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PHYSICAL REVIEW C VOLUME 3, NUMBER 6 JUNE 1971

Excitation Functions of ^{7}Be and ^{11}C Produced in Nitrogen by Low-Energy Protons

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The cross sections for the production of ^{11}C and ^{7}Be by protons from a ^{14}N target has been measured at energies from 5–24 MeV for ^{11}C and 13–42 MeV for ^{7}Be. A sharp rise above the thresholds for the ^{14}N(p,α) and ^{14}N$(p,2\alpha)$ reactions was observed, with maxima, respectively, around 200 and 45 mb.

INTRODUCTION

The measurement of the cross sections for the formation of ^{7}Be and ^{11}C in nitrogen is part of a larger program undertaken at Orsay in order to establish the excitation functions of Li, Be, and B in the bombardment of ^{12}C, ^{14}N, and ^{16}O by protons and α particles. In addition to their interest to the nuclear physicist, these excitation functions are essential to the astrophysicist for the study of many problems such as the nucleosynthesis of the L elements[1] (Li, Be, B), determination of their stellar abundances,[2] and the propagation of cosmic rays.[3] Also, ^{7}Be is used as a monitor for the measurement of the absolute cross sections of the stable isotopes of the light elements when a mass spectrometric method is used. In many geophysical investigations,[4] ^{7}Be is an interesting radioisotope, as it is formed continually by the interaction of the cosmic particles with the atmosphere, which is essentially composed of nitrogen.

The cross sections for production of ^{11}C and ^{7}Be have been known for a long time in ^{12}C and ^{16}O over a great range of energies, while in nitrogen very few measurements have been made, especially in the low-energy range: ^{11}C has been measured only between 5 and 6 MeV,[5] at 13 MeV,[6] and 50 MeV,[7] with a rather large uncertainty. In view

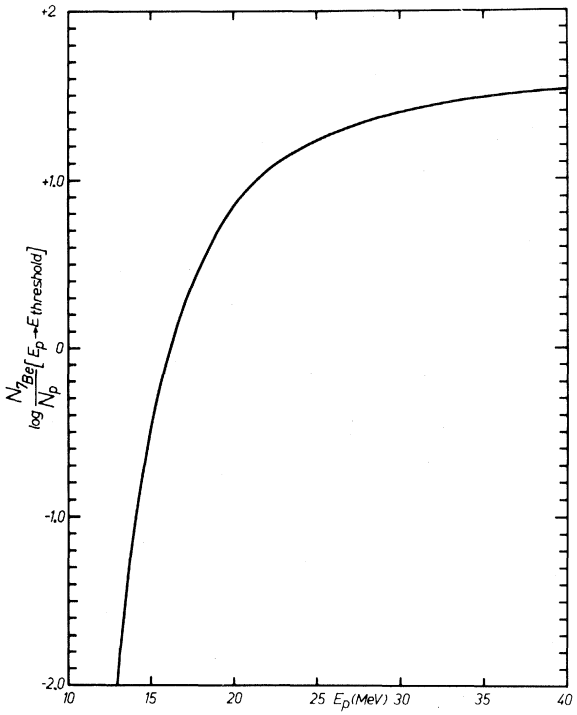

FIG. 1. Integral yield curve for ^{7}Be.

of the interest of these cross sections we have undertaken a more systematic study.

EXPERIMENTAL METHOD

The choice of the target was made so as to simplify as much as possible the technical aspects of the irradiations. A nitrogeneous compound without any boron, lithium, or any element which could contribute to an important extent to the formation of ^{7}Be and ^{11}C had to be selected which would be stable against the chemical effects of the irradiation. Vanadium nitride was finally chosen because it gave rise to a minimum of extra activity after the irradiations and because a chemical separation was not necessary. We measured the production of ^{7}Be and ^{11}C in pure vanadium at 24 MeV and found, in agreement with other measurements,[8] that it was less than 0.1% of the production of these nuclides in vanadium nitride. The main impurities of the target material were carbon and oxygen (0.1%). Before being irradiated the vanadium nitride powder was compressed into pellets 20 mm in diameter and 0.5 mm thick.

