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Ch. Miehé, Ph. Dessagne, J. Giovinazzo, G. Walter, J. Dudek
Centre de Recherches Nucléaires/IN2P3 et Université Louis Pasteur
67037 Strasbourg, France

C. Richard-Serre
IN2P3, 75781 Paris, France INPNPP

O. Tengblad
PPE Division/ISOLDE CERN, CH 1211 Geneva 23, Switzerland

M.J.G. Borge
Instituto de Estructura de la Materia, E 28006 Madrid, Spain

B. Jonson
Chalmers University of Technology, Göteborg, Sweden

and the ISOLDE Collaboration

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Abstract

The β delayed proton emission of the T_z=1/2 precursors ^{65}Ge, ^{69}Se, ^{73}Kr, ^{77}Sr is analysed in terms of statistical behaviour including fluctuation phenomena. Average values of level spacing, partial particle width and total level width are obtained for the proton emitting isotopes. Indications arise for specific structure effects in both the β strength function and the particle emission process.

Introduction

When going far off stability, the β^+-EC delayed particle emission offers an unparalleled access to the low spin states providing various spectroscopic information over a large excitation energy range, on levels that cannot be reached via in beam work.

In the A=70 neutron deficient mass region, this process is of special interest to be studied. First on the spectroscopic point of view, as a lot of specific features are observed or predicted in this area located along the N=Z line, which is therefore well suited to search for marked nuclear structure effects in both, the beta decay and the proton emission process. The unbound states, mainly populated by the electronic capture process, exhibit lifetimes in the vicinity of the electronic K shell filling time ($t \sim 2.0\ 10^{-16}$s) and proton-X-ray coincidence measurements allow the level widths to be approached[1]. Secondly in terms of average nuclear properties like mean level spacings and partial particle widths. Especially, the lack of data on level density in this mass region is conspicuous as outlined in a recent compilation[2]. Moreover as information in that field results mainly from neutron resonances data and reflects therefore the properties of the neutron rich nuclear matter, it is worthwhile to explore the proton rich side of the valley of stability.

The delayed proton emission of the T_z=1/2 precursors ^{65}Ge, ^{69}Se, ^{73}Kr and ^{77}Sr has been investigated with improved experimental conditions as compared to previous work[3,4,5]. In addition to the average nuclear properties, this new approach yields a more precise insight of the local behaviour of the quantities of interest, and allows to search for pronounced structure effects. In particular, strongly deformed proton unbound levels, which can be populated by the β^+-EC decay of T_z=1/2 precursors, are predicted in the emitters ^{65}Ga, ^{69}As, ^{73}Br and ^{77}Rb. Such states are expected to exibit short lifetimes for which a signature could be found from the proton-X coincidence data.

Experimental procedure

The ^{65}Ge and ^{69}Se nuclei have been obtained by fusion evaporation reactions induced on a ^{40}Ca target respectively by ^{28}Si and ^{32}S ion beams at tandem energies and collected using the He-jet technique.

The isotopes ^{73}Kr and ^{77}Sr have been produced by a Nobium target fragmentation, respectively at the ISOLDE II and ISOLDE PSB facilities at CERN with typical rates of 3.10^5 and $1.7\ 10^4$ atoms s^{-1}. In the case of ^{77}Sr, a chemical selectivity was used to avoid the ^{77}Rb contamination. This is achieved by selecting the SrF^+ molecular beam generated by adding a low partial pressure of CF4 in the ion source[6].

In all cases, the species of interest are collected on an aluminized mylar tape and transported to the counting station dedicated to the direct proton detection, as well as to proton-X and proton-gamma coincidences measurements. The delayed particles are detected either by a water cooled Si(Au) surface barrier (280 mm^2 sensitive area, 100 μm thickness) or by a boron implanted silicon detector subtending a solid angle of around 20 % of 4π. A typical FWHM of 15 to 17 keV has been obtained for the 5486 keV alpha line of ^{241}Am. A 300 mm^2 large area Si(Li) counter faces the proton detector in a close geometry, allowing efficient proton X-ray coincidence measurements. It covers a solid angle of 16 % of 4π and its energy resolving power is 310 eV at 14 keV. In addition, detailed β delayed γ-spectroscopy measurements have been performed to establish the overall decay scheme of the four isotopes[7,8].

