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# Activation cross section and isomeric cross-section ratio for the $^{93}$Nb$(n,\alpha)^{90}$Y$^{m,g}$ process

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Cross sections were measured for the $^{93}$Nb$(n,\alpha)^{90}$Y$^{m}$, $^{93}$Nb$(n,\alpha^{90}$Y$^{m+g}$, and $^{93}$Nb$(n,2n)^{92}$Nb$^{m}$ reactions from threshold up to 10.6 MeV. Use was made of the activation technique in combination with high-resolution $\gamma$-ray spectroscopy, except for the product $^{90}$Y$^{g}$ where radiochemical separation and $\beta^-$ ray counting were applied. The quasi-monoenergetic neutrons were produced via the $^2$H$(d,n)^3$He reaction using a deuterium gas target at a compact cyclotron. Statistical model calculations taking into account precompound effects (reported in the literature) agree reasonably well with the experimental excitation functions for the formation of both $^{90}$Y$^{m}$ and $^{90}$Y$^{m+g}$. The isomeric cross-section ratio for the $^{93}$Nb$(n,\alpha)^{90}$Y$^{m,g}$ reactions increases with energy. The model calculation gives somewhat lower values for the ratio.

## I. INTRODUCTION

Studies of excitation functions of neutron threshold reactions on medium mass nuclei are of considerable interest for testing nuclear models. Furthermore, the data for potential first wall constituents of a fusion reactor are of practical importance, especially for estimating nuclear heating, nuclear transmutation, and radiation damage effects. Most of the measurements to date deal with 14 MeV neutrons; at other energies, especially in the range of 4–10 MeV, where thresholds of many of the reactions lie, the available information is rather scanty. This was particularly true for $(n,\alpha)$ reaction on niobium. Several activation measurements existed in the vicinity of 14 MeV (cf. Refs. 1–7); however, the available data base in the 15–20 MeV range was weak (cf. Refs. 8 and 9) and that between threshold and 10 MeV scarce (Refs. 8 and 9). Recently we described some measurements in the energy range of 12.5–19.6 MeV (Ref. 10); now we report on a study in the region of 4.1–10.6 MeV.

In addition to reaction cross sections, isomer ratios are of fundamental interest for studying the spin dependence of the formation of isomeric states. The available information, especially as a function of incident neutron energy, is often unsatisfactory. We also report on the isomeric cross-section ratio of the $^{93}$Nb$(n,\alpha)^{90}$Y$^{m,g}$ process up to 20 MeV.

## II. EXPERIMENTAL

Cross sections were measured by activation and identification of the radioactive product. About 5 g Nb powder ($>99.5\%$) was packed in a polyethylene tube of 1.1 cm diameter and 1.2 cm length, Ni and Fe monitor foils were placed in front as well as at the back of the sample, and irradiation done with quasi-monoenergetic neutrons in the energy range of 4.1–10.6 MeV. The neutrons were produced via the $^2$H$(d,n)^3$He reaction using a deuterium gas target at our variable energy compact cyclotron (cf. Ref. 11). The samples were generally held at about 0.6 cm from the back of the beam stop of the deuterium gas target. The primary deuteron energy was varied between 3.0 and 8.0 MeV, and the mean neutron energy effective at each sample was calculated as described earlier (cf. Refs. 11 and 12). Irradiations were performed for 2.5–3 h in each case.

The mean neutron flux density effective for each sample was determined using the monitor reactions $^{58}$Ni$(n,p)^{58}$Co and $^{56}$Fe$(n,p)^{56}$Mn. The cross sections of both those reactions were taken from the ENDF/B-V file (Ref. 13). The mean neutron flux densities ranged between $9.5\times10^6$ and $3.70\times10^7$ cm$^{-2}$ s$^{-1}$.

The radioactivity of the reaction products $^{90}$Y$^{m}$ ($T_{1/2}=3.19$ h; $E_\gamma=480$ keV; $I_\gamma=91.4\%$) and $^{92}$Y$^{m}$ ($T_{1/2}=10.15$ d; $E_\gamma=934$ keV; $I_\gamma=99.2\%$) was determined using a 35 cm$^3$ Ge(Li) detector coupled to a multichannel analyzer. The count rates were corrected for self-absorption, pileup, coincidence loss, geometry, efficiency of the detector, and $\gamma$-ray abundance. The uncertainties involved in the various corrections have been described earlier.[10]

The $^{93}$Nb$(n,\alpha)^{90}$Y$^{g}$ reaction product ($T_{1/2}=64.1$ h) is a pure $\beta^-$ emitter ($E_\beta=2.3$ MeV; $I_\beta\geq99\%$). It was separated radiochemically (for details cf. Ref. 14). The overall chemical yield ranged between 77 and 94 % and was determined via neutron activation analysis. The separated $Y_2O_3$($^{90}$Y) sample was subjected to $\beta^-$ ray counting. The measurement was started about 30 h after the end of irradiation in order to allow complete decay of $^{90}$Y$^{m}$ to $^{90}$Y$^{g}$. The count rates were corrected for chemical yield, absorption in the counter window, finite-size geometry, and efficiency of the detector. The errors involved in all those corrections were somewhat higher than in $\gamma$-ray counting.

