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Исследование распада излучателей запаздывающих протонов ^{117}Ba, ^{119}Ba и ^{121}Ba

С помощью масс-сепаратора БЭМС-2 на пучке тяжелых ионов исследованы излучатели запаздывающих протонов $^{117,119,121}Ba$. Из измерений позитрон-протонных совпадений получены значения ($Q_0 - B_p$) этих изотопов: (7,9±0,3), (6,2±0,2) и (4,3±0,3) МэВ, соответственно, (Q_0 - энергия К-захвата, B_p - энергия связи протона в дочернем ядре). Проведен анализ формы протонных спектров с помощью статистической модели процесса, который указывает на наличие локального резонанса в силовой функции β-перехода при энергии возбуждения дочернего ядра около 5 МэВ.

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A Study of the Decay of the Delayed Proton Emitters ^{117}Ba, ^{119}Ba and ^{121}Ba

The delayed proton emitters $^{117,119,121}Ba$ have been investigated using the on-line BEMS-2 isotope separator. From measurements of positron-proton coincidences the ($Q_0 - B_p$) values for these isotopes (where Q_0 is the K-capture energy, and B_p is the proton binding energy of the daughter nucleus) have been obtained to be (7.9±0.3), (6.2±0.2) and (4.3±0.3) MeV, respectively. The shapes of proton spectra have been analysed within the framework of the statistical model. The analysis indicates the presence of a local resonance in the β-strength function at the 5 MeV excitation energy of the daughter nucleus.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

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1. INTRODUCTION

Delayed proton emission is a typical process for isotopes with a considerable neutron deficit. Studies of this process permit the extraction of information on the properties of nuclei far from the line of β-stability (see, e.g., reviews [1,2]). The measurement of positron-proton coincidences enables one to determine the energy of the β^+_p-decay, (Q_0-B_p), where Q_0 is the energy of the electron capture of the parent nucleus, and B_p is the proton binding energy of the daughter one [3,4]. This quantity is closely related to the mass difference between the initial and final nuclei and, therefore, may be used to verify the existing atomic mass formulae. An analysis of the smoothed shape of proton spectra provides information about the β-strength function [5,6].

The isotopes $^{117,119,121}Ba$ have first been identified in refs. [7,8,9]. A more detailed analysis of the properties of the proton emitters $^{119,121}Ba$ is contained in ref. [26], wherein the β^+_p-decay energies were measured and evidence for the presence of a local resonance in the β^+-strength function for these isotopes has been obtained at an excitation energy of about 5 MeV. In the present paper the results of measurements of the (Q_0-B_p) value for all the three emitters are presented. The performed analysis of the proton spectrum shape confirms the presence of the local resonance which manifests itself most vividly in the proton spectrum of ^{117}Ba.

2. EXPERIMENTAL TECHNIQUE

The experiments were carried out using an external beam of the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions. A metallic target prepared of enriched (90%) ^{92}Mo, about 2 mg/cm^2 thick, was bombarded with $^{32}S^{5+}$ ions (E_{max} = 190 MeV). The isotopes investigated were formed in the following reactions: $^{92}Mo(^{32}S,2p5n)^{117}Ba$, $^{92}Mo(^{32}S,2p3n)^{119}Ba$ and $^{92}Mo(^{32}S,2pn)^{121}Ba$. The target was placed in the vicinity of the high-temperature surface-ionization ion source of the BEMS-2 isotope separator, which provided the continuous separation of isotopes. The recoil nuclei knocked out by the beam from the target penetrated inside the ion source through a thin tantalum foil.

A detailed description of the BEMS-2 isotope separator is given in ref. /10/. A measuring device was located in the focal place of the isotope separator. An activity due to the isobar with a selected mass number was collected on a disk catcher (1.5-5 μm) and placed between the Si(Au) proton detector and scintillation β-counter. The small thickness (1 mm) of the scintillator provided a low sensitivity of the counter to the γ-ray background and the amplitude standardization of pulses as a result of the weak energy dependence of the specific energy loss of electrons. The β-channel efficiency measured using a ThC ion source was 42±2%. Signals from the β- and proton detectors were amplified and then fed to differential discriminators with a timing mark for the appearance of a pulse. The selection of true and random coincidences was performed using the combination of a time-to-pulse height converter and two conventional differential discriminators. The total resolving time of the experiments was 0.3 μs, which furnished a 100% detection of true coincidences. To reduce the background the electronic equipment was blocked during the passage of the beam. In the experiment the simultaneous recording of three proton spectra was performed, namely, without coincidence, in true and random coincidence with positrons.

