EXCITATION OF SHORT-LIVED ISOMERIC ACTIVITIES IN ^{77}Se, ^{122}Sb, ^{137}Ba, ^{167}Er AND ^{179}Hf USING 14.5 MeV NEUTRONS

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The cross-sections for the production of short-lived isomeric states in ^{77}Se, ^{122}Sb, ^{137}Ba, ^{167}Er and ^{179}Hf through the (n, 2n) and (n, n′) reactions using 14.5 MeV neutrons have been given. The (n, n′γ) cross-sections are reported for the first time. Estimates have been obtained for isomeric ratios and spin cut-off parameter using Huizenga and Vandenbosch method and Gilbert and Cameron level density model.

Introduction

Measurements of cross-sections for excitation of isomeric levels with short half-life using 14 MeV neutrons are very rare. It seems to be worthwhile to reinvestigate the reactions for which only one or two cross-sections measurements were performed. This work is a continuation of our earlier measurements [1–3] of cross-sections for excitation of short-living isomers in (n, 2n) reactions induced with 14.5 MeV neutrons. In addition to the (n, 2n) reaction other processes are energetically possible. For example the (n,n′) and the (n, γ) processes on the neighbouring stable isotopes, if present leads to excitation of the same isomers. To overcome this difficulty the natural and isotopically enriched targets have to be used. By comparing the activities produced in the two cases, it is possible to determine both the (n, n′ γ) and (n, 2n) coss-sections. The discrepancies between theoretically and experimentally derived cross-sections for the (n, 2n) reactions are probably also caused by the competition of the inelastic scattering of neutrons.

In our work isotopically enriched samples of ^{78}Se, ^{123}Sb, ^{137}Ba, ^{168}Er and ^{180}Hf were used (the enrichment was mostly 90% or more).

For ^{77}Se, ^{137}Ba and ^{167}Er isomers the contribution of the (n, n′ γ) reaction was determined. The most important contribution was found to be due to the (n, n′γ) reaction. The (n, γ) cross-section does not exceed 20 mb at 14 MeV neutron energy for all elements considered [4].

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Experimental methods and results

The (14.5±0.2) MeV neutrons were used for irradiations in our experiment. The neutron flux was monitored by counting the associated alpha particles from T/d, n/^{4}He reaction. The alphas were detected with the use of a solid state detector placed at 135° with respect to the direction of the deuteron beam. The sample weights were of the order of ten milligramms.

During neutron irradiations the samples placed in a plexiglass container were precisely positioned in front of the tritium target. The irradiated samples were brought to the gamma

