Competition between the emission of delayed protons and γ rays

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A competition between the decay by a proton channel and the decay by a γ channel of states excited in β^+ ($\mathscr{E}$) decay has been studied in the case of the nucleus ^{147}Dy. The experimental data contradict predictions of the statistical model for the emission of delayed particles.

The emission of particles from states excited by β transitions is a characteristic feature of nuclei which lie far from the stability region.[1] An understanding of the mechanisms of delayed processes is necessary for nuclear astrophysics and for the technology of nuclear reactors. It is also required for interpreting experimental data on nuclear decay. The probability for the emission of particles and their spectrum depend on both the probabilities for excitation of levels by β transitions and the probabilities for the decay of these states through various channels. In the analysis of experiments and in theoretical calculations of the probabilities for delayed processes it is assumed that the proton widths Γ_p are uncorrelated with the γ widths (Γ_γ) or the β-transition probabilities (I_β) (Ref. 1). More than 100 emitters of delayed neutrons, protons, and α particles have been identified so far, but there has been no experimental study of the competition between the emission of particles and the emission of γ rays in emitters of delayed particles.

In order to study the mechanism for the emission of delayed particles, we have developed a special apparatus which makes it possible to measure the probabilities for β decay through the ($\beta\gamma$), (βp), and ($\beta p\gamma$) channels as functions of the excitation energy. To detect the γ radiation, we use a NaI crystal 200 mm in diameter and 200 mm long with a well 40 mm in diameter and 100 mm long, in which a telescope of semiconductor detectors is installed to detect charged particles. The radioactive sources are placed in this well at a point 3 mm from the ΔE detector. The solid angle for the detection of protons is 20% of 4π, while that for the detection of the γ radiation is 98% or 4π. The energies of cascade γ transitions are summed in a scintillation crystal, so that the height of the pulses at the photomultiplier output are determined by the energies of the levels filled by β transitions. Measurements of the spectra of total absorption of the γ rays yield the probability density of β transitions and also make it possible to carry out an absolute calibration of the activity of the sources and to determine the difference between the masses of the parent and daughter nuclei. The spectrometer operates on line with the IRIS mass separator in the proton beam of the synchrocyclotron of the Leningrad Institute of Nuclear Physics. The experimental procedure is described in detail in Refs. 2 and 3.

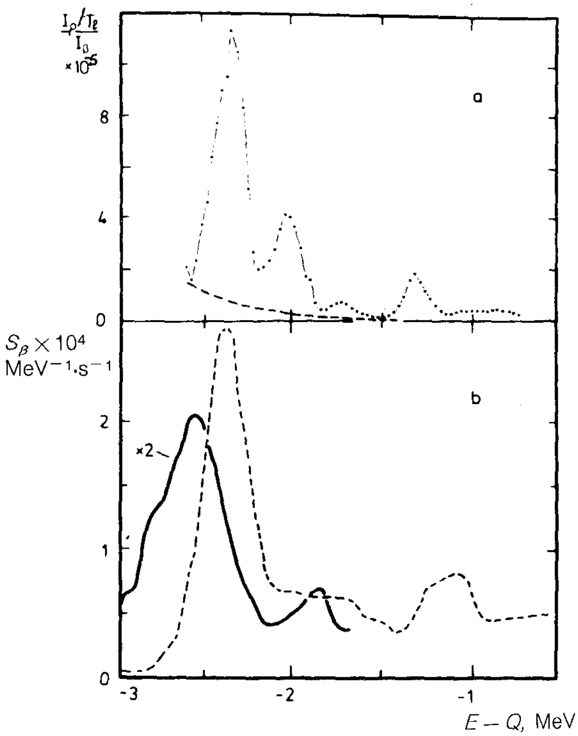

FIG. 1. a—Spectrum of delayed protons from ^{147}Dy; b—strength functions for the β decay of ^{147g}Dy and ^{147m}Dy (dashed line).

For the experiments we selected the decay of the nucleus ^{147}Dy. The use of a new procedure made it possible to obtain the first measurements of the strength function ($S\beta$) of the β decay for an emitter of delayed protons and to study the competition between the ($\beta\gamma$) and (βp) decay channels as a function of the energy of the β transitions. The ground state ($I^\pi = 1/2^+$) and the isomer state ($I^\pi = 11/2^-$) state of ^{147}Dy have approximately equal decay half-lives, 47(5) s and 55.7(5) s, respectively. This circumstance makes it difficult to separate the spectra corresponding to the decays of these states. The relatively small cross section for the production of ^{147}Dy in the ground state ($\sigma_m/\sigma_g \approx 4.5$) and the high intensity of the isomer transition (31% per decay), however, made it possible to work from the characteristic decay-accumulation curve to separate these spectra and to determine S_β for the two states. The experimental results are shown in Fig. 1.

