2+ or 3+) to the 0+ ground state, to the first 2+ level, and to the second 2+ level are usually successively hindered.

At the present time, there is considerable more information available for 1+ parents than for 2+ or 3+ parents. Also in this case the three transitions are all allowed. For such 1+ parents, the two largest positive values found to date for the difference $\Delta_{21}\log ft$ are the present value of >1.1 for the $Br^{80}\rightarrow Se^{80}$ decay and that of >0.8 obtained for the $Br^{78}\rightarrow Se^{78}$ decay in a recent investigation at this laboratory.[20] It would be interesting to examine the question of whether or not this effect could be generally larger for β^+ decays than for β^- decays. Pertinent to this point would be an investigation of the hitherto unobserved decay of Rb^{80} (1+) to the second level of Kr^{80}, which could provide a value of $\Delta_{21}\log ft$ to be compared to the present result for the $Br^{80}\rightarrow Se^{80}$ decay. Allowed transitions have been observed in the decay of Rb^{80} to the ground state and first 2+ level of Kr^{80}, each with a log-ft value of 4.6.[21]

ACKNOWLEDGMENTS

The authors wish to thank Dr. F. R. Metzger for many helpful suggestions and useful discussions. They also are indebted to Dr. C. P. Swann and Dr. S. M. Shafroth for their participation and interest in the experiment.

[20] R. Rikmenspoel and D. M. Van Patter, Nuclear Phys. 24, 494 (1961).

[21] R. W. Hoff, J. M. Hollander, and M. C. Michel, J. Inorg. Nucl. Chem. 18, 1 (1961).

PHYSICAL REVIEW VOLUME 126, NUMBER 1 APRIL 1, 1962

Excitation Function of the Reaction $Ti^{47}(n,p)Sc^{47}$ at Neutron Energies between 2.0 and 3.6 Mev

L. González, A. Trier, and J. J. van Loef*
Universidad de Chile, Instituto de Física y Matemáticas, Santiago, Chile

(Received November 9, 1961)

The relative cross section for $Ti^{47}(n,p)Sc^{47}$ has been measured by an activation method for neutron energies of 2.0 to 3.6 Mev. The absolute cross section at 3.55-Mev neutron energy is found to be 62.7±9.7 mb by comparing the absolute 160-kev gamma activity of Sc^{47} with the absolute beta activity of Si^{31} from the $P^{31}(n,p)Si^{31}$ reaction, which has a known cross section of 96.2±9.0 mb. The cross section rises from 40.1 mb at 1.99 Mev to 69.9 mb at 3.40 Mev. A comparison is made of the observed cross sections for $P^{31}(n,p)Si^{31}$, $S^{32}(n,p)P^{32}$, $Ti^{47}(n,p)Sc^{47}$, and $Ni^{58}(n,p)Co^{58}$ with a theoretical estimate based on the statistical theory of nuclear reactions with the assumption that only the ground states and possibly the first excited states of the residual nuclei contribute to the cross section.

INTRODUCTION

In this paper we report on measurements of the cross section for the reaction $Ti^{47}(n,p)Sc^{47}$. This work is part of an investigation of (n,p) cross sections of medium-weight isotopes.[1–3] These cross sections are of interest in connection with nuclear reaction theory, neutron detection and nuclear reactor physics. No data seem to be available on the $Ti^{47}(n,p)Sc^{47}$ reaction in the neutron energy range of 2.0 to 3.6 Mev.

The reaction has a positive Q value of 182.6±2.0 kev[4] and the product Sc^{47} decays with a half-life of 82.3 hr.[5] The ground state of Sc^{47} decays to the 160-kev excited state of Ti^{47} with a branching ratio of 0.63±0.03[5]; other transitions are to the ground state of Ti^{47}. We have measured the relative yield of the reaction $Ti^{47}(n,p)Sc^{47}$ through the 160-kev gamma ray of Ti^{47}. The absolute cross sections are obtained by comparing the Sc^{47} activity with the Si^{31} activity formed in the $P^{31}(n,p)Si^{31}$ reaction which has a cross section of 96.2±9.0 mb at 3.56-Mev neutron energy.[6]

EXPERIMENTAL PROCEDURE

The experimental equipment and procedure were the same as described by Rapaport and van Loef.[1] The excitation function was obtained by placing titanium samples at various angles around the d-D neutron source at a distance of 6 cm and irradiating them simultaneously. Irradiations were performed at deuteron energies of 600 kev (24 hr) and 400 kev (27 hr). In this way the neutron energy range from 2.0 to 3.6 Mev was covered in steps of about 200 kev. The neutron

* Now at the Philips Research Laboratories, Eindhoven, The Netherlands.

[1] J. Rapaport and J. J. van Loef, Phys. Rev. 114, 565 (1959).

[2] L. González, J. Rapaport, and J. J. van Loef, Phys. Rev. 120, 1319 (1960).

[3] J. J. van Loef, Nuclear Phys. 24, 340 (1961).

