Excitation functions of $^{46-50}$Ti$(n,p)^{46-50}$Sc processes

N. I. Molla* and S. M. Qaim
Institut für Nuklearchemie, Forschungszentrum Jülich GmbH, W-5170 Jülich, Federal Republic of Germany

H. Kalka
Institut für Kern- und Atomphysik, Technische Universität Dresden, 0-8027 Dresden, Federal Republic of Germany
(Received 18 February 1992)

Excitation functions were measured for the ^{49,50}Ti$(n,p)^{49,50}$Sc reactions from threshold to 10.5 MeV. Use was made of the activation technique in combination with high-resolution γ-ray spectroscopy and anticoincidence β^- counting. Nuclear model calculations using a computer code were performed for (n,p) reactions on ^{46,47,48,49,50}Ti. The experimental excitation functions are reproduced well by the calculation involving a fixed set of global parameters and only one variable parameter ("pairing shift") to take account of the odd-even and nuclear structure effects in the target nuclei.

PACS number(s): 25.40.Kv, 27.40.+z, 24.60.Dr, 24.60.Gv

Studies of excitation functions of neutron threshold reactions are of considerable significance in testing nuclear models. Of special interest are investigations on a series of isotopes of a particular target element, since they should shed some light on the effect of varying neutron binding energy on the reaction cross section. We chose to investigate the (n,p) reaction on the five stable isotopes of Ti, viz. ^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti, and ^{50}Ti. Rather extensive experimental information existed on the excitation functions of ^{46,47,48}Ti$(n,p)^{46,47,48}$Sc reactions from threshold to about 19 MeV (cf. Ref. [1]) and some recent studies further strengthened the data base (cf. Refs. [2–6]). Since those reactions are commonly used in neutron dosimetry, evaluations of the data were also performed in the framework of the statistical-precompound model using the codes GNASH, STAPRE, MAURINA, etc. (cf. Refs. [4,7]). For the ^{49,50}Ti$(n,p)^{49,50}$Sc reactions, on the other hand, data were available only in the energy region around 14 MeV (cf. Refs. [1,2]). The present work deals with some experimental studies on these two processes near their thresholds.

Over the last decade the concept of statistical multistep direct (SMD) and statistical multistep compound (SMC) theories (cf. Refs. [8,9] and citations therein) was developed primarily for the description of high-energy emission cross sections. In the energy region above about 20 MeV, where the older concepts of pure evaporation models and single-step direct processes do not work, the SMD and SMC models describe the emission spectra well. These models are derived directly from the nuclear Hamiltonian using statistical assumptions. The question arises whether it is possible to apply pure SMD and SMC models (without any equilibrium emission from a so-called r stage) to the description of low-energy data. In this sense, (n,p)-activation data constitute an interesting case to test these models. We performed calculations on the five (n,p) reactions mentioned above.

Cross sections were measured by the activation technique. For studies on the ^{50}Ti$(n,p)^{50}$Sc reaction, about 5 g Ti metal powder (>99.9%, Koch-Light, England) was pressed at 10 tonne/cm^2 to a disc (diam of 2 cm, thickness of 0.5 cm), sandwiched between Al monitor foils and irradiated in the 0° direction with quasimonoenergetic neutrons produced via the ^{2}H$(d,n)^3$He reaction on a D_2 gas target at the Jülich variable energy compact cyclotron CV 28 (cf. Ref. [10]). The radioactivity of the product ^{50}Sc ($T_{1/2}=1.7$ min, $E_\gamma=1544$ keV, $I_\gamma=100\%$) was determined via conventional Ge(Li) detector γ-ray spectroscopy.

In studies on the ^{49}Ti$(n,p)^{49}$Sc reaction, on the other hand, a highly enriched $^{49}TiO_2$ sample (supplied by Oak Ridge National Laboratory) was used. Its isotopic composition was ^{46}Ti (0.22%), ^{47}Ti (0.22%), ^{48}Ti (2.71%), ^{49}Ti (96.25%), and ^{50}Ti (0.60%). A spectrographic analysis of

TABLE I. Major uncertainties and their correlations in cross section measurements.

Source of uncertainty	Magnitude (%) ^{49}Ti$(n,p)^{49}$Sc	^{50}Ti$(n,p)^{50}$Sc
Uncorrelated		
Irradiation geometry	3	3
Determination of count rate	3–17	20–32
Correction for activity induced by background neutrons	2–5	2
Correlated		
Efficiency of detector	6	3
Self-absorption	3	1
Excitation function of monitor reaction	3–9	4
Decay data	5	3
Total	10–22 %	21–33 %

*Present address: Institute of Nuclear Science and Technology, Atomic Energy Research Establishment, Savar, Dhaka, Bangladesh.

