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CROSS-SECTIONS FOR THE ^{89}Y(n, n') ^{89m}Y AND ^{89}Y$(n, 2n)$ ^{88}Y REACTIONS

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Excitation curves for the ^{89}Y(n, n') ^{89m}Y reaction were measured in the neutron energy range 3–18 MeV and for the ^{89}Y$(n, 2n)$ ^{88}Y reaction in the energy range 13–18 MeV. The results obtained were interpreted in terms of the statistical nuclear reaction model. The problem of the competition between electromagnetic radiation emission and neutron emission from the highly excited compound nucleus states is discussed.

1. *Introduction*

Attempts at describing the $(n, 2n)$ reaction for medium weight nuclei statistically have shown that there is a systematic discrepancy between the theoretical and experimental excitation curves [1–3]. The theoretical cross-sections exceed the measured values in the whole range of incident neutron energies investigated, *i.e.* from the reaction threshold up to 8–9 MeV above the threshold. It is suggested that this effect may have arised because the decay of the compound nucleus through emission of electromagnetic radiation was not accounted for in the theoretical model [1–5].

It seems that in the case of de-excitation of high spin states gamma cascade emission can successfully compete with neutron evaporation. After the evaporation of the first neutron from the compound nucleus such states are populated with a relatively high probability. Because of rather high value of the binding energy the evaporation of the second neutron leads to low-exited states of the final nucleus. The spin distribution of such states is shifted

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towards low spins, what means that a neutron with low average energy would have to carry considerable angular momentum away from the nucleus. The probability of neutron emission decreases rapidly with increasing transferred angular momentum and, hence, the role of gamma emission may increase. As a result it should be expected that the cross-section for the (n, n') reaction will increase. It seemed right to check this supposition and compare the cross-sections for the (n, n') and $(n, 2n)$ reactions. In the present work the excitation curves for the $^{89}Y(n, n')\,^{89}Y$ reaction in the neutron ranges 2.7–4.0 MeV and 13.0–18.1 MeV and for the $^{89}Y(n, 2n)\,^{88}Y$ in the neutron energy range 13.3–17.6 MeV were measured.

2. *Experimental procedure*

Samples of yttrium dioxide were irradiated with neutrons from the $^{3}H(d, n)^{4}He$ and $^{2}H(d, n)^{3}He$ reactions. Tritium and deuterium targets were bombarded with deuterons accelerated in a 3 MeV Van de Graaff accelerator.

Changes in the neutron flux were measured during irradiation by counting the protons recoiled from polyethylene foil in a CsI scintillation counter for neutron energies above 13 MeV, and by means of a long counter for neutron energies below 4 MeV.

The measurement of the activities associated with the decay of the populated states consisted in the detection of two summed single gamma spectra by means of $2'' \times 2''$ NaI(Tl) spectrometers. Since the half-life of the metastable state in ^{89}Y is 16.1 sec, a programmed scaler gated by a single-channel analyser was used for measuring the counting rates under the photopeak of the 910 keV line due to the decay of this short lived state to the ground state. The shortest repetition time of the scaler was 2 sec.

The irradiated sample was transported in 0.8 sec to the spectrometer by means of a pneumatic tube conveyor. The neutron flux monitoring, the transfer of the sample, the counting time and the repetition time of the measurements were all accomplished automatically. The irradiation was repeated many times to collect sufficient statistics. The activity of ^{88}Y populated in the $^{89}Y(n, 2n)$ reaction was determined by measuring the annihilation gamma-rays of the 108 $d-\beta^{+}$ component.

The absolute neutron flux was determined by measuring the gamma-activities excited in (n, p) reactions with known cross-sections. The 842 keV, 928 keV and 847 keV gamma-rays in ^{27}A, ^{51}V and ^{56}Fe, respectively were monitored.

3. *Results*

The cross sections of the $^{89}Y(n, n')^{89}Y$ reaction in the energy range from 2.7 MeV to 4.0 MeV were determined relative to the cross-sections of the $^{27}Al(n, p)^{27}Mg$ reaction reported by Calvi *et al.* and Henkel [6].

In the neutron energy range from 13.0 MeV to 18.1 MeV the cross-sections for the $^{89}Y(n, n')\,^{89m}Y$ reaction refer to the cross-sections of the $^{51}V(n, p)^{51}Ti$ reaction, which heve been determined by Bormann *et al.* [3] with an accuracy of 8.5%.

