INTERPRETATION OF DELAYED NEUTRON EMISSION USING A NON-STATISTICAL APPROACH

A.A. Shihab-Eldin

Physics Department, Kuwait University, Kuwait, and Lawrence Berkeley Laboratory,
University of California, Berkely, California 94720, USA.

F.M. Nuh, W. Halverson and S.G. Prussin

Department of Nuclear Engineering, University of California, Berkeley, California 94720, USA.

W. Rudolph, H. Ohm and K.-L. Kratz

Institut für Kernchemie, Universität Mainz, D-65 Mainz, Germany.

Abstract

Experimental data on several delayed neutron emitting systems exhibit characteristics not accounted for by the normal statistical model. Using a single-particle approach, the locations and relative β-strengths to configurations in the emitter nuclides populated by allowed G.T. transitions have been calculated and are in qualitative agreement with strength function data for ^{85}As, ^{87}Br, ^{135}Sb and ^{137}I. Calculations of P_n-values for the bromine precursors A = 87 to 92 are also in good agreement with experimental data. The lack of high energy neutrons in spectra where excited states in the final nucleus are strongly populated can be traced qualitatively to particle-hole excitations contributing to the excited states.

Introduction

The recently measured delayed neutron spectra from fission-product precursors all show more or less pronounced peak structure[1-3]). For the precursors ^{85}As, ^{87}Br, ^{135}Sb and ^{137}I line structure dominates the measured spectra and, in addition, a marked lack of high energy neutrons is noted for ^{85}As and ^{135}Sb spectra even though neutron emission has been shown to populate levels in the final nuclei up to 3 MeV in excitation energy. In these cases analysis of neutron spectra has revealed correlations between neutron transition energies and differences in level energies in the final nuclei[3]). In this way a few intermediate levels have been shown to account for a large fraction of the total β^--intensity to levels in the energy range B_n to Q_β which represent but a small fraction of the total level density estimated with the formulae of Gilbert and Cameron[4]). The analysis leads to the conclusion that the β^--strength function is characterized by a peak in the vicinity of 6-7 MeV in the emitter nuclei ^{85}Se and ^{135}Te. For the case of ^{87}Br decay, a high resolution β^--strength function has been constructed by combining the decay scheme for levels below B_n with the line structure evident in the delayed neutron spectrum. In this case, the strength function exhibits a pronounced peak located in the vicinity of the neutron binding energy and indicates the onset of an additional peak as Q_β is approached.

Statistical model considerations

Fluctuations in the neutron spectra from these four precursors have been compared to those calculated from statistical model considerations according to the methods described by Jonson[5]) and Karnaukhov[6]). Level densities were estimated according to the method of Gilbert and Cameron[4]) and transmission coefficients were calculated with the optical model code OPTIC[7]). For ^{85}As and ^{135}Sb allowance for neutron decay to excited states was provided by inclusion of the levels and defined spins and parities for ^{84}Se and ^{134}Te as shown in the contribution to this conference of K.-L. Kratz et al.[3]). For all cases the simplifying assumption of constant β^--intensity per unit of energy for decay to levels in the energy range Q_β to B_n was used. This assumption overestimated the fluctuations as Q_β is approached. A comparison of the fluctuations predicted with this assumption to those obtained with a β^--strength proportional to the level density in the case of ^{135}Sb decay shows that no serious error is introduced with the constant β^--intensity assumption. The resultant experimental and model fluctuations are compared in figure 1 . For the ^{87}Br and ^{137}I neutron spectra, which are defined by small energy windows (Q_β-B_n) and for which neutron emission from levels in the emitter nuclides is constrained to populate only the ground state in the final nuclei, reasonable agreement between the experimental and predicted fluctuations is observed. However, for ^{85}As and ^{135}Sb which possess large energy windows and for which intense neutron emission to excited states occurs, the experimental results differ in both magnitude and variation with energy from the model predictions. Variation in Q_β, B_n and level densities about the mean values used in the calculations does not effect the general results.

All of these observations point to strong departures from statistical model expectations and can be explained by the persistance of rather discrete structure effects in the energy range 5-7 MeV in emitter nuclides and by the dependence of neutron emission on the magnitudes of particle-hole contributions to the wave functions of the low-lying levels in the final nuclei.

