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Delayed-Neutron Spectra Following Decay of ^{85}As and ^{135}Sb

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The delayed-neutron spectra following decay of 2.05-sec ^{85}As and 1.7-sec ^{135}Sb are found to consist of a small number of discrete lines and the fluctuations in the experimental spectra differ significantly from those calculated with a statistical model. The data indicate that the β-strength function for these decays contains narrow resonances in the energy range 5–8 MeV.

The phenomenon of β-delayed–neutron emission provides an interesting tool for studying nuclear properties at intermediate excitation energies in nuclei far off the stability line. Most of the delayed-neutron precursors so far known have been found among the fission products. Since in such nuclei the neutrons are emitted from regions of high level density, it has been assumed in the past that the delayed-neutron spectra should have a continuous shape.[1,2]

Because of experimental difficulties, high-resolution neutron spectra of individual neutron emitters in the fission-product region were not known until recently.[3,4] Of particular interest are the neutron spectra of nuclei having a large energy window ($Q_\beta - B_n$) for neutron emission; Q_β is the β-decay energy of the precursor nuclide (e.g., ^{85}As) and B_n the neutron binding energy of the emitter nuclide (e.g., ^{85}Se). In such cases the properties governing this decay mode should be revealed most clearly.

We have investigated the delayed-neutron emission of two nuclides with large energy windows, 2.05-sec ^{85}As and 1.7-sec ^{135}Sb. According to mass formulas,[5] their Q_β values are estimated to amount to 9.1 and 7.5 MeV, respectively, and the B_n values to 4.1 and 3.9 MeV. These nuclides were obtained from thermal-neutron–induced fission by radiochemical separations based on hydride volatilization and purification through selective absorption.[6] The whole separation procedures were performed automatically and provided counting samples within 2.5 sec after the end of irradiation.

Delayed-neutron spectra were measured with commercially available ^{3}He-ionization chambers[7] which exhibited a resolution of 22 keV for 1.0-MeV neutrons in these experiments. Detector resolutions, response functions, and efficiencies were measured with monoenergetic neutrons from the reaction ^{7}Li(p,n)^{7}Be. The contribution of scattered neutrons was checked via the neutron spectrum of ^{17}N, and was found to be less than 4% beyond 100 keV. Singles and coincidence

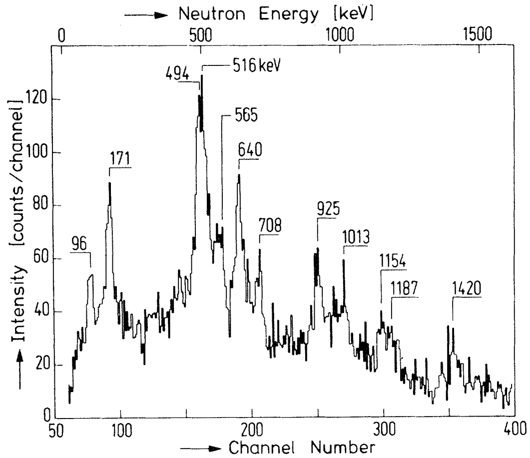

FIG. 1. Delayed-neutron spectrum following decay of 2.05-sec ^{85}As, corrected for relative detection efficiency.

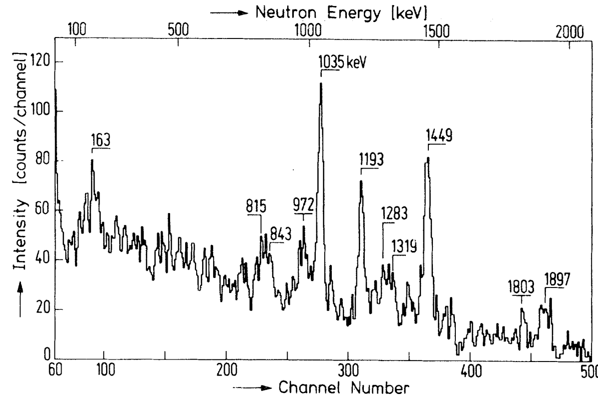

FIG. 2. Delayed-neutron spectrum following decay of 1.7-sec ^{135}Sb, corrected for relative detection efficiency.

γ-ray spectra were measured with conventional techniques using high-resolution Ge(Li) detectors.