Results and data analysis

The delayed proton energy spectra of the different $T_z = 1/2$ precursors range from around 1 MeV up to close to the Q_{EC}-Sp value (Fig.1a) and show a lot of well marked structures. High detection efficiency and good energy resolution permit to lower to 10^{-6} the measured β-EC branching and to establish the Gamow-Teller strength distributions up to around 97 % of the Q_{EC} windows.

From the proton-X-ray coincidence data, the total X(Z-2)/X(Z-1) ratio R_x, proportional to the mean level width over the whole excitation energy range concerned by the proton emission, could be inferred for the emitters ^{65}Ga, ^{69}As, ^{73}Br and ^{77}Rb. In the case of ^{69}As and ^{73}Br statistics were good enough to allow the X-ray ratios to be analysed according to the structure of the proton spectrum. The measured variation as a function of proton energy is reported in Fig.2.

With the aim to search for specific structure effects and to extract information on the average values of level spacing and reduced partial width, the registered data are compared to simulated distributions, calculated in the frame of the statistical model. In this approach the proton distribution is expressed by

$$I_p(E_p) = \langle I_\beta \rangle \frac{\langle \Gamma_p \rangle}{\langle \Gamma_p + k\Gamma_\gamma \rangle} \qquad \text{where} \qquad \Gamma_p = T_{\ell/2\pi\rho}$$

I_β is taken from the beta decay gross theory and the Back Shifted Fermi Gas model has been used to describe the level density ρ. The proton transmission coefficients T_ℓ, taken from the optical model for spherical nuclei can be modified to better reproduce the data. The factor k allows the level γ widths to be tuned with respect to the expected value for E1 transitions in the emitting nucleus.

Fluctuation phenomena characteristic of the statistical behaviour are introduced by Monte Carlo calculations in both, the level spacing distribution, for which a chaotic Wigner law has been used for each spin value, and the transition matrix elements $\langle I_\beta \rangle$ and $\langle \Gamma_p \rangle$, for which Porter Thomas distributions have been considered.

For each emitter, the contributions of the levels populated by allowed transitions are summed up. Only the lowest possible angular momentum has been taken into account for the emitted protons.

In the simulation the parameters have been adjusted to reproduce simultaneously the delayed proton energy spectra, the total X-ray ratios and, in the case of ^{69}Se and ^{73}Kr, the variation of this quantity with proton energy. The set of parameters yielding the best agreement is quoted in table I. The values are in the range of those expected in the mass region.

Table 1 : Parameters of the statistical simulation for the delayed proton emission yielding the best agreement with experiment, for the T_z=3/2 emitters.

Emitters	a (MeV)$^{-1}$	P (MeV)	k	R_X simulation	R_X experiment
^{65}Ga	9.0	1.59	1.0	0.16	0.16 ± 0.11
^{69}As	10.0	1.34	3.5	0.33	0.30 ± 0.05
^{73}Br	12.0	1.50	3.0	0.20	0.22 ± 0.01
^{77}Rb	11.0	1.46	2.0	0.14	0.15 ± 0.10

a : level density parameter
P : pairing energy
k : gamma width adjustment parameter

The agreement with experimental data is maintained by changing the level density parameter by ± 5 % and pairing energy by ± 10 %. Transmission coefficients had to be modified in order to favour low energy proton emission. One has to notice the very good agreement obtained for the total X-ray ratios in each case.

An estimate of the mean level spacing has also been inferred from the proton energy spectra by performing the autocorrelation analysis[9]. The values obtained for the different emitters are in rough agreement with what is expected from the Back Shifted Fermi Gas model[10] with the parameters of the simulation.

