic abundance. In the case of Rh^{103}, the level scheme up to 650 kev has been obtained from radioactive decay of Ru^{103} and Pd^{103}.[1] Also, levels at 300 and 363 kev have been observed from Coulomb excitation.[2]

In the case of Nb^{93}, the only level definitely established has been the metastable state at 29 kev, with a half-life of 3.65 years. Gamma rays of 270-, 530-, 690-, and 910-kev energy have been reported from inelastic scattering of 3.2-Mev neutrons, but no level scheme has been given.[3] Temmer and Heydenburg report an 850-kev gamma ray from Coulomb excitation.[2] In a previous report, we have listed a 710-kev gamma ray from Coulomb excitation.[4]

II. EXPERIMENTAL PROCEDURE

We have adapted the method suggested by Guernsey and Wattenberg for observation of low-energy gamma rays.[5] Our apparatus is shown in Fig. 1. The $Li^7(p,n)Be^7$ reaction is used as a neutron source, the lithium target being mounted on a probe cooled with liquid air. A lithium furnace is arranged so that targets may be evaporated directly in the vacuum system of the Van de Graaff generator. Targets 30 kev thick have been used for survey work, while 6 to 8 kev thick targets were used for the threshold measurements to get better resolution.

A lead cap $\frac{1}{2}$ inch thick serves to attenuate the 478-kev gamma ray from inelastic proton scattering in the lithium. For measurements of gamma-ray spectra, the scatterer is placed within the cap, adjacent to the crystal can. Background spectra are obtained with the scatterer on the outside of the lead, so that the same amount of material is always in the neutron beam.

The size of the sodium iodide crystal is kept small to minimize background due to inelastic neutron scattering in the iodine. For the observation of gamma rays from rhodium in the region between 300 and 400 kev, a crystal 3 mm thick and 35 mm in diameter was used. In the case of niobium, where gamma rays between 700 and 1000 kev were studied, a crystal 1 cm thick and 2 cm in diameter was found suitable.

III. RHODIUM

The rhodium scatterer was $1\frac{1}{2}$ inch square, $\frac{1}{8}$ inch thick, weighing 55 grams. Figure 2 shows the spectrum obtained from the rhodium at a neutron energy of 900 kev, using the 3-mm crystal. The peak at 200 kev is due to inelastic neutron scattering in iodine. From rhodium, gamma rays of 300- and 365-kev energy are seen. Using 2-Mev neutrons and the 1 cm crystal, a search was made for higher energy gamma rays. The results of this are seen in Fig. 3. A peak is seen at about 600 kev, but nothing definite can be seen elsewhere.

Figure 4 shows the yield of the 300- and 365-kev gamma rays as a function of neutron energy. The cross section was estimated by making a comparison with the yield of the 137-kev gamma ray from tantalum. The cross section for the production of this 137-kev gamma ray was taken as 0.7 barn at a neutron energy of 600 kev.[5]

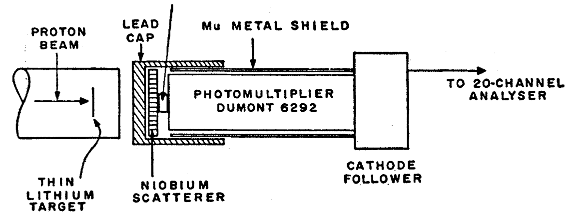

FIG. 1. Apparatus for detection of gamma rays from inelastic neutron scattering. The source of the proton beam is the Bartol-ONR Van de Graaff generator.

† Assisted by the U. S. Atomic Energy Commission.
* On leave of absence from Agra College, Agra, India.
[1] B. Saraf, Phys. Rev. **97**, 715 (1955).
[2] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).
[3] Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).
[4] Van Patter, Rothman, Mandeville, and Swann, J. Franklin Inst. **259**, 261 (1955).
[5] Guernsey and Wattenberg, Phys. Rev. **101**, 1516 (1956).

