EXCITATION CURVES FOR FAST NEUTRON INDUCED REACTIONS ON ^{71}Ga, ^{75}As, ^{80}Se, ^{82}Se, ^{117}Sn AND ^{118}Sn NUCLEI

By W. Grochulski**, S. El-Konsol*, and A. Marcinkowski***

Institute of Experimental Physics, University of Warsaw**
Institute of Nuclear Research, Warsaw***

(Received March 3, 1974; Revised version received May 6, 1974)

Excitation curves for (n, 2n) reactions on the target nuclei ^{71}Ga, ^{75}As, ^{80}Se, ^{82}Se, ^{118}Sn, and for (n, p) reactions on the target nuclei ^{71}Ga, ^{75}As, ^{117}Sn, as well as for the ^{117}Sn (n, n') ^{117m}Sn reaction were measured in the neutron energy range 13–18 MeV. The results obtained were compared with the predictions of the compound nucleus and precompound emission models.

1. Introduction

In this paper we present more data which further show that the compound nucleus theory can quantitatively account for the experimental cross section of the (n, 2n) reaction in a wide range of neutron energies. The excitation curves for the (n, n') and (n, p) reactions at neutron energies higher than 14 MeV do not seem to fit in the description provided by the compound nucleus model [1–3]. Experimental cross sections in this energy region are passing well above the compound nucleus values and show a very weak energy dependence. Such a behaviour of the excitation curves suggests the existence of a contribution of a reaction mechanism which is simpler than that of the compound nucleus.

In the present work we have tried to reproduce the measured reaction cross sections for the inelastic neutron scattering and the (n, p) reaction by assuming that the nucleon emission may occur before the thermal equilibrium is reached.

2. Experimental procedure

Samples of enriched ^{71}Ga (98.8%), ^{117}Sn (84.8%) and ^{118}Sn (92.2%), as well as natural high purity Arsenic and Selenium were irradiated with neutrons obtained from the ^{3}H(d, n)^{4}He reaction. Tritium absorbed targets were bombarded with deuterons

* On leave from the Nuclear Establishment, U. A. E.

** Address: Instytut Fizyki Doświadczalnej, Uniwersytet Warszawski, Hoża 69, 00-681 Warszawa, Poland.

*** Address: Instytut Badań Jądrowych, Hoża 69, 00-681 Warszawa, Poland.

accelerated in a 3 MeV Van de Graaff accelerator. To obtain monoenergetic neutrons, a suitable deuteron energy and neutron emission angle were selected. Changes in the neutron flux were measured during irradiation by counting the protons recoiled from a polyethylene foil in a CsI scintillation counter.

The γ-activities of the irradiated samples were measured using a 7.6×7.6 cm NaI(Tl) crystal spectrometer. The photopeak efficiencies of the scintillation crystal were taken from the tables of Crouthamel [4].

The absolute neutron flux was determined by measuring the γ-activities induced in the $^{56}Fe(n, p)^{56}Mn$ reaction [5]. The 2.58 h activity of the 847 keV γ-rays or β^- following the decay of ^{56}Mn was measured.

TABLE I

Decay data used in the cross section determination

Reaction	Measured γ-ray keV	Half-life	Branching ratio	Internal conv. coeff.
$^{71}Ga(n, p)^{71m}Zn$	609	4 h	1	
$^{71}Ga(n, 2n)^{70}Ga$	1040	21.1 min	0.03	
$^{75}As(n, p)^{75g}Ge$	264	82 min	0.11	
$^{75}As(n, p)^{75m}Ge$	139	48 s	1	1.44
$^{75}As(n, 2n)^{74}As$	511+		2×0.29	
	569+	17.9 d	0.618	
	600+		0.007	
	635		0.14	
$^{80}Se(n, 2n)^{79m}Se$	96	3.9 min	1	7.0
$^{82}Se(n, 2n)^{81m}Se$	103	57 min	1	9.0
$^{82}Se(n, 2n)^{81}Se$	β^-	18.6,57 min	1	
$^{117}Sn(n, p)^{117m}In$	158	115.8 min	0.47, 0.16	0.13
$^{117}Sn(n, p)^{117g}In$	158	44 min	0.47, 1	0.13
$^{117}Sn(n, n')^{117m}Sn$	158	14 d	1	0.13
$^{118}Sn(n, 2n)^{117m}Sn$	158	14 d	1	0.13

The decay of the metastable and ground states in ^{117}In are not independent; the partial branching ratios are given.

