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Total absorption spectroscopy of the β-delayed proton emitter ^{117}Ba

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Abstract. The very neutron-deficient ^{117}Ba nuclei were produced in ^{58}Ni-induced reactions on a ^{63}Cu target and selected for spectroscopic studies by using BaF$^+$ molecules formed in the ion source of the GSI on-line mass separator. The β-decay of ^{117}Ba was investigated by means of the total absorption γ-ray spectrometer and a telescope for β-delayed particle detection. In the analysis combining the β-delayed γ-ray and proton data the energy window available for β-delayed proton emission, the branching ratios for proton transitions to the ^{116}Xe levels and the β-feeding of the γ-ray and proton-emitting ^{117}Cs states were determined. The β-strength function for ^{117}Ba derived from the measured β-feeding distribution revealed the existence of a broad resonance structure at ^{117}Cs excitation energy of about 4–5 MeV. The results of the β-delayed proton studies and β-strength measurements are confronted with theoretical predictions.

PACS. 23.40.-s β decay; double β decay; electron and muon capture

1 Introduction

Recent progress in the decay studies of neutron-deficient barium isotopes has become possible due to the development of a chemically selective ion source for on-line mass separation of these nuclei [1]. By extraction of barium isotopes as molecular BaF$^+$ ions formed in the ion source, very pure samples of barium activities have been produced for spectroscopic studies. Thus the decays of four previously unaccessible barium isotopes $^{114-116,118}$Ba could be investigated for the first time [2]. More recently the fluorination technique was also applied to observe α emission from ^{114}Ba [3]. In continuing the studies of disintegration properties of light barium isotopes, we report in this paper on the decay of ^{117}Ba.

The decay of ^{117}Ba was studied for the first time by Bogdanov *et al.* [4,5] who observed β-delayed proton (βp) emission from this isotope, measured its half-life, and determined the energy window open for the βp decay. The analysis of the shape of βp spectra based on statistical-model calculations indicated the existence of a resonance structure in the β-strength distribution for ^{117}Ba [5,6]. The presence of the pronounced structure in the β-strength function was also indicated by the results of βp–γ-ray coincidence measurements [7].

Qualitatively, the concentration of the β-strength at the excitation energy of about 4 MeV can be understood within the single-quasiparticle model by taking into account the deformation as the microscopic-macroscopic calculation predicts a quadrupole deformation $\beta_2 = 0.29$ for the ground state of ^{117}Ba [8]. In the simple deformed single-quasiparticle picture the decay of ^{117}Ba proceeds mainly via the $\pi 7/2^+[413] \rightarrow \nu 5/2^+[413]$ and $\pi 9/2^+[404] \rightarrow \nu 7/2^+[404]$ allowed unhindered transitions to the three-quasiparticle states in ^{117}Cs. The latter ones are formed at 4–5 MeV excitation energy by the respective Gamow-Teller (GT) particle-hole pair, the odd neutron acting as a spectator.

Obviously, the βp measurements reported in refs. [5–7] probed only the part of the β-strength which proceeds to proton-emitting states of ^{117}Cs. To get a complete information on the β-strength distribution the feeding to all states within the Q_{EC} window —including proton and/or γ-decaying levels— has to be determined. So far, in the high-resolution $\beta\gamma$-ray measurements of ^{117}Ba only a few low-energy γ-rays could be identified and the available data were too scarce to construct a decay scheme [2].

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Certainly, more sensitive high-resolution measurements of ^{117}Ba would allow one to construct a partial decay scheme of this isotope. However, as it was demonstrated *e.g.* in the decay studies of odd tin isotopes [9], the high-resolution, low-efficiency measurements fail in general to record all of the many weak γ transitions depopulating highly excited states in the β-decay daughter. As a consequence, only apparent (incomplete) β-feeding of daughter states can be determined. A way to overcome the limitations of the low-efficiency, high-resolution γ-ray spectroscopy is a measurement of the β-feeding distribution by means of a total absorption spectroscopy technique. In this method the total energy released in the γ decay of levels is measured rather than the energy of individual γ transitions. Thus, the total absorption spectroscopy measurements give in principle direct information on the excitation energy and the β population of the nuclear levels. Recently, this technique was proven to provide reliable data on the β-feeding distribution in the $\beta\gamma$-ray decays of spherical nuclei in the ^{100}Sn [10] and ^{146}Gd [11,12] regions, as well as deformed, $N \approx Z$ nuclei in the $A \approx 75$ region [13,14].

