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The Thermal Neutron Activation Cross Sections of ^{132}Ba (n, γ) ^{133m}Ba and ^{134}Ba (n, γ) ^{135m}Ba Reactions

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The thermal neutron activation cross sections (σ_{act}) of ^{132}Ba (n, γ) ^{133m}Ba and ^{134}Ba (n, γ) ^{135m}Ba reactions have been determined from the analysis of the gamma-ray spectra of Ba activities which were produced by irradiating the natural Ba isotopes with thermal neutrons in a reactor. The spectra were measured by using a 22 cm^3 coaxial type Ge(Li) detector. By adopting the known value of σ_{act} (^{130}Ba)$=10\pm1$ b, the cross sections σ_{act} (^{132}Ba$\rightarrow^{133m}$Ba)$=0.98\pm0.15$ b and σ_{act} (^{134}Ba$\rightarrow^{135m}$Ba)$=0.33\pm0.06$ b were obtained.

I. Introduction

The medium weight nuclei ^{133}Ba and ^{135}Ba have their metastable states ^{133m}Ba and ^{135m}Ba, whose excitation energies are 288 keV and 268 keV and half-lives are 38.9 ± 0.1 hours and 28.7 ± 0.2 hours, respectively.[1] The decay schemes of these metastable states cited from the Nuclear Data Sheets are shown in Fig. 1.[2] The natural barium consists of seven stable isotopes and all of their activation or absorption cross sections for (n, γ) reaction with thermal neutrons have been reported by many authors.[3]~[7] However, activation cross sections of ^{132}Ba (n, γ) ^{133m}Ba and ^{134}Ba (n, γ) ^{135m}Ba have been measured by few authors as yet.[7] Recent developement of solid state detector provide another advantageous method to measure these cross sections. As is well known, an activation cross section σ_{act} can be calculated from the formulae,

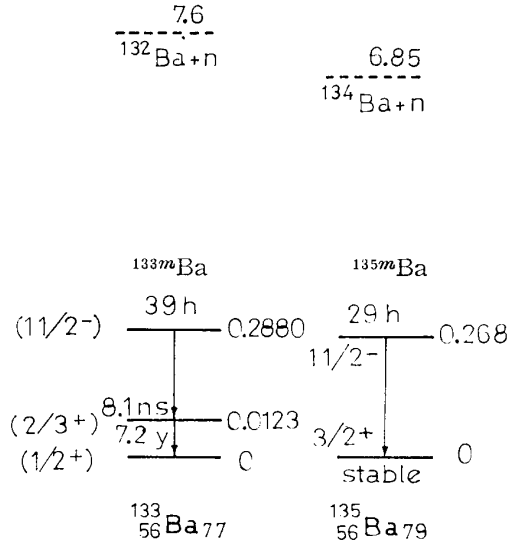

Fig. 1. Decay schemes of ^{133m}Ba and ^{135m}Ba cited from Nuclear Data Sheets.[2]

$$\sigma_{act}=(3.7\times10^{34})A/N\phi(1-\exp(-\varepsilon T_{irr}/T))\times\exp(-\varepsilon T_w/T), \quad (1)$$

$$A=n(1+\alpha_k)/B\eta\Omega, \quad (2)$$

where, A denotes the amounts of the induced radioactivity (in Curie) produced from the target nuclei, n the photopeak counts, η the relative photopeak efficiency, B the total transition intensity of the gamma-rays under consideration and Ω the solid angle subtended by the detector. Furthermore, T means the half-life of the nucleus produced by this reaction, T_{irr} the irradiation time, T_w the time between the end of the irradiation and the start of the measurement of the activities, N the numbers of the reacting nuclei and ϕ the neutron flux density. ε denotes $\log_e 2(=0.693)$. In a case that a target element consists