In Table I we listed the energies of the measured γ-rays, as well as other decay characteristics for the residual nuclei of the investigated reactions, adopted in the present data analysis.

3. Results

The results of the cross section measurements are presented in Table II. The errors shown contain the statistical errors as well as the systematic errors. The latter ones amount to 6-14% for the (n, 2n) reactions and to 10–21% for the (n, n') and (n, p) reactions.

TABLE II

Experimental cross sections

Neutron energy MeV	13±0.1	13.4±0.1	13.9±0.1	14.5±0.1	15.1±0.2	15.4±0.2	15.9±0.2	16.5±0.1	17.3±0.2	17.8±0.2
Reactions	Cross Section [mb]									
^{71}Ga(n, p)^{71m}Zn	13.2±2.1	10.0±1.6	9.1±1.4	10.0±1.6	11.0±1.7	9.2±1.4	6.8±2.2	9.1±2.4	12.1±1.9	12.1±2.0
^{71}Ga(n, 2n)^{70}Ga	950±136	1098±83	1153±90	1135±105	1130±100	1148±104	1144±140	1046±134	1032±126	1121±285
^{75}As(n, p)^{75m}Ge	12.4±2.1	23.3±3.5	20.7±3.1	21.1±3.2	18.2±2.7	17.9±2.7	10.7±1.4	8.9±1.6	—	—
^{75}As(n, p)^{75}Ge	28.5±4.1	28.8±4.0	38.1±5.3	31.2±4.2	26.5±3.7	30.4±4.3	27.6±3.9	19.9±2.8	12.5±1.9	12.4±1.8
^{75}As(n, 2n)^{74}As	955±100	890±65	955±67	1027±75	1109±82	—	1299±135	1312±136	1245±200	1321±137
^{80}Se(n, 2n)^{79m}Se	193±47	196±28	165±25	189±27	203±29	186±27	192±46	178±44	190±47	180±33
^{82}Se(n, 2n)^{81m}Se	1506±345	1702±230	1692±227	1587±218	1628±219	1616±208	1796±322	1715±285	1520±316	1425±240
^{82}Se(n, 2n)^{81}Se*	0.42±0.12	0.42±0.04	0.46±0.07	0.37±0.03	0.46±0.05	0.41±0.04	0.47±0.11	0.43±0.09	0.37±0.05	0.48±0.08
^{117}Sn(n, p)^{117}In	10.2±2.9	10.0±2.1	9.5±2.1	9.6±2.1	12.1±2.6	11.2±2.4	14.41±3.0	16.0±3.4	19.72±4.2	—
^{117}Sn(n, n')^{117m}Sn	416±99	287±44	272±35	284±32	255±37	286±30	320±52	—	—	—
^{117}Sn(n, p)^{117}In*	3.2±1.6	4.0±1.9	—	—	4.0±0.6	4.5±1.4	2.6±0.7	2.8±1.2	—	—
^{81}Sn(n, 2n)^{117m}Sn	624±103	761±85	808±87	794±109	805±87	890±98	1055±193	770±108	1124±260	—

* isomeric ratio σ_g/σ_m.

They consist of uncertainties: a) in the integration of the pulse height spectrum ranging up to 8% for (n, 2n) reactions and up to 18% for the other ones, b) caused by fluctuations of the beam current during irradiation 1%, c) of counter efficiency 3%, d) of γ-ray attenuation in the sample 5–10% (for γ-ray energies lower than 300 keV), e) of cross section of the monitoring reaction 3–5%.

The neutron energy spread was determined by calculating the effective energy distributions of the neutrons incident on the samples. The irradiation geometry, the dependence of the neutron energy on the emission angle and the deuteron energy loss in the titanium-tritium layer were taken into account.