The delayed-neutron spectra following the decay of ^{85}As and ^{135}Sb are shown in Figs. 1 and 2. To obtain reasonable counting statistics, spectra from 90 separations (As) and 210 separations (Sb) were accumulated. A dominant feature of both spectra is the prominent line structure with densities small compared to the expected level densities [e.g., the number of neutron lines for ^{85}As decay (~20) account for about 1% of the levels available through allowed β decay[8]]. The energies and intensities of neutron lines were obtained by computer analysis using the code SAMPO.[9] That the line structure accounts for the majority ($\gtrsim 60\%$) of the total neutron intensity has been shown through a spectrum-stripping procedure utilizing complete response functions for monoenergetic neutrons. After accounting for the neutron line intensity and the spectral distribution due to thermal neutrons and γ-ray pileup, the fraction of intensity remaining amounted to no more than 35% of the total. Statistical and possible systematic errors preclude a unique definition of the nature of the remaining intensity, although the presence of an underlying, continuous neutron distribution cannot be ruled out.

A second feature of both spectra is the absence of appreciable neutron intensity above 1.6 MeV (^{85}As) and 2.0 MeV (^{135}Sb) even though larger ranges are possible for the neutron energies. Through γ-ray studies we have been able to demonstrate that this effect is not due to the location of the principal β-decay intensity to levels immediately above B_n, but rather to the dominance of neutron emission from intermediate levels to excited states in the final nuclides.

In the case of arsenic, neutron emission following ^{85}As decay populates excited states in ^{84}Se. The same states may also be populated in the β decay of the 5.3-sec ^{84}As. The deexciting γ rays should then be identical. This was indeed observed for several strong γ rays which show complex decay curves with components of 2.05- and 5.3-sec half-life. This interpretation has been confirmed by comparison of the relative intensities of the two components in the decay of the 1455-keV γ ray in arsenic samples obtained from thermal-neutron-induced fission of ^{235}U and ^{233}U. The intensity ratio of these components was found to vary in direct proportion to the ratio of the absolute cumulative yields of ^{85}As and ^{84}As. From these and other experiments we have been able to deduce that 72% of the neutron emission from intermediate levels in ^{85}Se populates excited states up to at least 3.3 MeV in ^{84}Se (Fig. 3). Through comparison of the neutron energies with level energies in ^{84}Se, we conclude that the extent of neutron decay of intermediate levels in ^{85}Se to more than one level in ^{84}Se is small. The majority of the line intensity represents decay of individual levels in ^{85}Se.

Experimental results on ^{135}Sb are less comprehensive than those described above but are sufficient to demonstrate neutron emission to excited states in ^{134}Te.

Two interpretations of the peak structure in delayed-particle spectra have been proposed so far. Shelev and Rudstam[3] suggested that for the ^{137}I

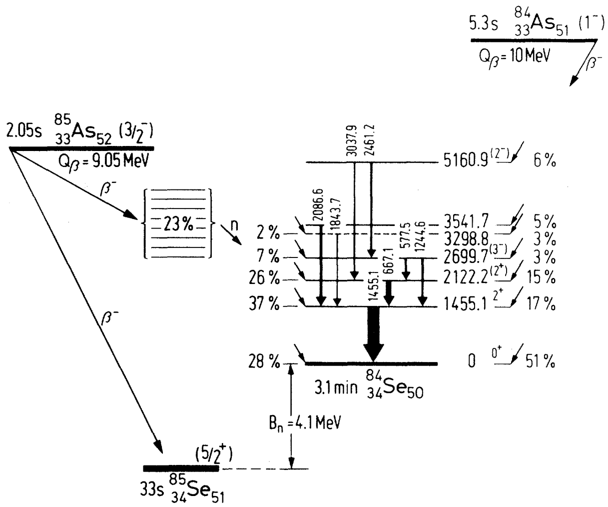

FIG. 3. Decay of ^{85}As and ^{84}As into levels of ^{84}Se. The branchings of ^{85}As into ^{84}Se are normalized to 100%, but contribute in total 23% of the transitions of ^{85}As.

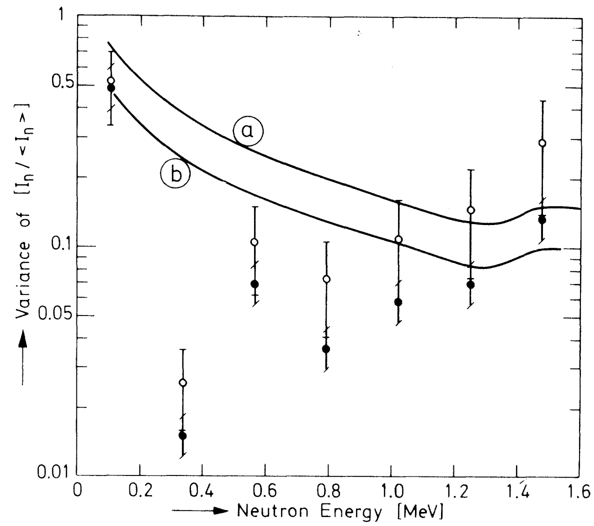

FIG. 4. Fluctuations in the neutron intensity in the ^{85}As delayed-neutron spectrum. The theoretical curves were calculated (Refs. 10–12), assuming (a) $B_n = 4.1$ MeV, and (b) $B_n = 4.5$ MeV. Experimental fluctuations were calculated according to Ref. 11 (closed circles) and Ref. 12 (open circles). In both cases Gaussian smoothed spectra were obtained with $\sigma = 38$ keV and variances were calculated for 240-keV energy intervals.

delayed-neutron spectrum the mean spacing of the apparent neutron lines compares favorably with the mean level spacing in the emitter nucleus ^{137}Xe. Application of this concept to the neutron spectrum of ^{85}As seems inappropriate. The peaks are much more widely spaced than can be accounted for by spin-dependent level-density calculations with shell corrections.

