New Delayed-Neutron-Emitting Isotope: Be^{12}†

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Delayed neutrons with a half-life of 11.4±0.5 msec have been observed in the GeV-energy proton irradiation of targets of N^{15} and heavier nuclei but not from N^{14} and lighter nuclei. This new activity has been assigned to Be^{12}. Cross sections for production of this nuclide from N^{15}, O^{16}, O^{18}, F, Na, and Al have been measured. From cross-section systematics, it is estimated that delayed neutrons are emitted in about 7% of the decays. Upper limits for the delayed-neutron branches of He^8 and B^{13} have been set at 3 and 0.3%, respectively.

INTRODUCTION

In the course of our studies of the cross sections for production of the delayed-neutron-emitting nuclides Li^9, C^{16}, and N^{17} reported in a forthcoming paper,[1] we have observed a short-lived neutron activity in irradiated O^{18} targets. The series of experiments reported in this paper was undertaken in order to identify this new activity.

The experimental technique is similar to that described in Ref. 1 with the following modifications. The target was placed in the 2.2-GeV external proton beam of the Cosmotron and was not moved between beam pulses. Three $B^{10}F_3$ proportional counters contained in a paraffin block 25 in.×15 in.×9 in. were used to detect the neutrons. The target was $6\frac{1}{2}$ in. from the 25-×15-in. face. The counter was shielded on five sides by cadmium and two inches of paraffin, and on the side facing the target by $\frac{1}{4}$ in. of Boral (Al-clad boron sheet). This shielding was sufficient to eliminate stray neutrons which otherwise gave rise to spurious short-lived components (1–2-msec apparent half-life).[2] The counter became paralyzed during the beam burst but recovered within 10 msec. Monitoring of the proton flux through the targets was accomplished by means of measurements of the Na^{24} production in 0.001-in. Al foils placed on the upstream sides of the targets. The Cosmotron external beam was pulsed every $2\frac{1}{2}$ sec for 1 msec. A 400-channel multiscaler with a channel width of 1 msec was triggered at the same time. The proton-beam intensity was adjusted so as to keep the dead-time correction below 5%. Nine targets ranging from B to Al were investigated. They are listed in Table I.

Table I. Targets.

Target element	Form	Container	Thickness (g/cm²)
B	Powder	A[a]	0.31
C	Polystyrene	None	1.3
N^{14}	NH_4NO_3 powder	B[b]	1.99
N^{15}	NH_4NO_3 powder	B	1.43
O^{16}	Water	B	1.87
O^{18}	Water	B	2.08
F	Teflon	None	2.61
Na	Metal	None	1.26
Al	Metal	None	0.86

[a] Container A: Lucite 3-in.×3-in.×$\frac{1}{4}$-in. with 2-mil polyethylene windows.
[b] Container B: Lucite $1\frac{1}{2}$-in.-diam $\frac{3}{4}$-in.-thick with 1-mil Mylar windows.

The decay curves obtained were analyzed by a least-squares procedure[3] in terms of four half-life components. One of these was taken as unknown while the other three were those of Li^9, C^{16}, and N^{17} (176,[1] 740, and 4140 msec, respectively). The weighted-average result for the unknown half-life was 11.4±0.5 msec. This half-life was then used in the analysis of the decay curves from all the targets to obtain the initial activity of the new isotope and to calculate the cross section for its formation. In these calculations it was assumed that the counting efficiency for the neutrons from the new 11-msec activity was the same as that of Li^9. The efficiency of our counters for the latter was determined from the observed Li^9 activity induced in O^{18} and F and the known cross sections for its formation from these targets.[1]

In calculating the cross sections for N^{14} and N^{15} corrections were applied for the contribution of oxygen present in the target material. For some of the irradiations (B, C, Na, and Al targets) the production of Li^9 from the target was used as an internal monitor and the Li^9 cross sections were then also taken from Ref. 1. The measured cross sections are presented in Table II. For B, C, and N^{14} targets, the initial activities of the 11-msec components were less than their statistical errors. Thus, the cross sections listed are upper limits based on twice the standard deviation.

DISCUSSION

It is shown in Ref. 1 that as the mass of the target nucleus is increased, a given neutron excess nuclide will first be produced in appreciable yield in a (p,xp) reaction. Since the nuclide in question is produced from ${}_7N_8{}^{15}$, ${}_8O_8{}^{16}$, and heavier targets, but not from ${}_7N_7{}^{14}$ and

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[1] I. Dostrovsky, R. Davis, Jr., A. M. Poskanzer, and P. L. Reeder (to be published).
[2] F. J. M. Farley and B. S. Carter, Nucl. Instr. Methods 28, 279 (1964).
[3] J. B. Cumming, in *Applications of Computers to Nuclear and Radiochemistry*, edited by G. D. O'Kelley (Office of Technical Services, Washington, D. C., 1963).