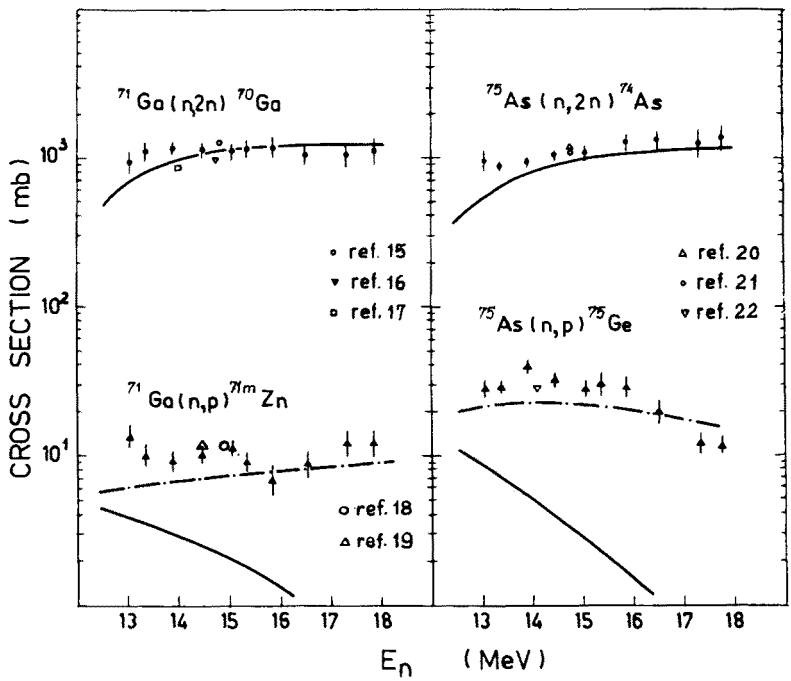

Fig. 1. Comparison of experimental cross sections for (n, 2n) and (n, p) reactions on ^{71}Ga and ^{75}As target nuclei with the calculated ones. The solid lines are the compound nucleus cross sections, the dott-dashed lines are the precompound cross sections normalized to the difference between experimental values and the compound nucleus cross sections. The sum of both compound and precompound contributions reproduces the experimental cross sections for the (n, p) reactions well

The excitation curves measured in the present work are in good agreement with most of the single measurements done at neutron energy close to 14 MeV. See Figs 1 and 2.

For the ^{75}As(n, 2n) ^{74}As reaction, the excitation curve was measured by Prestwood and Bayhurst [6] in the whole energy range accessible in the present experiment. Our results reproduce well the cross sections measured by Prestwood and Bayhurst.