From the decay rates of the activation products the contributions due to background neutrons, which were produced via the interaction of deuterons with structural materials of the gas target as well as via the breakup of deuterons on $D_2$ gas, were subtracted. For the former contribution our own gas in/out results were used (cf. Ref. 11), whereas for the breakup contribution literature data (cf. Refs. 15 and 16) were applied. From the thus

 

TABLE I. Activation cross sections for some fast neutron induced reactions on niobium.

| Mean neutron energy effective at Nb sample[a] (MeV) | Cross section[b] (mb) | | | |
|---|---|---|---|---|
| | $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^m$ | $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^{m+g}$ | $^{93}\mathrm{Nb}(n,2n)^{92}\mathrm{Nb}^m$ | $^{93}\mathrm{Nb}(n,n'\alpha)^{89}\mathrm{Y}^m$ |
| 4.15±0.15 | 0.04±0.004 | 0.10±0.01 | | |
| 4.98±0.16 | 0.11±0.012 | 0.34±0.03 | | |
| 5.51±0.16 | 0.17±0.015 | 0.37±0.03 | | |
| 6.09±0.16 | 0.35±0.03 | 0.64±0.06 | | |
| 6.62±0.17 | 0.49±0.05 | 0.87±0.07 | | |
| 7.15±0.17 | 0.65±0.05 | 1.29±0.11 | | |
| 7.65±0.18 | 0.79±0.06 | 1.33±0.11 | | |
| 8.16±0.19 | 1.01±0.08 | 1.68±0.13 | | |
| 8.65±0.20 | 1.06±0.08 | 1.70±0.13 | | |
| 9.09±0.22 | 1.41±0.11 | 1.90±0.15 | 1.2±0.1 | |
| 9.67±0.23 | 1.87±0.16 | 2.88±0.25 | 17.0±1.5 | |
| 10.21±0.23 | 1.96±0.19 | 2.83±0.28 | 86.5±8.7 | <0.1 |
| 10.61±0.24 | 2.63±0.31 | 3.89±0.45 | 163.0±19.0 | <0.1 |

[a]The deviations do not give errors; they show energy spreads due to angle of emission and deuteron energy loss in the gas target.

[b]The errors describe the overall errors which were obtained by combining the statistical and systematic errors in quadrature. For details see text.

corrected decay rates the cross sections were calculated using the known activation equation. The major sources of errors and their estimated magnitudes were similar to those described earlier (cf. Ref. 17).

## III. RESULTS AND DISCUSSION

Measurements were done at 13 neutron energies between 4.1 and 10.6 MeV and the cross-section data are presented in Table I. The total error amounts to between 8 and 12 %. Over the reported energy range the cross sections for the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^m$ reaction have been measured for the first time. For the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^{m+g}$ process a few data points existed in the literature (Refs. 8 and 9). Our work constitutes a detailed study in this energy region. In the case of the $^{93}\mathrm{Nb}(n,2n)^{92}\mathrm{Nb}^m$ reaction detailed information was available in the 12–20 MeV region (for a recent review cf. Ref. 10). However, only a few preliminary data points (Ref. 8), modified for detector efficiency (Ref. 18), existed between the reaction threshold and 10.6 MeV. Our measurements provide some additional useful information near the threshold of this reaction. The cross section of the $^{93}\mathrm{Nb}(n,n\alpha)^{89}\mathrm{Y}^m$ ($T_{1/2}=16$ s) process has been reported so far only at 14–15 MeV (cf. Ref. 19). In the present work we could not positively identify the reaction product, and only an upper limit of the cross section is given.

The excitation functions of the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^m$ and $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^{m+g}$ reactions up to 20 MeV, covering both the present measurements and the literature data[1-10] are shown in Figs. 1 and 2, respectively. For energy points very close to each other, e.g., in our previous work,[10] the data were averaged. The transition from the present *dd*-neutron data ($E_n \leq 10.6$ MeV) to the *dt*-neutron data (obtained using either a 14 MeV neutron generator or a Van de Graaff machine) is smooth and the whole excitation curve for each reaction appears to be consistent.

Detailed statistical model calculations taking into account precompound effects have been performed at Vienna using the code STAPRE for fast neutron induced reactions on $^{93}$Nb (cf. Ref. 20). The preequilibrium emission was considered for first-chance processes in the frame of the exciton model. For the $\alpha$-preformation parameter a value of 0.18 was taken. The calculated results are shown in Figs. 1 and 2. For the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^m$ reaction the agreement between experimental data and calculation is good (within 15%). In the case of the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^{m+g}$ process as well the calculation and experimental data

