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Excitation functions of (n,t) reactions on ^{27}Al, ^{59}Co, and ^{93}Nb

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Cross sections were measured for (n,t) reactions on ^{27}Al, ^{59}Co, and ^{93}Nb over the incident neutron energy region of 16 to 20 MeV using activation and tritium counting. Three or four segments of the material under investigation were so arranged that a compact hemispherical geometry was obtained. The incident neutrons were produced by the ^{3}H$(d,n)^{4}$He reaction and the neutron energy spectrum effective for each segment was determined via Monte Carlo calculations. After irradiation, the accumulated tritium was separated from each segment by vacuum extraction and its activity determined by low-level anticoincidence β^- counting in the gas phase. The (n,t) cross section increases with the incident neutron energy. The excitation function of the (n,t) reaction on ^{27}Al is described well by Hauser-Feshbach calculations; in the case of ^{59}Co and ^{93}Nb, however, the calculated cross section values are appreciably smaller than the experimental data, suggesting that for those nuclei the contributions of statistical processes are rather small.

[NUCLEAR REACTIONS ^{27}Al, ^{59}Co, ^{93}Nb (n,t); $E_n = 16-20$ MeV; measured σ; Hauser-Feshbach analysis.]

I. INTRODUCTION

The (n,t) reaction is known to occur mainly in the light mass region and is primarily of a direct nature, involving both deuteron "pickup" and triton "knockout" (cf., e.g., Refs. 1–3). In the medium and heavy mass regions triton emission occurs only with a very low probability (cf. Ref. 4).

Most of the studies on (n,t) reactions performed so far have been limited to investigations in the 14 MeV region (cf. Refs. 1–7) or with broad neutron spectra produced by breakup of 53 or 30 MeV deuterons on Be.[8–10] Except for ^{6,7}Li and ^{10}B the energy dependence of the (n,t) cross section has not been investigated. Bormann *et al.*[11] reported summed cross sections for the processes ^{32}S$[(n,t)+(n,dn)+(n,p2n)]^{30}$P and ^{40}Ca$[(n,t)+(n,dn)+(n,p2n)]^{38}$K in the energy region of 14 to 20 MeV; (n,t) cross sections, however, cannot be deduced from those data.

This work describes the first systematic study of the energy dependence of the (n,t) reaction cross section for nuclei with $Z > 12$.

II. EXPERIMENTAL

Cross sections for the monoisotopic elements Al, Co, and Nb were measured as a function of neutron energy by the activation method involving vacuum separation and low-level gas phase β^- counting of accumulated tritium. The pertinent techniques are described below.

A. Irradiations

The expected low cross sections of (n,t) reactions necessitated a very compact source-sample assembly so that all the neutrons emitted in the forward hemisphere from a dt-neutron source could be used for irradiations. The schematic irradiation geometry is shown in Fig. 1. The material investigated, in the form of three or four segments, was so arranged that a half-spherical geometry was obtained. Aluminium segments were prepared by melting powdered aluminium (purity 99.999%, Koch-Light, England) in an argon atmosphere and moulding. In the case of cobalt (purity 99.9%, Goodfellow Metals, England) and niobium (purity 99.9%, Heraeus, Germany) foils and sheets were cut and placed together to achieve nearly half-spherical geometry. Aluminium segments were heated to 600 °C prior to irradiation and cobalt and niobium to 900 °C. In order to avoid tritium contamination from the Ti(T) target the sample had to be placed in an aluminium capsule. Irradiations were carried out for $\sim$ 50 h with neutrons produced by bombarding a water-cooled Ti(T) layer ($\sim$ 2 mg/cm^2 thick) on a 0.3 mm Ag backing with 3 MeV deuterons at 50 μA from a Van de Graaff machine.

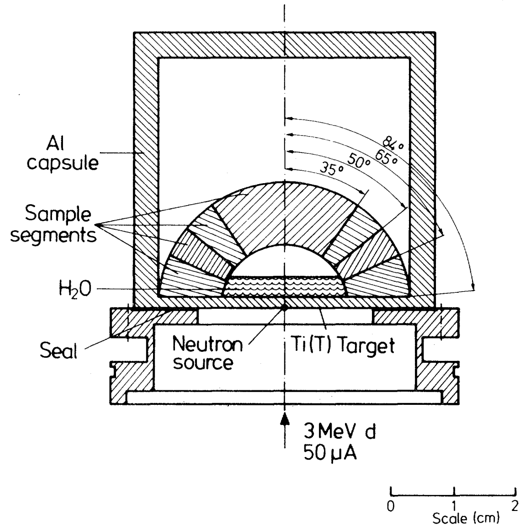

FIG. 1. Hemispherical compact geometrical arrangement of sample segments for irradiation with neutrons ($E_n = 16$ to 20 MeV) produced by bombardment of a Ti(T) target with 3 MeV deuterons at 50 μA.