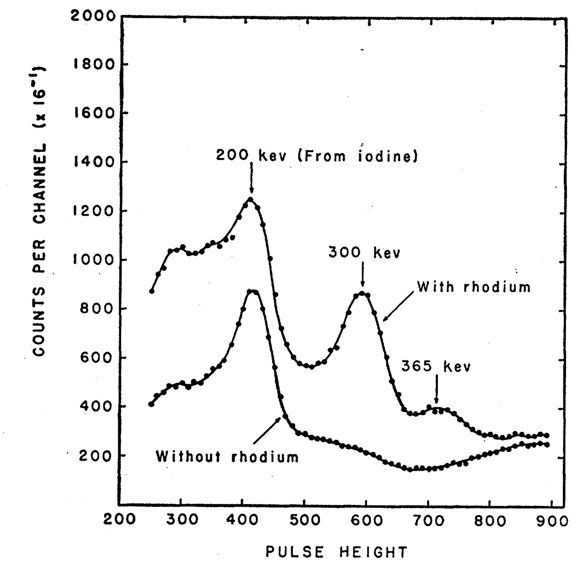

FIG. 2. Gamma-ray spectrum from inelastic neutron scattering in rhodium. $E_n = 900$ kev.

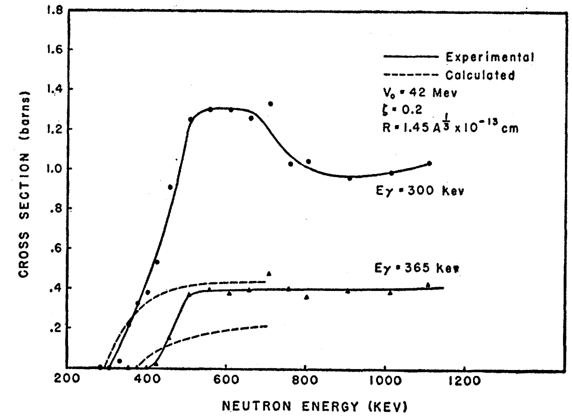

FIG. 4. Yield of gamma rays from rhodium.

The error on this estimate is about $\pm 20\%$, in addition to possible error in the tantalum reference cross section.

The theoretical cross section shown in Fig. 4 was calculated by the Hauser-Feshbach method, using the level scheme obtained by Saraf,[1] and illustrated in Fig. 5. All theoretical cross sections in tihs paper have been calculated on the basis of a square potential well, with parameters indicated in the figures. Where no imaginary part of the potential is given, the black nuclear model has been used. In Fig. 4 it is seen that the theoretical cross section is considerably smaller than that obtained experimentally.

The 300- and 365-kev gamma rays may be identified with those obtained from the decay of Pd^{103}, shown in Fig. 5. Since the threshold has not as yet been obtained for the 600-kev gamma ray, it is not possible to say definitely that this is the same as the 610-kev transition shown in the decay of Ru^{103}. After corrections are made for relative detection efficiency in the sodium iodide crystal, the intensity of the 600-kev gamma ray appears to be approximately the same as that of the 365-kev gamma ray, at an incident neutron energy of 2 Mev.

According to the Hauser-Feshbach theory, the amount of excitation of a given level depends to a large degree upon the spin difference between the ground state and the given level. If the 600-kev gamma ray originated in the $g_{7/2}$ level, then we should expect to see the 495-kev gamma ray from the $d_{5/2}$ level with at least equal intensity. This is not observed. Similarly, one would expect the intensity of the 495-kev gamma ray to have the same order of magnitude as the 365-kev gamma ray. Since this is not observed, it appears that the 300- and 365-kev levels, which are considered to be

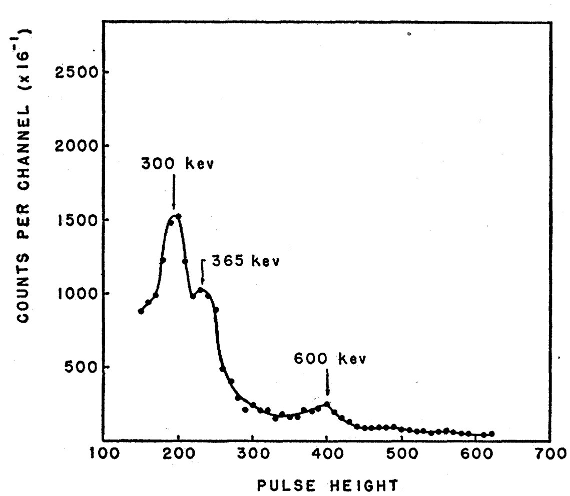

FIG. 3. Gamma-ray spectrum from inelastic neutron scattering in rhodium (1-cm crystal). Background has been subtracted. $E_n = 2$ Mev.

