BRIEF REPORTS

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Resonance neutron capture in ^{136}Ba

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The neutron capture cross section of ^{136}Ba, which was determined recently with the Karlsruhe 4π barium fluoride detector, has been reanalyzed in the low energy region using a shape analysis program. Parameters of 45 resonances were extracted which allow a more reliable determination of the averaged cross section below 20 keV. The results confirm our first analysis and the reported stellar cross sections. Accordingly, the results of the s-process studies based on these data remain unchanged.

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The neutron capture cross sections of the barium isotopes are of vital importance for investigations of the stellar nucleosynthesis in the s process [1] for the following reasons: (i) Barium is one of the six elements with two even s-only isotopes, defining the strength of possible branchings in the s-process path [2]. The strength of these branchings yields information on the physical conditions during stellar He burning [3]. (ii) The isotope ^{136}Ba represents similar to ^{124}Te and ^{150}Sm, an important normalization point of the $N_s\langle\sigma\rangle$ curve in the region of the steep decrease at the magic neutron number N=82. (iii) The pronounced isotopic anomalies of barium discovered in meteoritic inclusions [4–6] can only be interpreted in terms of a pure s-process origin if accurate capture cross sections are known. (iv) The element barium abundance is clearly dominated by the s process and can, therefore, be used as an s-process indicator in astronomical observations.

In a recent publication [1] we have reported on neutron capture studies of four barium isotopes, using the Karlsruhe 4π barium fluoride detector [7] for registration of capture events. In this work a significant branching of the s-process path at ^{134}Cs was observed for the first time, which is sensitive to the s-process temperature. The classical approach as well as a stellar model [8] failed to reproduce the empirical $N_s\langle\sigma\rangle$ value for ^{136}Ba, both yielding a significant overproduction. Since these results are critically dependent on the value of the neutron capture cross section of this isotope it was important to improve the data analysis adopted in this work. The capture cross section of ^{136}Ba is sufficiently small that single resonances were resolved up to about 20 keV neutron energy even with the rather short flight path of that experiment. In Ref. [1], however, the cross section was determined simply by averaging the observed capture yield. This simplification may cause some doubts on the results at low neutron energies, where a significant background due to capture of scattered neutrons had to be subtracted. Therefore, these data have been reanalyzed using a shape analysis program for determining the resonance parameters. From these parameters new and more reliable values for the low energy part of the stellar cross sections were derived, an improvement that is especially important for comparison with stellar model calculations which indicate that most of the s process takes place at thermal energies of 12 keV or even less [8,9].

A detailed description of the experiment and data evaluation has been given in Ref. [1]. Neutrons were produced via the ^{7}Li$(p,n)^7$Be reaction using the pulsed proton beam of the Karlsruhe 3.75 MV Van de Graaff accelerator. Capture events were registered with the Karlsruhe 4π barium fluoride detector [7]. The experimental time resolution was about 1 ns and the neutron flight path 78 cm. The sample consisted of 6.5 g $BaCO_3$ enriched in ^{136}Ba to 92.7%. Three runs were performed with different neutron spectra which could be analyzed down to 2.8, 5, and 7 keV, respectively.

For all three runs the capture yield was analyzed with the FANAC code [10]. The global input parameters like strength functions or nuclear radii for ^{136}Ba and the impurity isotopes ^{12}C and ^{16}O were the same as used in the calculations of the multiple scattering and self-shielding corrections in the evaluation of averaged cross sections [1]. The resonance energies and the neutron widths of s-wave resonances were taken from Ref. [13].

In a first survey, the energies of well-isolated resonances were determined and compared to the data of Ref. [13]. For two runs the agreement was better than 10 eV in the whole energy range. In the third run a deviation was observed, which increased linearly with energy, reaching 100 eV at 20 keV (Fig. 1). This corresponds to a flight path

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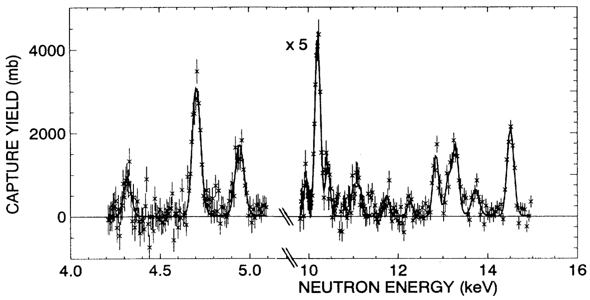

FIG. 1. The neutron capture yield of ^{136}Ba of one run in the energy range from 4 to 5 and from 10 to 15 keV (crosses with error bars) and the corresponding FANAC fit.

uncertainty of 0.25%, slightly larger than the assumed systematic uncertainty of 0.1%. In the final fits the resonance energies of weak resonances or uncompletely resolved doublets were adopted from Ref. [13] and only Γ_γ was considered as a free parameter.