3. EXPERIMENTAL RESULTS AND DISCUSSION

a) The β^+p -decay energy

Figure 1 shows the proton spectra of ^{119}Ba in coincidence (histogram 1) and without coincidence (histogram 2). One can easily see that the inclusion of coincidences leads to the suppression of the high-energy part of the spectrum, because the increase in the delayed proton energy corresponds to a decrease in the partial energy of the transition. In this case the relative probability of electron capture making no contribution to the coincidence spectrum increases. The ratios of integral intensities of protons measured in coincidence

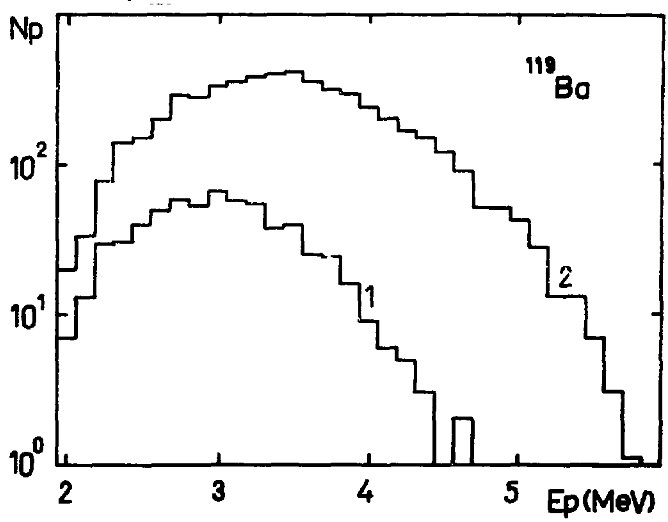

Fig. 1. Delayed proton spectrum of ^{119}Ba in coincidence (1) and without coincidence (2) with positrons.

to all measured protons are equal to (28$\pm$1.6), (12.1$\pm$0.5) and (2.1$\pm$0.4)% for ^{117}Ba, ^{119}Ba and ^{121}Ba, respectively.

Although the total sensitivity of the employed plastic scintillator to γ-rays is as low as (0.65$\pm$$\pm$0.15)% in the energy range $0.6 \geq E \geq 0.15$ MeV, the ratios obtained contain a contribution from the $p\gamma$ coincidences associated with the population of the low-lying states of the daughter nucleus during the proton decay. Neglecting this contribution will lead to the overestimation of the value of the average probability of positron emission before delayed proton emission, $\bar{R}$, determined from these ratios and, consequently, to the overestimation of the (Q_0-B_p)value, this overestimation being the more substantial the smaller the value of the ratio.

To take the contribution from $p\gamma$-coincidences into account additional experiments were carried out in which a plastic scintillator 17 mm thick was used as a β-counter. The use of a "thick" scintillator results in a factor of 10 increase in the partial contribution from $p\gamma$-coincidences since the total efficiency of γ-ray detection increases to (6.5$\pm$0.4)%. The efficiency of detecting βp-coincidences remains unchanged in this case as the experimental geometry and energy thresholds do not change. By comparing the relative yields of protons in coincidence for two scintillators one can derive data on the average number of γ-rays per one emitted proton (γ/p) and estimate the contribution from $p\gamma$ coincidences. The γ/p values measured for the ^{119,121}Ba emitters are equal to 0.6$\pm$0.2 and 1.0$\pm$0.15, respectively, and the total contributions from $p\gamma$-coincidences taking the γ-transition conversion into account are equal to (1.5$\pm$0.3) and (2.0$\pm$0.13)%, respectively. After making this correction and taking the β-channel efficiency into account, the experimental values of $\bar{R}$ are equal to (69$\pm$5), (25$\pm$2) and (0.2$\pm$1.2)% for ^{117}Ba, ^{119}Ba and ^{121}Ba, respectively.

The ratio of the intensities between protons emitted after positron decay and all emitted protons with energy E may be presented in the form