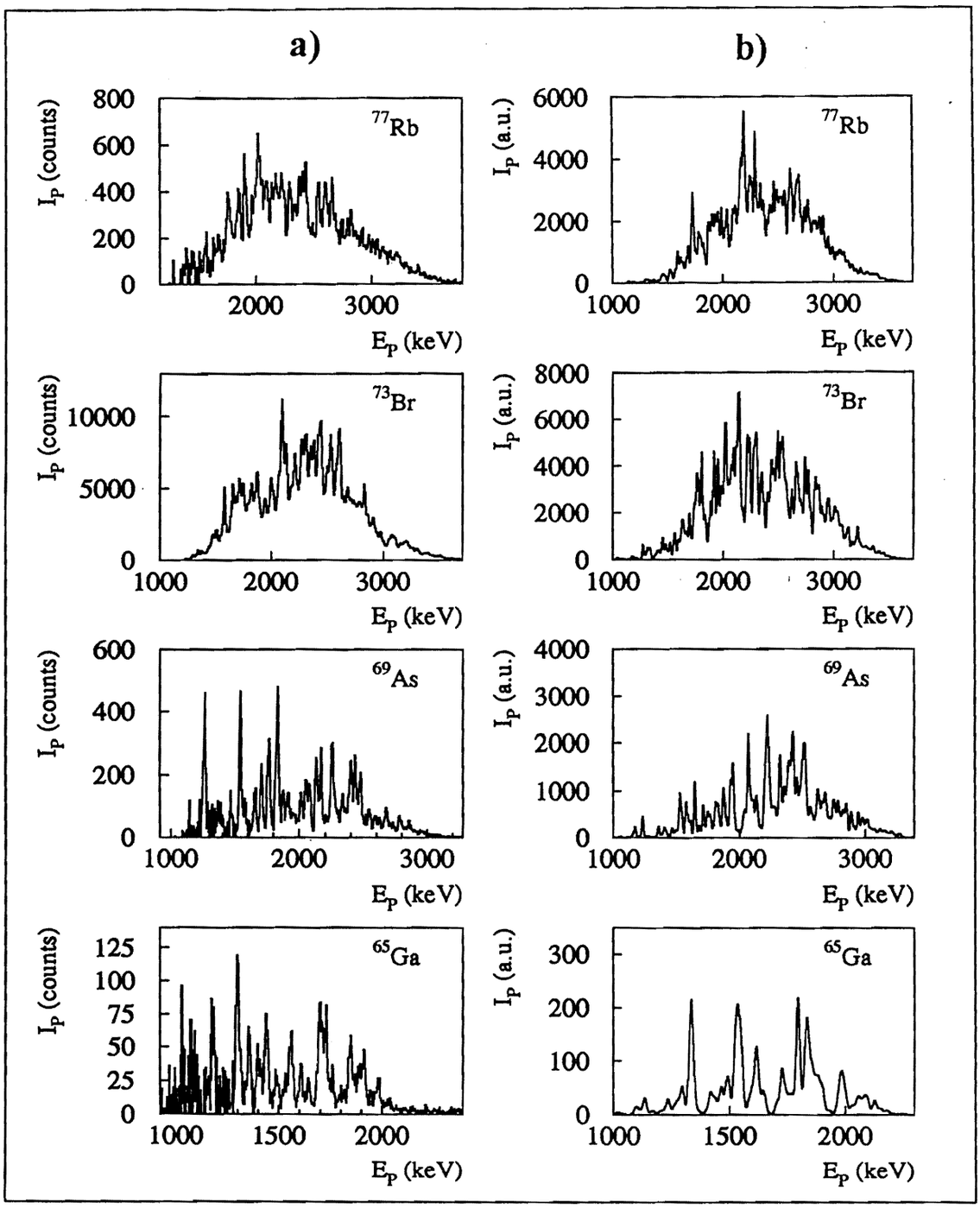

Fig.1 : a) Experimental proton energy distribution for the emitters ^{65}Ga, ^{69}As, ^{73}Br and ^{77}Rb.
b) Simulated spectra : statistical behaviour including fluctuation phenomena.

Signatures for specific structure effects can be obtained by the qualitative comparisons of the experimental data, and the calculated distributions reflecting the statistical behaviour.