The irradiations were performed with several accelerators: the King tandem and the variable-energy cyclotron at the Centre d'Etudes Nuclé-

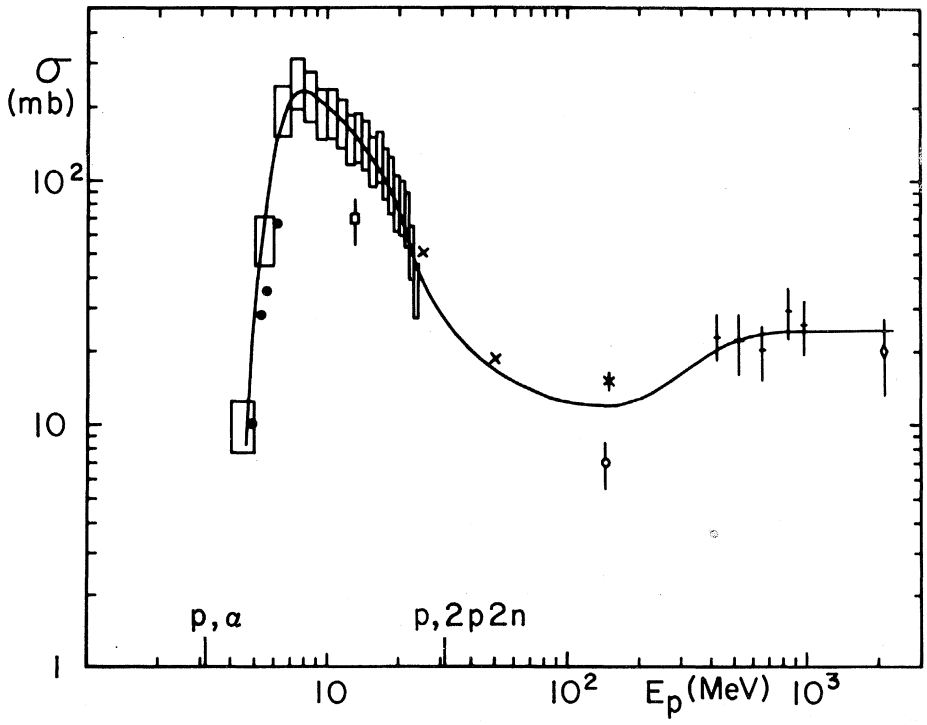

FIG. 2. Excitation function for the production of ^{11}C in the proton bombardment of nitrogen. ●, Blaser, Marmier, Sempert (Ref. 5); □, MacLeod and Reid (Ref. 6); ○, A. B. Clegg, K. J. Foley, G. L. Salmon, and R. E. Segel, Proc. Phys. Soc. (London) 78, 681 (1961); ×, Valentin *et al.* (Ref. 7); ▬, J. L. Symonds, J. Warren, and J. D. Joung, Proc. Phys. Soc. (London) A70, 824 (1957); ◇, P. A. Benioff, University of California Radiation Laboratory Report No. UCRL-8780, 1959 (unpublished) and Phys. Rev. 119, 316 (1960); ▯, present data.

aires de Saclay for the irradiations below 24 MeV, and the variable-energy cyclotron of the University of Milano above this value and up to 42 MeV. The targets were exposed to the external beam. In order to produce sufficient ^{11}C activity a beam of 0.1 μA for a few minutes was sufficient. For ^{7}Be, 1 μA during 20–60 min was required. The target was mounted in a Faraday cup. The charge collected on this beam stopper was measured by an integrator circuit.

For the lowest energies, when the beam is stopped in the vanadium nitride, an integral yield curve was measured with energy increments of 1 MeV. For the higher energies, when the beam was only degraded and not stopped in the target, the irradiations were performed in such a way that the incident energy on a target was equal to the emergent energy from the target of the preceeding irradiation. Thus we avoided straggling in a target stack and had more precision on the irradiation energy in the analysis of the results. Still there remained the uncertainty in the energy-loss calculations of a compound, and in the adjustment of the proton energy.