In this paper we present results of advanced β-decay studies of ^{117}Ba performed at the GSI on-line mass separator by using the total absorption spectrometer TAS [15] equipped with auxiliary detectors for β-delayed particle detection. This instrument offers a unique possibility for complete studies of the β-decay process involving β-delayed particle emission.

The following section describes the experimental techniques applied in the ^{117}Ba decay measurement. Section 3 presents the details of the analysis of the TAS γ-ray and βp spectra. In sect. 4 the results of the measurements are discussed and compared with predictions of theoretical models. Section 5 gives a summary.

2 Experimental techniques

^{117}Ba was produced in the reaction of a 4.9 MeV/u ^{58}Ni beam and a 2 mg/cm^2 thick ^{63}Cu target. Reaction products recoiling out of the target were stopped in a tantalum catcher inside the hot ion source of the GSI on-line mass separator. By using the cavity-type thermoionizer operating at 2300–2400 K all contaminants except cesium isotopes were removed. The latter were suppressed by a factor greater than 10^5 by addition of CF$_4$ vapour into the ion source. While the thermoionizer converts very efficiently barium to BaF$^+$ ions, CsF$^+$ molecular ions are not formed in the ion source [1].

The isotopically pure ^{117}BaF$^+$ beam was implanted into a transport tape which periodically moved the collected activity into the center of the TAS. The main component of the TAS is a large (⌀36 cm × 36 cm) NaI(Tl) crystal for γ-ray detection. A cylindrical well along the crystal's symmetry axis accommodates an assembly of auxiliary detectors. In the ^{117}Ba decay studies, the standard set-up of two silicon β-particle detectors and germanium X-ray detector was modified by replacing one of the β counters by a telescope for β-delayed particle detection.

The radioactive sources were positioned in air between the 600 μm thick β detector and the telescope consisting of a 35 μm, 150 mm^2 ΔE silicon detector placed at the distance of 1.5 mm from the tape, and a 550 μm, 450 mm^2 E detector mounted 3 mm behind the ΔE counter. The efficiency of the telescope determined in the on-line measurement amounted to $(37 \pm 4)\%$. The βp energy spectra were obtained by coincident summation of the ΔE and E signals, corrected for the average energy loss of protons in air. The corrections were calculated by using the SRIM code [16].

The TAS γ-ray detectors were energy calibrated by using γ-ray sources, the silicon detectors were calibrated using conversion electrons and/or a ^{148}Gd α source as well as a precise pulse generator.

3 Data analysis and results

3.1 Feeding of excited levels by proton emission

In the measurements of βp emitters the TAS crystal registers cascades of γ-rays de-exciting levels in the β-decay daughter as well as γ-rays emitted from the states populated by proton emission. The total absorption spectrum of the γ transitions in the final nucleus can be extracted from the TAS spectrum by requiring coincidence between the TAS signals and protons registered in the ΔE-E telescope. Figure 1 shows the TAS spectrum gated by the protons emitted after β-decay of ^{117}Ba. The three dominant peaks that appear in this spectrum correspond to βp transitions to specific ^{116}Xe levels: The 1022 keV peak indicates proton transitions to the ^{116}Xe ground state after positron decay of ^{117}Ba, while the 394 keV and 394 + 1022 keV peaks correspond to the βp decay to the first-excited state of ^{116}Xe after EC (ECp) and positron (β^+p) decay, respectively. We note that in the case of the EC decay, the proton transition to the ground state of the final nucleus leaves no signal in the TAS crystal.

In an ideal total absorption spectrometer all members of the γ cascade depopulating an excited state would be

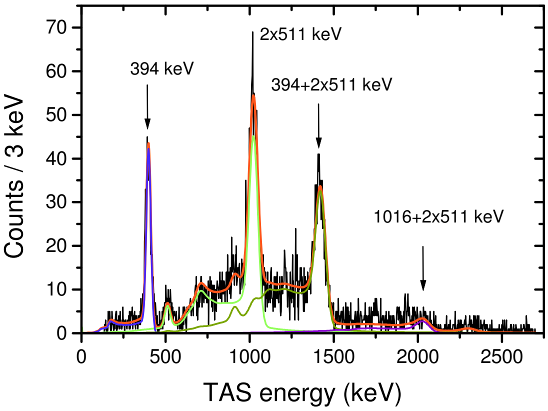

Fig. 1. TAS γ-ray spectrum gated by βp from ^{117}Ba decay. Experimental data (histogram) are compared with the results obtained by simulations. Solid lines indicate components corresponding to βp transitions to selected ^{116}Xe levels.