The resolution in neutron energy is dominated by the 0.75 ns pulse width of the proton beam, the 1.0 ns time resolution of the gamma-ray detector, and by the thickness of the sample (5.1 mm). This results in an energy resolution of ±70 eV at 10 keV, ±50 eV at 7 keV, and ±32 eV at 5 keV. Thus, the broad s-wave resonance at 7.22 keV (Γ_n=140 eV) is the only case, where the shape could be resolved. Therefore, the Γ_n values given in Ref. [13] were used as fixed parameters in our analysis of s-wave resonances.

For the neutron width of individual p-wave resonances there is no experimental information. In the present experiment the shape of these resonances is completely determined by the time resolution and the flight path length variations due to the sample dimensions. Therefore, there is no way to obtain the individual parameters Γ_n or Γ_γ. The only quantity that can be determined is the resonance area $A_\gamma = g\Gamma_n\Gamma_\gamma/(\Gamma_n + \Gamma_\gamma)$.

A rough estimate of the neutron width can be calculated according to the relation [14]

$$g_J \langle \Gamma_n \rangle_{lJ} = \nu_{lJ} g_J D_J S_l \sqrt{E} v_l(E),$$

where the quantities g, D, S, ν, and v_l denote the statistical weight factor, the mean level spacing, the strength function, the number of possible channel spins, and the penetrability factor, respectively. For p-wave resonances, this expression reduces to

$$g\langle \Gamma_n \rangle_1 = D_s S_1 \sqrt{E} \frac{(kR)^2}{1+(kR)^2},$$

yielding Γ_n values between 40 and 300 meV in the energy range of interest, which may serve as a first-order estimate.

The resonance area can be written in the following form:

$$\frac{1}{A_\gamma} = \frac{1}{g\Gamma_n} + \frac{1}{g\Gamma_\gamma}.$$

Therefore, possible combinations of $g\Gamma_n$ and $g\Gamma_\gamma$ for a fixed value of A_γ are located on a hyperbola in the $g\Gamma_n$, $g\Gamma_\gamma$ plane. Thus, $g\Gamma_n$ and $g\Gamma_\gamma$ are always larger than A_γ, reaching this value in their asymptotic limit. To determine the resonance area the values of A_γ given in Ref. [13] were used as a first guess. In repeated fits $g\Gamma_n$ was fixed to $3 \times A_\gamma$, $2 \times A_\gamma$ and $1.5 \times A_\gamma$, respectively, and Γ_γ was adjusted as a free parameter. This procedure was repeated for both possible values of $g = 1, 2$. In this way the sensitivity of A_γ on the input parameters was determined on the central part of the hyperbola, where the values of most resonances are located. The main reason for varying the neutron width in a reasonable interval was to study its influence on the correction for multiple scattering and self-shielding and hence on the determined resonance area.

The analyzed values of A_γ for 45 resonances are compiled in Table I. The results represent the weighted averages of all three runs. In Fig. 1, the capture yield is shown together with the fitted curve in the energy range from 4 to 5 and 10 to 15 keV, respectively.

Only statistical uncertainties are quoted in Table I. The corrections for multiple scattering and self-shielding are included in the FANAC code [10]. The largest correction of $\sim$50% of the observed yield is found for the broad s-wave resonance at 7.22 keV. The respective values for the other s-wave resonances are 27% (3.46 keV), 12% (6.14 keV), 8% (9.98, 13.8, 17.3 keV), and 3% (4.95 keV). For the p-wave resonances, the corrections are in general 3–5 %. The uncertainty of this correction is 3–5 % for most resonances. Only for strong s-wave resonances, where the size of the correction amounts up to 50% of the observed yield, the uncertainties are 5–10 % [11,12]. Therefore, the resulting systematic uncertainties are always much smaller than the statistical uncertainties. The systematic differences in the results obtained with different $g\Gamma_n$ values are less than 1% above 10 keV and less than 3% below and can be neglected compared to the statistical uncertainties. The only exception are the two very strong resonances at 2.835 and 4.713 keV. Here, the variation of the individual results of the 6 fits from the average value was ±7%, the results for large $g\Gamma_n$ values being systematically larger. This is due to the increasing self-absorption in these strong resonances which has to be compensated by an increasing resonance area in order to fit the experimental capture yield.