The radioactivity of ^{11}C and ^{7}Be was measured by the classical methods of γ spectrometry. ^{11}C is a β^{+} emitter and was measured by its annihilation γ ray of 511 keV, distinguished from the other β^{+} emitters by its half-life of 20 min. These β^{+} emitters had a longer half-life and a lower activity so that the measurements were easiest in the two hours following the irradiations. The samples were mounted between two aluminum annihilators and measured by two NaI(Tl) scintillators in coin-

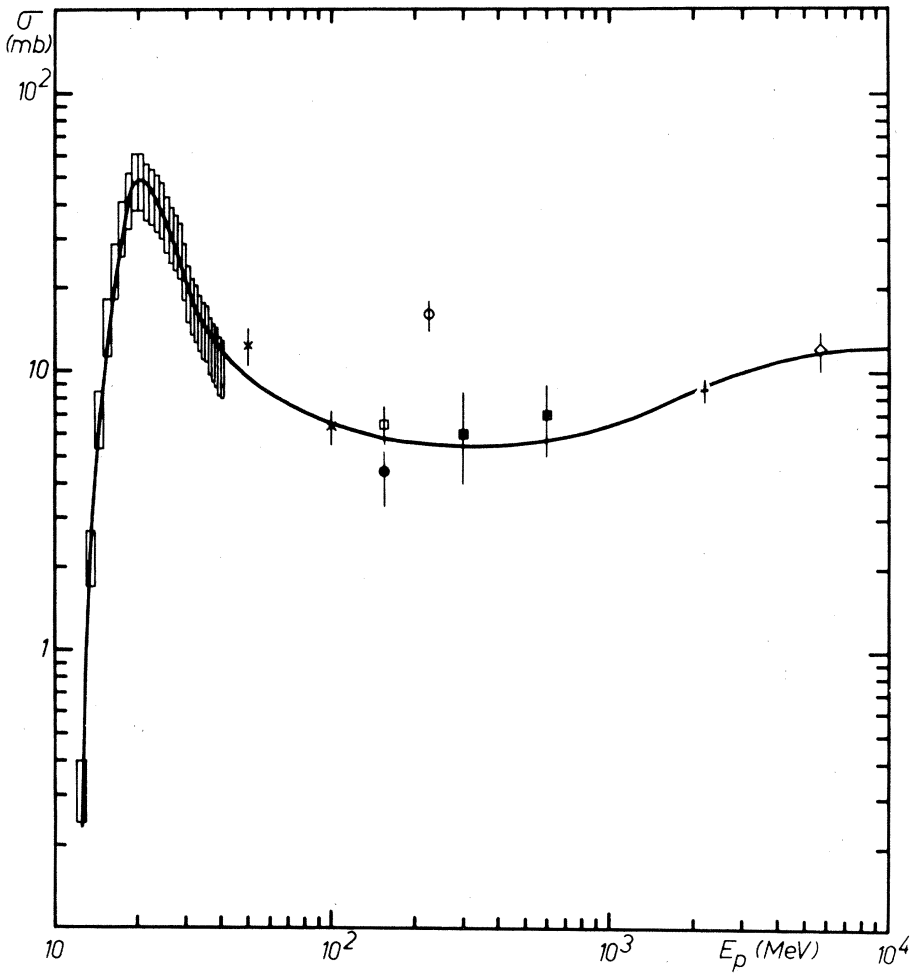

FIG. 3. Excitation function for the production of ^{7}Be in the proton bombardment of nitrogen. ×, R. Bimbot, private communication; ●, R. George, Thêse 3e cycle, Institut De Physique Nucléaire, Orsay, 1962 (unpublished); □, L. Valentin, G. Albouy, J. P. Cohen, and M. Gusakow, Phys. Letters 7, 163 (1963); ○, M. Honda and D. Lal, Phys. Rev. 118, 1618 (1960); ▬, P. L. Reeder, J. Inorg. Nucl. Chem. 27, 1879 (1965); ◇, P. A. Benioff, University of California Radiation Laboratory Report No. UCRL-8780, 1959 (unpublished); Phys. Rev. 119, 316 (1960); ■, M. Barbier and S. Régnier, to be published; [], present data.

cidence. ^{7}Be-decay characteristics were taken as $\tau = 53.6$ day and 10.3% electron-capture branching to the 477-keV level. A high-resolution Ge(Li) γ spectrometer was used because of the important contribution of 511-keV photons due to positron annihilation from the radioelements formed in the vanadium.