Table 1. Branching ratios for βp decay of ^{117}Ba to ^{116}Xe states. The last three columns show the branching ratios resulting from the statistical-model calculations performed assuming $3/2^-$, $3/2^+$ or $5/2^+$ for the spin and parity of ^{117}Ba. The uncertainties of the calculated branching ratios account only for the uncertainty of the proton separation value.

^{116}Xe levels		βp branching ratio (%)			
E_f(keV)	I^π	Exp.	Calc.		
			$3/2^-$	$3/2^+$	$5/2^+$
0	0^+	6.5±0.9	9±2	7±1	1.6±0.3
394	2^+	7±1	9±2	8±2	7 ±2
918	4^+	0.7±0.2	0.4±0.1	0.1±0.1	1±0.1
1016	(2^+)	1.2±0.2	0.5±0.1	0.7±0.2	0.5±0.1
1322	(2^+)	0.5±0.2	0.2±0.1	0.2±0.1	0.2±0.1
Total		16±3	19±3	16±3	10±2

added up to yield an output signal whose amplitude corresponds to the excitation energy of the state. The registered signal provides an unambiguous signature of the feeding at this excitation energy. For any real instrument with limited efficiency and resolution, the determination of the β-feeding distribution from the measured spectra requires knowledge of the detector response function and application of deconvolution procedures.

To construct the TAS response functions for the γ decays of ^{116}Xe levels populated in the βp decay of ^{117}Ba we adopted the energies and the decay patterns of ^{116}Xe states known from the literature [17]. For all γ-rays appearing in the decay scheme the response of TAS was simulated by using the GEANT3 package [18]. The detector response for cascades of γ transitions was constructed by folding the TAS spectra simulated for individual γ-rays. The quality of the simulation of γ-ray cascades was verified by comparing the generated detector response with the TAS spectra measured for the ^{60}Co and ^{24}Na calibration sources. Very good agreement between the measured and simulated spectra was achieved. The TAS response for positrons was obtained by simulating their interaction with the different materials present in the detector. The energy spectrum of positrons was sampled from the theoretical distribution with the end-point fixed by the ^{117}Ba Q_{EC} value (see, sect. 3.3) and the excitation energy of the ^{117}Cs levels fed in the β^+-decay. The response of the TAS for the β^+-decay to an excited state was constructed by folding the detector response for positrons with the responses for all γ cascades de-exciting the populated level.

Finally, the shape of the βp-gated TAS spectrum was described as a superposition of the simulated TAS responses for the de-excitation of the ^{116}Xe states. Levels up to the (2_3^+) state at 1322 keV were considered and the intensities of the proton transitions to these levels were treated as fit parameters in a χ^2 minimization procedure. As illustrated in fig. 1, a good description of the βp-gated TAS spectrum was obtained. Table 1 shows the resulting total (β^+p + ECp) intensities of transitions to the ^{116}Xe states. The branching ratios given in the table were normalized to the ^{117}Ba βp decay probability of (16 ± 3)%. The latter value was determined from the number of protons and the number of ^{117}Ba decays observed in the telescope and NaI crystal of the TAS, respectively. The relative intensities of βp transitions for the ground state, the 394 keV and the 1016 keV level of ^{116}Xe agree with earlier results [7].

3.2 Beta-feeding distribution

In the decays of βp emitters the intensity of β transitions is distributed over γ and/or proton-emitting states of the daughter nucleus. The β-feeding of the γ-decaying states can be determined from the analysis of the total absorption γ-ray spectra while the βp energy spectra contain information on the feeding of proton-emitting states.

3.2.1 Beta-feeding of γ-decaying states

The TAS spectra for the case of γ-ray cascades de-exciting levels populated in β^+ or EC decay can be obtained by requiring coincidence between the TAS signals and positrons or by recording TAS signals in coincidence with the X-rays accompanying the EC decay, respectively. The X-ray gated TAS spectra are free from any isobaric contaminants but the low efficiency of the X-ray detector severely limits the statistics of the X-ray coincident spectra. In the case of ^{117}Ba decay studies it turned out to be too low to provide a useful information on the EC decay mode of this isotope.

The β^+-TAS coincidences can be collected with much higher efficiency but the spectra obtained are usually contaminated by events from other β emitters present in the radioactive sources investigated. Contributions from such unwanted activities have to be determined in dedicated measurements and subtracted from the contaminated TAS spectrum. Figure 2 shows the TAS spectrum gated by the positrons registered in the β detector during 30 hours of ^{117}Ba measurement with a 5.6 s/3 s collection/decay period cycle. The spectrum has already been corrected for the contamination by the ^{117}Ba decay products, mainly ^{117}Cs(8.4 s) activity. The contribution of the daughter activity was determined in a separate measurement with a 5.6 s/16 s collection/decay cycle.