A naive shell-model approach

Martinsen and Randrup[8]) and Randrup[9]) have shown that distinct structure effects persist in the vicinity of the positions of configurations populated by allowed G.T. decays in the tail of the G.T. giant resonance. These calculations were based on a shell-model approach including pairing correlations and a residual G.T. interaction. Using a similar shell-model approach but neglecting all residual interactions except for the allowance of scattering of neutron pairs in the valence shell of the precursor nuclei, we have calculated the energies of such configurations. Level diagrams for neutrons and protons were obtained with a Woods-Saxon potential for ^{85}Se and ^{135}Te which were assumed to hold, at least schematically, for the level diagrams of adjacent nuclei. Reduced transition probabilities, B'(GT), were also calculated for all allowed decays in the extreme single-

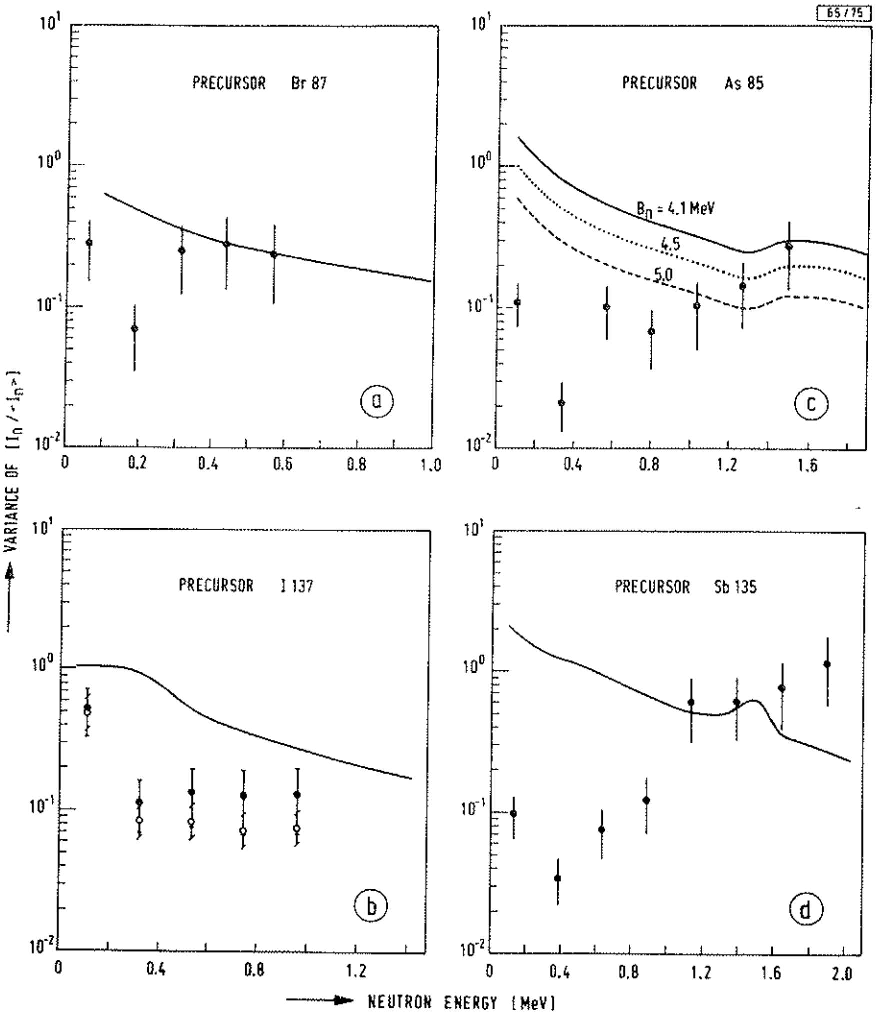

Figure 1 Comparison of experimental and statistical model fluctuations for delayed neutron spectra from ^{85}As, ^{87}Br, ^{135}Sb and ^{137}I.

particle limit. In figures 2,3 and 4, the locations of these resonances are compared to the β^--strength functions deduced from experiments for ^{87}Br, ^{85}As and ^{135}Sb. Remarkable agreement between the locations of high β^--strength in the experimental distributions and the calculated resonances is observed. In all cases, the low-lying resonances are due to scattering of neutron pairs among valence orbitals and for ^{87}Br, the location of this resonance is quite close to the two lowest odd parity states populated in β^--decay (log ft∿6.4)$^{10)}$.