TABLE II. Fast neutron-induced activation cross sections.

Mean neutron energy effective at Ti sample[a] (MeV)	Reaction cross section (mb)	
	^{49}Ti(n,p)^{49}Sc	^{50}Ti(n,p)^{50}Sc
6.48±0.27	5.3±1.0	
7.52±0.31	4.5±1.0	
8.53±0.31	9.0±1.0	
9.49±0.39	13.7±1.9	
9.98±0.40	13.0±2.0	1.2±0.4
10.47±0.39	19.2±2.3	2.6±0.6

[a]The deviations do not give errors; they show energy spreads due to angle of emission.

the sample showed that its chemical purity was >99.9%. About 0.05 g of the material was packed in a polyethylene bag, sandwiched between Fe or Al foils, and irradiated as described above. The radioactivity of the product ^{49}Sc ($T_{1/2}=57.2$ min, $E_{\beta^-}=2.0$ MeV, $I_{\beta^-}=100\%$) was measured via anticoincidence β^- counting. A complete analysis of the decay curve was done and the contribution of ^{49}Sc determined. The neutron flux density in the energy region up to 7.5 MeV was determined via the ^{56}Fe(n,p)^{56}Mn monitor reaction [7] and between 8.5 and 10.5 MeV via the ^{27}Al(n,α)^{24}Na reaction [11].

The average neutron energy effective at each sample was obtained by calculation [10,12,13]. The decay rates of both ^{49}Sc and ^{50}Sc were corrected for contributions from background neutrons (gas-out/gas-in results [10] and breakup of deuterons on D_2 gas [14]). Cross sections were then obtained using the well-known activation equation. The sources of errors were similar to those in our earlier activation measurements [10,12,13]; the major uncertainties, their correlations and magnitudes are given in Table I.

We applied the analytical SMD/SMC model presented earlier [15–17]. Both the SMD and the SMC parts were calculated by the same residual interaction V. The calculations were performed with a global parameter set which

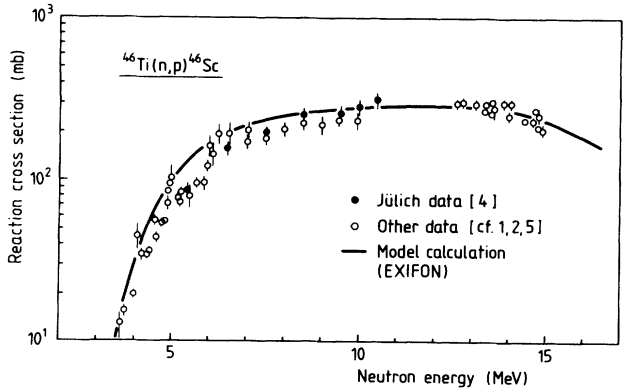

FIG. 1. Excitation function of the ^{46}Ti(n,p)^{46}Sc reaction. Typical error bars in the experimental data are shown. The curve describes the results of model calculation.

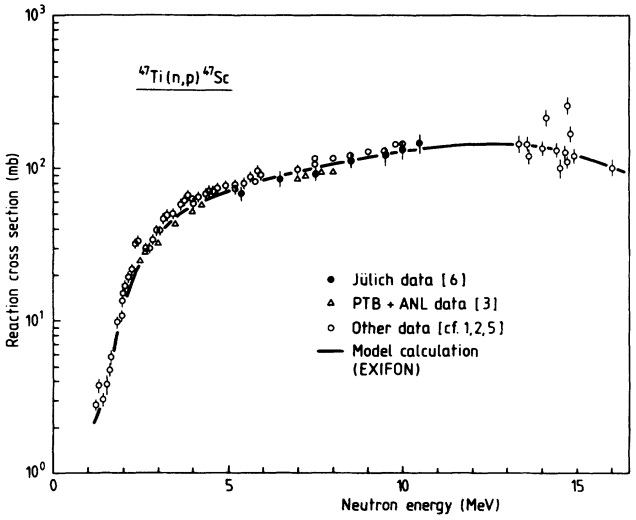

FIG. 2. Excitation function of the ^{47}Ti(n,p)^{47}Sc reaction. Other details are the same as for Fig. 1.

describe emission data at energies up to 80 MeV. However, since at lower energies shell-structure effects become important and a description using only one global parameter set for the whole mass range $A \geq 20$ is impossible, we introduced one free parameter—the pairing shift Δ.