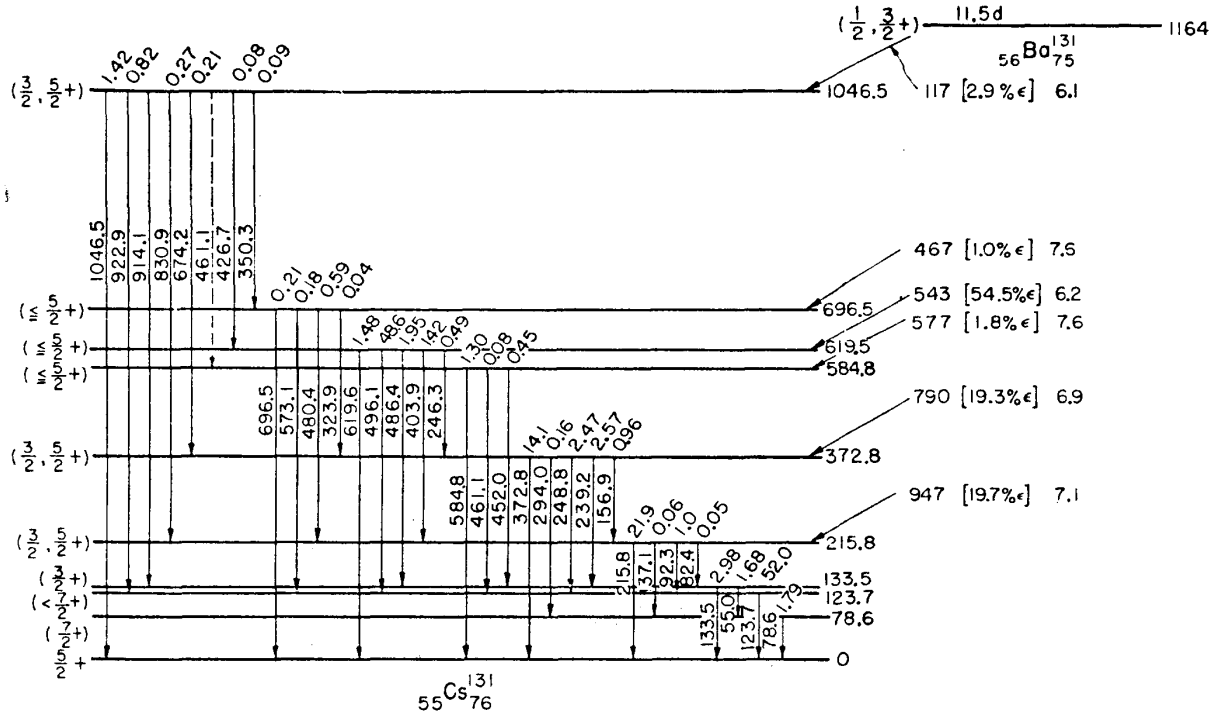

Fig. 2. Decay scheme of ^{131}Ba proposed by Kelly and Horen.[8]

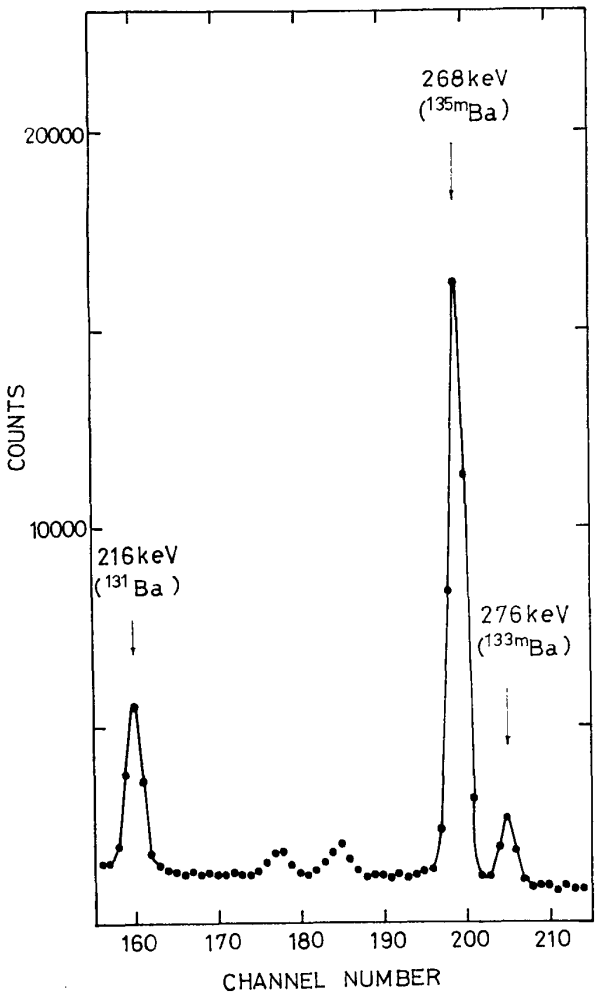

Fig. 3. Gamma-ray spectrum of Ba activities.

of several isotopes, by utilizing these relations, relative activation cross sections can be obtained regardless of the values of ϕ and Ω as well as absolute value of N, provided a gamma-ray spectrum of the induced radioactivities are measured.

In this paper, activation cross sections of ^{132}Ba (n, γ) ^{133m}Ba and ^{134}Ba (n, γ) ^{135m}Ba are determined on the basis of this method in connection with that of ^{130}Ba. The decay scheme of ^{131}Ba proposed by Kelly and Horen[8] is shown in Fig. 2.