The strength function data obtained by Johansen et al.$^{11)}$ and Aleklett et al.$^{12)}$ by total absorption techniques indicate that the locations of local variations in log ft vary only slowly with A in the vicinity of nuclides considered here. This conclusion is also expected from shell-model considerations and we have assumed that the ^{85}Se single-particle level diagram can be applied crudely to the krypton emitters populated by all bromine precursors A = 87 to 92. Within the model, neutron emission probabilities should be calculated according to

$$P_n = \frac{\sum_{i,B_n<E_x<Q_\beta} B_i(GT)\,f_i}{\sum_{i,0<E_x<Q_\beta} B_i(GT)\,f_i}$$

The P_n-values obtained in this way are listed in Table 1 and are compared to experimental values evaluated by K.-L. Kratz$^{13)}$. Again, remarkable agreement is observed with the exception of ^{88}Br. In this case, the $p_{1/2}\rightarrow p_{3/2}$ resonance is calculated to lie just below B_n, and if allowance is made for a spreading width of the magnitude seen in the experimental strength function of ^{87}Br, the calculated value will rise appreciably. Inclusion of spreading widths in other cases should not change results to a large extent.

The agreement seen between the calculations outlined here and experimental data might be somewhat fortuitous. Nevertheless, the basis of the model appears well founded and more realistic calculations are being explored.