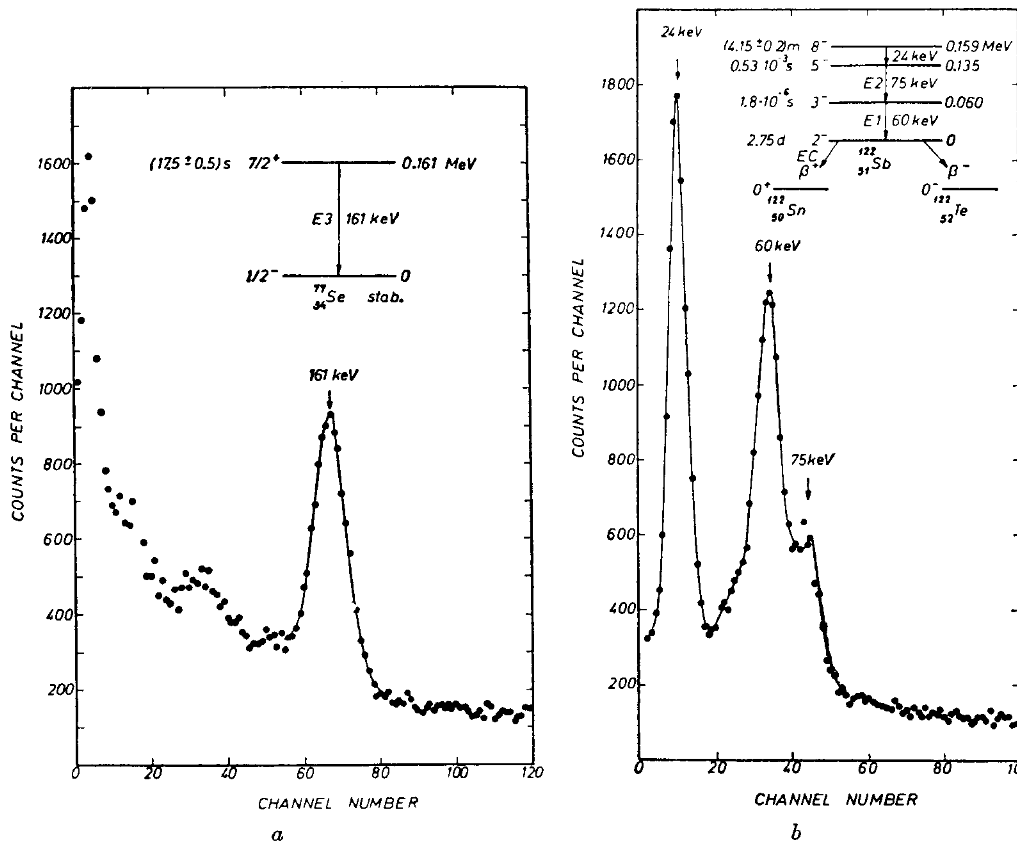

Fig. 1. The typical examples of spectre for ^{77m}Se and ^{122m}Sb

spectrometer with the use of a pneumatic transport system [5]. The gamma spectra were measured using a $1\frac{1}{2}\times 1''$ NaI(Tl) crystal and a 400 channel pulse height analyser. The times of irradiation, transport, counting and return to irradiation position were controlled to within a fraction of a second.

The cross-section formula valid in our case was given in our earlier work [3].

The solid angle of the extended thick sample with respect to the extended neutron source has been evaluated using a method similar as applied by Konijn and Tollander [6].

The efficiency T_{tot} for an extended source was calculated using the method proposed by Grosjean [7] generalized for the case of a nonuniform axially symetric neutron distribution at the sample.

The gamma rays spectra for investigated samples are shown in Fig. 1., 2 and 3.

The sample activities detected by the NaI(Tl) crystal were corrected for the background, the self-absorption of gamma rays in the sample and the dead time of the pulse height analyser. The nuclear reaction was assigned by half lives and γ-energies of the product nucleus.

