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Resonance Structure in the Beta-Strength Function Indicated by Beta-Delayed Particle Emission from ^{110,112}I, ^{113}Xe, ^{114,116}Cs, and ^{117}Ba

P. Tidemand-Petersson, A. Płochocki

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Gesellschaft für Schwerionenforschung mbH
Planckstr. 1 · Postfach 110541 · D-6100 Darmstadt 11 · Germany

RESONANCE STRUCTURE IN THE BETA-STRENGTH FUNCTION INDICATED BY BETA-DELAYED PARTICLE EMISSION FROM $^{110,112}I$, ^{113}Xe, $^{114,116}Cs$ AND ^{117}Ba

P. Tidemand-Petersson[1)]

GSI-Darmstadt, D-6100 Darmstadt, Federal Republic of Germany

and

A. Płochocki

Institute of Experimental Physics, University of Warsaw, 00-681 Warsaw, Poland

ABSTRACT

The beta-delayed proton and alpha-particle emission from the precursors $^{110,112}I$, ^{113}Xe, $^{114,116}Cs$ and ^{117}Ba has been investigated using fusion-evaporation reactions, on-line mass separation and decay spectroscopy. Comparison of the results with theory revealed that satisfactory agreement is only achieved by introducing into the beta-strength function a resonance, whose position and strength agree with results of simplified Nilsson-model calculations.

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1) Present address: II. Physikalisches Institut, Universität Göttingen, Bunsenstr. 7-9, D-3400 Göttingen, Fed. Rep. of Germany

Beta-delayed particle emission is a two-step process, which for medium-mass and heavy precursors involves a large number of states in the intermediate nuclei. It is, therefore, described theoretically by the statistical model [1,2], which combines the treatments of the beta decay and the subsequent particle emission. Accordingly, the information extracted from ß-delayed particle spectroscopy is normally concerned with gross properties of the nuclides like level density and strength functions.

Following the studies of ^{114}Cs [3], for which a resonance in the underlying **ß-strength function** S_β [4] was proposed, we have undertaken a systematic investigation of ß-delayed particle emission from precursors with $50 \leq Z \leq 56$. The identification of $^{103,105}Sn$ has been published [5], and the experimental details and the observed decay properties of the precursors from tellurium through cesium will be presented in a more extended paper [6]. Suffice it therefore here to mention that the activity was produced in ^{58}Ni-induced fusion-evaporation reactions followed by on-line mass separation. In this letter we shall focus on the conclusions drawn from comparisons of measured intensities and energy distributions with the corresponding calculated quantities for the lightest known isotopes of iodine, xenon, cesium and barium, while for the tin isotopes the intensities did not suffice for such studies.

Some of the precursors treated here have already been investigated by other groups [7-9]. However, this represents the first attempt to perform a more complete study of the process in this mass region, it includes for the first time the iodine isotopes, and it takes advantage of the additional data which have recently become available on precursors in this region from more detailed studies, e.g. application of the particle X-ray coincidence technique (PXCT) on ^{99}Cd and ^{115}Xe [10] and ^{113}Xe [11], thus allowing more reliable extrapolations to be made for the nuclides studied here.

By comparison of experimental spectra with the corresponding ones from statistical-model calculations, conspicuous deviations were met, when i) constant S_β, ii) level densities from Gilbert and Cameron [12,13] and iii) γ-emission widths from Cameron [14] (in the following this combination is referred to as standard parameters) were applied: in analogy to what has been reported for ^{109}Te [15], ^{114}Cs [3] and $^{117,119}Ba$ [9], the precursors $^{110,112}I$ and ^{113}Xe also show experimental spectra having their maxima at particle energies being 0.3 - 1.7 MeV higher than those of the calculated ones. As an example, fig. 1 shows the particle spectra of ^{110}I.

Furthermore, we have for the first time compared the experimental and calculated energy dependence of the fraction of proton emissions feeding an excited state in the daughter nucleus. The results for the precursor ^{113}Xe, displayed in fig. 2, show clearly, that the curve (a) obtained with standard parameters fails to reproduce the experimental ratios, especially where the latter are decreasing between 3 and 4 MeV proton energy.