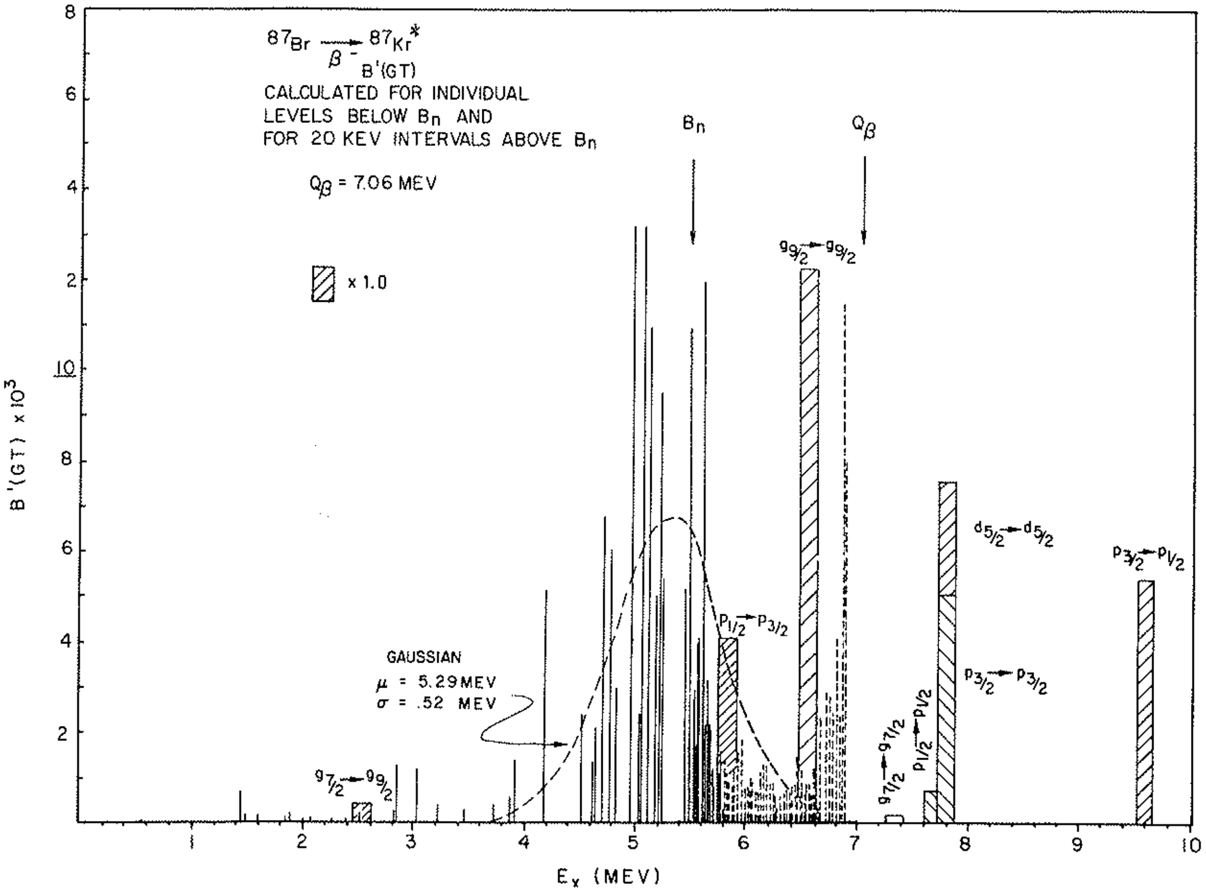

Figure 2 Comparison of experimental β-strength function with model calculations for ^{87}Br decay.

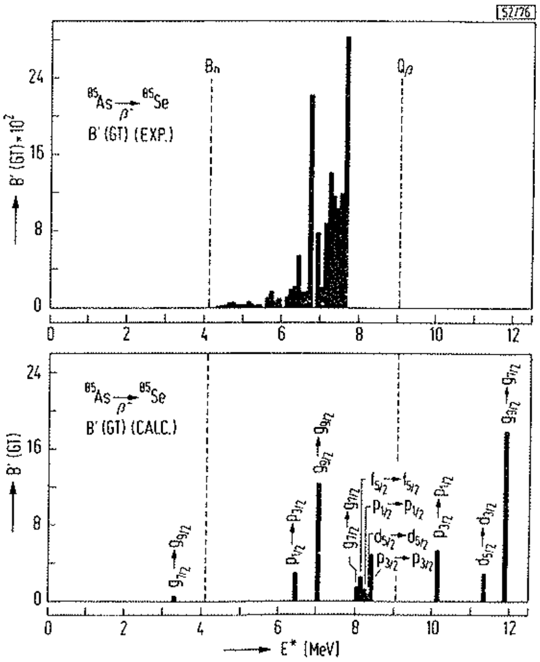

Figure 3 Comparison of experimental β-strength function with model calculations for ^{85}As decay.

Table 1

COMPARISON OF EXPERIMENTAL AND CALCULATED P_n VALUES FOR BROMINE DELAYED NEUTRON PRECURSORS.

PRECURSOR	P_n^{exp}(%)[a]	P_n^{calc}(%)	P_n^{calc}/P_n^{exp}
^{87}Br	2.56(0.38)	4.09	1.6
^{88}Br	6.47(0.70)	1.13	0.17
^{89}Br	12.5(2.0)	21.3	1.7
^{90}Br	18.8(3.9)	31.3	1.7
^{91}Br	14.1(3.6)	24.3	1.7
^{92}Br	24.5(10.2)	26.9	1.1

[a] K.-L. Kratz, private communication (1976) - based on experimental Y_n and Y_f.

