EXCITATION OF ISOMERIC ACTIVITIES IN ^{131,133,135}Ba BY 14.8 MeV NEUTRONS

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The cross-sections for the production of isomeric states in $^{131, 133, 135}$ Ba through the $(n,2n)$ reaction using 14.8 MeV neutrons have been given. Estimates been obtained for isomeric ratios using the Huizenga and Vandenbosch method and the Gilbert and Cameron level density model.

1. *Introduction*

The existence of isomerism in all odd-A isotopes of Ba is a well established fact. It is of interest to investigate the cross-section for excitation of isomeric activities in Ba in order to obtain more information on the possible trend of the isomeric cross-section against the neutron number. The decay scheme of ^{129m}Ba is not well known. The cross--section for excitation of ^{137m}Ba was determined in our earlier paper [1].

2. *Experimental procedure*

The cross-section measurements were carried out by the activation method. Natural "specpure" barium in the form of $BaCO_3$ powder pressed into flat tables of known weight and area were irradiated by 14.8 MeV neutrons from the neutron generator. The neutron flux in the sample position was about 10^9 n/sec cm^2 and was monitored by counting alpha particles from the $T(d, n)^4He$ reaction. A solid state detector was used. During neutron irradiation the samples (surrounded by a cadmium sheet) placed in a lucite container

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were precisely positioned in front of the tritium target. The activity of the irradiated samples were measured using 8 cm^3 Ge(Li) and 1.5″ × 1″ NaI(Tl) gamma-ray detectors. The activities studied were unambiguously identified in all the cases by their half-lives and gamma-ray energies.

3. *Results*

Table I summarizes the cross-sections obtained in the present paper together with the values of half-lives, gamma-ray energies and conversion coefficients use din the calculations. The estimated error in our measurements is of the order of $\pm 10\%$ for $^{133,\,135}$Ba

TABLE I

Cross-sections for $(n, 2n)$ and $(n, n'\gamma)$ reactions with 14.8 MeV neutrons (present paper)

Target, reactions and isomeric nucleus	Half-life	E keV	Conversion coefficient	Measured cross-section (mb)
^{132}Ba $(n, 2n)$ ^{131m}Ba	14.6 min	107	0.9 ± 0.15	696 ± 120
^{134}Ba$(n, 2n)$ ^{133m}Ba	38.9 h	276	3.45 ± 0.20	827 ± 80
^{136}Ba$(n, 2n)$ ^{135m}Ba	28.7 h	268	3.82 ± 0.20	1294 ± 120
^{135}Ba$(n, n'\gamma)$ ^{135m}Ba				

and $\pm 20\%$ for ^{131}Ba. The literature values of half-lives were used in the cross-section determination as it was assumed that these were more accurate than our observed values.

A short comment about the nuclei considered is given below

^{132}Ba$(n, 2n)^{131m}$Ba.

The 14.6 min metastable state formed in the ^{132}Ba$(n, 2n)^{131m}$Ba reaction decays to the ground state trough a cascade of the 78 and 107 keV gamma-rays. The formation cross-section for the isomeric state was calculated using the intensity of the 107 keV gamma-ray which was very prominent in the spectrum. There are no published results available for the cross-section for excitation of this isomeric activity with 14–15 MeV neutrons.

^{134}Ba$(n, 2n)^{133m}$Ba and ^{136}Ba$(n, 2n)$ + ^{135}Ba$(n, n'\gamma)^{135m}$Ba.

The ^{133m}Ba and ^{135m}Ba nuclides were known to possess M4 isomers with high spin (11/2$^-$). ^{133m}Ba$(T_{1/2} = 38.9\ h)$ lies 288 keV above the ground state and decays by emission of two subsequent gamma rays to the ground state of ^{133}Ba. The energies of the gamma rays are 276 and 12 keV respectively. The^{135m} Ba spectrum includes only a 268 keV transition to the ground state of^{135} Ba. The 268 keV and 276 keV gamma rays were well resolved in the Ge(Li) spectrum (Fig. 1). The values of cross-sections for the production of ^{133m}Ba from ^{134}Ba$(n, 2n)^{133m}$ Ba reaction and ^{135m}Ba from ^{136}Ba$(n, 2n)^{135m}$ Ba and ^{135}Ba$(n,n'\gamma)$reactions wer edetermined by measuring the intensities of 276 and 268 keV gamma lines, respectively. The excitation of ^{135m}Ba is expected in inelastic scattering of 14.8 MeV neutrons on ^{135}Ba.

