CROSS SECTIONS FOR THE FAST NEUTRON INDUCED REACTIONS ON RUBIDIUM ISOTOPES

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(Received May 20, 1975)

The cross sections for the (n, 2n), (n, p) and (n, α) reactions on the target nuclei ^{85}Rb and ^{87}Rb were measured by the activation technique in the neutron energy range from 13 MeV to 18 MeV. The experimental excitation curves are interpreted in terms of the compound nucleus and the precompound emission models.

1. Introduction

We report in this paper the results of measurements of excitation curves for some neutron induced reactions on ^{85}Rb and ^{87}Rb. Although a number of investigations (e. g. Refs [1–4]) were carried out concerning the ^{85}Rb(n, 2n) ^{84g,m}Rb and ^{87}Rb(n, 2n) ^{86g,m}Rb reactions, the discrepancies existing between the results obtained by various investigators make it still impossible to consider the cross sections of these reactions to be accurate. It seemed that an independent careful measurement would allow a more reliable evaluation of the existing data.

We have measured both the total cross sections and the cross sections for a population of the isomeric states in the residual nuclei of the (n, 2n) reactions. The cross sections for the ^{85}Rb(n, 2n) ^{84}Rb reaction measured by us confirm the results obtained by Bormann et al. [2] and Wagener [3], and differ considerably from those measured by Prestwood and Bayhurst [1]. In the case of the ^{85}Rb(n, 2n)^{84m}Rb reaction our results agree well with those obtained by Wagener [3], which are almost twice as high as the cross sections measured by Bormann et al. [2]. The excitation curve for the ^{87}Rb(n, 2n) ^{86}Rb reaction measured by Prestwood and Bayhurst is well reproduced in our experiment. The excitation curve for the ^{87}Rb(n, 2n) ^{87m}Rb reaction was not measured previously and we can compare our results only with the single measurements performed at neutron energies near 14 MeV by Husein et al. [5], whose result agrees well with ours, and by Minetti et al. [6], who gives a cross section value twice as high.

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The excitation curves for the $^{85}Rb(n, p)\,^{85m}Kr$ and $^{85}Rb(n, \alpha)\,^{82}Br$ reactions were measured by Bormann et al. [4]. Besides, a few single measurements at neutron energies close to 14 MeV were performed [5–8]. The excitation curve for the first reaction we have measured follows precisely the results of Bormann et al., whereas our cross sections for the (n, α) reaction are lower than those obtained by these authors.

The purpose of this paper is to present a detailed analysis of the excitation curves in terms of the statistical model for nuclear reactions in order to indicate to what extent can this model account quantitatively for the observed reaction yields. The deviations between the experiment and the theory existing for the (n, p) reaction are assumed to be due to the Coulomb barrier which suppresses the proton emission from a compound nucleus. The observed yield for this reaction seems to be connected mainly with a pre-equilibrium emission.

2. *Experimental procedure*

Samples of natural high purity RbCl were irradiated with neutrons obtained from the $^{2}H(d, n)\,^{3}He$ and $^{3}H(d, n)\,^{4}He$ reactions. Tritium or deuterium absorbed in a Zr foil were used as targets. The deuterons were accelerated in the 3 MeV Van de Graaff accelerator. The neutron energy was selected by a suitable choice of the emission angle. The changes in the neutron flux during irradiation were controlled by counting the proton recoils from a polyethylene foil in a CsI(Tl) scintillation crystal.

The γ-activities of the irradiated samples were measured using a 7.6×7.6 cm NaI(Tl) crystal and a 30 cm^3 Ge(Li) spectrometers. The photopeak efficiences of the scintillation crystal were taken from the tables of Crouthamel [9], and the relative efficiency of the Ge(Li) detector was determined by the use of radioactive sources ^{133}Ba, ^{169}Yb and ^{226}Ra [10, 11].

In the case of the $^{85}Rb(n, 2n)\,^{84g,m}Rb$ reactions the 20.0 min activity of the ^{84m}Rb and the 33 d activity of the ^{84g}Rb were determined by measuring the 464 keV and 880 keV γ-rays, respectively.

In the case of the $^{87}Rb(n, 2n)\,^{86g,m}Rb$ reactions the 1.02 min and the 17.9 d activities of the ^{86}Rb ground and metastable states were followed by measuring the 556 keV and 1078 keV γ-rays, respectively.