The cross-sections measured are presented in Fig. 1 and Table I. Our results in the low energy range are in good agreement with the results obtained by Shafroth *et al.* [7], who

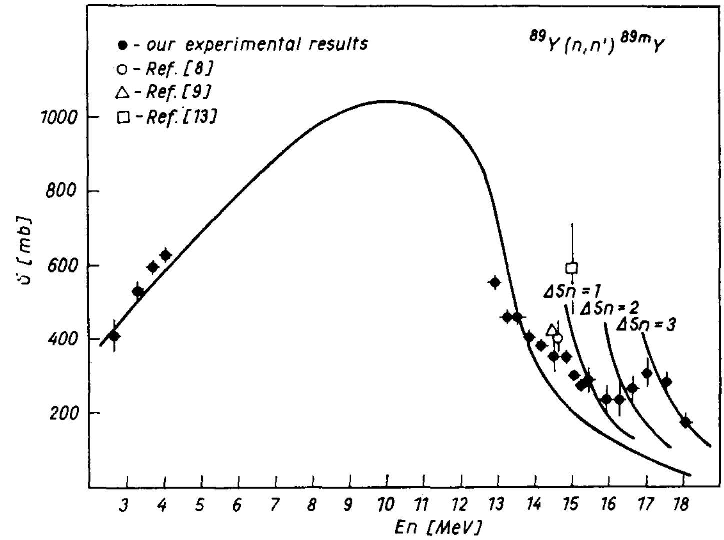

Fig. 1. Excitation curve for the ^{89}Y(n, n') ^{89}Y reaction. The solid line presents theoretical calculations

TABLE I

Cross-section for the ^{89}Y(n, n') ^{89m}Y reaction

E_n (MeV)	E_n (MeV)	σ (mb)
2.69	±0.08	405.8±43.6
3.31	±0.10	531.6±23.2
3.83	±0.10	598.5±11.3
4.01	±0.11	627.8±11.9
12.99	±0.14	552.8±13.2
13.29	±0.08	458.9±10.8
13.55	±0.08	458.8±10.8
13.87	±0.11	402.3±8.4
14.19	±0.07	381.4±13.1
14.54	±0.16	352.2±43.0
14.83	±0.15	350.1±8.4
15.08	±0.18	298.9±13.1
15.27	±0.18	271.7±6.1
15.42	±0.18	283.2±25.1
15.94	±0.18	235.1±27.4
16.31	±0.19	237.2±47.8
16.65	±0.23	263.3±24.3
17.08	±0.09	309.3±29.8
17.58	±0.09	281.1±17.5
18.07	±0.13	173.6±12.0

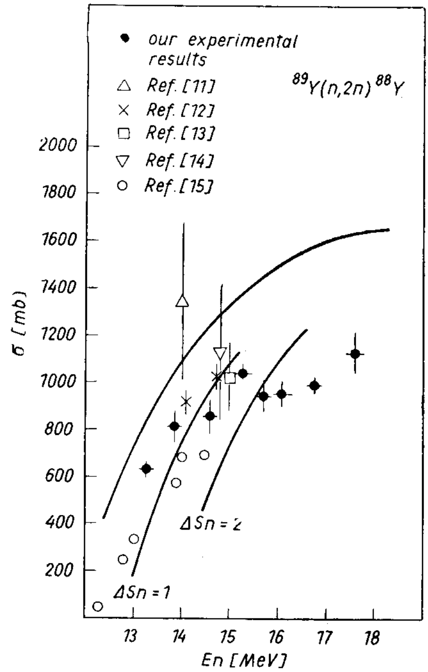

Fig. 2. Excitation curve for the ^{89}Y$(n, 2n)$ reactions. The solid lines represent theoretical calculations. $\Delta S_n = 1{,}2$ denotes the increased values of the neutron binding energy in ^{89}Y

TABLE II

Cross-sections for the ^{89}Y$(n, 2n)$ ^{88}Y reaction

E_n (MeV)	E_n (MeV)	σ (mb)
13.29	± 0.08	621.9 ± 7.1
13.87	± 0.11	811.6 ± 43.1
14.61	± 0.11	856.3 ± 58.7
15.27	± 0.15	1040.4 ± 18.8
15.71	± 0.14	947.9 ± 46.0
16.08	± 0.18	954.3 ± 40.9
16.74	± 0.15	997.4 ± 35.1
17.58	± 0.09	1128.0 ± 72.0

measured the cross-sections for the population of separate levels in the inelastic neutron scattering by the time of flight method. In the high energy range our results agree with those of [8] and [9].

The cross-sections for the ^{89}Y$(n, 2n)^{88}$Y reaction were measured by us with reference to the well known cross-sections of the ^{56}Fe(n, p) ^{56}Mn reaction [10], which were estimated with an accuracy of about 6%. The results of our measurements for this case are shown in

Fig. 2 and in Table II. They are in agreement with the cross-sections measured previously up to a neutron energy of 15 MeV [11–15].

The errors shown in Tables I and II and Figs 1 and 2 refer to statistical errors only.