The resonance at 4.713 needs special consideration as a value of $g\Gamma_n$ of 2000 meV was published in Ref. [13]. This is nearly a factor of 10 larger than A_γ and thus very unlikely, but certainly not excluded within the fluctuations of a Porter Thomas distribution. The final result given in Table I is based on this neutron width and the uncertainty is dominated by the 30% uncertainty of Γ_n.

It has to be stressed that the present experiment was not designed to determine resonance parameters, and therefore cannot compete in this respect with LINAC experiments using a much longer flight path. As indicated in Table I several of the resonances were not completely resolved from their neighbors. Therefore, the sum of both resonances should always be used in a comparison with other data. The purpose of the experiment was to determine reliable average cross sections, and in this case, the split of the capture strength in a resonance doublet is not important. Nevertheless, in a surprisingly large number of cases, the individual parameters of the unresolved resonances were found to agree for all three runs within their statistical uncertainties. However, the true value of

TABLE I. Resonance areas of capture resonances in ^{136}Ba

Resonance energy[a] (keV)	$g\Gamma_n\Gamma_\gamma/(\Gamma_n+\Gamma_\gamma)$ (meV)	Uncertainty (%)	Orbital angular momentum
2.835[b]	106.3	7.7	
3.419[c]	58.3	16.1	
3.464[c]	73.7	28.4	0
3.553	36.8	22.1	
4.326	53.1	16.0	
4.713	338.0[d]	8.9	
4.959	184.5	7.2	0
6.139[c]	107.4	20.0	0
6.181[c]	77.5	15.4	
6.657	66.8	12.4	
7.060	44.4	13.7	
7.220	86.4	20.6	0
7.571	134.8	5.1	
7.765	22.5	25.1	
8.822[c]	108.5	7.5	
8.932[c]	141.6	6.4	
9.198	20.9	31.9	
9.989	86.1	12.9	0
10.21[c]	131.4	10.5	
10.28[c]	168.7	7.4	
10.47	75.1	9.6	
11.05[c]	56.4	12.6	
11.18[c]	56.1	12.5	
11.80	47.3	14.8	
12.33	37.1	18.9	
12.92	148.7	5.4	
13.19[c]	95.1	8.4	
13.35[c]	181.2	4.7	
13.80	98.0	11.0	0
14.58	306.1	2.9	
15.22	91.1	8.1	
15.65	124.0	6.4	
16.18[c]	116.9	9.9	
16.27[c]	49.5	20.8	
17.02[c]	70.9	14.2	
17.11[c]	156.3	8.4	
17.35	138.8	8.7	0
17.97[c]	71.8	12.1	
18.08[c]	149.8	7.9	
18.54[c]	219.9	4.4	
18.72[c]	48.2	17.2	
18.94	106.2	7.8	
19.26	135.3	5.9	
19.83[c]	350.8	3.6	
19.97[c]	84.0	14.6	

[a]Taken from Ref. [13].
[b]Resonance not observed in previous work [13].
[c]Unresolved doublet.
[d]Value and uncertainty are based on g=2, Γ_n =1000±300 from Ref. [13]. If the evaluation is made as for the other resonances the result would be 245.5±17.1 meV.

TABLE II. Averaged capture cross section of ^{136}Ba.

Neutron energy interval (keV)	Capture cross section (mb)[a] Present work	From Ref. [1]
3–5	354.1 ± 20.8	382.4 ± 31.7
5–7.5	97.5 ± 8.2	165.4 ± 12.4
7.5–10	99.2 ± 3.7	102.6 ± 6.2
10–12.5	89.0 ± 3.8	90.9 ± 4.0
12.5–15	100.4 ± 2.4	107.4 ± 3.1
15–20	88.7 ± 1.9	99.3 ± 1.6

[a]Including statistical uncertainty.

the neutron width of one or the other resonance may be significantly outside the region considered by the fits, as for example in case of the resonance at 4.713 keV. This limitation of the present experiment can only be neutralized with experimental neutron widths from transmission measurements. The related systematic uncertainty is difficult to estimate but can be sizable for a few individual resonances. The stellar cross section, however, is determined by the area of many resonances and for such an ensemble the uncertainty should be significantly smaller.