In order to compare the experimental delayed-neutron spectra with predictions of a statistical model we have followed the general method for nonoverlapping levels discussed by Hansen,[10] Karnaukhov, Bogdanov, and Petrov,[11] and Jonson[12] where the fluctuations in the experimental data are compared with those calculated theoretically. The conditions $\Delta E \gg D \gg \Gamma$, required for validity of this method, are sufficiently well approximated that Erickson fluctuations are not significant in this case. Transmission coefficients for neutrons were taken from optical-model calculations[13] and level densities were calculated using the formulation of Gilbert and Cameron.[8] Only allowed β transitions were considered. Neutron emission to the four excited states in ^{84}Se has been included in the theoretical calculations using the energies, spins, and parities of levels given in Fig. 3. In Fig. 4 we show the theoretical curves for the variance $(I_n/\langle I\rangle)$ along with the experimental values calculated by the methods outlined by Karnaukhov, Bogdanov, and Petrov[11] and Jonson[12] for the ^{85}As delayed-neutron spectrum. It is evident that unlike the theoretical predictions, the experimental fluctuations are an increasing function of energy above 100 keV. This result is not affected by variation in optical-model parameters. The magnitude of fluctuations is strongly dependent upon the level density and only weakly dependent upon variation in the partial widths for neutron and γ decay.

We conclude from these comparisons and the experimental data that the β-strength function for levels in the energy range 5–8 MeV in the emitter nuclides ^{85}Se and ^{135}Te must possess strong local resonances not accounted for in the simple statistical model.

Unless large, local fluctuations in the level density occur that are not contained in the normal-level density formulations, the data indicate high selectivity in β decay and in the subsequent neutron emission to levels in the final nucleus, as evidenced by the lack of high-energy neutrons in these spectra. For the case of ^{85}As decay, the data indicate that the resonances in the β-strength function are centered at about 7 MeV in ^{85}Se. An estimate of the $\log ft$ values for the β transitions preceeding neutron emission leads to values between 4 and 6, showing that allowed transitions are involved.

These observat'ons might be explained in terms of particle-hole structures involving the $d_{5/2}$ or $g_{9/2}$ proton orbitals. The last two neutrons in ^{85}As occupy the $d_{5/2}$ orbital just beyond the closed shell $N=50$. A crude estimate locates the energy of the two-particle, one-hole configuration $[\pi(d_{5/2})^1(f_{5/2})^{-1};\ \nu(d_{5/2})^1]$ at 6–7 MeV in ^{85}Se, and the more complex structure resulting from decay of a $g_{9/2}$ neutron should lie within several MeV of this energy. It is possible that the selectivity in β decay is probing that part of the particle-hole structure in ^{85}Se contained in the antianalog state (AIAS) orthogonal to the analog state (IAS) of the ^{85}As ground state. Using the value of 110 MeV for the Lane potential,[14] the AIAS is calculated to lie near 6.3 MeV in ^{85}Se and should have its strength spread by strong coupling to core polarization states.[15] Since the strength of Gamow-Teller β decay to the AIAS is proportional to that of the $\Delta T=1$, $M1$ γ transition between the IAS and the AIAS, this correlation may possibly serve as the basis for interpretation of the structure in the delayed-neutron spectrum from ^{85}As.

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Pion Production in the Regime of Target Fragmentation*

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We examine the energy dependence of π^+ and π^- production in pp collisions for incident laboratory momenta between 6 and 400 GeV/c. The cross section for pion emission into the backward hemisphere in the laboratory frame falls substantially with incident momentum. This departure from the hypothesis of limiting fragmentation for momenta in excess of 20 GeV/c is consistent with an energy dependence of the form expected on the basis of Mueller-Regge ideas.

Pion production in hadronic interactions can be classified into two general categories. One is the "central" regime of particle production, typified through the production of particles whose longitudinal momenta, as calculated in the center-of-mass frame, are small ($|p_l^*| \lesssim 0.1p_0^*$, where p_0^* is the incident momentum in the center of mass); the invariant cross section for pion production for small p_l^* is known to rise substantially as the incident energy increases.[1] The non-