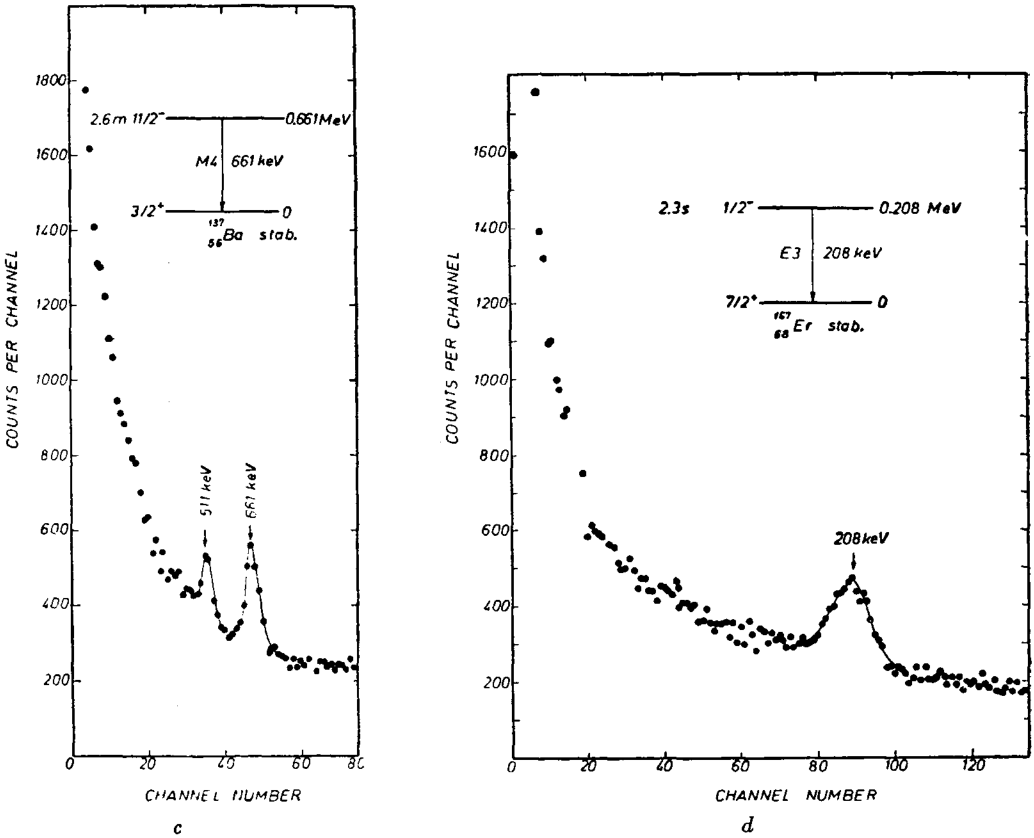

Fig. 2. The typical examples of spectra for ^{137m}Ba and ^{167m}Er

The measured cross-sections and the spectroscopic data used in the calculations of the cross-sections is summarized in Table I together with the values obtained by other authors.

Errors affixed to the cross-sections account for the errors of: the counting efficiency, peak-to-total ratios, statistics and geometry, sample weight, neutron flux and the conversion coefficients. Some of the cross-sections reported here are discussed individually for special reasons.

In the case of ^{77}Se, ^{137}Ba, ^{167}Er and ^{179}Hf the isomeric states could also be produced with 3 MeV neutrons from d—D selfformed source in zirconium layer. A new tritium target minimize this effect. The large error accompanying the cross-section for excitation of ^{122m}Sb

isomer arise from the strong overlapping of the gamma-ray photo peaks. Table I presents a good agreement between the cross-sections measured in our work and the results of other authors for the Sb, Er and Hf isotopes.

The cross-sections for the ^{180}Hf/n, 2n/^{179m}Hf reaction was measured with the use of an enriched target (96%). For ^{179}Hf(n, n'γ) ^{179m}Hf the cross-section of the (n, n'γ) was not determined because of some others reactions exsist, leading to the formation of short-lived