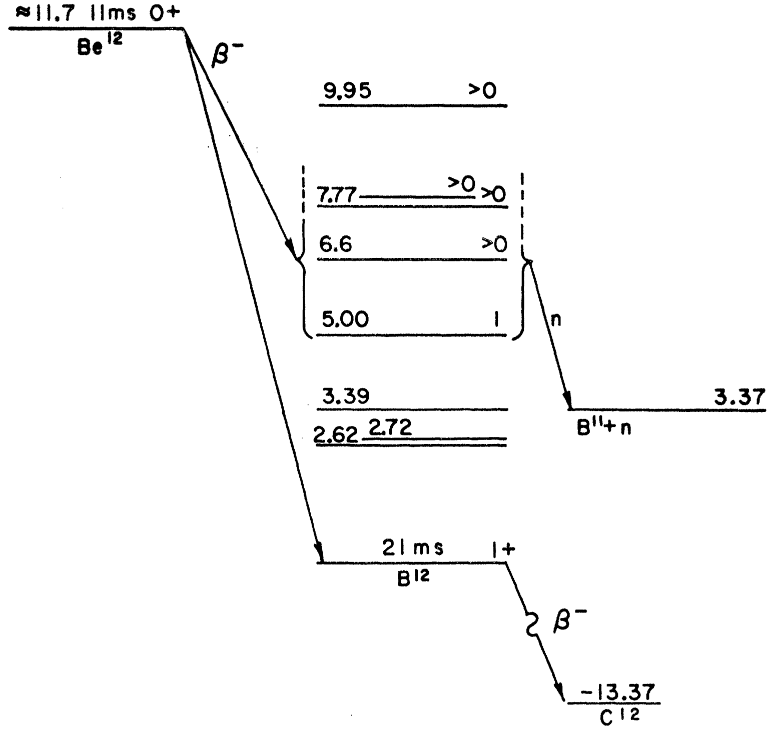

FIG. 1. Partial decay scheme for Be^{12} showing only the levels of B^{12} which possibly could have assignments of 1+.

lighter targets, it is concluded that it is an isotope containing eight neutrons. Of the possible isotones, ${}_6C_8{}^{14}$ and ${}_5B_8{}^{13}$ are known. The latter has a half-life of 18.6±0.5 msec and an upper limit for the neutron-emitting branch of $1\frac{1}{2}\%$.[4] ${}_3Li_8{}^{11}$ and lighter nuclides are predicted to be particle-unstable.[5] We therefore assign the new 11-msec activity to ${}_4Be_8{}^{12}$. This assignment is in agreement with the prediction of Baz', Gol'danskii, and Zel'dovich,[5] that Be^{12} is particle-stable and has a half-life of about 10 msec.

Be^{12} is produced from N^{15} by a $(p,4p)$ reaction. We have previously measured[1] a $(p,4p)$ cross section of 230 μb for the production of Li^9 from C^{12}. Assuming that the cross sections for both reactions are the same, we estimate that the neutron emitting branch of Be^{12} is 7%. Based on the data in Ref. 1 we estimate that this assumption is good to within a factor of 2.

A partial decay scheme for Be^{12} is shown in Fig. 1. Of the known levels[6] of B^{12}, there are shown only those which possibly can be populated by allowed beta transitions. Gol'danskii[7] has estimated the maximum beta energy of Be^{12} to be between 9.3 and 12.9 MeV. However, a somewhat better estimate may be obtained in the following way. Kurath[8] has calculated that the ground-state transition has a log ft of 3.5. Together with our half-life, this indicates that the $E_{\beta\max}\approx 11.7$ MeV. This is within the range estimated by Gol'danskii. A transition to the 5.00-MeV level with the same log ft value would be consistent with our rough estimate of the neutron branch. However, Kurath[8] did not calculate any branch to an excited state as big as 1% of that for the ground state. This remains unexplained.

Nefkens[9] has reported observing the beta decay of He^8 with a 30±20-msec half-life. By analyzing our decay curve for the boron target with a 30-msec half-life instead of 11 msec, we obtain a two-sigma upper limit of 8 μb with no improvement in the goodness of fit. Assuming the same cross section as for the $C^{12}(p,4p)Li^9$

TABLE II. Cross sections for the production of Be^{12} by 2.2-GeV protons (neutron-emitting branch only).