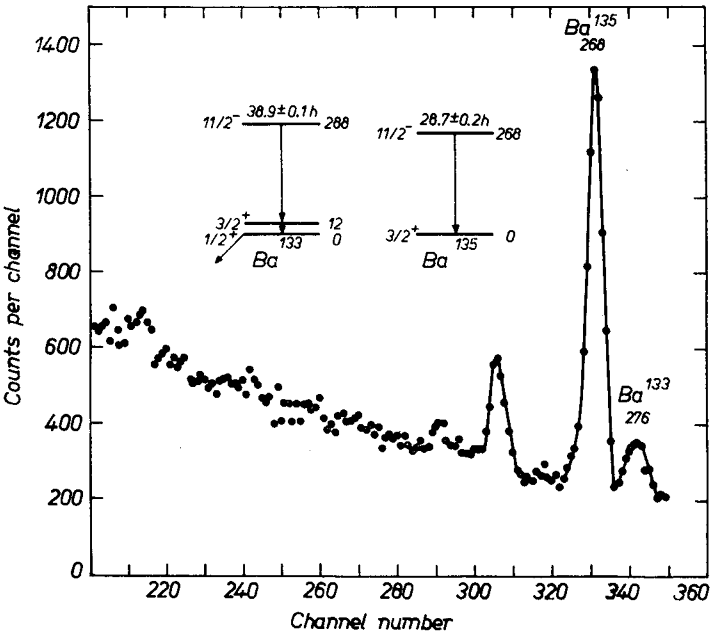

Fig. 1. Gamma-ray spectrum from the decay of ^{133m} Ba and ^{135m} Ba taken with Ge(Li) spectrometer

4. *Discussion*

In this work only the metastable state cross-sections σ_m was measured. The experimental total cross-sections ($\sigma_{tot} = \sigma_m + \sigma_g$, where σ_g is the ground state cross-section) is known only for ^{132}Ba$(n, 2n)$ ^{131}Ba$(T_{1/2} = 11\ d)$ [2] and cannot be determined by the activation method for ^{134}Ba$(n, 2n)^{133}$Ba (very long half-life equal 7.7y) and ^{136}Ba$(n, 2n)$ ^{135}Ba (stable). Recently Pearlstein [3] computed total cross-sections at neutron energies 13.1, 14.1 and 15.1 MeV for a large number of isotopes. These cross-sections are in good agreement with the experimental data available. The errors of these semiempirical predictions have been assumed to be as large as $\pm 15\%$. Using our results for σ_m and Pearlstein's predictions for σ_{tot} we can estimate the "experimental" isomeric cross-section ratios $\frac{\sigma_m}{\sigma_{tot}}$. The theoretical isomeric cross-section ratios were calculated on the basis of the statistical theory of nuclear reactions using the method described by Huizenga and Vandenbosch [4] (Table II). This method is restricted to compound type reactions only. The compound nucleus mechanism for $(n, 2n)$ reaction is well established. The values of penetrability factors for neutrons were taken from Ref. [5]. The composite model for nuclear level densities proposed by Gilbert and Cameron [6] was used in computations.

Fig. 2A shows the metastable state cross-sections measured in this work (together with the cross-sections for excitation of ^{137m}Ba in $(n, 2n)$ reaction taken from our earlier work [1])plotted as a function of neutron number for constant spin value of isomeric level. It can be seen from this figure that the measured metastable cross-sections for ^{135m}Ba

TABLE II

Isomeric cross-section ratios for $^{131, 133, 135, 137}Ba$

Reaction	I_m	I_g	σ_m exp. (mb)	σ_{tot} estim. from [3] (mb)	$\left(\frac{\sigma_m}{\sigma_{tot}}\right)_{exp}$	$\left(\frac{\sigma_m}{\sigma_{tot}}\right)_{calc}$
$^{132}Ba(n,2n)^{131}Ba$	11/2⁻	1/2⁺	696	1690 ± 15%	0.41 ± 0.09	0.51
$^{134}Ba(n,2n)^{133}Ba$	11/2⁻	1/2⁺	827	1720 ± 15%	0.48 ± 0.08	0.62
$^{136}Ba(n,2n)^{135}Ba$	11/2⁻	3/2⁺	1294	1725 ± 15%	0.75 ± 0.13	0.62
$^{138}Ba(n,2n)^{137}Ba$	11/2⁻	3/2⁺	1048	1900 ± 15%	0.55 ± 0.1	0.63