The simulated proton energy distributions (Fig.1b), when compared to the experimental ones, stress the fact that most of the resonance like structures can be interpreted as fluctuation phenomena. Nevertheless in the case of ^{65}Ge and ^{69}Se a few resonances, which are not expected from the simulations, are observed experimentally at low energy. They have to be related to local variations of the β strength functions.

For ^{69}As and ^{73}Br, a qualitative comparison can be made between the experimental X-ray ratios as a function of proton energy and the corresponding calculated distributions. The overall increasing trend with energy is well reproduced by the simulated mean behaviour for both emitters (Fig.2a). Introducing the fluctuations[11] most of the points are within the statistical frame (Fig.2b). A few of them still remain apart and could indicate specific structure effects in the proton emission. One has to mention that for ^{73}Br, protons decaying to the 2^+ state in the daugther nucleus contribute for 20 % to the energy spectrum, what gives rise to the fact that two excitation energy ranges are surimposed in the presented distributions.

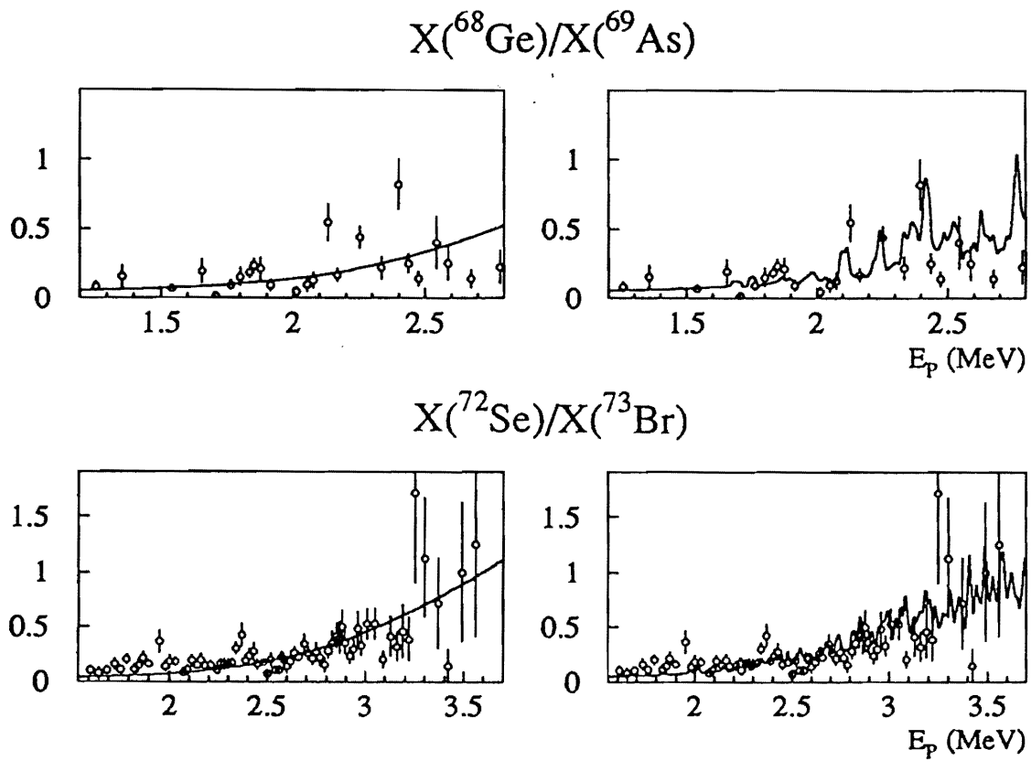

Fig.2 : X-ray ratios distributions as a function of proton energy for the emitters ^{69}As and ^{73}Br. Experimental points are compared to **a)** the mean statistical behaviour **b)** the statistical behaviour including fluctuation phenomena.

Concluding remarks

The data obtained and their statistical analysis reveal the importance of the fluctuation phenomena in the region under study. Nevertheless indications remain for specific structure effects in both the β strength function and the proton emission process. For the considered nuclei, the mean level spacings deduced from our results are in agreement with what is expected from the systematics. Calculations of the β strength functions and proton penetrabilities, taking into account large nuclear deformation in this mass region, would be of great interest and allow a further step in the analysis of the data.

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