$$R(E_p) = \sum_f a_f(E_p)[1+W_\epsilon(Q)/W_{\beta^+}(Q)]^{-1} , \qquad (1)$$

where $a_f(E_p)$ is the fraction of protons with energy E_p, corresponding to the decay to the final state of the daughter nucleus with an excitation energy E_f; W_ϵ/W_{β^+} is the ratio between the probabilities of electron capture and positron decay. It is known that for allowed transitions W_ϵ/W_{β^+} is independent of nuclear matrix elements and, at a given value of Z, determined only by the transition energy, $Q = Q_0 - B_p - E_f - E_p A/(A+1)$. To determine (Q_0-B_p) the experimental value of $\bar{R}$ was compared with the calculated one obtained by averaging over the proton spectrum. In the absence of decays to the excited states of the daughter nucleus the $\bar{R}$ value is only a function of (Q_0-B_p) and the value of the latter may be found with an accuracy not poorer than ± 100 keV[3]. In the cases where decays to excited states cannot be neglected the accuracy of the determination of (Q_0-B_p) from the β^+p-coincidences becomes lower due to the necessity of using the theoretical values of the a_f coefficients. The calculation of $a_f(E_p)$ was carried out on the basis of the statistical model of delayed proton emission[1,2,5,6] using the values of energies and spins of final states from refs.[11,12] * and the values of W_ϵ/W_{β^+} from ref.[13]. Figure 2 shows the dependence of $\bar{R}$ on (Q_0-B_p) for ^{117}Ba, which was calculated for the most probable spin values of the initial nucleus. From this figure

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* The first excited states of ^{116}Xe are: 2^+ (0.39 MeV), 4^+(0.92 MeV) and 6^+(1.51 MeV), of ^{118}Xe are: 2^+(0.34 MeV), 4^+(0.81 MeV) and 6^+(1.40 MeV), and of ^{120}Xe are: 2^+(0.32 MeV), 4^+(0.79 MeV) and 6^+(1.39 MeV).

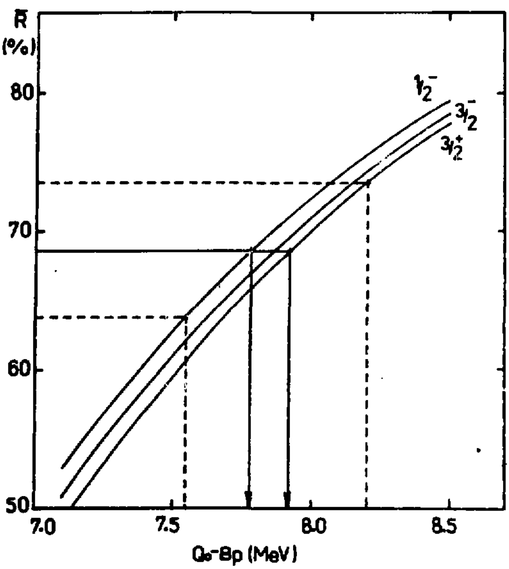

Fig. 2. Relative probability of positron emission per one emitted proton for ^{117}Ba as a function of the $Q_0 - B_p$ value. The calculated curves are given for the ^{117}Ba spin values of $1/2^-$ and $3/2^\pm$. The arrows show the region of possible $Q_0 - B_p$ values, associated with the nuclear spin uncertainiy, and the dashed lines indicate the error due to the statistical accuracy of the measurements.

it follows that the uncertainty due to the spin value leads to an additional ambiguity in the value of (Q_0-B_p) obtained from the comparison with experiment. This ambiguity however is not very great (about 150 keV).

The net results on the (Q_0-B_p) values for the isotopes ^{117,119,121}Ba, obtained from the comparison of the experimental $\bar{R}$ value with calculation, are

Table

Some characteristics of the delayed proton emitters $^{117,119,121}Ba$:
$T_{1/2}$ is a half-life, (Q_0-B_p) is the energy of the β^+p-decay, p/β^+ is the proton branching (the theoretical branching values are calculated using the statistical model of delayed proton emission; the spins of the ground states of barium isotopes used in the calculations are given in parentheses).

Isotope	$T_{1/2}$ (s)	Q_0-B_p (MeV) experiment	Q_0-B_p (MeV) mass formula calculation /14/	/15/	/16/	/17/	/18/	p/β^+ calculation	p/β^+ experiment
^{117}Ba	1.9±0.2	7.9±0.3	8.1	8.5	9.1	8.9	9.5	9×10^{-2} $(3/2^+)$ 4.5×10^{-2} $(3/2^-)$	–
^{119}Ba	5.4±0.3	6.2±0.2	6.1	6.5	6.9	6.8	7.2	4.6×10^{-3} $(5/2^+)$ 1.7×10^{-3} $(5/2^-)$	–
^{121}Ba	29.7±1.5	4.2±0.3	4.2	4.4	4.8	4.6	5.4	1.2×10^{-4} $(5/2^+)$ 3.3×10^{-5} $(5/2^-)$	$(2\pm1)\times10^{-4}$

shown in the Table. In the estimation of errors spin values were assumed to be $1/2^-$ and $3/2^{\pm}$ for ^{117}Ba, and $3/2^{\pm}$ and $5/2^{\pm}$ for the isotopes $^{119,121}Ba$ (in addition, the lower limit of the (Q_0-B_p) value for ^{121}Ba was estimated from the end point of the proton spectrum).