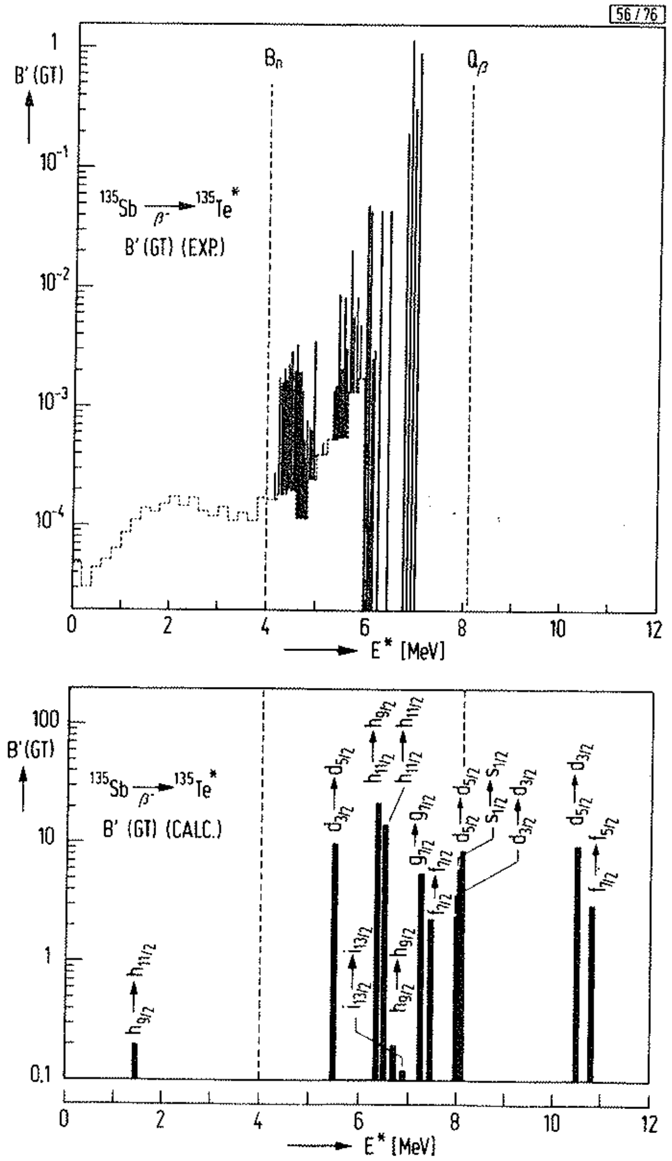

Figure 4 Comparison of experimental β-strength function with model calculations for ^{135}Sb decay.

Neutron decay to excited states

Over and above selectivity in β^--decay, the absence of high energy neutrons in the spectra from ^{85}As and ^{135}Sb indicates preferential neutron emission from intermediate emitter levels to excited states in the final nuclei. In all cases the intensities of high energy neutron transitions from intermediate levels in ^{135}Te are very much lower than those expected from transmission coefficient ratios[14]). Gamma-ray and neutron measurements on the rubidium delayed neutron precursors have shown similar results[14]).

Qualitatively, the strong neutron emission to low-lying excited states may be explained by the magnitude of particle-hole excitations in the wave functions of those states. As an example we have considered the delayed neutron system $^{135}Sb(\beta^-)\ {}^{135}Te^*(n)^{134}Te$. Using the Woods-Saxon level diagram calculated for ^{135}Te, it is apparent that the principle part of the β^--strength to levels above B_n populates core polarization and spin-flip configurations. The connection between these and the leading terms in the ground and first excited states in ^{134}Te is outlined in figure 5. The leading terms in the ground-state wave function arise from the lowest-order shell-model configuration, those due to proton and neutron pair scattering and two proton - 1p 1h neutron excitations. On the other hand, the leading terms in the low-lying excited states are due to two proton excitations and two proton, neutron particle-hole excitations. Decay of the intermediate core polarization and spin-flip states in the emitter ^{135}Te can occur by those admixtures in the wave functions obtained by scattering events that lead to a neutron in an unbound state. In the figure it is seen that such events lead to the leading terms in the excited states but only to second-order terms in the