TABLE I

Decay data used in the cross section determination

Reaction	Measured γ-ray keV	Branching ratio	Internal conv. coeff.
$^{85}Rb(n, 2n)^{84}Rb$	880	0.74	—
$^{85}Rb(n, 2n)^{84m}Rb$	464	0.32	0.1
$^{85}Rb(n, p)^{85m}Kr$	305	0.23	0.04
$^{85}Rb(n, \alpha)^{82}Br$	550	0.72	0.0007
$^{87}Rb(n, 2n)^{86}Rb$	1078	0.088	—
$^{87}Rb(n, 2n)^{86m}Rb$	556	1.0	—

TABLE II

Experimental cross sections*

Neutron energy MeV	4.1 ± 0.7	4.3 ± 0.6	13.0 ± 0.2	13.3 ± 0.1	13.8 ± 0.1	14.5 ± 0.1	15.1 ± 0.2	15.4 ± 0.2	16.0 ± 0.2	16.6 ± 0.1	17.3 ± 0.1	17.8 ± 0.1
Reaction												
$^{85}Rb(n, 2n)^{84}Rb$			839 ± 51	844 ± 48	1107 ± 62	1205 ± 69	1178 ± 63	1008 ± 57	1253 ± 75	1318 ± 77		
$^{85}Rb(n, 2n)^{84m}Rb$			370 ± 21	405 ± 23	468 ± 25	491 ± 27	530 ± 23	525 ± 28	603 ± 33	600 ± 33	640 ± 36	671 ± 38
$^{85}Rb(n\ p)^{85m}Kr$	1.2 ± 0.4	0.8 ± 0.3	3.8 ± 0.8	4.0 ± 0.7	4.1 ± 0.9	3.7 ± 0.8	4.8 ± 1.0	4.8 ± 0.8	4.1 ± 0.8	3.1 ± 0.6		
$^{85}Rb(n, \alpha)^{82}Br$			4.6 ± 0.4	3.9 ± 0.3	5.1 ± 0.5	5.3 ± 0.5	5.5 ± 0.5	4.3 ± 0.4	6.6 ± 0.5	5.8 ± 0.3		
$^{87}Rb(n, 2n)^{86}Rb$			1240 ± 115	1090 ± 107	1127 ± 112	1307 ± 140	1126 ± 120	1176 ± 120	1209 ± 98	1027 ± 95		
$^{87}Rb(n\ 2n)^{86m}Rb$			295 ± 41	501 ± 51	491 ± 46	518 ± 48	601 ± 36	630 ± 38	522 ± 68	567 ± 67	580 ± 55	543 ± 54

* the units are milibarns.

In order to obtain the cross sections of the ^{85}Rb(n, p) ^{85m}Kr and ^{85}Rb(n, α) ^{82}Br reactions we have measured the 4.4 h and the 35.4 h activities of ^{85m}Kr and ^{82}Br, which decay via a 305 keV and 550 keV γ-ray emission.

The absolute cross sections for the investigated reactions were determined relative to that for the monitoring reaction ^{56}Fe(n, p) ^{56}Mn, ^{64}Zn(n, 2n)^{63}Zn (for reaction leading to the short-living ^{86}Rb metastable state) and ^{64}Zn(n, p) ^{64}Cu (for 4 MeV neutrons). The cross sections of the monitoring reactions were taken from Refs. [12, 13].

In Table I we list the energies of the measured γ-rays, as well as the branching ratios and internal convertion coefficients adopted in the present data analysis.

3. Results

The results of the cross section measurements are presented in Table II and in Figs 1–3. The errors listed contain the statistical errors as well as the systematic ones. The systematic errors contain the uncertainties: a) of the integration of the pulse height spectrum ranging for the (n, 2n) and (n, α) reaction from 2.5% to 6.8% and up to 17% for the (n, p) re-