Calculations were performed with the code EXIFON (version 2.0) [18] using the following global parameters: strength of surface-delta interaction [19], $F_0=27.5$ MeV; radius parameter [20], $r_0=1.21+4.0A^{-2/3}-15A^{-4/3}$ fm; potential depth [21], $V_0=52-0.3E_\alpha$ MeV; fermi energy, $E_F=33$ MeV; optical model potential [22], Wilmore and Hodgson (for neutrons) and Perey *et al.* (for protons).

Here, the single-particle state density of bound particles (and holes) was taken as $g=4\rho(E_F)$, where

$$\rho(E)=(2\pi\hbar)^{-3}4\pi\mathcal{V}m(2mE)^{1/2}$$

is the common state density in the nuclear volume

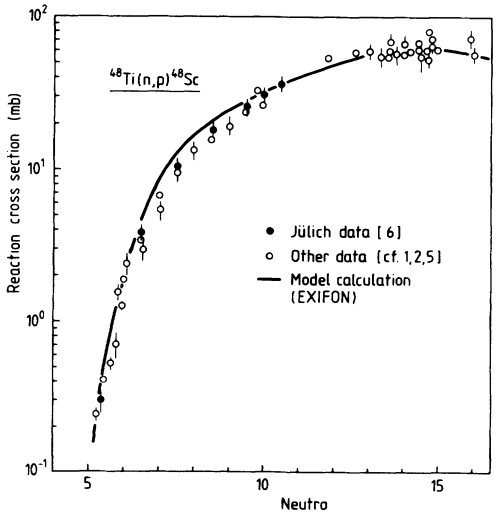

FIG. 3. Excitation function of the ^{48}Ti(n,p)^{48}Sc reaction. Other details are the same as for Fig. 1.

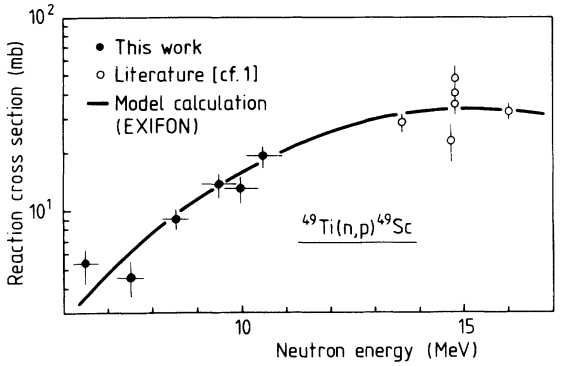

FIG. 4. Excitation function of the ^{49}Ti$(n,p)^{49}$Sc reaction. Other details are the same as for Fig. 1.

$\mathcal{V}=4\pi R^3/3$ and $R=r_0 A^{1/3}$.

The pairing effects were taken into account by using the effective binding energies B_c^{eff}. For a system of $A=N+Z$ nucleons the effective neutron (proton) binding energy is defined as

$$B_n^{\text{eff}}=B_n\pm\Delta_n \quad \text{for} \begin{bmatrix}\text{odd}\\ \text{even}\end{bmatrix} N ,$$

$$B_p^{\text{eff}}=B_p\pm\Delta_p \quad \text{for} \begin{bmatrix}\text{odd}\\ \text{even}\end{bmatrix} Z ,$$

where $B_{n(p)}$ is the exact neutron (proton) binding energy. The standard pairing shift is $\Delta_n=\Delta_p=12.8A^{-1/2}$ MeV taken from [23].

The only free parameter in the present calculations was Δ_p, and the value (in MeV) used for each titanium isotope was ^{46}Ti (1.50), ^{47}Ti (2.40), ^{48}Ti (0.30), ^{49}Ti (0.90), ^{50}Ti (1.10).

The measured cross sections are presented in Table II. In the case of ^{49}Ti$(n,p)^{49}$Sc reaction the total error amounts to between 11 and 22%; for ^{50}Ti$(n,p)^{50}$Sc it is between 23 and 33%. Over the reported energy range the cross sections for both reactions have been measured for the first time.