The 1022 keV peak visible in the β^+-gated TAS spectrum is a signature of possible feeding of the ^{117}Cs ground state, while the absence of pronounced structures in the high-energy part of the spectrum indicates large spreading of the β-strength at high ^{117}Cs excitation energies.

The deconvolution of the measured spectrum into the β^+-feeding distribution was hampered by the lack of information on the decay patterns of ^{117}Cs levels, these data being needed to construct response functions for the de-excitation of states populated in the ^{117}Ba decay. To solve this problem a schematic model was applied in which the excitation energy of the ^{117}Cs was divided into 200 keV bins. It was assumed that the β-decay of ^{117}Ba with a spin and parity $I_0^{\pi_0}$ proceeds (to the bin centroids) via allowed β transitions. These transitions populate ^{117}Cs

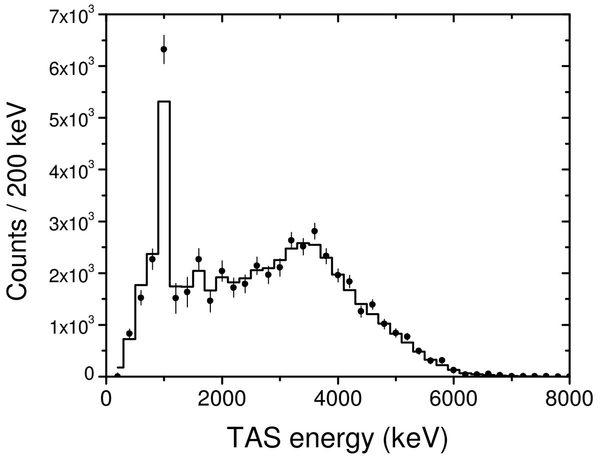

Fig. 2. Total absorption γ-ray spectrum measured for the positron decay of ^{117}Ba (full circles with uncertainties). The solid-line histogram shows the result of the fit obtained by using the simulated decay patterns of ^{117}Cs states and adjusting the intensities of the $^{117}\mathrm{Ba} \rightarrow {}^{117}\mathrm{Cs}$ positron transitions to reproduce the measured spectrum.

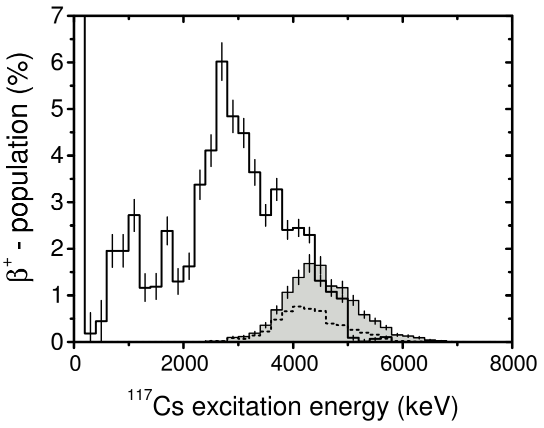

Fig. 3. Population of ^{117}Cs states in the positron decay of ^{117}Ba. The blank histogram shows the population of the γ-decaying states, the shaded histogram the β^+-feeding of proton-emitting states, and the dotted histogram the contribution of the proton transitions to the ^{116}Xe ground state.

states with spins and parities $I_i^{\pi_i} = I_0^{\pi_0}$, $I_0^{\pi_0} \pm 1$ with a probability proportional to the number of spin I_i projections. The process of the γ-ray de-excitation of the levels was treated as a sequence of transitions proceeding from the initial bin via intermediate levels to the ground state. The average partial radiation widths $\langle \Gamma_\gamma^{if} \rangle$ for the $i \rightarrow f$ inter-bin transitions were derived from the statistical model of nuclear electromagnetic de-excitation. Within this approach the radiation widths for $E1$, $M1$ and $E2$ transitions were calculated by using the γ-strength function models proposed by Kopecky *et al.* [19] and the level density formula resulting from the back-shifted Fermi gas model [20]. The model parameters were adopted following the systematic trends in the $A = 110$–120 mass region. Branching ratios for a γ transition between states i and f were calculated as $b_{if} = \langle \Gamma_\gamma^{if} \rangle / \sum_f \langle \Gamma_\gamma^{if} \rangle$. Having a model for the decay scheme of excited states, the TAS response function was constructed by folding the simulated TAS spectra for individual γ transitions within the inter-bin cascades. The contribution of specific de-excitation paths was weighted by the respective branching ratios. The presence of positrons was accounted for by folding the detector response for these particles with the responses for the γ-ray cascades de-exciting the level under consideration.

