BETA-DELAYED TWO-NEUTRON EMISSION FROM $^{30,31,32}\text{Na}$

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ABSTRACT

Beta-delayed two-neutron emission from mass-separated samples of short-lived sodium isotopes has been detected both by n-n time correlations with a "long counter" and by γ -spectroscopic identification of daughter products with mass A-2. The observed cases (intensities per beta decay) are ^{30}Na ($1.2 \pm 0.2\%$), ^{31}Na ($0.70 \pm 0.25\%$) and ^{32}Na ($5.1 \pm 1.8\%$). The results are in good agreement with a simple model of beta-delayed particle emission.

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Beta-delayed emission of two neutrons has recently been detected for the first time [1] in the decay of 8.5 ms ^{11}Li . This decay mode is also to be expected in the heavier elements and especially in those with odd Z , as may be seen from an inspection of theoretical mass tables. The element sodium ($Z = 11$) is a particularly favourable case, as its neutron-rich isotopes can be produced [2-4] in high yields through mass separation of fragmentation products from reactions with high-energy protons. We report here the application of two different experimental methods for demonstrating that the β^- decays of the isotopes $^{30-32}\text{Na}$ are accompanied by 2n emission.

One series of experiments was based on the n-n time correlation method, which has already been discussed in some detail in the previous work [1]. The radioactivity was produced by bombarding a target of uranium carbide at 2000° C with 600 MeV protons from the CERN synchro-cyclotron. After mass separation in the ISOLDE separator, the isotope of interest was directed to the centre of a 60 cm long paraffin-filled cylinder containing eight ^3He proportional counters. With the detectors connected in parallel, a search was made by time correlation techniques for pairs of neutron events with the characteristic mean time of 120 μs for residence in the detector.

The experimental time correlation spectra for $^{30,32}\text{Na}$ are shown in Fig. 1. The intensity of the correlated events relative to the total singles neutron counts determines the proportion of 2n events when allowance is made for randoms, correlated background, dead-time losses and, of course, the efficiency of the neutron detector. The latter was determined with neutrons arising from ^{238}U spontaneous fission. The final results are given in Table 1.

The second series of experiments used the 24 GeV proton beam from the CERN synchrotron to bombard an iridium target at high temperature. After separation in the mass spectrometer [5], the beam of interest was directed to the end of a thin Al collecting tube viewed by a Ge(Li) detector. The presence of one- and two-neutron decay processes is revealed by the appearance of gamma rays belonging to lower mass chains than the one collected. Absolute intensities were obtained from the γ spectra, from monitoring of the beta radioactivity during the collection and from counting of the sodium ions before and after the collection. Fig. 2 shows the presence of mass-28 lines in the gamma spectrum of a sample produced in a long collection at mass 30. The resulting branching ratio is given in Table 1. For the case of ^{32}Na , the gamma spectra measured on-line showed contributions from the decays of ^{32}Na , ^{31}Al and ^{30}Mg , so that the relative contributions of zero-, one- and two-neutron emission could be deduced, as shown in Table 1. At mass 31 no γ -rays above background were observed.

It will be seen from Table 1 that $^{30-32}\text{Na}$ are beta-delayed two-neutron emitters and that the intensities measured by the two methods agree well. The final values that we have adopted for p_{2n} are ^{30}Na ($1.2 \pm 0.2\%$), ^{31}Na ($0.70 \pm 0.25\%$) and ^{32}Na ($5.1 \pm 1.8\%$).

It is interesting to examine whether the high intensities obtained for the $(\beta, 2n)$ process are compatible with a simple statistical model for beta-delayed processes. Previous calculations [6] have been extended to include 2n emission through the following modifications. The emission of neutrons is assumed to dominate entirely over gamma emission at an energy δ above the neutron separation energy S_n , where the quantity δ is taken to be 50 keV. The beta feed $\beta(E)$ to the excitation energy E in the daughter (mass A) is that of the gross theory of beta decay [7] with

a modified-Lorentz shape for the giant resonance. The branching ratio for emitting exactly one neutron relative to that for emitting one or more neutrons can now be written

$$P_1 = \frac{\int_{S_n + \delta}^{Q_\beta} \pi_1(E) \beta(E) dE}{\int_{S_n + \delta}^{Q_\beta} \beta(E) dE}$$

where

$$\pi_1(E) = \begin{cases} 1 & \text{for } S_{2n} + 2\delta \geq E \geq S_n + \delta \\ 1 - \frac{\int_{S_{2n} + \delta}^{E - \delta} \Gamma_n(E, E_1) \rho(E_1 - S_n) dE_1}{\int_{S_n}^{E - \delta} \Gamma_n(E, E_1') \rho(E_1' - S_n) dE_1'} & \text{for } E > S_{2n} + 2\delta \end{cases}$$