Keeping in mind the success of the statistical model in the cases of $^{115,117}Xe$ [1] and $^{118,120}Cs$ [2], which are situated close to the precursors studied here, it is natural to question, which of the parameters entering the calculations may cause deviations for the more neutron-deficient precursors. In the following the variations performed in the attempt to bring simultaneously particle spectra and branching ratios in accordance with the experimental results are described.

Previous and recent measurements of $Q_{EC}-S_p$ values [6,8,9,16], i.e. the energy available for proton emission, and Q_α-values [17] have yielded decay-energy parameters for ^{110}I, ^{113}Xe, $^{114,116}Cs$ and ^{117}Ba. It is therefore obvious that wrong assumptions on nuclear masses cannot be responsible for the discrepancies. Furthermore, only minor changes in the

positions of the maxima of the calculated spectra result from variations of the energies, as long as they are kept within the limits given e.g. by different mass predictions.

The interpretation of PXCT and (n,γ) experiments led Hardy to the conclusion [18] that the Gilbert-Cameron level densities [12,13] are generally too low. With an enhanced level density the predicted γ-emission level widths Γ_γ were considered [18] to be correct within a factor of two, when calculated using the prescription of Bartholomew et al. [19]. The formula of Cameron [14], which is used for Γ_γ in our calculations, is known to yield values somewhat smaller than those of Bartholomew et al., and we have consequently, in line with the interpretation of the first PXCT experiments [20-22], introduced multiplicative correction factors to Γ_γ and the level-density parameter $\underline{a}$. With a chosen upper limit of 1.33 for the $\underline{a}$-factor, it appeared that in order to shift the calculated spectra all the way to agreement with experiment, enhancement factors for Γ_γ ranging from 8 and upwards were needed. For ^{110}I e.g., a factor of 10 together with the 33% increase of $\underline{a}$ sufficed only to bring the proton spectrum half of the way to agreement (see curve II in fig. 1), and simultaneously the calculated proton branching ratio was reduced by an order of magnitude from $3.5 \cdot 10^{-2}$, which is already slightly lower than the experimental value $(11 \pm 3) \cdot 10^{-2}$ [6,16]. Furthermore such variations for ^{113}Xe did not eliminate the disagreement of the 2^+-feeding in ^{112}Te (see fig. 2), and it was therefore concluded, that even if the level density and γ-ray emission widths may be predicted too low, they cannot alone be responsible for the observed deviations.

Variations of the optical-model parameters, which are entering the particle-emission widths and were taken from Becchetti and Greenless [23], had essentially the same effect as an enhancement of $\underline{a}$, when the changes were restricted to imply a shift of the maxima of the calculated spectra towards higher energies, since in both cases the proton-emission level widths were reduced. We have, therefore, finally focussed our attention onto the β-strength function S_β. In order to study the local behaviour of S_β, we have performed simplified Nilsson-plus-pairing model calculations, including also blocking effects. We applied here potential parameters ($\kappa_p = 0.0662$, $\mu_p = 0.540$, $\kappa_n = 0.0637$ and $\mu_n = 0.450$) and deformation parameters ε (only quadrupole deformation was considered, and the values are given in fig. 3) as recommended by Ekström et al. [24]. The pairing-gap parameters were averaged for this region and taken to be Δ_p = 1.2 MeV and Δ_n = 1.3 MeV.

Due to the occupation coefficients, only two allowed-unhindered (au) β-transitions can contribute essentially to S_β in this area: $(7/2+[413])_\pi \rightarrow (5/2+[413])_\nu$ and $(9/2+[404])_\pi \rightarrow (7/2+[404])_\nu$. They both originate from the paired-nucleon system in the precursors and thus lead to 4(3)-quasiparticle states in the even(odd)-A daughters. The position and relative strength of these transitions were calculated for the eight precursors shown in fig. 3. For ^{113}Xe and ^{114}Cs we derived also all allowed-hindered (ah) and first forbidden (1f) β-transitions leading to states situated above the pairing gap [2,4] and below the Q_{EC}-value in the daughter nuclides. To obtain the strength of the various transitions, we assumed average ft-values, corrected for pairing and statistical factors [25], of $1.6\cdot10^4$, $2.5\cdot10^5$ and $3.2\cdot10^6$ for au, ah and 1f transitions, respectively. Because of the large number of ah and 1f transitions (∿200 for each precursor), the average values are assumed to work well for these transitions. But since transition probabilities are distributed according to the Porter-Thomas law [26], it may well be that the assumed strengths of the two au transitions deviate considerably from the real ones. In order to estimate the accuracy of the applied values, we used the calculated strengths to obtain theoretical half-lives of 4.2 s and 2.0 s for ^{113}Xe and