To obtain information on the relative feeding of the ^{117}Cs states in the positron decay of ^{117}Ba the shape of the β-gated TAS spectrum was fitted by the superposition of the simulated TAS responses for the de-excitation of ^{117}Cs levels. Figure 3 shows that the β^+ population of the γ-decaying ^{117}Cs states resulting from the fitting procedure gives, as illustrated in fig. 2, a reasonable description of the measured TAS spectrum.

3.2.2 Beta-feeding of proton-emitting states

The β-feeding of proton-emitting states can be obtained by adding the proton spectra corresponding to transitions to the final states. To restore the excitation energy of proton-emitting states, the energy scale of the βp spectra has to be shifted to account for the recoil effect, proton separation energy (S_p) and excitation energy of the specific final state.

The individual components of the total βp spectrum can be selected by setting a coincidence condition on the energy observed in the TAS crystal. As an example, fig. 3 shows, drawn as a function of ^{117}Cs excitation energy, the spectrum of protons gated by the 1022 keV peak visible in the TAS spectrum (see fig. 1). This condition selects β^+p transitions to the ^{116}Xe ground state. The shaded histogram in fig. 3 shows the β^+-feeding distribution of proton-emitting ^{117}Cs states with contributions from all final states included. The intensities of the proton spectra were corrected for the efficiencies of the telescope and the TAS gate. The latter values were determined in the analysis of the proton-gated TAS spectra.

A comparison of the β^+-feeding of γ-decaying and proton-emitting states, displayed in fig. 3, indicates that for the ^{117}Cs with the proton separation energy $S_\mathrm{p} = (690 \pm 60)$ keV [21,22], the proton emission starts to outweigh the γ-decay at the excitation energy of about 4.5 MeV.

3.2.3 (EC+ β^+)-feeding and β-strength distribution

The β^+ intensity distribution for ^{117}Ba was obtained by adding up the population of states obtained from the analysis of the TAS γ-ray data (see sect. 3.2.1) and the feeding of the states resulting from the analysis of the β^+p spectra (see sect. 3.2.2). The total (EC+β^+) intensities of the β-decay branches were calculated by using the experimentally determined β^+ population and by applying the theoretical values of the EC/β^+ decay ratio [23]. The upper part of fig. 4 shows the resulting (EC+β^+)-feeding distribution (normalized to 100%) for the decay of ^{117}Ba. These

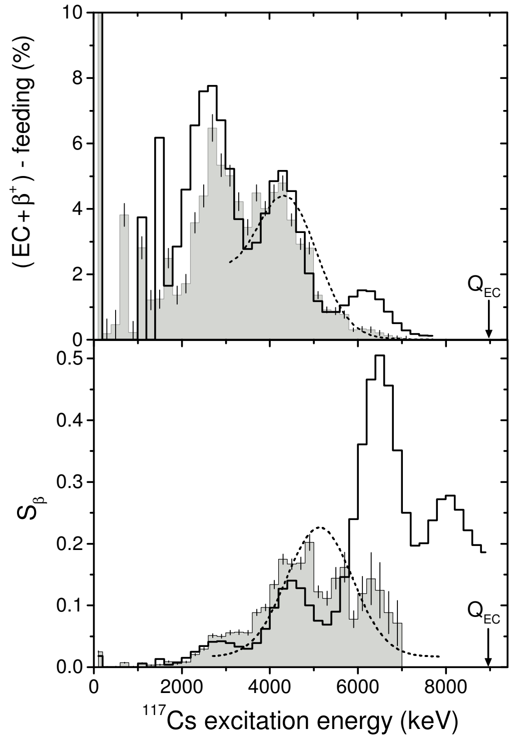

Fig. 4. Upper part: (EC+β^+)-feeding distributions (integrated in 200 keV energy intervals) for the decay of ^{117}Ba, determined experimentally (shaded histogram), predicted by the pn-QRPA calculation [25] (blank histogram) and resulting from the schematic β-strength model proposed in ref. [6] (dotted line). The experimental uncertainties shown account for contributions from counting statistics and the EC/β^+ ratio. Lower part: Beta-strength distributions corresponding to the intensity distributions shown in the upper part of the figure, *i.e.* those from experiment (shaded histogram), obtained in pn-QRPA calculations [25] (blank histogram) and proposed (with arbitrary normalization) in ref. [6] (dotted line). The experimental $Q_{\rm EC}$ value is indicated by an arrow.

data yield a $(20 \pm 4)\%$ population of the ground state and reveal enhanced feeding of a group of states between 2 and 5 MeV ^{117}Cs excitation energy.