A standard ^{7}Be source was used to calibrate the Ge(Li) spectrometer. Its absolute γ activity was measured by the Service de Metrologie of the Centre d'Etudes Nucléaires de Saclay. In the same way the absolute ^{11}C activity of one target was measured and used afterwards to calibrate the NaI(Tl) crystal spectrometer.

RESULTS AND DISCUSSION

We have plotted in Fig. 1 the number of atoms formed in the target material integrated from threshold to the incident energy. This curve was differentiated to obtain the yield in 1-MeV increments. The necessary range-energy curves were obtained from tables[9] given in terms of the stopping-power parameter I.[10]

The cross sections were determined in the usual manner. The results are given in Figs. 2 and 3. Errors involved in the cross-section determinations may be classified as systematic and random. Systematic errors are associated with radioactive reference sources, integrated charges in the Faraday cup, and nitrogen content of the target and proton ranges. The uncertainty in the activity of the reference sources was 5% for ^{7}Be and 10% for ^{11}C. The activity of these sources had been measured by a 3-in.$\times$3-in. NaI crystal coupled to a 400-channel pulse-height analyser calibrated for standard γ sources against a $4\pi\beta$ proportional counter. An error of $\pm$3% was taken for the number of incident protons. The amount of nitrogen in the vanadium nitride was measured using a derivative of the Kjeldahl method. The value obtained agreed within the quoted error (18 ± 1.7%) with that given by the supplier. The uncertainty in the range of protons in vanadium nitride was estimated to be 3%. The root mean square method applied to the preceding errors gives a total systematic error of 12% for the ^{7}Be measurements and 15% for the ^{11}C measurements.

Random errors are connected with activity determinations. The uncertainty in the measured activity is mainly due to the determination of the area of the 511-keV photopeak; we estimated it to be 5%. In summary, then, the ^{7}Be cross sections are known with an uncertainty of $\pm$17%, while the uncertainty for ^{11}C is $\pm$20% for energies lower than 12 MeV, and $\pm$25% for higher energies.

A possible contribution by the reaction ^{11}B(p, n)-^{11}C has also been investigated. This reaction has a maximum cross section of 300 mb around 10 MeV. We have supposed the ^{11}C cross section measured at 5 MeV to be entirely due to this reaction. Thus the maximum amount of boron present in VN would have to be 1.25%. In this extreme case the fraction of ^{11}C formed in boron at the maximum of the excitation function would be less than 10% of the ^{11}C measured.

As seen in Figs. 2 and 3, the excitation functions we have measured fit the cross-section values already measured by other authors at higher energies. The high cross sections obtained for ^{11}C, which undergoes β decay to ^{11}B with a 20-min half-life, show the importance of nitrogen in the formation of boron at relatively low proton energies.

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They are indebted to Yves Bisson for his careful technical assistance, to Y. Legrand of Saclay for the calibration of the standard sources, and to Dr. G. Delarue for his hospitality in the chemistry laboratory of l'Institut National des Sciences et Techniques Nucléaires of Saclay where the ^{11}C measurements were performed.

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$$\log\langle I_{VN}\rangle=\frac{1}{\rho_{VN}}\left\langle\frac{A}{Z}\right\rangle_{VN}\left[\frac{Z_N\rho_N}{A_N}\log I_N+\frac{Z_V\rho_V}{A_V}\log I_V\right].$$

ρ_{VN} is the specific mass of the vanadium nitride used, and

$$\left\langle\frac{Z}{A}\right\rangle_{VN}=\frac{1}{\rho_{VN}}\left[\frac{Z_N\rho_N}{A_N}+\frac{Z_V\rho_V}{A_V}\right].$$

ρ_N and ρ_V are the partial densities of nitrogen and vanadium in the vanadium nitride. The mean atomic excitation energy I of nitrogen is known experimentally; for vanadium it has been calculated following a relation due to Sternheimer: $I/Z=9.76+58.8Z^{-1.18}$ eV. Finally, the value $\langle I_{VN}\rangle=200$ eV was obtained.