Target	σ (μb)
B	< 5
C	< 1.2
N^{14}	< 1.3
N^{15}	15.9±0.8
O^{16}	3.3±0.3
O^{18}	103 ±3
F	12.0±0.7
Na	7.3±1.4
Al	3.5±1.0

[4] A. Marques, A. J. P. L. Policarpo, and W. R. Phillips, Nucl. Phys. **36**, 45 (1962).
[5] A. I. Baz', V. I. Gol'danskii, and Ya. B. Zel'dovich, Usp. Fiz. Nauk **72**, 211 (1960) [English transl.: Soviet Phys.—Usp. 3, 729 (1961)].
[6] T. Lauritsen and F. Ajzenberg-Selove, *Energy Levels of Light Nuclei* (National Academy of Science, National Research Council, Washington, D. C. 1962).
[7] V. I. Gol'danskii (private communication).
[8] D. Kurath (private communication).
[9] B. M. K. Nefkens, Phys. Rev. Letters **10**, 243 (1963).

reaction, we obtain an upper limit of 3% for the neutron branch of He^8. If He^8 exists, this indicates that the transition to the 3.22-MeV level of Li^8 has a log ft value greater than 4.0 (using the He^8 mass estimated in Ref. 5).

To search for neutrons from B^{13}, the decay curve from the N^{15} target was reanalyzed with the addition of an 18.6-msec component and an upper limit of 5 μb was obtained. Estimating a $(p,3p)$ cross section from our previous work,[1] we obtain an upper limit of 0.3% for the delayed neutron branch of B^{13}, which is somewhat lower than the previous limit of Marques *et al.*[4]

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Study of the Gamma-Ray Spectra Emitted in the Resonance Capture of Neutrons by ^{19}F†

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Gamma-ray spectra have been measured at the 27-keV (2^-) and the 49-keV (1^-) resonances of $^{19}F(n,\gamma)^{20}F$. The $E1$ transition to ground is virtually absent at both resonances, while the other $E1$'s have strengths that appear normal when compared with heavier nuclei in which the radiation widths are proportional to level spacing. A description is given of the two-parameter instrument by means of which it is possible to measure simultaneously the neutron energy (flight time) and gamma-ray pulse-height spectra for radiative neutron capture.

I. INTRODUCTION

Spectra of prompt gamma rays emitted following capture of thermal neutrons by nuclei have been studied for more than ten years.[1] These studies have (a) revealed the location of many hitherto unobserved bound states, (b) established spins, parities and lifetimes of states in certain situations where conditions were particularly favorable, and (c) revealed by means of certain systematic features of the spectra, characteristic trends in nuclei with mass number and aspects of the mechanism of neutron capture.

Measurements of the type just described have utilized the copious sources of thermal neutrons that reactors provide. As interest in the subject has grown and instrumentation progressed, the study of *resonant* neutron-capture spectra became possible; the first success was with electron linac neutrons,[2] but more recently reactor neutrons have also been successfully employed.[3] These experiments have been most successful at neutron energies below about 2 keV, although some work has been done with fast neutrons.[4]

It would be especially interesting to be able to extend (n,γ) measurements into the keV region and higher because many resonance levels with known angular momentum and parity occur in nuclei for which level spacings are of the order of kilovolts. Such nuclei appear either at the lower quarter of the nuclear-mass scale or in the neighborhood of closed shells. Study of neutron-capture gamma-ray spectra in such nuclei affords at once the opportunity of studying the mechanism of neutron capture at resonances of known spin and parity and of assigning spin and parity to additional levels.

In the earliest studies on thermal-neutron capture,[5] it was found that strong ground-state gamma rays were the exception rather than the rule. This finding might at first have been expected on the basis of the statistical model that the transition probabilities are expected to be proportional to the density of final states. However, strong gamma rays were observed to low-lying levels when those levels were p states according to the shell model. These transitions generally corresponded to $E1$ transitions. Particularly notable exceptions were ^{20}F and ^{28}Al in which strong high-energy transitions of type

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[1] L. V. Groshev, V. N. Lutsenko, A. M. Davidov, and V. I. Pelekhov, *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).
[2] H. H. Landon and E. R. Rae, Phys. Rev. **107**, 1333 (1957).
[3] R. T. Carpenter and L. M. Bollinger, Nucl. Phys. **21**, 66 (1960).
[4] I. Bergqvist and N. Starfelt, Nucl. Phys. **39**, 529 (1962).
[5] B. B. Kinsey and G. A. Bartholomew, Physica **18**, 1112 (1952).