All these isotopes belong to the new region of deformed nuclei with $50<Z$ and $N<82$. The possible spin values indicated follow from the level scheme taking into account the uncertainty of the calculational parameters (see, e.g., refs. [17,19]).

The comparison of the results with the predictions of different mass formulae [14-18] shows that, as in the Te region, the mass formulae of Garvey-Kelson and Zeldes [14,15] turn out to be the most realistic. Some characteristics of the delayed proton emitters $^{117,119,121}Ba$ are presented in the Table.

b) Analysis of the proton spectrum shape

The obtained values of (Q_0-B_p) were used to analyze the shapes of proton spectra in the framework of the statistical model of delayed proton emission [5,6]. This model involves the average values both for the probabilities of β transitions to proton-unstable states and the decay probabilities of these states. Within the framework of this model the delayed proton spectrum may be written in the following form:

$$\frac{\Delta N(E_p)}{\Delta E_p} \sim \sum_{if} g(I,I_i) f(Z,Q_0-E) S_\beta \frac{\Gamma_p^{if}}{\Gamma^i}, \qquad (2)$$

where $g(I,I_i)$ is the statistical weight factor for the β^+-transition of the nucleus with spin I to a state with spin I_i; $f(Z,Q_0-E)$ is the Fermi integral function taking into account both positron decay and electron capture [13]; S_β is the β-strength function equal to the total reduced transition probability per unit interval of the daughter nucleus excitation energy; Γ_p^{if} is the average proton width for the decay from a state with spin I_i to the final state with spin I_f ; $\Gamma^i = \Gamma_\gamma^i + \sum_f \Gamma_p^{if}$ is the full width determined by the radiative and total proton widths. It is assumed that the averaging interval ΔE_p is considerably larger than the level spacing. [6]

For $g(I, I_i)$ the expression $g = (2I_i+1)/3(2I+1)$ [6] was used. For the excitation energy E the following relation is valid

$$E = B_p + E_f + \varepsilon_p A/A-1, \qquad (3)$$

where A is the mass number of the initial nucleus. The proton widths were calculated using the known optical model formula and transmission coefficients from ref. [20] and level density parameters from ref. [21]. The radiative widths were found using the semiempirical formula from ref. [22].

In a first approximation it was assumed that the β^+-strength function is constant within the limits of excitation energy corresponding to the proton spectrum. This assumption agrees with the present-day theoretical concepts (see, e.g., ref. [23]) according to which for the allowed β^+-decay of nuclei with $N > Z$ the region of real transitions covers the "tail" of the giant Gamow-Teller resonance, wherein the strength function changes slightly. However, the local resonance associated with simple configurations well populated in β^+-transitions can cover this smooth behaviour of S_β.

Evidence for such an unusual behaviour of the strength function has been obtained in the studies of the proton spectra of ^{109}Te [24] and ^{115}Xe. [6] In the case of ^{109}Te the local resonance manifests itself most vividly. For these nuclei resonances were associated with the transition of the proton from the closed shell $g_{9/2}$ to the neutron $g_{7/2}$, which led to the formation of a three-quasiparticle state. This state appeared to be "spread" over the real states of the nucleus due to the residual interaction.

The analysis described in this section has been made to obtain information about the β-strength function for ^{117,119,121}Ba. From estimates of the average values of the strength function $\overline{S_\beta = (ft)^{-1}}$, made under the assumption of the S_β constancy at excitation energies exceeding the pairing cut-off [23] one can conclude that these isotopes underwent the allowed Gamow-Teller β^+-decay. The $\bar{S}_\beta$ values for ^{117,119,121}Ba are equal to 4.5×10^{-5} MeV^{-1} s^{-1} 4.1×10^{-5} MeV^{-1} s^{-1} and 3.0×10^{-5} MeV^{-1} s^{-1} respectively. In these estimates the experimentally obtained half-lives and the calculated values of Q_0 [15] were used.

The β-decay of barium isotopes was considered in ref. [25] using a microscopic model taking deformation, pairing and Gamow-Teller forces into account. The calculations predict a maximum in the β^+-strength function for the isotopes ^{117,119,121}Ba at the 5-7 MeV excitation energies of the daughter isotopes. This maximum should be mainly due to the allowed transitions p[404↑]→n[404↓]and p[413↑]→n[413↓].

The position of resonances is only slightly sensitive to the spins of the ground states of the nuclei involved in the β-decay and one should expect that the resonance character of S_β will manifest itself in the form of delayed proton spectra.