^{114}Cs, respectively. These values agree reasonably well with the experimental values of 2.74±0.08 s [6] and 0.57±0.02 s [3], but are both slightly too high, thus indicating that the strength of the au transitions is indeed of the same order of magnitude as the average value, but maybe slightly larger. The resulting S_β for ^{113}Xe and ^{114}Cs are given together with the au transitions for the remaining precursors in fig. 3.

The presence of the strong au β-transitions, which in reality are assumed to be distributed over several final levels, was in our statistical-model calculations taken into account by adding to the constant S_β, that was applied earlier [1,2,4], a Gaussian resonance. The parameters of the Gaussian (position in excitation energy, strength relative to the constant term and width) were then varied until agreement between experimental and calculated proton spectra was obtained. Because of the similarity of the precursors treated here, the width was demanded to be the same in all cases. The β-strength functions resulting for the six cases investigated here, are shown in fig. 3 together with independently derived strengths for ^{115}Xe [1] and ^{119}Ba [9]. The resonance for ^{116}Cs is exceptional in the sense that the position corresponds to the proton energy at which the maximum intensity was obtained also for constant S_β, thus explaining why agreement in spectral position could be achieved without modification [8]. We wish to stress, however, that the introduction of a resonance in S_β brought the spectral shape more in accordance with the experimentally observed one.

The generally satisfactory agreement between the derived S_β-resonances and the calculated au transitions together with the fact that the fitting procedure of the proton spectra brought also considerably better agreement for the α-spectra (fig. 1b) and the energy dependence of the branching to the excited states for the ^{113}Xe precursor (fig. 2), are taken as evidence for the presence of the S_β-resonances. Especially the trend shown in fig. 2 can only be reproduced by theory under assumption of such a resonance.

In conclusion we thus state that the β-decay of the most neutron-deficient nuclides studied in the region above the Z = 50 shell have sufficiently large Q-values to make resonances, arising from the population of 3- or 4-quasiparticle states via allowed-unhindered β-transitions, observable. This is also supported by earlier results for ^{109}Te [15] and ^{117,119,121}Ba [9] as well as by theoretical arguments [27-29]. Although proposed enhancements of γ-emission level widths and level densities were included into the statistical-model calculations, agreement with all experimental data from the β-delayed particle precursors could only be achieved by the introduction of a resonance in the β-strength function.

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Figure Captions

Fig. 1: Experimental (histograms) and calculated β-delayed proton (a) and α-particle (b) spectra of ^{110}I. The theoretical curves were obtained with the statistical model applying (I): standard parameters (see text for explanation), (II): constant β-strength function S_β, enhanced level-density parameter $\underline{a}' = 1.33 \cdot \underline{a}$ and γ-emission widths $\Gamma'_\gamma = 10 \cdot \Gamma_\gamma$, and (III): $S_\beta = 0.1 + \frac{2.0}{0.7 \cdot \sqrt{2\pi}} \cdot \exp\{-\frac{(E-8.0)^2}{2 \cdot 0.7^2}\}$, where E is the excitation energy in the intermediate nucleus ^{110}Te in MeV, and the enlarged values $\underline{a}' = 1.33 \cdot \underline{a}$ and $\Gamma'_\gamma = 3 \cdot \Gamma_\gamma$. In all cases we used for ^{110}I: $I^\pi = 1^+$ and Q_{EC} = 11.44 MeV, and for ^{110}Te: S_p = 3.36 MeV and Q_α = 2.72 MeV. For each calculated set of spectra, a scaling factor brought the proton spectrum to the same height as the experimental one, and the same factor was then applied to the α-spectrum, so that the area under the smooth α-spectra relative to that of the histogram can be taken as a mass of how well the calculations reproduce the experimental p/α-ratio.