The experimental data which have previously been available have made it possible to compare strength functions only for different isotopes.[2] These new results make it possible to compare values of S_β for the decay of the ground and isomer states of the same nucleus. In Fig. 1, the energy is reckoned from the ground state of the ^{147}Tb daughter nucleus. The maximum of S_β for the decay of the ground state corresponds to an energy of 3.95 MeV, while that for the decay of the isomer corresponds to 4.85 MeV. In Fig. 2 the energies are reckoned from the corresponding parent states, and the energies of the resonances in S_β^g and S_β^m differ by only ~0.15 MeV. The approxi-

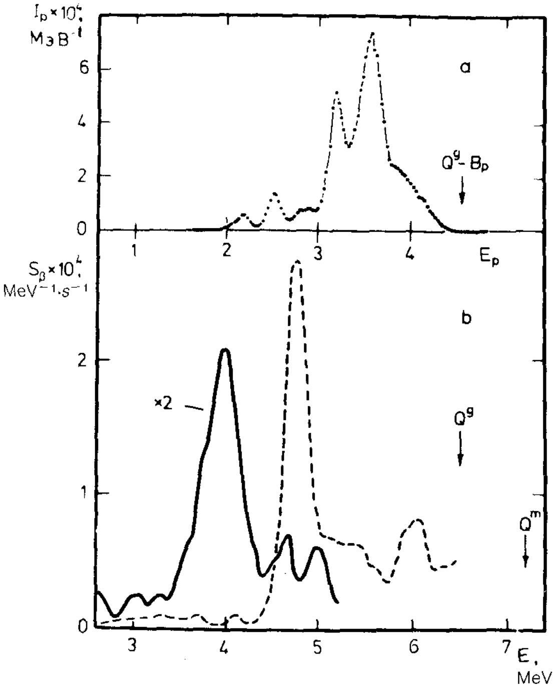

FIG. 2. a—Comparison of the experimental dependence of the quantity $I_p/(I_\beta T_l)$ with that calculated from the statistical model (the dashed line); b—strength functions for β decay of ^{147g}Dy and ^{147m}Dy (dashed line).

mate equality of these energies means that the resonances in S_β are due to collective charge-exchange excitations of the parent nuclei, and the role of one-particle effects is relatively minor.

Figure 1a shows the spectrum of delayed protons for the decay of ^{147}Dy. This figure corresponds to the decay of ^{147}Dy, since the probability for the emission of delayed protons in the decay of the ^{147}Dy ground state is, according to our data, considerably higher than that for the decay of the isomer: $B_p^g = 4.5(20) \times 10^{-4}$ versus $B_p^m < 10^{-5}$. Only in the energy region $E_p = 2.7$–3.0 MeV can the spectrum have an admixture from the decay of ^{147m}Dy. Measurements of the proton spectrum by the method of $(p\gamma)$ coincidences showed that the probability for proton transitions to excited states of ^{146}Gd is neglibly small, so that the intensities of the proton transitions are related to the intensities of β transtions by $\Gamma_p \ll \Gamma_\gamma$:

$$I_p(E_p) = I_\beta(E)\frac{\Gamma_p(E_p)}{\Gamma_\gamma(E)} \qquad E_p = (E - B_p)\frac{A-1}{A} \tag{1}$$

In the standard statistical approach we then have the following expression for the ratio of the probabilities for β decay through the (βp) and $(\beta\gamma)$ channels, averaged over the energy interval ΔE:

$$\frac{\langle I_p(E_p)\rangle / T_{ej}}{\langle I_\beta(E)\rangle} = \frac{1}{6\pi(2j_0 + 1)\rho_0(E)\langle \Gamma_\gamma \rangle} \tag{2}$$

where j_0 is the spin of the parent nucleus, T_{jl} are the transmission coefficients determining the probabilities for the crossing of the potential barrier by protons, and $\rho_j = (2j+1)\rho_0$ is the density of levels. The averaging interval ΔE is determined by the energy resolution; it is 0.19–0.22 MeV for both the proton and γ channels of the spectrometer. The value of the left side of expression (2) can be found from our experimental data. The result is shown by the solid line in Fig. 2a. The right side of expression (2), shown by the dashed line in the same figure, was calculated in the present study from the data of Ref. 4, where the ^{147}Tb level density was found through a statistical analysis of the spectrum of delayed protons from ^{147}Dy, measured with an energy resolution ~ 8 keV. We also used the parametrization of the experimental data on Γ_γ proposed in Ref. 5. The figure reveals a striking discrepancy between the experimental data and the statistical model. The curve found from the ratio of the experimental intensities runs well above the calculated curve and has several well-defined peaks, the most intense of which falls in the region of resonances in S_β. We can thus say that there is a positive correlation between Γ_p and S_β. An important point is that these maxima are essentially equidistant and cannot be explained on the basis of statistical fluctuations.

Our results show that the emission of delayed particles is a nonstatistical process. It would be important to carry out a systematic study of emitters of delayed particles and to derive a theory which incorporates the nonstatistical nature of the mechanisms for both the excitation of levels by β transitions and the decay of these states by various channels.

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