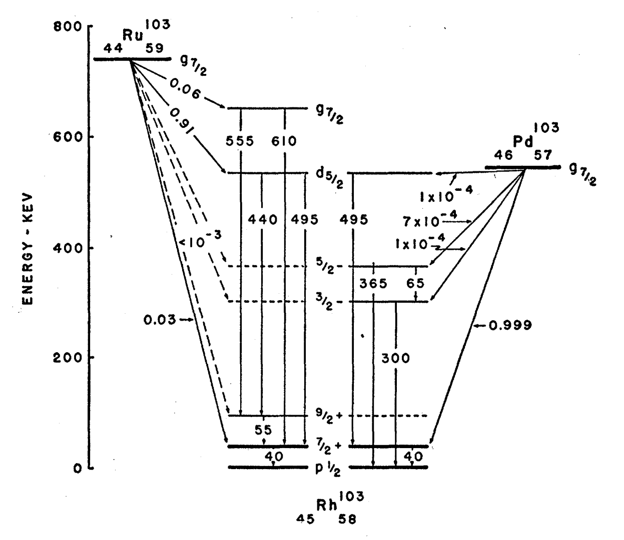

FIG. 5. Energy levels of Rh^{103}.

rotational states, are excited by inelastic neutron scattering to a greater degree than might be expected by the straightforward application of the theory.

IV. NIOBIUM

The niobium scatterer was 2 inches square, $\frac{1}{4}$ inch thick, and weighed 127 grams. Figure 6 shows the gamma-ray spectrum obtained with a neutron energy of 1.2 Mev. The first peak is the 632-kev gamma ray from inelastic neutron scattering in iodine. Gamma rays from niobium are seen at 736 and 957 kev. Figure 7 shows the cross section for excitation of these gamma rays as a function of energy.

The cross sections were estimated by comparison with the yield of the 845-kev gamma ray from Fe^{56}. The cross section for excitation of the 845-kev gamma ray

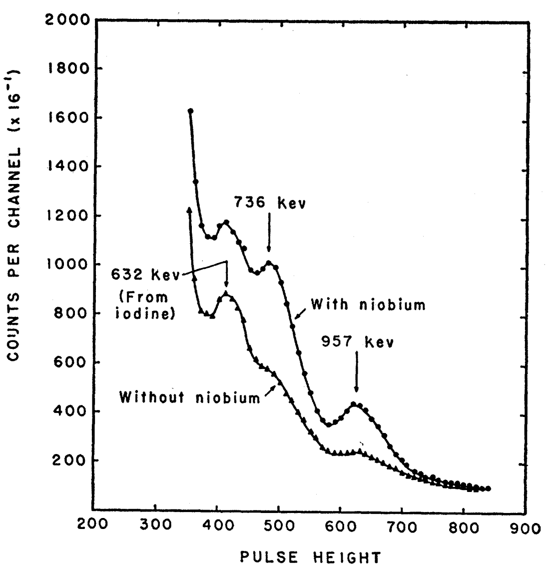

FIG. 6. Gamma-ray spectrum from inelastic neutron scattering in niobium. $E={}_n1.2$ Mev.

was obtained from the Brookhaven compilation of cross sections.[6] However, the cross sections given in this compilation were reduced by 27% to make an agreement with the value given by Day[7] at $E_n=2.56$ Mev.

The cross sections used for reference were: 0.57 barn at $E_n=1.65$ Mev, and 0.23 barn at $E_n=0.870$ Mev. The latter energy is at the peak of the first resonance above the threshold for the production of the 845-kev gamma ray.