B. Neutron energies

As shown in Fig. 1 each segment covered a certain angular range and was therefore exposed to a corresponding primary neutron energy range. Neutron scattering in the cooling water, the sample, and/or the surrounding capsule modifies slightly the primary neutron spectrum. A Monte Carlo calculation was therefore carried out to determine the neutron spectrum seen by each segment. Neutrons scattered in the cooling water were assumed to originate from the (point) source, while all neutrons scattered in the surrounding capsule were assumed to originate from the inner wall of that capsule. No multiple scattering was taken into account. Calculations showed that above the thresholds of the respective flux monitor reactions only 4 – 6 % of the neutrons fall outside the normal energy range of the primary neutrons. They stem essentially from elastic scattering in the sample. The neutron energy ranges effective for various segments are given in Table I.

TABLE I. Experimental data on energy dependent (n,t) cross section measurements for Al, Co, and Nb.

Sample[a]	(segment)	Weight (g)	Angular range	Neutron energy range (MeV)	$\langle\Phi\rangle$ (10^7 cm^{-2} s^{-1})	^{3}H (dps)	$\sigma_{n,t}/\sigma_{\text{mon}}$	$\sigma_{n,t}$ (mb)
Al	(1)	7.71	0 – 35°	19.1±0.5	1.37±0.08	3.46±0.16	(1.01±0.06)×10^{-1}	4.83±0.36
	(2)	6.60	35 – 50°	18.3±0.4	0.99±0.06	2.02±0.09	(7.69±0.43)×10^{-2}	4.57±0.34
	(3)	8.07	50 – 65°	17.4±0.5	0.77±0.05	1.70±0.08	(5.57±0.31)×10^{-2}	4.05±0.30
	(4)	7.42	65 – 83°	16.3±0.6	0.70±0.04	1.24±0.06	(3.83±0.22)×10^{-2}	3.50±0.27
Co	(1)	29.09	0 – 40°	19.0±0.6	2.46±0.19	3.12±0.14	(1.92±0.11)×10^{-3}	1.61±0.15
	(2)	40.28	40 – 65°	17.7±0.8	1.90±0.15	2.52±0.12	(1.41±0.08)×10^{-3}	1.22±0.11
	(3)	27.50	65 – 83°	16.3±0.6	1.83±0.14	1.17±0.06	(1.00±0.06)×10^{-3}	0.86±0.08
Nb	(1)	28.05	0 – 40°	19.0±0.6	0.78±0.08	0.46±0.02	(3.21±0.18)×10^{-3}	1.08±0.12
	(2)	39.49	40 – 65°	17.7±0.8	0.52±0.05	0.32±0.02	(2.05±0.12)×10^{-3}	0.79±0.09
	(3)	28.15	65 – 83°	16.3±0.6	0.40±0.04	0.10±0.01	(1.16±0.07)×10^{-3}	0.46±0.05

[a]Irradiation times were Al (47.32 h), Co (41.40 h), and Nb (47.00 h).

C. Neutron flux determination

For calculating (n,t) cross sections the neutron flux densities averaged over the volume of the respective segment have to be known. Since the segments were rather thick and the irradiation geometry not sufficiently accurately known, we relied on the use of internal standards, based on the cross sections for the monitor reactions $^{27}Al(n,\alpha)$ ^{24}Na, $^{59}Co(n,2n)^{58}Co$, and $^{93}Nb(n,2n)$ $^{92}Nb^m$, respectively, which are known with accuracies of $\pm5\%$, $\pm7\%$, and $\pm10\%$.[12–14] The γ activities of ^{24}Na, ^{58}Co, and $^{92}Nb^m$ were determined by a large size Ge(Li) detector with a counting distance greater than 10 cm, where the counting efficiency was known to $\pm3\%$. The statistical accuracy for the γ counting was between ±1.0 and $\pm1.6\%$. The results of the Monte Carlo calculations were used to correct for the effect of neutrons falling outside the energy range of the primary neutrons.

The values obtained for the average flux density are given in Table I. They are consistent with results obtained from two other external methods, viz., proton recoil counting with a telescope placed in the 130° direction at 80 cm from the neutron source, and ^{58}Co activity counting from a small piece of cobalt activated in the 0° direction at 25 cm from the source. The results from the two external methods, however, are not very accurate due to the lack of knowledge of the exact irradiation geometry.

D. Separation and gas phase counting of tritium

Each irradiated segment was heated at 1000 °C in a vacuum system in hydrogen atmosphere, and the accumulated tritium was pumped out.[8] The tritium was then mixed with methane and the mixture transferred to a gas counting tube; its activity was determined by low-level anticoincidence β^- counting in the gas phase.[8] The vacuum extraction process was repeated until no more tritium could be detected. By correcting for the efficiency of the gas counting system, which was determined using tritium gas standards supplied by the CEA-Bureau National de Métrologie, Saclay, France, the disintegration rate of tritium was obtained. Typical disintegration rates of tritium obtained from each segment are given in Table I. The errors contain systematic components of $\pm4\%$ as uncertainty of the counting efficiency and $\pm2\%$ as uncertainty for the quantitative tritium extraction. Statistical errors vary between ±0.6 and $\pm2.9\%$.