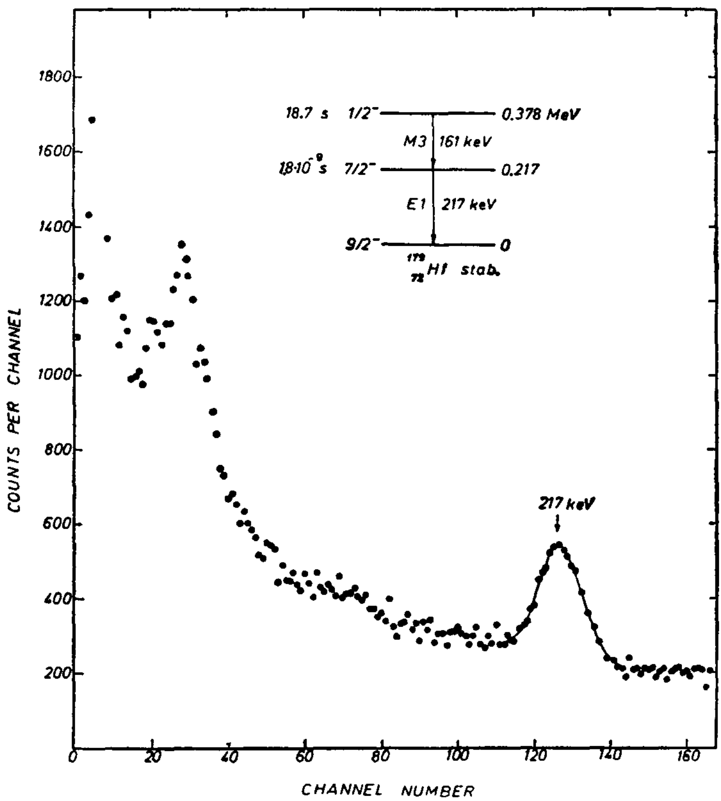

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Fig. 3. The typical example of spectrum for ^{77m}Se, ^{122m}Sb, ^{137m}Ba, ^{167m}Er and ^{179m}Hf

nuclides which emitting gamma quanta with the approximately the same energy. These anwanted activities are: 6.4 s ^{177}Yb from ^{180}Hf(n, α) ^{177m}Yb, ^{179}Hf(n, ^{3}He) ^{177m}Yb, $E_\gamma = 229$ keV; 4s ^{178m}Hf from ^{178}Hf(n, n'γ) ^{178m}Hf, ^{177}Hf(n, γ) ^{178m}Hf, $E_\gamma = 213$ keV; 19s ^{179m}Hf from ^{179}Hf(n, n'γ) ^{179m}Hf, ^{178}Hf(n, γ) ^{179m}Hf, $E_\gamma = 217$ keV; 5.5h ^{180m}Hf from ^{180}Hf(n, n'γ) ^{180m}Hf, $E_\gamma = 215$ keV.

The contribution of the long living (n, p) reaction products to the isomeric states investigated in our work was found to be negligible. Contribution due to the (n, γ) reaction also may be ignored.

TABLE I

Target, reactions and isomeric nucleus	Half life of product (sec)	Ref.	Energy of gamma transition (keV)	Ref.	Conversion coefficient	Ref.	Cross-sections measured in our work $E_n = 14.5$ MeV	Cross-sections measured in other works mb	E_n(MeV)	Ref.
^{78}Se/n, 2n) ^{77m}Se	17.5±0.5	[8]	161	[8]	0.79±0.06	[9]	703±70	738±40	14.7	[10]
^{77}Se/n, n′) ^{77m}Se							593±60			
								1013±120	14.7	[12]
^{123}Sb(n, 2n) ^{122m}Sb	249	[8]	60	[8]	0.65	[9]	731±73	686±60	14.7	[13]
								547±79	14.1	[14]
^{138}Ba(n, 2n) ^{137m}Ba	153.5±0.2	[15]	661	[8]	0.098	[9]		1250±100	14.8	[16]
^{137}Ba(n, n′) ^{137m}Ba							1048±100	1105±110	14.5	[3]
							365±36			
^{168}Er(n, 2n) ^{167m}Er	2.3	[8]	208	[8]	0.46	[9]		690±110	14.8	[17]
^{167}Er(n, n′) ^{167m}Er							403±40	190±24	14.6	[11]*e*
							343±34			
^{180}Hf(n, 2n) ^{179m}Hf	18.7	[8]	217	[8]	0.055 (tot)	[9]	690±70	570±50	14.8	[17]

Statistical model calculations

For the reactions considered in this work and in our earlier work [3] only the metastable cross-section σ_m was measured. The ground state cross-section σ_g cannot be measured with the activation method because it is either stable or very long living. Where σ_m was measured, σ_g was evaluated by subtracting the experimental σ_m value from the theoretical[1] total cross-section ($\sigma_T = \sigma_m + \sigma_g$).