It was of interest to make an accurate determination of the thresholds for the production of the two gamma rays from niobium. For this purpose lithium targets 6 kev thick were used, and the neutron energy corrected

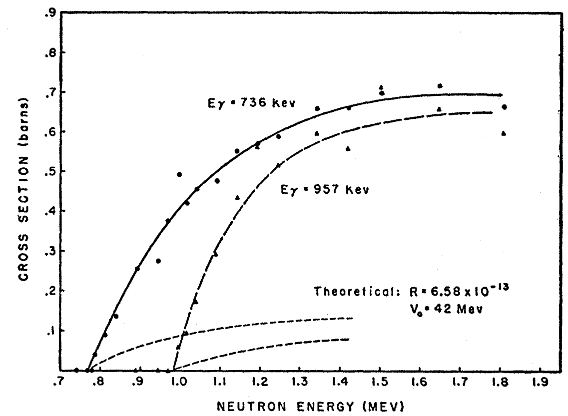

FIG. 7. Yield of gamma rays from niobium as a function of neutron energy.

for target thickness. Fresh targets were made frequently to minimize the effect of target thickening due to aging.

The Van de Graaff generator was calibrated by using the threshold of the $Li^7(p,n)Be^7$ reaction at $E_p=1.881$ Mev. By means of this calibration we were able to reproduce the threshold for the production of the 845-kev gamma ray from Fe^{56} to within ± 5 kev on repeated occasions.

The results of the threshold measurements on niobium are shown in Fig. 8 and in Table I. It is seen that the level energy for both excited states is higher than the photon energy by approximately 30 kev, within the limits of error. This fact indicates that in both cases the gamma-ray transition is to the 29-kev metastable state, rather than to the ground state.

The nature of this transition, together with the magnitude of the cross section for production of the gamma rays enables one to make some arguments concerning the spin and parities of the 764- and 977-kev levels.

The ground state of Nb^{93} is known to have a spin of $9/2+$, while the metastable state has a spin of $1/2-$. The spins of the two higher states must be such that

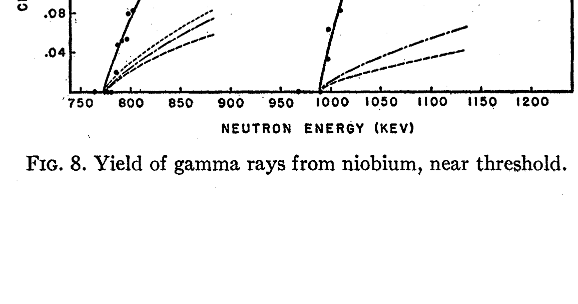

FIG. 8. Yield of gamma rays from niobium, near threshold.

---

[6] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).

[7] R. B. Day, Phys. Rev. **102**, 767 (1956).

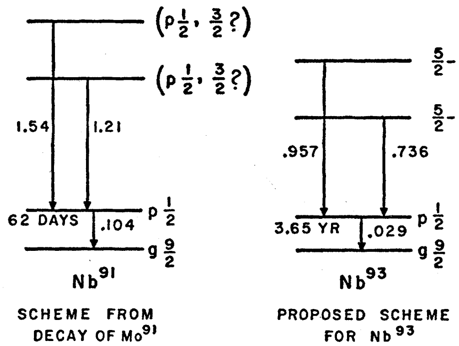

FIG. 9. Energy levels of Nb^{91} and Nb^{93}.

electromagnetic transitions go preferentially to the metastable state rather than to the ground state. The highest value of spin which meets this requirement is $5/2-$. The use of this spin value for the 764- and 977-kev level results in an $E2$ transition to the metastable state, and an $M2$ transition to the ground state, which meets the requirement. Using $5/2+$, on the other hand, would give an $E2$ transition to the ground state, and an $M2$ transition to the metastable state, which would be an undesirable condition in this case.

Examination of the measured cross sections shown in Figs. 7 and 8 indicates that the spin of the excited states should not be lower than 5/2. A number of theoretical calculations have been made of the cross sections, using various potential parameters and spins. The theoretical curves shown in Figs. 7 and 8 were calculated using a spin of $5/2-$ and the strong interaction model. In addition, a calculation was made with a complex potential, using $R=6.58\times10^{-13}$ cm, $V_0=42$ Mev, and $\zeta=0.2$. This gave a result which was practically identical with that of the strong-interaction model, using the same well depth and radius.