Here, $\Gamma_n(E, E_1)$ denotes the width for neutron emission to the excitation energy $(E_1 - S_n)$ in the intermediate nucleus (mass $A-1$) with the level density $\rho(E_1 - S_n)$. For $^{30-32}\text{Na}$ it is permissible to neglect the emission of 3 or more neutrons so that the relative probability of 2n emission is $1 - P_1$. The quantity p_{2n}/p_n defined in Table 1 may therefore be approximated as $(1 - P_1)/[P_1 + 2(1 - P_1)]$. The results obtained on the basis approximations for Γ_n and ρ [6] and mass extrapolations [8] are given in Table 1.

A comparison of the experimental and calculated results shows that the gross theory of beta decay allows us to understand the magnitude of the 1n and 2n branches. Furthermore, the measured and calculated half-lives indicate the extent to which the absolute value of the beta strength function can be trusted. It is probably worth underlining that the calculations shown here do not represent a fit but emerge from a standard set of parameters used in previous work.

The experiments demonstrate that beta-delayed two-neutron emission is not a rare process far from stability. It is therefore important to take this mechanism into account in the calculation of yields in the astrophysical r-process [9].

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Table 1

Experimental branching ratios
for beta-delayed two neutron emission

Isotope $T_{1/2}(\text{ms})$	Experimental branching ratios ^{a)}				Calculated values		
	P_n	P_{1n}	$P_{2n}/P_n^{b)}$	P_{2n}	P_{2n}/P_n	P_{1n}	$T_{1/2}(\text{ms})$
^{30}Na 53	$0.33 \pm 0.04^e)$	$0.26 \pm 0.04^d)$	0.042 ± 0.008	$\begin{cases} 0.0130 \pm 0.0025^b) \\ 0.0115 \pm 0.0025^e) \end{cases}$	0.07	0.12	59
^{31}Na 17			0.023 ± 0.005	$0.0070 \pm 0.0025^b)$	0.006	0.36	89
^{32}Na 14.5		$0.10 \pm 0.04^e)$	0.24 ± 0.05	$\begin{cases} 0.050 \pm 0.019^b) \\ 0.055 \pm 0.025^e) \end{cases}$	0.20	0.13	40

a) The probability per beta decay for a process leading to the emission of i neutrons is denoted p_{in} , so that $\sum_{i=0}^{\infty} p_{in} \equiv 1$. The usual total branching ratio for beta-delayed neutron emission is $p_n = \sum_{i=1}^{\infty} i p_{in}$.

b) From neutron measurements (this work). It has been assumed that

$$p_{in} (i \geq 3) = 0.$$

c) From ref. 2.

d) From ref. 3.

e) From γ -spectroscopy (this work).

FIGURE CAPTIONS

Fig. 1 : Measured n-n time correlations for the isotopes ^{30}Na and ^{32}Na .

The measuring time was 14.3 h and 7.4 h, respectively. For the ^{30}Na measurement, the initial beam intensity was reduced by a factor of about 30 in order to improve the ratio of true to random events. The dashed lines indicate the mean contributions of random n-n correlations.

Fig. 2 : a) The gamma rays after 10 h collection of ^{30}Na . The 942 and 1342 keV rays originate in the decay of 21.8 h ^{28}Mg and the 1779 keV ray in the decay of its daughter product ^{28}Al .

b) The same spectrum as (a), but with the mass spectrometer set at mass 29.8 instead of 30. Only background lines remain, which proves that the ^{28}Mg lines in (a) are not due to cross-contamination in the spectrometer.

Fig. 1

Fig. 2