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Cross-Section and Polarization Measurements for the ^{3}H(^{3}He, n)^{5}Li Reaction*

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Measurements of the angular distribution and polarization of neutrons from the reaction ^{3}H(^{3}He,n)^{5}Li have been made for mean ^{3}He bombarding energies of 2.70 and 3.55 MeV. Polarizations were measured using a ^{4}He gas scintillator, and cross sections were determined using a liquid scintillator employing pulse-shape discrimination. Contributions from the three-body breakup channel ^{3}H(^{3}He,np)^{4}He were removed by assuming these neutrons to be unpolarized and to have a statistical energy distribution in the high-energy portion of the neutron spectrum. The angular distribution of neutrons from the reaction ^{3}H(^{3}He,n)^{5}Li exhibits a broad peak in the vicinity of $\theta_{c.m.}=45°$. The neutron polarization was found to be negative at all angles investigated, and reaches a minimum value of -0.30 at $\theta_{c.m.}=125°$, $E_{^3He}=2.7$ MeV. Excitation functions for the cross section were measured at laboratory angles of 0 and 40° for ^{3}He energies between 0.7 and 3.8 MeV. The reaction data can be reproduced qualitatively with a simple two-nucleon-transfer distorted-wave Born-approximation calculation, but the ^{3}He-^{3}H potential parameters used do not reproduce published elastic scattering data at somewhat higher energy.

I. INTRODUCTION

Among the nuclear reactions involving very light nuclei, those in which the entrance channel consists of ^{3}He + ^{3}H have as yet not been studied very extensively; in particular, the ^{3}H(^{3}He, n)^{5}Li reaction has received very little attention to date.[1,2] The study of this reaction is complicated by the fact that ^{5}Li is unbound and the neutrons are emitted in the presence of neutrons from three-body breakup into $\alpha+n+p$. Using a proton recoil telescope, Barry, Batchelor, and Macefield (BBM)[2] observed the spectrum of neutrons produced by bombarding tritium with ^{3}He consists of a prominent peak corresponding to neutrons from the two-body final state ^{5}Li + n ($Q=10.13$ MeV), superimposed on a continuum of neutrons from the three-body final state ^{4}He + n + p and from the breakup of unstable members of other two-body states. For a ^{3}He bombarding energy of 3.2 MeV, the angular distribution of neutrons from ^{3}H(^{3}He, n)^{5}Li was found to exhibit a broad peak near 40° (lab), somewhat suggestive of an $l=1$ double stripping process involving transfer of two protons from ^{3}He to ^{3}H. The possibility of two-nucleon transfer from the triton to the ^{3}He particle, which might also be expected to occur in this reaction, could not be excluded by the data of BBM.

Angular-distribution measurements on the mirror reaction ^{3}He(^{3}H, p)^{5}He have been confined for the most part to bombarding energies below 1100 keV.[3,4] To the extent that Coulomb effects can be neglected, the angular distribution for this reaction should be the same as for ^{3}H(^{3}He, n)^{5}Li. Kühn and Schlenk[3] observed the angular distribution in ^{3}He(^{3}H, p)^{5}He to change smoothly from near-isotropy at a bombarding energy of 460 keV to distributions broadly peaked around 80° (c.m.) at a bombarding energy near 1100 keV.

It is of interest to see to what extent the ^{3}H-(^{3}He, n)^{5}Li and ^{3}He(^{3}H, p)^{5}He reactions can be regarded as two-body reactions separate from other processes such as breakup into ^{4}He + n + p. If, for example, the ^{3}H(^{3}He, n)^{5}Li reaction should proceed