It is seen that variation of the model parameters may make a difference of a factor of two in the calculated cross section. Variation of the spin of the excited state makes a greater difference. Using a spin of 3/2 rather than 5/2 reduces the cross section by a factor which varies from 9 near the threshold to 3 at 880 kev neutron energy.

For this reason, $5/2-$ remains the most probable assignment for the spin and parity of the two excited states, even though there exists a large discrepancy between the calculated and experimental cross sections.

Figure 9 gives a comparison between the level scheme proposed for Nb^{93} and the scheme for Nb^{91} which has been given by Smith *et al.*[8] from the decay of Mo^{91}. These nuclei differ only by two neutrons, and there may be seen a similarity between the level positions and the gamma-ray transitions.

From the point of view of the shell model, there is

[8] Smith, Gove, Henry, and Becker, Phys. Rev. **104**, 706 (1956).

TABLE I. Niobium-inelastic neutron scattering. All energies are given in kilovolts.

	First gamma ray	Second gamma ray
Threshold energy	772±8	987±10
Level energy	764±8	977±10
Gamma-ray energy	736±8	957±10
Difference	28±11	20±14
Level energy $=-Q=E_{th}[1-(1/A+1)]$		

some justification in giving a spin of $5/2-$ to the 764-kev level. The $p_{1/2}$ state is obtained by moving a proton from the $p_{1/2}$ shell up to the $g_{9/2}$ shell, so that the spin of the nucleus is determined by the hole left in the $p_{1/2}$ shell. Similarly, the next state may be obtained by moving a proton up from the $f_{5/2}$ shell, which is adjacent to the $p_{1/2}$ shell.

V. GAMMA RAYS FROM PROTONS ON NIOBIUM

In an earlier investigation[4] at this laboratory of the gamma rays produced from the bombardment of a thick niobium target by 2.75–4.0 Mev protons, two gamma rays of energies 0.71 and 0.87 Mev were observed. The excitation curve of the 0.87-Mev gamma ray did not rise rapidly enough to agree with Coulomb excitation, and hence this gamma ray was assigned to the excitation of the 0.874-Mev level of Mo^{94}, from the $Nb^{93}(p,\gamma)Mo^{94}$ reaction. The excitation curve of the 0.71-Mev gamma ray did agree with the theoretical curve for electric excitation of a 0.71-Mev level in Nb^{93}, within the experimental error of about $\pm5\%$. Following the first preliminary report of these results,[4] gamma-gamma coincidence measurements were made and both the 0.71- and 0.87-Mev gamma rays were found to be in coincidence with gamma radiation of energy greater than 1.8 Mev. Since these gamma rays were observed at 2.75-Mev bombarding energy, they cannot be assigned to levels of Nb^{93}. Similarly, because of the Q value of -1.27 ± 0.04 Mev[9] of the $Nb^{93}(p,n)Mo^{93}$ reaction, and the known levels[10] of Mo ^{93}, these gamma rays cannot be ascribed to the $Nb^{93}(p,n)Mo^{93}$ reaction. Hence the only reasonable assignment is to the $Nb^{93}(p,\gamma)Mo^{94}$ reaction, and the earlier assignment of the 0.71-Mev gamma ray to the Coulomb excitation of Nb^{93} must now be withdrawn.

ACKNOWLEDGMENT

The writers wish to express their appreciation of the kind interest of Dr. W. F. G. Swann, Director of The Bartol Research Foundation.

Note added in proof.—Using a magnetic proton spectrometer, an attempt has been made to observe inelastic proton scattering from Nb^{93}, with $Ep=4.4$ Mev. However, the cross section was too small to observe.

[9] R. Patterson, Phys. Rev. **95**, 303 (1954).
[10] J. J. Kraushaar, Phys. Rev. **92**, 318 (1953); Forsthoff, Goeckermann, and Naumann, Phys. Rev. **90**, 1004 (1953).