The distribution shown in the upper part of fig. 4 was used to calculate the respective β-strength function according to the formula: $S_\beta = (3834\,{\rm s})/ft$. The $Q_{\rm EC}$ value of (8990 ± 260) keV as determined in sect. 3.3 and the half-life $T_{1/2} = (1.75 \pm 0.07)$ s [7] were used in the calculations.

The integrated (up to the 6.5 MeV excitation energy) β-strength amounts to (2.4 ± 0.1). We note that although the βp transitions represent only a $(16 \pm 3)\%$ branch in the decay of ^{117}Ba, they represent a fraction of more than 60% of the total observed S_β.

3.3 Determination of $Q_{\rm EC} - S_{\rm p}$ value

The ratio of the EC-delayed and β^+-delayed proton spectra ($I_{\rm ECp}/I_{\beta {\rm p}}$) plotted as a function of the energy of emitted particles depends only on the energy window open for the βp emission and can be used to determine the $Q_{\rm EC} - S_{\rm p}$ energy difference. Figure 5 shows the $I_{\rm ECp}/I_{\beta^+{\rm p}}$ ratio as a function of proton energy in the decay of ^{117}Ba to the first-excited 2^+ state of ^{116}Xe. The respective proton spectra were obtained by setting the gate condition on the 394 and $394 + 1022$ keV lines in the TAS spectrum (see fig. 1) and corrected for the TAS gate efficiencies. The experimental data points were fitted by the theoretical $I_{\rm ECp}/I_{\beta {\rm p}}$ ratio with the $Q_{\rm EC} - S_{\rm p}$ energy difference as the only free parameter. The χ^2 minimization procedure yielded the $Q_{\rm EC} - S_{\rm p}$ value of (8300 ± 250) keV, in agreement with the $Q_{\rm EC} - S_{\rm p} = (7900 \pm 300)$ keV determined by Bogdanov *et al.* [5]. The $Q_{\rm EC} - S_{\rm p}$ value determined in this work, together with the recently measured ^{117}Cs proton separation energy $S_{\rm p} = (690 \pm 60)$ keV [21,22] yields $Q_{\rm EC} = (8990 \pm 260)$ keV for ^{117}Ba, close to the $Q_{\rm EC}$ value of (9160 ± 310) keV derived from systematic trends [24].

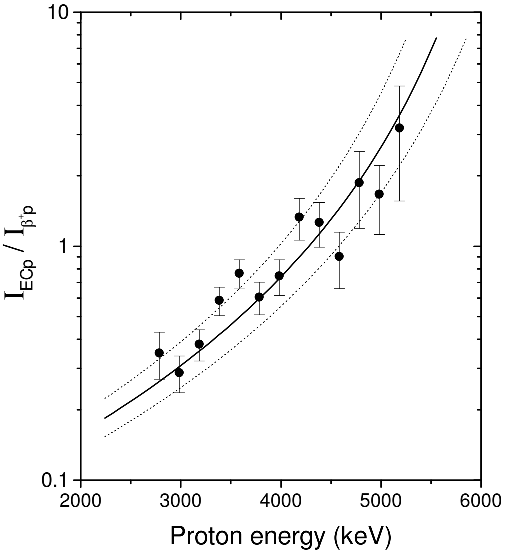

Fig. 5. The $I_{\rm ECp}/I_{\beta^+{\rm p}}$ ratio as a function of proton energy in the ^{117}Ba βp decay to the first-excited 2^+ state in ^{116}Xe. The solid line represents the best fit of the theoretical $I_{\rm ECp}/I_{\beta^+{\rm p}}$ ratio to the data points, yielding a $Q_{\rm EC} - S_{\rm p}$ value of 8300 keV. The dotted lines indicate the $I_{\rm ECp}/I_{\beta^+{\rm p}}$ ratio calculated for the $Q_{\rm EC} - S_{\rm p}$ changed by the standard deviation of ± 250 keV.

4 Discussion

The analysis of the TAS data allowed us to extract quantities which can be directly compared to the theoretical predictions or used as input parameters in model calculations.