E. Calculation of cross sections

From the experimental data given in Table I the (n,t) cross sections were deduced, which are given in Table I together with the determined cross section ratios. A half-life value of 12.35 ± 0.02 y for tritium was used. Throughout this work total errors were obtained by summing the statistical and systematic errors in quadrature.

III. RESULTS AND DISCUSSION

The cross section data obtained in this work are plotted in Fig. 2 as a function of incident neutron energy. Also shown are earlier data obtained in the 14 MeV energy region.[7] Three conclusions can be drawn:

(i) For all the three target nuclei (^{27}Al, ^{59}Co, and ^{93}Nb) the transition of the (n,t) cross section value from the 14 MeV region to higher energies is smooth.

(ii) The (n,t) cross section increases with the increasing incident neutron energy.

(iii) For the same incident neutron energy the (n,t) cross section decreases with the increasing mass of the target nucleus.

In order to shed some light on the mechanism of triton emission from excited nuclei, Hauser-Feshbach calculations incorporating the first chance emission of nucleons (neutrons and protons) as well as complex particles (deuterons, tritons, ^3He, and ^4He) have been performed by Qaim *et al.*[15] for energies around 14 MeV. In the present work we extended these calculations to energies from the threshold of each reaction up to 20 MeV, in steps of 1 MeV. For each reaction product all the low-lying levels[16–18] extending up to an excitation energy beyond which the level density could be treated statistically were considered. In general, this covered an excitation energy region up to about 3 MeV. The energy levels in the continuum were obtained using the composite level density formula given by Gilbert and Cameron.[19] If the level density parameter a was not given in Ref. 19, the approximation $a \sim A/7.5$ was employed. The optical model parameters used for calculations of transmission coefficients of various particles have been listed.[15] Cross sections were calculated for the

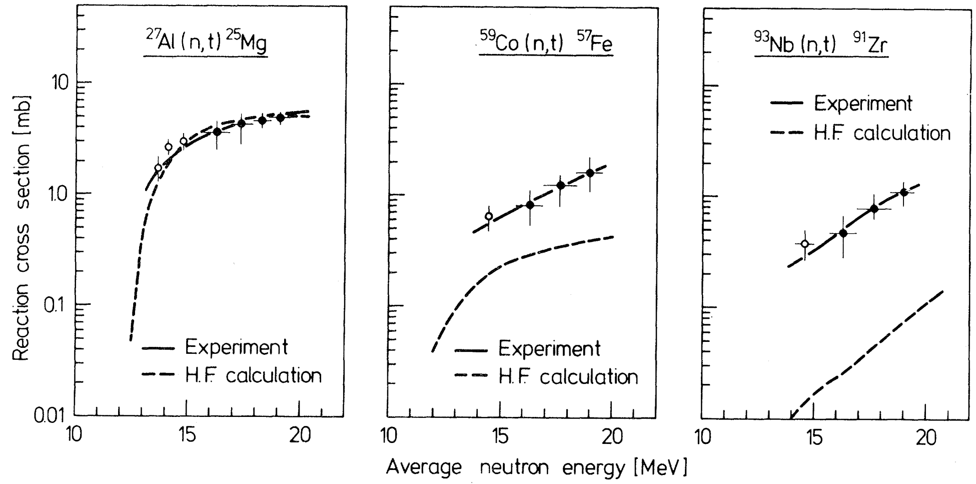

FIG. 2. Excitation functions of (n,t) reactions on ^{27}Al, ^{59}Co, and ^{93}Nb. Points and solid lines describe the experimental data and trends; full points are the results of this work, open points are based on measurements in the 14 MeV region (Ref. 7). The dashed lines give results of Hauser-Feshbach calculations.

discrete levels fed and for the levels in the continuum in energy intervals of 0.1 MeV up to the maximum excitation energy of the final nucleus.

The calculated excitation functions for the (n,t) reactions on ^{27}Al, ^{59}Co, and ^{93}Nb are shown in Fig. 2 together with the experimental data. The remarkably good agreement between experimental values and calculations for ^{27}Al over the whole investigated energy range confirms and further elaborates our conclusion[15] at 14.6 MeV that contributions of statistical processes to triton emission are important in this mass region. In the case of ^{59}Co and ^{93}Nb, however, although the shapes of experimental and calculated excitation functions are somewhat similar, the magnitudes are quite different. We conclude that for those nuclei the contributions of statistical processes to the (n,t) cross section are small and that those contributions decrease with the increasing mass of the target nucleus.

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