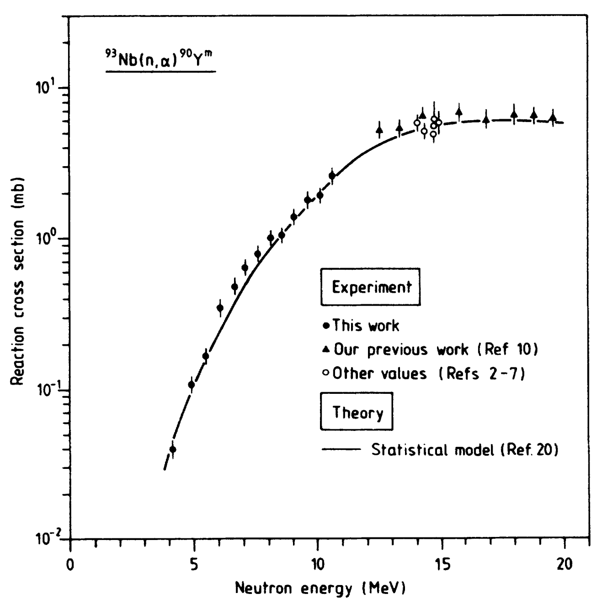


FIG. 1. Excitation function of the $^{93}\mathrm{Nb}(n,\alpha)^{90}\mathrm{Y}^m$ ($T_{1/2}=3.19$ h) reaction.

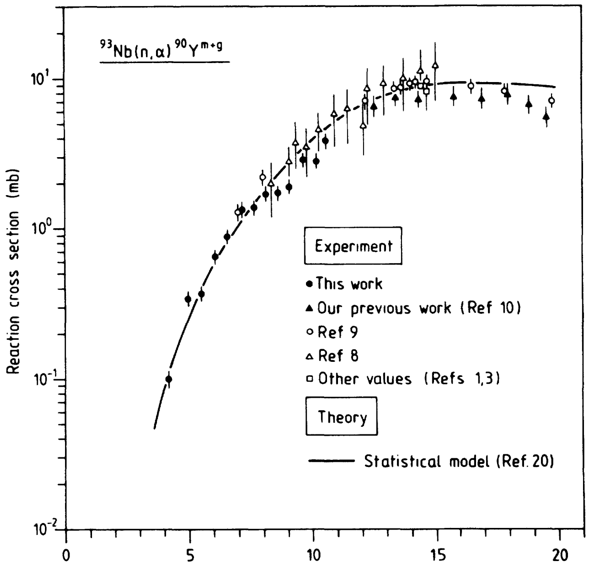


FIG. 2. Excitation function of the $^{93}$Nb$(n,\alpha)^{90}$Y$^{g}$ ($T_{1/2}=64.1$ h) reaction. The cross-section values give a sum of $\sigma_m$ and $\sigma_g$.

agree up to 15 MeV. At higher energies, however, the calculated values are about 30% higher. In general, it is concluded that $\alpha$ emission from the excited nucleus $^{94}$Nb* is described well up to a neutron energy of 20 MeV by a combination of compound and precompound processes.

The experimental isomeric cross-section ratio $(\sigma m/\sigma m+\sigma g)$ for the isomeric pair $^{90}$Y$^{m,g}$ determined from our own measurements (this work and Ref. 10) is shown in Fig. 3 as a function of incident neutron energy. The ratio increases with energy, reaching a maximum value of $\sim 0.9$ at $E_n \geq 17$ MeV. This behavior may be understood in terms of the spins of the two states concerned. With the increasing energy of the incident neutron the probability of compound nucleus formation in higher angular momentum states increases, the subsequent deexcitation of which favors the product nuclear

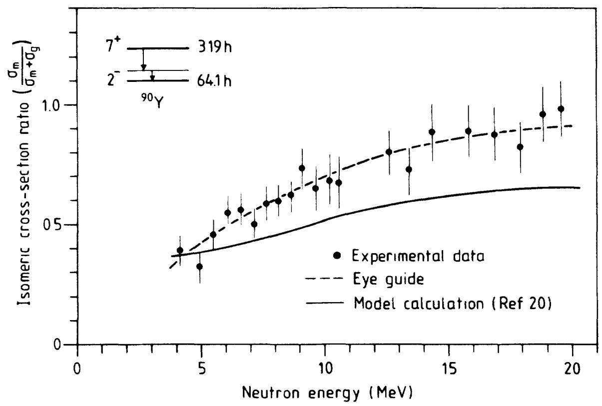


FIG. 3. Isomeric cross-section ratio $(\sigma m/\sigma m+\sigma g)$ for the isomeric pair $^{90}$Y$^{m,g}$ [formed via $(n,\alpha)$ reaction on $^{93}$Nb] plotted as a function of incident neutron energy.

state with the higher spin. The metastable state $^{90}$Y$^{m}$ has a spin $7^+$ compared to $2^-$ for the ground-state $^{90}$Y$^{g}$. It appears that at $E_n \geq 17$ MeV the $\alpha$ transition from $^{94}$Nb* populates mainly the metastable state.

The isomeric cross-section ratio obtained from the model calculation[20] is also shown in Fig. 3. The calculated values are somewhat lower than the experimental values: about 25% between 8 and 10 MeV and about 30% between 10 and 20 MeV. A consideration of the absolute cross-section data for the metastable and ground states suggests that the low value of the ratio is not due to an underestimate of the contribution of the high-spin isomer. For $E_n$ above about 8 MeV, the cross section to the low-spin ground state appears to be overestimated.

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