II. Experiments

The activities measured were produced by irradiating the natural Ba compound Ba $(NO_3)_2$, with thermal neutrons in the Research Reactor of Kyoto University at Kumatori for 1 hour. The neutron flux density was 4.7×10^{12} $n/cm^2 \cdot sec$. The gamma-ray spectra were measured by using a ORTEC 22 cm^3 coaxial type Ge(Li) detector connected to ORTEC electronic circuits followed by a TMC 1024-channel pulse height analyzer. The measurement was started about 22houres after the irradiation in order to minimize the contribution of the 85 min ^{139}Ba activity. Any gamma-rays originated from nuclei other than

^{131}Ba, ^{133m}Ba and ^{135m}Ba were hardly observed in the spectra. The gamma-ray spectrum is partly shown in Fig. 3. Three well resolved prominent peaks located at 216 keV, 268 keV and 276 keV correspond to the 216 keV transitions in ^{131}Cs, the isomeric transition of ^{135m}Ba to the ground state of ^{135}Ba and that of ^{133m}Ba to the first excited state of ^{133}Ba, respectively.

III. Results and Discussion

As is seen in Fig. 3, the well resolved peaks which owing to high resolution of Ge(Li) detector enable us to estimate the yields of ^{132}Ba (n, γ) ^{133m}Ba and ^{134}Ba (n, γ) ^{135m}Ba relative to that of ^{130}Ba (n, γ) ^{131}Ba by the aid of eq. (2). The values of conversion coefficient α_k, total transition intensity B and relative peak efficiency of Ge(Li) detector η listed in Table 1 were used in the calculations. True photopeak counts for the three nuclei were estimated by subtracting the Compton part due to higher components of gamma-rays from the measured photopeake counts. The results are 9629 ± 171, 37465 ± 225 and 4166 ± 129 for 216 keV, 268 keV and 276 keV gamma-rays, respectively. By inserting these values to eqs. (1) and (2), relative activation cross sections are given as

Table 1. Adopted values in calculating the cross sections.

Energy of gamma-rays	216 keV	268 keV	276 keV
Conversion coefficient (α_k)	0.093 ± 0.010[a]	3.82 ± 0.20[b]	3.45 ± 0.20[c]
Total transetion intensity (B) %	21.9[a]	100	100
Relative peak efficiency (η)[d] of Ge(Li)	85	70	69

a) W. H. Kelly and D. J. Horen.[8]
b) A. C. G. Mitchell *et al.*[9]
c) J. E. Thun *et al.*[10]
d) O. Uehara, private communication.

$$\frac{\sigma_{act}(^{132}\mathrm{Ba} \rightarrow ^{133m}\mathrm{Ba})}{\sigma_{act}(^{130}\mathrm{Ba})} = 0.098 \pm 0.009,$$

$$\frac{\sigma_{act}(^{134}\mathrm{Ba} \rightarrow ^{135m}\mathrm{Ba})}{\sigma_{act}(^{130}\mathrm{Ba})} = 0.033 \pm 0.003,$$

where natural abundance of 0.101 %, 0.097 % and 2.42 %[6] were applied to the numbers of atomes N in eq. (1) for ^{130}Ba, ^{132}Ba and ^{134}Ba, respectively, since only the ratios are significant in our treatments.

Finally, adopting the known value of 10 ± 1 b for the activation cross section of ^{130}Ba,[3] we reach to the following results:

$$\sigma_{act}(^{132}\mathrm{Ba} \rightarrow ^{133m}\mathrm{Ba}) = 0.98 \pm 0.15 \text{ b},$$

$$\sigma_{act}(^{134}\mathrm{Ba} \rightarrow ^{135m}\mathrm{Ba}) = 0.33 \pm 0.06 \text{ b}.$$

These values may be compared to those of 4.1 ± 1.5 b or <0.15 b for ^{132}Ba (n, γ) ^{133m}Ba and 0.158 ± 0.042 b for ^{134}Ba (n, γ) ^{135m}Ba which are cited in "Nuclear Data".[7] A value of the activation cross section of ^{130}Ba given in the reference[7] is 11 ± 3 b, being in agreement with the adopted value of 10 ± 1 b within the experimental error. For ^{132}Ba (n, γ) ^{133m}Ba agreement of these values is not so wrong. For ^{134}Ba (n, γ) ^{135m}Ba, however, it should be noticed that the discrepancies between the cited values and the one obtained in the present work are large in both cases.

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