4. Theoretical calculations

The theoretical calculations of the cross-sections were performed according to the developed statistical formalism described in detail earlier [1], [2]. The theoretical spectrum of the inelastically scattered neutrons was divided into two parts. The high energy tail of the spectrum corresponding to excitation energies (left after the first neutron emission) lower than the threshold for the $(n, 2n)$ reaction was assigned to the (n, n') reaction. The rest of the spectrum contributed to the cross-section of the $(n, 2n)$ reaction. Since the concept of level density is meaningless for excitation energies involved in the $^{89}Y(n, n')\,^{89m}Y$ reaction for the low neutron energy range as well as in the $^{89}Y(n, 2n)^{88}Y$ reaction for neutron energies just above the threshold, the individual levels, if their spins and parities are known were accounted for in the calculations. The probability of neutron emission, modified to account for the population of the individual levels, is given in [2].

For excitation energies above the highest of the known levels we assumed a level density with no free parameters, as described in [16]. The importance of separate levels was neglected for the $^{89}Y(n, n')^{89}Y$ reaction for neutron energies higher than 13 MeV.

The competition of the proton emission was taken into account in each step of the reactions considered and alpha particle emission was assumed to be negligible.

The solid lines in Figs 1 and 2 present the results of our calculations. The rough approximation in accounting for the competetive gamma-ray emission with respect to the evaporation of the second neutron [1], [2] [3], which involves an effective increase of the binding energy (in our case that of the neutron in the ^{89}Y nucleus) by ΔS_n, is marked by $\Delta S_n = 1, 2$ and 3 MeV.

5. Comparison of theoretical and experimental results

From a comparison of the experimental and calculated values of the cross-sections for the $^{89}Y(n, 2n)^{88}Y$ reaction (Fig. 2) it is seen that over the whole range of incident neutron energies the experimental cross-sections lie well below the theoretical ones. This systematical discrepancy was observed in all the cases we investigated [1], [2]. If we accept the explantation of this effect as suggested in [3] and [5] and described briefly in Section 1, it may be expected that the measured values of the cross-sections fo rthe $^{89}Y(n, n')^{89m}Y$ reaction will exceed the calculated ones.

From Fig. 1 it is seen that this is true in the case investigated.

The rough approximation in accounting for the competition between gamma emission and neutron emission mentioned above, what is equivalent to assuming that in the energy interval ΔS_n above the $(n, 2n)$ reaction threshold the (n, n') reaction predominates because of the spin forbiddeness of neutron emission, describes the deviation of experimental results from the theoretical ones fairly well for both $^{89}Y(n, n')^{89m}Y$ and $^{89}Y(n, 2n)^{88}Y$ reactions in the investigated neutron energy range. However, the quantitative description is unsatisfactory.

As was shown in [1], [2] and [17], the isomeric ratios are well described by the theoretical model used. Taking this into account the sum rule should be valid, viz.,

$$\int [\sigma^{\text{theor}}(n, 2n) - \sigma^{\text{exp}}(n, 2n)]\, dE_n = \int \left(1 + \frac{\sigma_g}{\sigma_m}\right)^{\text{theor}} [\sigma^{\text{exp}}(n, n')^m - \sigma^{\text{theor}}(n, n')^m]\, dE_n$$

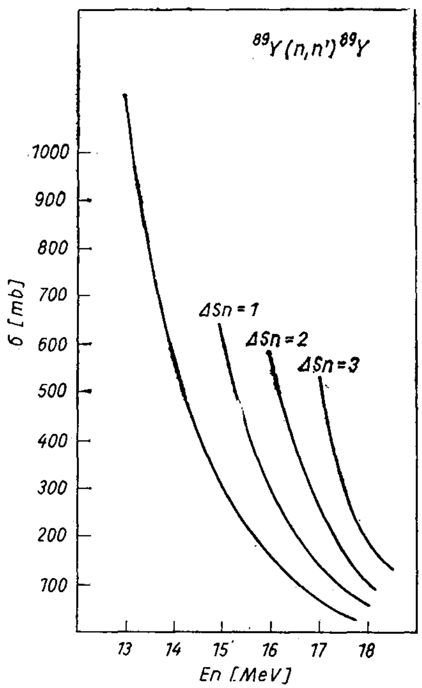

Fig. 3. Theoretical excitation curves for the ^{89}Y(n, n') ^{89}Y reaction. $\Delta S_n = 1, 2, 3$ denotes the increased values of the neutron binding energy in the ^{89}Y nucleus

Applying this rule to the results presented in Figs 1, 2 and 3 we obtain

$$(1920 \pm 250)\ \text{MeV} \cdot \text{mb} \neq (995 \pm 200)\ \text{MeV} \cdot \text{mb}$$

Provided there are no systematical errors the disagreement between the experimental and theoretical cross-sections considered may be ascribed only in part to the effect of angular momentum on the decay of compound states.

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