In the lower part of fig. 4 the experimentally determined β-strength distribution is compared to the results of the pn-QRPA calculations of Hirsch *et al.* [25] and to the β-strength function proposed by Tidemand-Petersson [6]. The latter distribution results from the analysis of the ^{117}Ba βp spectrum where a resonance in the β-strength function had to be introduced to properly describe the spectral shape and the relative branching ratios of the observed βp transitions. Such analysis can probe only the part of the β-strength distribution which is placed at proton-emitting states, *i.e.* at ^{117}Cs excitation energies higher than 3 MeV. In this excitation energy range the schematic model of β-strength function proposed in ref. [6] roughly reproduces the position and the spreading of the measured β-strength, as shown in fig. 4.

The pn-QRPA calculations reasonably well describe the measured β-strength distribution up to the excitation energy of about 5.5 MeV. However, there is no experimental evidence for the strength predicted by the theory to lie at ≈ 6.5 MeV which should result in the β-feeding intensity exceeding by far the experimental value (see upper part of fig. 4).

In the pn-QRPA calculations the position of the resonance structure depends on the strength of the particle-hole (ph) force of the GT residual interaction, whereas the interaction in the particle-particle (pp) channel and the deformation effects are responsible for the suppression and redistribution of the calculated β-strength. In the calculations performed in ref. [25] the strength of the pp and ph interaction was fixed within an isotopic chain and adjusted to reproduce the known half-lives. As was verified *e.g.* by the half-life measurements of the very neutron-deficient barium isotopes [2], such procedure turns out to be successful in predicting the half-lives of unknown nuclei. However, due to the very strong dependence of the statistical rate function f on the transition energy, the β-decay probability is determined mainly by the transitions to the lowest-lying states. Moreover, as discussed in ref. [25], the values obtained for the strength of the ph and pp interactions are rather uncertain. These arguments may, at least partially, explain why the reasonable agreement between the calculated and measured β-strength distribution at low excitations, and the related agreement with respect to half-lives, do not withstand a disagreement between theory and experiment at higher excitation energies.

The survey investigations of the βp emitters in the *trans*-tin region [7] have led to the conclusion that the statistical model [26,27] gives an adequate description of the βp decay process. However, this general statement was undermined by the unresolved questions regarding the proper choice of the model parameters and applied description of the β-strength function. The results of the present study of the ^{117}Ba decay have provided experimental information on the β-feeding distribution that has allowed us to make a further step in testing the statistical model of the βp decay. Within this model the partial proton widths of ^{117}Cs levels decaying to the ground state and excited levels of ^{116}Xe were calculated using the set of optical-model potential parameters proposed by Johnson *et al.* [28] and the back-shifted Fermi gas level density formula [20]. The total radiation widths of the ^{117}Cs states were calculated according to the prescription outlined in sect. 3.2.1.

Table 1 shows the branching ratios for the βp transitions to the ^{116}Xe states calculated assuming spin and parity $3/2^-$, $3/2^+$ and $5/2^+$ for the decaying ^{117}Ba state. These values of spins and parities correspond to the quantum numbers of Nilsson orbitals located at the neutrons Fermi level in the β_2 deformation range 0.15–0.3. A comparison of the experimental and calculated branching ratios indicates that the assumption of the decay of a $5/2^+$ state results in a strong underestimation of the feeding of the ^{116}Xe ground state. For the spin 3/2 the measured values are, within given uncertainties, reproduced by the model for both parities. The final assignment of the parity of the decaying ^{117}Ba state has been based on the observation that the feeding of the ^{117}Cs ground state occurs with a $\log ft$ value of 5.2. Such low $\log ft$ value excludes β transitions involving a parity change and implies the same parity of the ^{117}Ba and the ^{117}Cs ground states. Since the parity of the ^{117}Cs can be safely assumed to be positive, we assign $I_0^{\pi_0} = 3/2^+$ to the ^{117}Ba ground state. This conclusion is in agreement with the predictions of the microscopic-macroscopic calculations of Möller *et al.* [8].

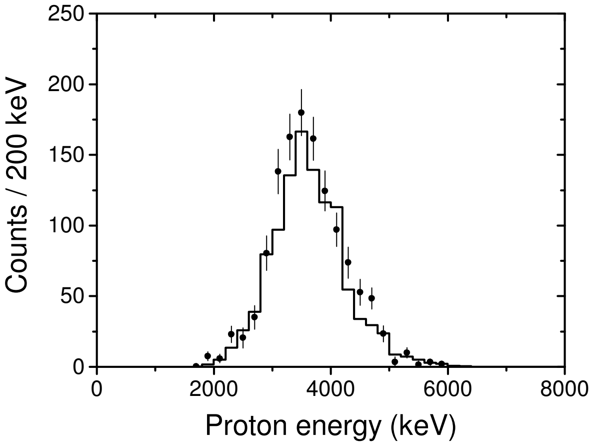

Fig. 6. Energy spectrum of protons emitted after positron decay of ^{117}Ba to the ^{116}Xe ground state. The histogram shows the results of the statistical-model calculations performed assuming $3/2^+$ for the spin and parity of ^{117}Ba and using the experimental β^+-feeding distribution.