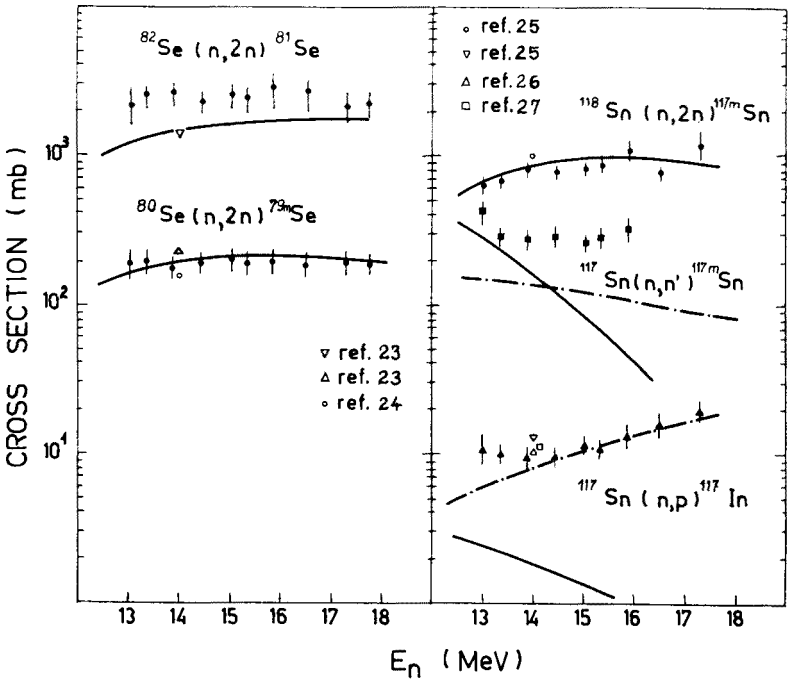

Fig. 2. Comparison of experimental cross sections for (n, 2n), (n, p) and (n, n') reactions on ^{80}Se, ^{82}Se, ^{117}Sn and ^{118}Sn nuclei. The solid lines are the compound nucleus cross sections, the dott-dashed lines are the precompound cross sections normalized to the difference between the experimental values and the compound nucleus cross sections

4. Comparison between theory and experiment

The compound nucleus model for nuclear reactions was applied in the calculations of the excitation curves. Angular momentum effects and photon emission from the continuum of states were included in the formalism in the way described in Refs [7, 8].

The decay to known low excited levels was treated separately, and for higher excitation energies the microscopic model for the level density was employed [9]. The optical model transmission coefficients were obtained using the code ALA [10] and the parameters of Björklund and Fernbach [11]. The binding energies were taken from Garvey et al. [12].

The preequilibrium contribution was evaluated by integration over the closed-form expression describing the spectrum of nucleons emitted prior to the formation of the compound nucleus. In the frame of the simple exciton model [13] we have:

$$\frac{d\sigma}{d\varepsilon} = \frac{(2s+1)m}{4\pi^3|M|^2\hbar^2} \cdot \frac{1}{g^4}\sigma_a \frac{\varepsilon\sigma_b}{E^3} \sum_{\substack{n=n_0 \\ (\Delta n=+2)}}^{\bar{n}} (n+1)^2(n-1)\left(\frac{U}{E}\right)^{n-2}. \qquad (1)$$

Here n, n_0, and $\bar{n}$ are the number of excitons, the initial number of excitons, and the number of excitons corresponding to the most probable configuration at equilibrium, respectively. M is the average matrix element of residual interaction and g is the density of single particle states. E is the excitation energy of the state from which the emission takes place, U — the excitation energy after nucleon emission, ε — the energy of the emitted nucleon, σ_a and σ_b the optical model cross sections for absorption of the projectile a and the emitted particle b, respectively, and m, s — the mass and spin of b.

The calculations were performed with $n_0 = 3$, which corresponds to the initial configuration of 2p1h. As the magnitude of the average matrix element M for the two-body interaction creating a particle-hole pair ($\Delta n = +2$) is not well known, the cross sections for the preequilibrium processes were normalized to the difference between measured values and the compound nucleus cross sections. This procedure allows us to evaluate M. The values of M we have obtained are in accordance with the results of Bragga-Marcazzan et al. [14].

The (n, 2n) reaction cross sections are generally satisfactorily reproduced by the compound nucleus model, without any use of adjustable parameters. This is shown in Figs 1 and 2. In the case of the ^{82}Se (n, 2n)^{81}Se reaction, the measured values appear to be considerably higher than the calculated ones. This seems to be connected with the inaccuracies of the decay characteristics adopted in evaluation of the cross section for the discussed reaction. The main uncertainty is due to the internal convertion coefficient for the 103 keV isomeric transition in ^{81}Se. This value was measured by Drabkin et al. [28], who obtained 8.6 ± 2.4.

For the (n, n') and (n, p) reactions the experimental excitation curves do not fit the compound nucleus theory predictions. Simpler reaction mechanisms seem to contribute considerably when the energy and the target mass number increase, and dominate for $A \approx 100$ at neutron energies higher than 14 MeV. Similar conclusions were drawn previously from the analysis of energy and angular distributions of the reaction products [14, 29]. The presence of preequilibrium contribution requires a proper reduction of the compound nucleus cross sections. However, this was not done in the present work because of lack of accurate knowledge about the total preequilibrium component, summed over all the reaction channels of importance.

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