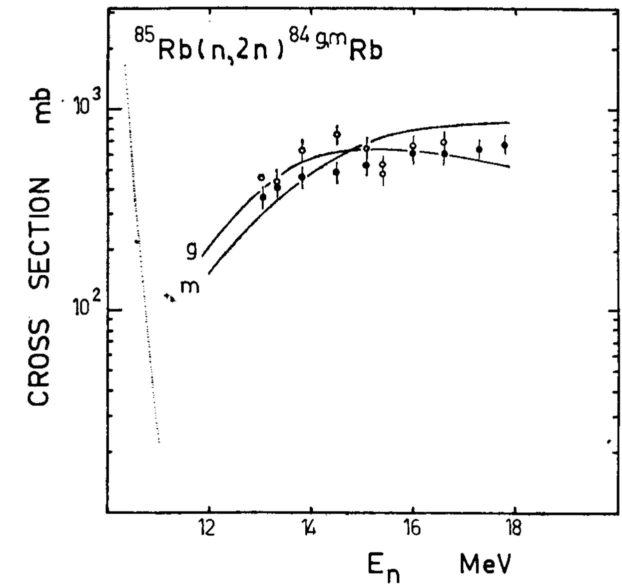

Fig. 1. Comparison of the experimental cross sections for the ^{85}Rb(n, 2n)^{84g,m}Rb reactions with the calculated ones. The solid lines are the compound nucleus cross sections for the population of the ground (g) and metastable (m) states of the residual nucleus

action, b) caused by fluctuations of the beam current during irradiation, less than 1%, c) of counter efficiency amounting to 3% for the (n, 2n) and (n, α) reactions and to 6% for the (n, p) reaction, d) of γ-ray attenuation in the sample 2% (only for the 305 keV γ-transition), e) of cross section of the monitoring reaction, 3.5% – 5.6% for the ^{56}Fe(n, p) ^{56}Mn reaction, 7%–9% for the ^{64}Zn(n, 2n) ^{63}Zn reaction and 20% for the ^{64}Zn(n,p) ^{64}Cu reaction.

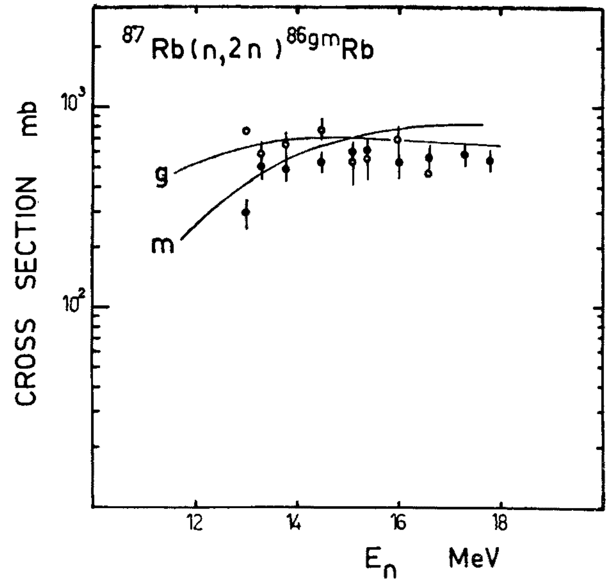

Fig. 2. Comparison of the experimental cross sections for the ^{87}Rb(n, 2n)^{86g,m}Rb reactions with the calculated ones. The solid lines are the compound nucleus cross sections for the population of the ground (g) and metastable (m) states of the residual nucleus. Open and closed circles, in Figs 1 and 2, are the experimental cross sections for population of the ground and metastable states, respectively

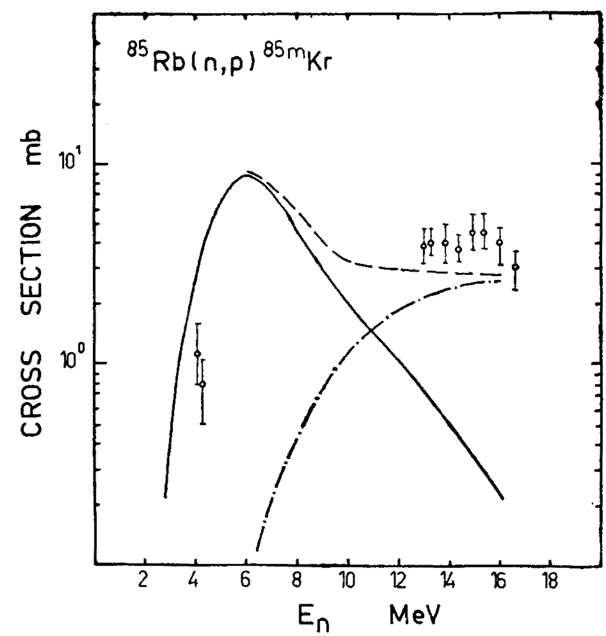

Fig. 3. Comparison of the experimental cross sections for the ^{85}Rb(n, p)^{85m}Kr reaction with the calculated ones. The solid line is the compound nucleus cross section, the dot-dashed line is the precompound cross section and the dashed line is the sum of both