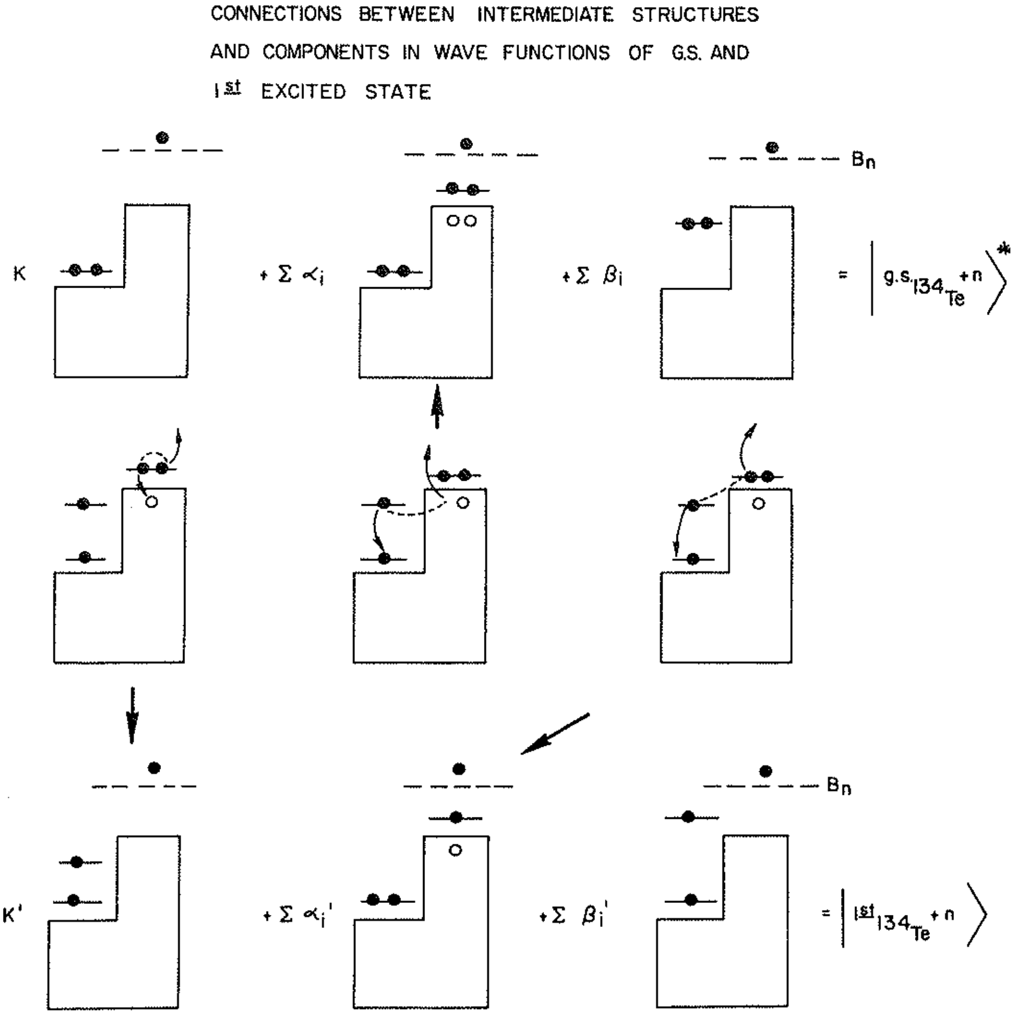

Figure 5 Schematic of decay of intermediate levels in ^{135}Te to levels in ^{134}Te.

ground state. As excitation energies of the intermediate levels increase where neutron emission can probe many levels containing the main strength of particle-hole excitations, neutron branching ratios should approach those expected from transmission coefficient ratios alone.

We conclude that at the energies probed in delayed neutron emission, structure effects have not been averaged to the extent required by the compound nucleus hypothesis. Such structure effects may be expected to affect gamma widths of levels also. In the region of the light-massed delayed neutron precursors (A∼90), correlations between neutron and gamma-ray widths for p-wave resonances can be explained by the valence capture model of Lane[16]). At least for those levels in the vicinity of B_n from which p-wave neutrons must be emitted, enhanced dipole emission may be observed.

References

1). S. Shalev and G. Rudstam, Nucl. Phys. A230 (1974) 153.
2). G. Rudstam and S. Shalev, Nucl. Phys. A235 (1974) 397.
3). K.-L. Kratz et al., contribution to this conference.
4). A. Gilbert and A.G.W. Cameron, Can. J. Phys. 43 (1965) 1446.
5). B. Jonson, Ph.D. Thesis, Chalmers University of Technology, Gothenburg, Sweden (1972), unpublished.
6). V.A. Karnaukhov et al., Nucl. Phys. A206 (1973) 583.
7). N. Glendening, private communication (1976).
8). P.O. Martinsen and J. Randrup, Nucl. Phys. A195 (1972) 26.
9). J. Randrup, Nucl. Phys. A207 (1973) 209.
10). F.M. Nuh et al., to be published.
11). K.H. Johansen et al., Nucl. Phys. A203 (1973) 481.
12). K. Aleklett et al., Nucl. Phys. A246 (1975) 425.
13). K.-L. Kratz, private communication (1976).
14). K.-L. Kratz et al., submitted to Phys. Rev. Lett.
15). K.-L. Kratz, private communication (1976).
16). see for example, S.F. Mughabghab et al., Phys. Rev. Lett. 26 (1971) 1118.