With the ^{117}Ba spin and parity fixed to $3/2^+$ we performed calculations of the energy spectra of β-delayed protons emitted in the decay of this isotope. Figure 6 shows the comparison of the measured and calculated spectra of β^+-delayed protons emitted to the ground state of ^{116}Xe. A very good description of the shape and the intensity of the measured proton spectrum was obtained. Since the experimental β-feeding distribution was used in the calculations, the very good agreement between the measured and calculated proton spectra indicates that the statistical model with the set of optical model, level density and the γ-strength function parameters applied, properly describes the evolution of the ratio of the partial proton decay and the total decay width with the excitation energy of ^{117}Cs.

Another constraint on the input parameters of the statistical model can be obtained by using the proton–X-ray coincidence technique (PXCT). It has been demonstrated that this method yields information on the lifetime of the proton-emitting nuclear levels [29].

When the ^{117}Ba decays by the K-electron capture to the excited nuclear state it produces a vacancy in the atomic K-shell. If the excited ^{117}Cs state is proton unstable then, depending on whether the vacancy was filled before or after the proton emission, the X-rays related to the filling process are emitted characteristic for cesium or xenon, respectively. The relative intensities of the Xe KX- and Cs KX-ray peaks observed in coincidence with protons relate the nuclear level lifetime and the lifetime of the cesium K-shell vacancy. The latter value amounts to $5.3 \cdot 10^{-17}$ s [30].

The TAS enables a refinement of the PXCT measurements by introducing the possibility of selecting the final state populated in the βp decay. In the PXCT analysis of the ^{117}Ba decay, proton transitions to the ^{116}Xe 2^+ state were selected by setting a gate on the 394 keV peak in the TAS spectrum. In the double (proton and TAS) gated X-ray spectrum only a few counts at the position of Xe KX-rays were observed resulting in an upper limit of 0.04 for the XeKX/CsKX intensity ratio. This value is consistent with the calculated XeKX/CsKX intensity ratio of 0.02 which corresponds to an average value of 70 meV for the total width of ^{117}Cs levels at an excitation energy of 4.5 MeV.

5 Summary

In summary, the β-decay of ^{117}Ba was studied at the GSI on-line mass separator. The application of the chemically selective ion source of the separator enabled the preparation of very clean ^{117}Ba sources for spectroscopic studies. The decay of ^{117}Ba was investigated by using the TAS spectrometer equipped with a telescope for βp detection. The measured spectra of totally absorbed γ-rays and β-delayed protons were used to derive the β-feeding of excited states in ^{117}Cs and to determine branching ratios for βp transitions to ^{116}Xe levels.

The β-strength distribution obtained from the combined analysis of the $\beta\gamma$ and βp data revealed the existence of a broad resonance at a ^{117}Cs excitation energy of about 4.5 MeV. The observed β-strength distribution is reasonably well reproduced by pn-QRPA calculations up to an excitation energy of about 5.5 MeV but there is no experimental evidence for the GT-strength predicted by the theory to lie at ≈ 6.5 MeV excitation energy. This deficiency of the model is most probably due to the uncertainty in estimating the strength of residual interactions used in the calculations.

The experimentally determined β-strength distribution was used in statistical-model calculations of the βp process. The branching ratios and the shape of the proton spectra were well reproduced. This observation indicates that the statistical model offers a satisfactory description of the βp emission process, provided the key input parameters of the model (Q_{EC} and S_{p} value, β-strength function, spins and parities of initial and final states) are reliably determined. In particular, the statistical model appears to properly describe the competition between the γ-ray and the proton emission from highly excited states.

The experimental method presented in this work demonstrates the possibility of comprehensive decay studies of β-delayed particle emitters. As such nuclei are usually characterized by large Q_{EC} values, the β-strength distribution can be investigated and confronted with theoretical predictions over a broad range of excitation energies. In this context we note that reliable data on the GT-strength distribution in the decays of neutron-deficient nuclei in the ^{100}Sn [10] and ^{146}Gd [11,12] regions are already available and that very recently β-strength functions for the deformed nuclei in the $A \approx 75$ region were measured [13,14]. These data offer a unique possibility to test theoretical calculations and/or to determine relevant model parameters.

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