Fig. 2: The fraction of β-delayed protons from ^{113}Xe observed in coincidence with the $2^+ \rightarrow 0^+$ γ-transition in ^{112}Te (the decay process is shown as inset) given as function of the proton energy. The experimental points are shown together with three curves resulting from statistical-model calculations under assumption of $I^\pi(^{113}Xe) = 5/2^+$ and application of (a): standard parameters (see text),

(b): constant S_β , $\underline{a}'=1.33\cdot\underline{a}$ and $\Gamma'_\gamma=2.5\cdot\Gamma_\gamma$, and

(c): $S_\beta = 0.1 + 0.02\cdot E + \frac{1.5}{0.7\cdot\sqrt{2\pi}} \exp\{-\frac{(E-5.65)^2}{2\cdot 0.7^2}\}$, enhanced level density (as "b") and unchanged γ-emission widths (for nomenclature, see caption for fig. 1). The last curve is clearly offering the best agreement with the experimental points, which represent the sum of data from two individual measurements.

Fig. 3: Comparison of β-strengths resulting from the Nilsson-model calculations described in the text, with those obtained from a fitting procedure. For six of the precursors the vertical bars represent the two important allowed-unhindered β-transitions: $7/2[413]_\pi \rightarrow 5/2[413]_\nu$ (filled bars) and $9/2[404]_\pi \rightarrow 7/2[404]_\nu$, whereas for ^{113}Xe and ^{114}Cs the histograms give the sum of all allowed and first-forbidden β-transitions leading to levels situated above the pairing gap, but below the Q_{EC}-value. The quadrupole deformations applied for the individual nuclides are given in the figure; for ^{116}Cs is shown, as an example, the dependence on deformation. For ^{115}Xe the β-strength was taken from ref. [1], while for ^{119}Ba the curve represents a smooth version of the $S_\beta \cong I_p(\text{exp.})/I_p(\text{calc.})$ ratio of ref. [9]. For the remaining six precursors the curves are the strength functions offering the best agreement with the experimental β-delayed proton spectra (see text). The vertical dashed lines indicate the region of excitation energy available for β-delayed proton studies: $S_p<E<Q_{EC}$.