TABLE II

Reaction	I_m	I_g	σ_m exp (mb)	σ_{tot} estim. from [18] (mb)	$\left(\frac{\sigma_m}{\sigma_{tot}}\right)$ exp.	$\left(\frac{\sigma_m}{\sigma_{tot}}\right)$ calc.	Spin cut-off parameter estimated from Cameron [22]	Spin cut-off parameter estimated from our exp.
$^{78}Se(n,2n)^{77}Se$	7/2	1/2	703	1030	0.70	0.82	3.6	—
$^{123}Sb(n,2n)^{122}Sb$	8	2	731	1750	0.42	0.44	4.35	—
$^{138}Ba(n,2n)^{137}Ba$	11/2	3/2	1105	1900	0.60	0.63	4.6	—
$^{140}Ce(n, 2n)^{139}Ce$	11/2	3/2	1280	1850	0.69	0.57	3.74	—
$^{142}Nd(n,2n)^{141}Nd$	11/2	3/2	1069	1720	0.62	0.66	4.83	—
$^{144}Sm(n,2n(^{143}Sm$	11/2	3/2	564	1530	0.37	0.65	5	3.8±0.3
$^{168}Er(n, 2n)^{167}Er$	1/2	7/2	403	2150	0.19	0.10	4.6	2.5±0.3
$^{180}Hf(n,2n)^{179}Hf$	1/2	9/2	680	1900	0.36	0.17	4.75	2.4±0.3

The isomeric cross-section ratios $\left(\text{defined as } \frac{\sigma_m}{\sigma_g} \text{ or } \frac{\sigma_m}{\sigma_{tot}}\right)$ for investigated nuclei were calculated with the Huizenga and Vandenbosch method [20]. This method is restricted to compound type reactions only. If we assume a compound-nucleus mechanism for the (n, 2n) reaction and the spins of the isomers considered, the isomeric ratio should yield information about the spin cut-off parameter (which characterizes the spin dependence of the assumed nuclear level-density model).

The values of penetrability factors for neutrons were taken by us from Mani and Melkanoff [21]. The composite model for nuclear level densities proposed by Gilbert and Cameron [22] was used. In their representation a constant nuclear temperature approximation applies below some defined excitation energy and the Fermi gas description applies at higher energies.

In Table II a comparison is made between the calculated and experimental isomeric cross-section ratios. The accordance is satisfactory for Se, Sb, Ba, Ce and Nd. We point out, however, that in calculations for these nuclei the spin cut-off parameter obtained simply from Gilbert and Cameron's model was used. It seems that the method of Huizenga and Vandenbosch and the Gilbert and Cameron level density model is quite useful for some nuclei.

[1] Recently Pearlstein [18] computed total cross-sections at neutron energies 13.1, 14.1 and 15.1 MeV for large number of isotopes which agree excellently with the available experimental data. More recently Gardner [19] attempted to estimate (n, 2n) cross-sections by relating them to charge -particle reaction cross-sections such as (p, 2n) and (α, 2n). Gardner's predicted absolute (n, 2n) cross-sections for 14–15 MeV neutrons agree with Pearlstein's predictions.