[4] *1960 Nuclear Data Tables, Consistent Set of Q-values*, Part 1, United States Atomic Energy Commission.

[5] Adopted from *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[6] J. A. Grundl, R. L. Henkel, and B. L. Perkins, Phys. Rev. 109, 425 (1958).

TABLE I. Cross sections for $Ti^{47}(n,p)Sc^{47}$.

Source reaction $D(d,n)He^3$	θ_{lab} from neutron source	Relative angular distribution of source (measured)	Neutron energy (Mev)[a]	Initial counting rate per minute[b]	Cross sections (mb)[c]
$E_d=600$ kev	0°	1.00	3.55±0.10	560	62.7±7.7
	30°	0.71	3.40±0.10	444	69.9±8.9
	60°	0.38	3.04±0.11	214	63.3±8.4
	90°	0.26	2.58±0.10	127	54.6±7.8
	115°	0.29	2.21±0.07	147	56.8±7.8
	143°	0.42	1.99±0.05	150	40.1±5.5
$E_d=400$ kev	0°	1.00	3.27±0.11	436	58.7±7.5
	30°	0.72	3.15±0.11	349	65.4±8.3
	60°	0.40	2.88±0.10	200	67.0±8.5
	90°	0.28	2.53±0.05	131	62.1±8.5
	115°	0.32	2.24±0.07	149	62.1±8.2
	143°	0.46	2.05±0.05	157	45.2±5.7

[a] The neutron energy spread at the sample due to target thickness and angular spread.
[b] Corrected for escape peak and background.
[c] Standard deviations given do not include uncertainty of the cross section for $P^{31}(n,p)S^{31}$ at 3.56 Mev.

yield was monitored with a long counter during the irradiations.

A titanium sample consisted of four disks, each 15 mm in diameter and 0.5-mm thick, made out of pure titanium sheet.[7]

The integrated neutron flux during each irradiation was obtained through red phosphorus samples about 80 mg/cm² thick placed on top of the titanium sample at the zero-degree position. The phosphorus samples were changed after periods of eight hours of irradiation, which required shutting down the accelerator for a few minutes each time. The 2.65-hr activity produced in the $P^{31}(n,p)Si^{31}$ reaction was measured with a calibrated 2π proportional flow counter.[1]

The Sc^{47} activities were determined through the photopeak intensity of the 160-kev gamma ray in the decay of Ti^{47}. The measurements were carried out in a well-type NaI(Tl) scintillation spectrometer using a Harshaw type 7F8 crystal and incorporating a 20-channel pulse height analyzer. The spectrometer was calibrated by means of activated titanium disks which were compared with a standard Ce^{144} source on a scintillation spectrometer using a NaI(Tl) crystal $1\frac{1}{2}$ in. in diameter and 1-in. thick. The 134-kev gamma ray of Ce^{144} was used in the intercomparison and a correction was applied to account for the difference in sensitivity at 134 and 160 kev. Escape-peak corrections were applied. The total detection efficiency of the well-type spectrometer at 160 kev for the titanium samples used in the irradiations was determined to be 0.65±6.5% (standard deviation); this total efficiency is defined as the ratio of the photopeak counting rate corrected for escape peak and background to the true sample activity and therefore includes geometry factors and self-absorption effects.

No activities other than Sc^{47} were observed after irradiation of titanium with *d*-D neutrons. However, irradiation with $Be^9(d,n)B^{10}$ neutrons at a deuteron energy of 600 kev produced long-lived gamma ray activities of ~910 and ~1140 kev attributed to the reaction $Ti^{46}(n,p)Sc^{46}$ ($Q=-1.583$ Mev[4]). The observed half-life of Sc^{47} was 83.2±2.0 hr.

TABLE II. Sources of error considered for the $Ti^{47}(n,p)Sc^{47}$ data.

Counting statistics[a,b]
Angular distribution[a]
Absolute measurement of Si^{31} activity[a] } neutron flux[a]
$P^{31}(n,p)Si^{31}$ cross section at $E_n=3.56$ Mev[a] } neutron flux[a]
Calibration of well crystal spectrometer[a]
Branching ratio of Sc^{47} ground-state decay[a]
Correction for neutron beam attenuation in titanium samples during irradiation[c]

[a] Standard deviation measured or calculated.
[b] Standard deviation varied for different titanium samples.
[c] Standard deviation assumed.

RESULTS FOR $Ti^{47}(n,p)Sc^{47}$

The results of the irradiations are given in Table I and the figure. The $Ti^{47}(n,p)Sc^{47}$ absolute cross section of 62.7±9.7 mb over-all standard deviation at 3.55-Mev neutron energy has been based on the absolute cross section for the $P^{31}(n,p)Si^{31}$ reaction at 3.56-Mev neutron energy measured at Los Alamos.[6] The normalization of the neutron flux in the forward direction at $E_d=400$ kev with that at $E_d=600$ kev was based on the com-

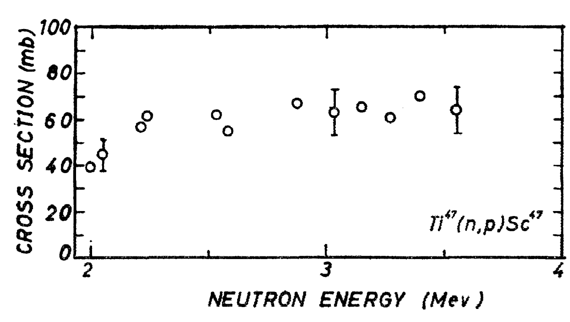

FIG. 1. Experimental values of cross section for the $Ti^{47}(n,p)Sc^{47}$ reaction.