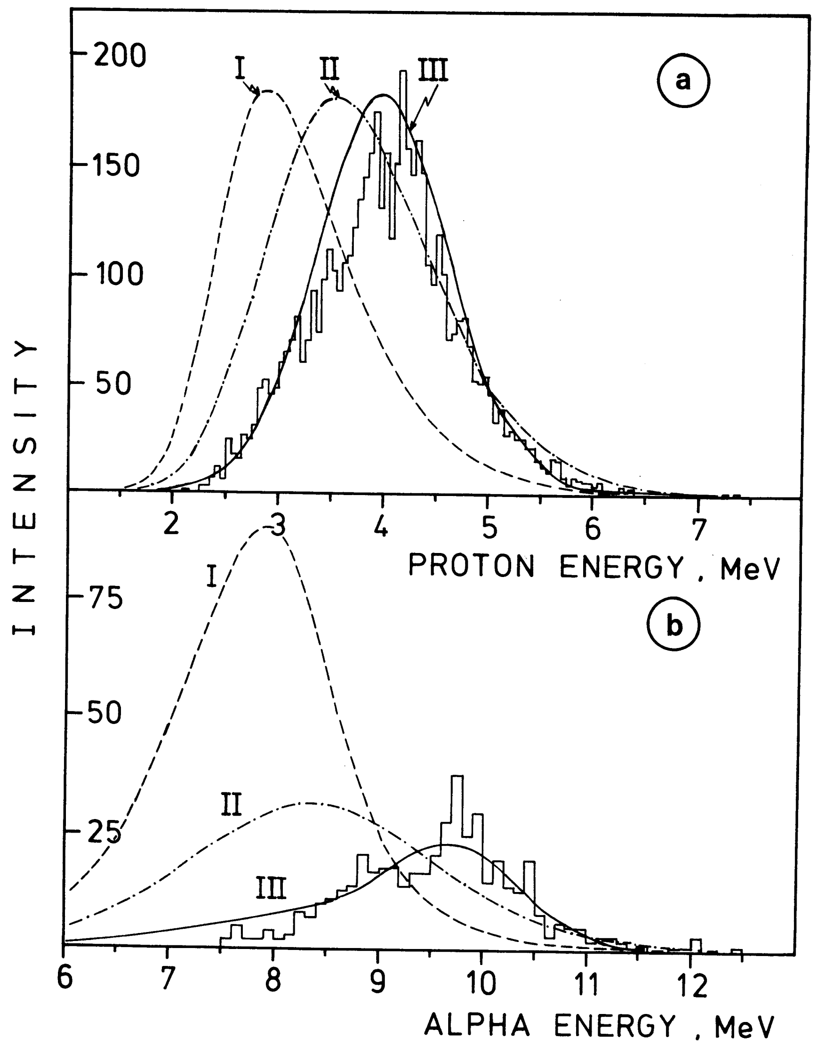
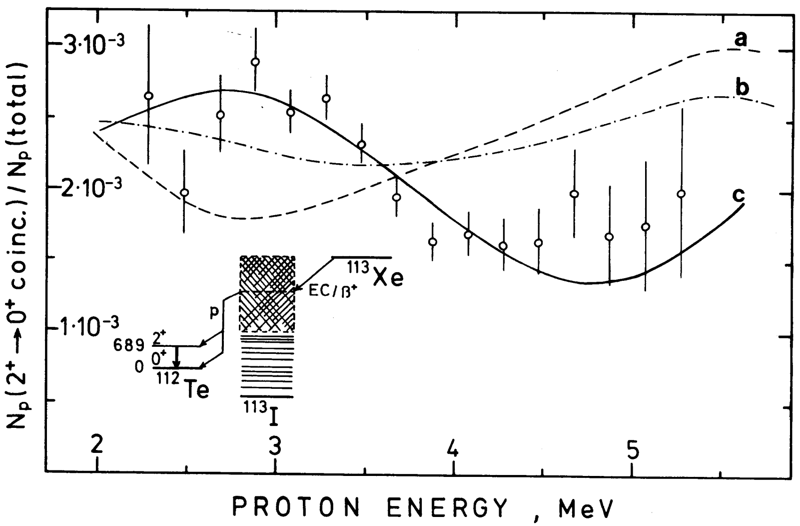
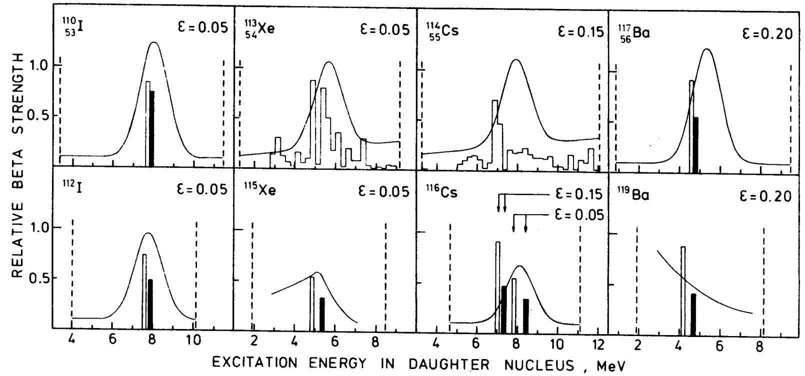


fig. 1



$N_p(2^+ \to 0^+$ coinc.$) / N_p$(total)
3·10⁻³
2·10⁻³
1·10⁻³
a
b
c
689 2⁺
0 0⁺
112Te
113I
113Xe
EC/β⁺
p
2
3
4
5
PROTON ENERGY , MeV

fig. 2



RELATIVE BETA STRENGTH
110 53I
ε=0.05
113 54Xe
ε=0.05
114 55Cs
ε=0.15
117 56Ba
ε=0.20
112I
ε=0.05
115Xe
ε=0.05
116Cs
ε=0.15
ε=0.05
119Ba
ε=0.20
EXCITATION ENERGY IN DAUGHTER NUCLEUS , MeV

fig. 3