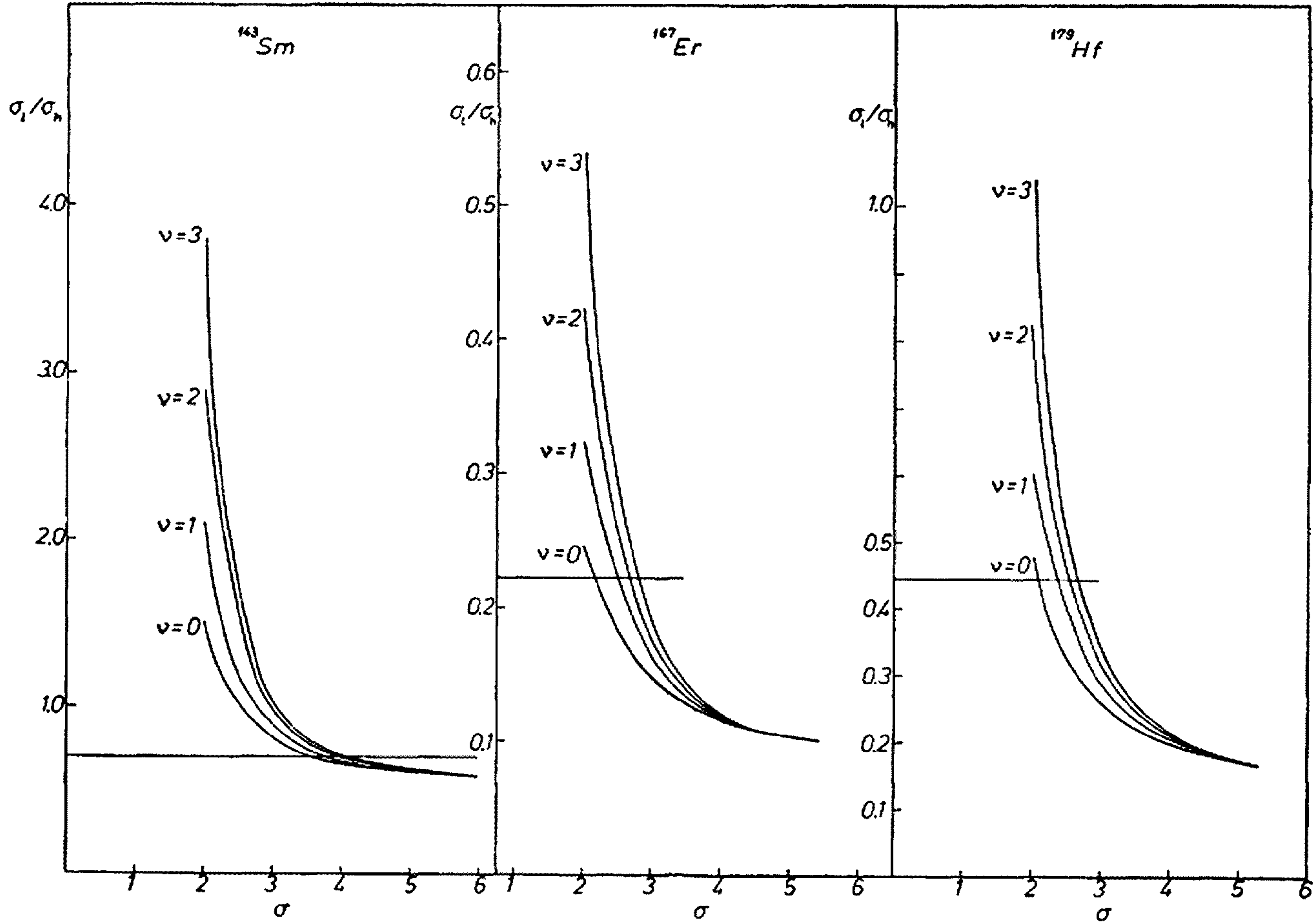

Fig. 4. Comparison of the measured isomeric cross-section ratios with the theoretical curves plotted in terms of the spin cut-off parameter σ and the multiplicity ν

The isomeric ratio for Sm (for which the experimental values of σ_m and σ_g exist [4]) Er and Hf were calculated for many values of the spin cut-off parameter and different numbers ν of the γ-rays emitted in the deexcitation cascade. Results are given in Fig. 2.

The experimental isomeric cross-section ratio was defined as the ratio of the cross-section σ_l for the population of the lower spin state to the cross-section σ_h for the population of the higher spin state. A mean values of the spin cut-off parameter can be evaluated as (3.8 ± 0.3) for ^{143}Sm (2.5 ± 0.3) for ^{167}Er and (2.4 ± 0.3) for ^{179}Hf. These values are lower than the calculated ones obtained from the formula given in [22]. Aurther study of the rare-earth region (for which scarce information can be found) might lead to further examples of this type.

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