A comparison of the experimental proton spectra of ^{117,119,121}Ba with the spectra calculated in terms of the statistical model assuming the constant S_β value is presented in fig. 3. The calculation was made for spins $3/2^\pm$ for ^{117}Ba and $5/2^\pm$ for ^{119,121}Ba.

It should be noted that for ^{121}Ba the value of $\gamma/p = 1.0 \pm 0.15$ can be regarded as an argument supporting spin $5/2^+$ as the statistical model calculations yield the values of $\gamma/p = 0.4$ for spin $3/2^+$ and 0.8 for spin $5/2^+$, which practically do not change with wide range variations of Q_0 and B_p. The comparison of the calculated and experimental values of the proton branching also favour spin $5/2^+$ (see table). The proton binding energies in ^{117,119,121}Cs

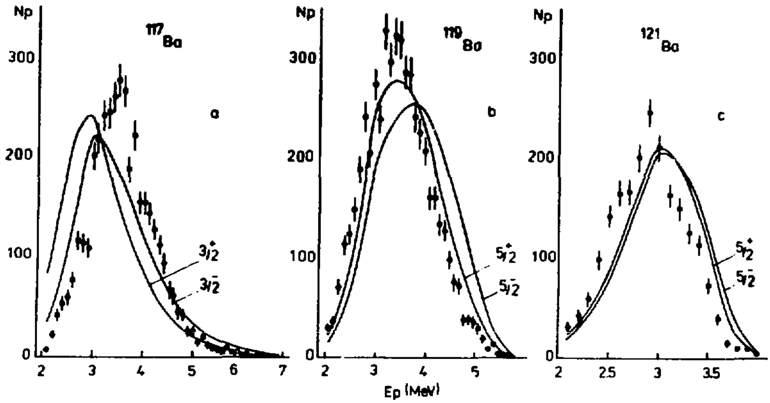

Fig. 3. Comparison of the delayed proton spectra of ^{117,119,121}Ba with statistical model calculations.

are taken to be equal to 0.85, 1.63 and 2.30 MeV, respectively [15].

One can see that the calculation reproduces the "gross" structure of the proton spectra only qualitatively, quantitative agreement being absent.

The ratio of the intensities of the experimental and calculated spectra, which reflects the behaviour of the strength function is presented in fig. 4. In the case of the lightest barium isotope, ^{117}Ba, the resonance in S_β is the most pronounced. For both of the assumed values of $I^\pi = 3/2^{\pm}$, the behaviour of the dependence remains unchanged and indicates the presence of the resonance at a proton energy $E_p \sim 4$ MeV, i.e., at an excitation energy $E \sim 5$ MeV (3). In going to the heavier isotopes ^{119,121}Ba the increase in the proton binding energy B_p in the daughter nuclei and the displacement of the resonance to the region of the lower excitation energies lead to that the resonance in the proton spectrum

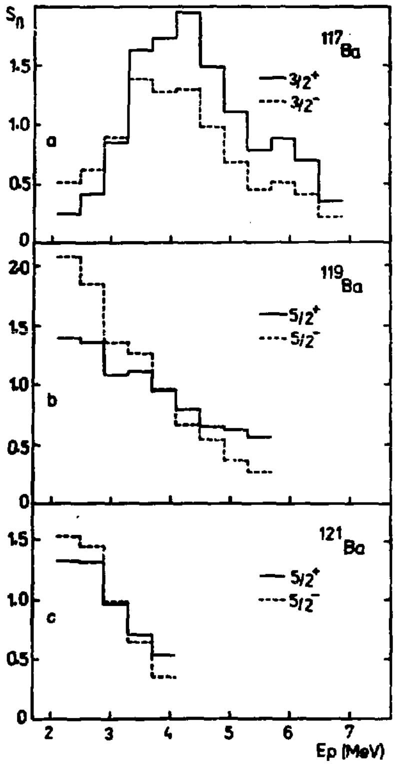

Fig. 4. Ratio (averaged over a 400 keV interval) of the experimental and calculated proton spectra of ^{117,119,121}Ba.

should be expected at energies $E_p \sim$ 2–3 MeV., i.e., on the boundary of the observed proton spectrum. In fact, it is reasonable to interpret the histograms shown in figs. 4b and 4c just in this way, although one cannot exclude that in the case of $^{119,121}Ba$ the deviation of the statistical model spectrum from the experimental one may be due to the anomaly available in the proton width, as it is observed in the region wherein $\Gamma_p < \Gamma_\gamma$.

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