If the present results are compared with the data of Ref. [13] the resonance areas are in general larger by 10 – 20 %. Prominent exceptions are the two s-wave resonances at 3.46 and 7.22 keV and the p-wave resonance at 4.71 keV, for which significantly lower values were obtained.

In the present experiment, the resonance at 4.713 keV was also checked for a possible superposition of a resonance at 4.698 keV in ^{138}Ba (Ref. [15]) because of a 4.4% ^{138}Ba impurity in the sample material. However, this contribution can be neglected since even the strongest low energy resonance in ^{138}Ba at 7.850 keV, which is completely separated from any ^{136}Ba resonances, was not observed in our spectra.

The resonance at 2.825 keV was observed for the first time. The very weak resonances at 3.145, 4.850, 5.052, 13.89, and 16.08 keV quoted in Ref. [13] could not be verified from the present data.

From the resonance parameters given in Table I average capture cross sections were derived according to the description of Macklin and Gibbons [16] which are compared in Table II to our previous results. The capture area is defined as

$$CA = (2\pi^2/k^2)A_\gamma[b \times eV]$$

with the proper value[1] for k^2:

$$k^2 = 0.004\,826[A/(A+1.008\,665)]^2 \times E_{\rm res}[b^{-1}],$$

where $E_{\rm res}$ is the resonance energy in keV. The average cross section is the sum of the capture area of all resonances in the respective energy interval, divided by the energy of the interval. Within the quoted statistical uncertainties, the agreement is quite satisfactory. A

[1]There is a misprint in the equation of k^2 in Ref. [16].

maximum discrepancy of three times the statistical uncertainty is observed only in the intervals from 5 to 7.5 keV and from 15 to 20 keV. The first interval is an extreme case since 40% (5–6 keV) is completely free of resonances. There, a small positive yield is observed in the experiment which is probably the background from the strong scattering resonance at 7.22 keV (Γ_n=140 eV).

Good agreement is found in the energy interval from 3 to 5 keV. This data point of our previous evaluation had not been used in the calculation of stellar cross sections since systematic uncertainties in background subtraction could not be excluded. The good agreement with the present resonance analysis shows, however, that this interval can be reliably included in the determination of the Maxwellian averaged cross sections. This reduces the uncertainty at low kT values, since the uncertainty of 20%, which was assumed in this energy interval could be reduced to 6%.

Using on the results of Table II revised Maxwellian averaged cross sections for kT values from 10 to 30 keV were calculated according to Ref. [16] and as described in detail by Beer, Voss, and Winters [17]. The values are given in Table III together with our previous results. The differences are marginal and well within the quoted uncertainties. At kT=10 keV the total uncertainty is reduced from 5.7 to 4.2%. If the Maxwellian average cross sections are calculated directly from the resonance parameters of Table I in the energy interval from 3 to 20 keV instead of using the averaged cross sections of Table II, the results differ by only 0.7%.

TABLE III. Maxwellian averaged neutron capture cross sections of ^{136}Ba.

Thermal energy kT (keV)	$\langle\sigma v\rangle/v_T$ (mb)[a] Present work	From Ref. [1]
10	109.7 ± 4.6	114.9± 6.5
12	99.3 ± 3.9	103.5 ± 5.2
20	74.9 ± 2.7	77.4 ± 3.0
25	66.5 ± 2.3	68.4 ± 2.5
30	60.6 ± 2.1	62.0 ± 2.1

[a]With total uncertainty.

The improved analysis of the neutron capture cross section of ^{136}Ba in the energy range from 2.8 to 20 keV yielded the resonance areas of 45 resonances. The resulting averaged cross sections are in good agreement with the values from a first analysis which was based on the observed capture yield [1], thus confirming the reliability of background subtraction in experiments with the Karlsruhe 4π barium fluoride detector. For the Maxwellian averaged cross sections slightly improved values could be derived at low kT values. The previous statements of the s-process studies based on these cross sections [1] remain unchanged.

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