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LETTER TO THE EDITOR

Population of excited states in delayed neutron emission

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Abstract. Gamma rays have been detected in coincidence with delayed neutrons following the decay of ^{95}Rb, ^{90}Br and ^{85}As. The energies of the first excited states of ^{94}Sr and ^{89}Kr are identified as 837 keV and 424 keV respectively.

The process of delayed neutron emission has been known for very many years but it is only comparatively recently that improved techniques have permitted detailed studies of the decay systematics. In most discussions of the delayed neutron decay process it is assumed—for ease of calculation if for no other reason—that the neutron emission always leaves the final nucleus in its ground state. However, in several cases, the available energy is amply sufficient for the decay to proceed via an excited state in this final nucleus, which would then de-excite by gamma-ray emission. Such a process would therefore involve the sequential emission of a beta particle, a neutron and a gamma ray and is referred to below, for convenience, as the BNG mode. The existence of such a triple decay mode was inferred for the case of ^{85}As (Kratz *et al* 1973) from measurements of the decay constant of the gamma ray corresponding to the de-excitation of the first excited state of ^{84}Se. In the cases of ^{95}Rb, ^{96}Rb and ^{97}Rb a second group of workers (G Siegert 1974, private communication) has identified in each of the gamma-ray spectra for these individual isotopes a line which appears also (and more strongly) in the spectrum of the isotope whose mass is one unit lower. Again a plausible explanation of this would be the occurrence of the BNG decay mode. We report here some preliminary results of an experiment designed to observe this decay mode more directly, performed as part of a comprehensive study of delayed neutron systematics.

Three runs were performed using the on-line mass separator Lohengrin (Moll *et al* 1970) to select fission products of mass 85, 90 and 95. In the first of these the mass 85 products (of ionic charge $q = 20$) were mixed with others of mass 102 ($q = 24$) because the separation is on the basis of A/q rather than A alone, but the other masses were free from contamination to at least the 1 in 100 level. Relevant information (taken from Tomlinson 1973 and Amiel 1969) about the nuclides of interest is given in table 1, where P_n is the probability for delayed neutron emission, Q_β is the Q value of the β ray, B_n is the neutron binding energy and $T_{1/2}$ is the half-life of the β decay. Tne fission products

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Table 1.

Precursor	Fission yield (%)	P_n (%)	Q_β (MeV)	B_n (MeV)	$T_{1/2}$ (s)
^{85}As	0·49	20	9·1	4·1	2·03
^{90}Br	1·75	12	10·3	6·4	1·63
^{95}Rb	0·36	7·1	7·9	4·9	0·36

were collected (from the exit slit of Lohengrin) on a continuous-loop moving tape system and passed with a minimum of dead distance to a roller system which concentrated 1·5 m of tape in a zig-zag pattern between two detectors and then to a reservoir which held some 800 m of tape. The tape speed was chosen in each case to optimize the yield of the isobar concerned on the basis of its known half-life. The two detectors were a 7·6 cm diameter × 7·6 cm NaI(Tl) detector for gamma rays and a 12·7 cm diameter × 5 cm NE213 liquid scintillator† for neutron detection. The pulse-height spectrum was recorded for all events in the NaI(Tl) detector which were detected in coincidence with those in the neutron detector, the latter being further required to have the shape appropriate to a neutron interaction. The acceptable range of pulse heights from the neutron detector was defined by a single-channel analyser to cover the recoil-proton energy range of 180 keV to 1·5 MeV. Because of the low energies involved and because of the necessity to operate with a non-ideal pulse-shape discrimination (PSD), the gamma-ray rejection ratio was only some 20/1. Since the neutron flux at the NE213 was only a small fraction of the gamma flux (of the order of P_n) a large fraction of the events labelled 'neutrons' by the PSD system was in fact wrongly attributed, but since the ratio of 'neutron' output pulses to all input pulses to the PSD units increased markedly when the tape was running from the value observed during background runs, it was possible to extract useful information from the data. This is summarized in table 2 and the following notes.

Table 2.

Precursor	True single neutron detection rate (s^{-1})	Total coincidence rate (s^{-1})	E_γ (keV)	Photopeak count rate (min^{-1})	Interpretation	Note
^{95}Rb	1·5	0·22	845	1·3	BNG (837·4 keV)	1
			360		Presumed γ–γ	2
^{90}Br	2·6	0·25	417	1·9	BNG (424 keV)	3
^{85}As	2·6	0 17	304		Presumed γ–γ	4
			687	(uncertain)	BNG (667 keV)	5
			1440	(uncertain)	BNG (1·445 MeV)	6

Note 1. This has been observed as a very strong line in the gamma-ray spectrum of the decay of ^{94}Rb, and as a very weak line in the spectrum of ^{95}Rb, by the Lohengrin group (unpublished data 1974). It can therefore appear in our n–γ coincidence spectrum

† Supplied by Nuclear Enterprises Ltd, Edinburgh, Scotland.

only because it results from the BNG decay mode of ^{95}Rb. In the decay of ^{94}Rb it appears, of course, from the normal β–γ decay mode. The 7 keV discrepancy in energy is within the estimated uncertainty of our gamma-ray energy calibration. The value of 837·4 keV, taken from Ge(Li) spectra, is the reliable one.

Note 2. This presumably is the 352·5 keV line seen strongly in the β–γ decay of ^{95}Rb, interpreted (G Siegert 1974, private communication) as the decay of the first excited state of ^{95}Sr and therefore fed in numerous γ–γ cascades. It appears in our coincidence spectrum as a result of insufficient gamma-ray rejection by the PSD system.

Note 3. There is a strong line at about 424 keV in the gamma-ray spectrum from ^{89}Br, which is weakly present also in ^{90}Br (unpublished Lohengrin data, spring 1974). Again the discrepancy in energy is not significant. All the evidence supports the identification as BNG mode.

Note 4. We have no positive information about this line, which was not observed by Kratz *et al* (1973) in the decay of ^{85}As. Its interpretation as γ–γ is therefore speculative. The mass 85 fission products collected in this experiment were, as noted earlier, mixed with other masses—notably 102—and it is possible that the 304 keV line comes from that mass chain, about which little is known, except that it does not include a significant delayed neutron emitter.

Notes 5 and 6. These correspond to the BNG decay modes inferred by Kratz *et al* (1973). Unfortunately, because of the low yield and consequent poor signal-to-background ratio, we were not able to make reliable and quantitative measurements, although the energy assignments are more certain. Our preliminary assessment, however, does not support the relative yields proposed by Kratz *et al.*

Where only one gamma-ray line is observed in a BNG decay it is clear that this line should correspond to the decay of the first excited state of the final nucleus. Thus the measurements reported here provide a measure of the energies of the first excited states of ^{94}Sr and ^{89}Kr from the BNG decay of ^{95}Rb and ^{90}Br respectively.

Thus we have definite evidence for the presence of the BNG mode in the decay of ^{95}Rb, ^{90}Br and ^{85}As. The energies of the first excited states of ^{94}Sr and ^{89}Kr are deduced to be 837·4 keV and 424 ± 2 keV respectively.

In future measurements we hope to obtain more quantitative information from which branching ratios of the neutrons to the ground and excited states of the final nuclei can be deduced.

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