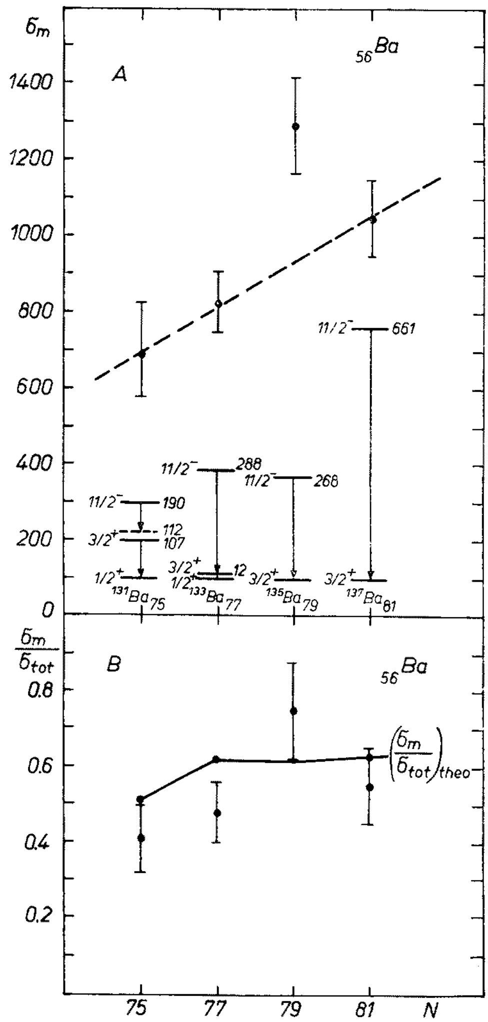

Fig. 2. A Cross-sections for the excitation of (11/2⁻) isomeric levels in odd-A isotopes of Ba by 14.8 MeV neutrons in $(n, 2n)$ reaction as a function of the neutron number. B. The calculated and experimental values of isomeric ratios for the same isotopes as a function of neutron number

deviate considerably from other values. On the other hand the calculated isomeric cross-section ratios follow a smooth curve (Fig. 2B) when plotted as a function of neutron number.

The calculated and experimental isomeric ratios are in agreement within the experimental errors. A possible explanation for the deviation of cross-section for excitation of ^{135m}Ba lies in the strong contribution of the ^{135}Ba $(n, n'\gamma)$ ^{135m}Ba process to $(n, 2n)$ reaction. Although the separated isotope of ^{135}Ba was not available in the present work, an attempt was made to estimate the $(n,n'\gamma)$ cross-section for ^{135}Ba. It is seen from Fig. 2A that the value of metastable cross-section for ^{136}Ba$(n, 2n)$ ^{135m}Ba reaction is about 950 mb. The constancy of the theoretical isomeric cross-section ratio (Fig. 2B) for neighbouring nuclei of ^{135}Ba suggests a similar value for this nucleus. Using the theoretical isomeric cross-section ratio and Pearlstein's total cross-section value for ^{136}Ba$(n, 2n)$ ^{135}Ba reaction at 14.8 MeV neutron energy, it is possible to give an upper limit for σ_m of 1080 mb. The experimental value for ^{136}Ba$(n, 2n)$ ^{135m}Ba$+^{135}$Ba$(n, n'\gamma)^{135m}$Ba reaction is 1294 mb. Comparison of these two values and errors yields the uper limit for the contribution of the ^{135}Ba$(n, n'\gamma)$ reaction as < 500 mb. To establish a trend in the σ_m cross-section for the $(n, 2n)$ reaction as a function of the neutron number N, one has to disregard the experimental point corresponding to ^{135}Ba, since in this case there is an essential contribution from the $(n, n'\gamma)$ process. Through the remaining three points one may draw a straight line, as shown in Fig. 2A, which corresponds to a systematic increase in σ_m with N.

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