[7] Donated by Atlas Titanium Limited, Welland, Ontario, through the courtesy of Mr. E. W. Christie.

parison of the activities of the phosphorus samples and on interpolating the $P^{31}(n,p)Si^{31}$ cross section from the data of Grundl *et al.*

A correction was applied to the data to account for neutron beam attenuation in the samples during irradiation. Corrections for inelastic and multiple scattering as well as corrections accounting for neutron energy degradation in the target assembly (bronze) and sample-supporting ring (aluminum) have been neglected. Table II lists the sources of error which have been considered.

DISCUSSION

The (n,p) reaction is similar to the inelastic scattering of neutrons, the cross sections for which are known for a large number of individual levels in the residual or target nucleus.[8] The two reaction modes differ in so far as the penetrability of the outgoing particle is concerned. Whereas the (n,n') reaction can take place at neutron energies just exceeding the energy of the excited state, the (n,p) reaction at threshold is strongly inhibited due to the Coulomb barrier. In medium-weight nuclei, the outgoing protons should have energies of a few Mev in order to obtain (n,p) reaction cross sections in the millibarn range. As a consequence, at 3-Mev incident neutron energy the (n,p) reaction preferably leads to the ground-state and to the very low-lying excited states of the residual nucleus.[9]

A rough calculation is made of the $Ti^{47}(n,p)Sc^{47}$ reaction cross section on the assumption that ground-state protons are emitted only, since the first excited state of Sc^{47} most likely is at 0.82 Mev.[10] Similar calculations of (n,p) reaction cross sections in Ni^{58}, P^{31}, and S^{32} were made and compared to the experimental values reported in the literature.[2,6,11] In the case of the $S^{32}(n,p)P^{32}$ reaction, the transition to the 77-kev first excited state of P^{32} was assumed to occur with the same probability as the ground-state transition. In $Ni^{58}(n,p)Co^{58}$, the transition to the 25-kev isomeric state of Co^{58} was not considered because of its high spin. The calculated cross sections together with the experimental ones are given in Table III.

TABLE III. Cross-section calculations.[a,b,c]

Reaction	Character of target nucleus	Neutron energy (Mev)	Calculated cross section (mb)	Experimental cross section (mb)[d]
$P^{31}(n,p)Si^{31}$	Odd Z−even N	3	85	82
		4	135	98
		5	169	124
$S^{32}(n,p)P^{32}$	Even Z−even N	3	89	130
		4	171	225
		5	210	275
$Ti^{47}(n,p)Sc^{47}$	Even Z−odd N	2	24	40
		3	96	63
		4	165	···
		5	204	···
$Ni^{58}(n,p)Co^{58}$	Even Z−even N	2	15	120
		3	69	195
		4	132	···
		5	177	···

[a] Barrier transmission coefficients for neutrons from reference 12. A complex diffuse well was used with radius parameter 1.45 fermi, diffuseness parameter 0.35 fermi. Real part of potential about 40 Mev. See text.
[b] Barrier transmission coefficients for protons from reference 13. A square well of radius 1.5 $A^{\frac{1}{3}}$ fermi and depth 20 Mev was used.
[c] The cross sections for the $Ni^{58}(n,p)Co^{58}$ reaction given in reference 2 are too high by about 9%, due to a systematic error (erratum to be published).
[d] Interpolated from experimental excitation functions averaged over resonances. Figures are approximate.

The transmission coefficients for neutrons were taken from the tables of Beyster *et al.*[12] As no coefficients were available for phosphorus and nickel, those of adjacent sulfur and iron, respectively, were used.

The proton transmission coefficients were derived from the tables of Shapiro[13] by linear interpolation. In view of the roughness of our calculations, the agreement between the experimental and calculated cross sections seems to be fair.

[8] D. A. Lind and R. B. Day, Ann. Phys. **12**, 485 (1961).
[9] This has also been suggested by Dr. P. A. Moldauer (private communication).
[10] P. C. Simms, N. Benczer-Koller, and C. S. Wu, Phys. Rev. **121**, 1174 (1961).
[11] L. Allen, Jr., W. A. Biggers, R. J. Prestwood, and R. K. Smith, Phys. Rev. **107**, 1363 (1957).
[12] R. G. Beyster, J. R. Schrandt, M. Walt, and E. W. Salmi, Los Alamos Scientific Laboratory Report LA-2099, 1957 (unpublished).
[13] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).