The neutron energy spread was determined by calculation of the effective energy distribution of the neutrons incident on the samples with the aid of a Monte-Carlo code LOS [14]. The irradiation geometry, the dependence of the neutron energy on the emission angle, and the deuteron energy loss in the zirconium-tritium or zirconium-deuterium layers were taken into account in this calculation.

4. Theoretical description of the excitation curves

The statistical model for nuclear reactions was applied in the calculations of the excitation curves. Angular momentum effects and γ-emission from the continuum of states were included in the formalism [15]. They decay to known discrete states of the nuclei was treated independently, and for excitation energies surpassing the energy of the highest known level, the level density, calculated using the superconductor model [16], was applied to describe the excited level spectrum. No adjustable parameters were used in these calculations. The strength of the γ-transitions competing with the particle emission is assumed to be retarded in respect to the single particle Weisskopf estimates by a factor 10^{-3} for E1 transitions and by a factor 10^{-1} for the M1 transitions. The strength of the E2 transitions was supposed to be enhanced by a factor 30. This assumption defines the γ-cascade with the quadrupole component amounting to several tens of percent, as observed for transitions at low excitation energies [23, 24].

The neutron and proton transmission coefficients applied were calculated using the optical model code ALA [17] and the parameters of Moldauer [18] and Björklund and Fernbach [19]. The binding energies were taken from the tables of Garvey et al. [20]. The absolute cross sections supplied by the compound nucleus model are compared with the experimental results in Figs 1–3. The experimental cross sections for the population of the isomeric states in the (n, 2n) reaction do not rise as steep as the theory predicts; the theoretical values at neutron energies surpassing 15 MeV are about 30% higher than those obtained by the experiment. However, the overall agreement between the theory and the experiment seems to be satisfactory. Especially the intersection of the theoretical excitation curves for the population of the ground and the metastable states at about 15 MeV seems to be reproduced by the experiment.

The situation is quite different in the case of the ^{85}Rb(n, p) ^{85m}Kr reaction, Fig. 3. Here the experimental cross sections at the neutron energy ranging from 13 MeV to 16 MeV are lying well above the compound nucleus theory predictions. This seems to be connected with the contribution of the direct and intermediate reaction mechanism. The absolute yields of protons emitted prior to the formation of the compound state were calculated according to the hybrid preequilibrium model proposed by Blann [21]. We used the HYBRID code [22] to perform the calculations. The intranuclear transition rate was derived from the imaginary optical potential. We have used the most transparent, Gaussian, form of the optical potential, with the parameters of Björklund and Fernbach [19]. This denotes a long mean free path of nucleons in nuclear matter and a high preequilibrium emission yield. Since the preequilibrium models do not take into account the angular momenta of the states involved, the cross sections for the population of different final states with definite spin values cannot be separated. In order to obtain the preequilibrium cross section for the population of the metastable state of the residual nucleus, the simple $(2I_m+1)/(2I_g+1)$ rule was applied for division of the total yield between the metastable and ground state. The results of the theoretical calculations for the ^{85}Rb(n, p) ^{85m}Kr reaction are compared with the experiment in Fig. 3. The multitude of uncertainties involved in the preequilibrium calculations make the preequilibrium yields uncertain at least within a factor of two. The compound nucleus cross section of the (n, p) reaction, which make only about 0.5% of the total absorption cross section, is not better defined. Bearing this in mind the reproducibility of the experimental results seems to be satisfactory.

The authors wish to thank the Van de Graaff accelerator crew for helpful cooperation during the experiment. We are also grateful to Professor M. Blann, who supplied us with the HYBRID programme for preequilibrium cross section calculation.

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