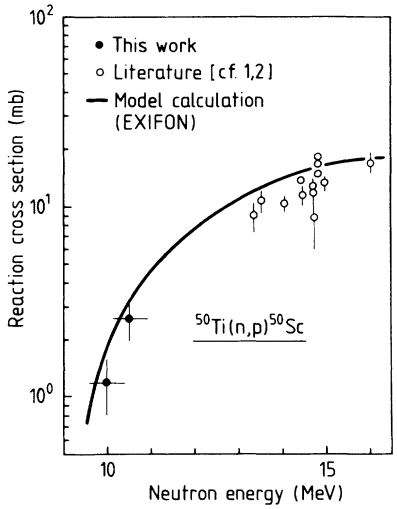

FIG. 5. Excitation function of the ^{50}Ti$(n,p)^{50}$Sc reaction. Other details are the same as for Fig. 1.

The experimental data as well as the results of nuclear model calculations on the five reactions under consideration are shown in Figs. 1–5 as a function of neutron energy. All the measured excitation functions are reproduced well by our calculations over the whole energy range. This shows that the SMD/SMC model with a chosen and fixed set of global parameters describes the first chance proton emission at excitation energies <25 MeV rather well, with only one free parameter ("pairing shift") taking account of the odd-even and nuclear structure effects in the target nuclei.

It would be of interest to extend such systematic studies to other mass regions and reaction types.

We thank Professor G. Stöcklin and Professor D. Seeliger for their initiative regarding this collaborative program between Jülich and Dresden. N. I. Molla thanks the Commission of the European Communities for financial support.

[1] V. McLane, C. L. Dunford, and P. F. Rose, *Neutron Cross Sections* (Academic, New York, 1988), Vol. 2.

[2] Y. Ikeda, C. Konno, K. Oishi, T. Nakamura, H. Miyade, K. Kawade, H. Yamamoto, and T. Katoh, Japan Atomic Energy Research Institute Report JAERI-1312, 1988.

[3] W. Mannhart, D. L. Smith, and J. W. Meadows, in *Proceedings of the Specialists' Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications,* ANL, 1989, edited by M. Wagner and H. Vonach (OECD, Paris, 1990), p. 121.

[4] N. I. Molla, S. M. Qaim, and M. Uhl, Phys. Rev. C **42**, 1540 (1990).

[5] N. I. Molla, S. M. Qaim, H. Liskien, and R. Widera, Appl. Radiat. Isotopes **42**, 337 (1991).

[6] S. M. Qaim, N. I. Molla, R. Wölfle, and G. Stöcklin, in *Proceedings of the International Conference on Nuclear Data for Science and Technology,* Jülich, Germany, 1991, edited by S. M. Qaim (Springer Verlag, Berlin, 1992), p. 297.

[7] Evaluated Nuclear Data File (ENDF)/B-V, Dosimetry File (1979), issued by National Nuclear Data Center, Brookhaven National Laboratory, received as computer listing in NEA Data Bank, Saclay, France.

[8] A. J. Koning and J. M. Akkermans, Ann. Phys. (N.Y.) **208**, 216 (1991).

[9] R. Bonetti, M. B. Chadwick, P. E. Hodgson, B. V. Carlson, and M. S. Hussein, Phys. Rep. **202**, 171 (1991).

[10] S. M. Qaim, R. Wölfle, M. M. Rahman, and H. Ollig, Nucl. Sci. Eng. **88**, 143 (1984).

[11] H. Vonach, in *Nuclear Data Standards for Nuclear Measurements* (IAEA Technical Reports Series 227, 1983), p. 59.

[12] A. Suhaimi, R. Wölfle, S. M. Qaim, and G. Stöcklin, Radiochimica Acta **40**, 113 (1986).
[13] S. M. Qaim and R. Wölfle, Nucl. Sci. Eng. **96**, 52 (1987).
[14] J. W. Meadows and D. L. Smith, Argonne National Laboratory Report ANL/NDM-53, 1980.
[15] H. Kalka, M. Torjman, and D. Seeliger, Phys. Rev. C **40**, 1619 (1989).
[16] H. Kalka, M. Torjman, H. N. Lien, R. Lopez, and D. Seeliger, Z. Phys. A **335**, 163 (1990).
[17] H. Kalka, Z. Phys. A (in press).
[18] H. Kalka, EXIFON—A Statistical Multistep Reaction Code (1991), NEA Data Bank, Saclay, France.
[19] A. Faessler, Fortschr. Phys. **16**, 309 (1968).
[20] I. Angeli, J. Csikai, and A. Algora Pineda, *Proceedings of the 17th International Symposium on Nuclear Physics,* Gaussig, Zentralinstitut für Kernforschung (Report ZfK-646, 1987), p. 103.
[21] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.
[22] A. Chatterjee, K. H. N. Murthy, and S. K. Gupta, Pramana **16**, 391 (1981).
[23] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).