Production of $^{14,15}O$, ^{18}F, and ^{19}Ne radioactive nuclei from (p,n) reactions up to 30 MeV

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Total cross sections for proton-induced reactions on $^{14,15}N$, ^{18}O, and ^{19}F targets were measured by the activation method, up to 30 MeV. Yields of nuclei of astrophysical interest, i.e., $^{14,15}O$, ^{18}F, ^{19}Ne were obtained.

I. INTRODUCTION

The so-called hot carbon-nitrogen-oxygen (CNO) cycle takes place in particular stellar environments, e.g., novae and supernovae:[1] Light radioactive nuclei in the 13–20 mass unit range are involved in a set of radiative capture reactions competing with their β^+ decay rate. Owing to the short lifetime of most of those nuclei, the study of the radiative capture reactions requests the development of radioactive beams; a project aiming at the production and the acceleration of such beams is presently under way at Louvain-la-Neuve.[2] Radioactive nuclei will be produced by proton-induced reactions on suitable targets, up to a 30 MeV energy.

A first paper[3] (hereafter referred to as I) has dealt with the ^{13}N production by the $^{13}C(p,n)$ and the $^{16}O(p,a)$ reactions. The present paper reports on cross sections for the production of ^{14}O, ^{15}O, ^{18}F, ^{19}Ne nuclei by proton-induced reactions; in each case, other positron-emitter radioactive nuclei, i.e., "contaminants," were also detected and their production cross section was measured.

II. EXPERIMENTAL PROCEDURE

The experimental setup was related in detail in I. In short, a proton beam from the CYCLONE cyclotron bombarded either a cell containing ^{14}N, ^{15}N, or ^{18}O gas under a 10 bar typical pressure, or a LiF powder target. Behind the target, the beam was integrated in a beryllium stopper protected against secondary electrons. The beam energy was varied by inserting aluminium degraders in front of the target. The stainless-steel cylindrical gas cell, of 2 cm length and 4 cm diam was limited by 1 mm thick aluminum windows, while the LiF powder was pressed between two 4 cm diam and 1 mm thick beryllium windows.

Cross sections were measured by the activation method. Immediately after the end of the irradiation, 511 keV annihilation γ-rays from the sample were detected in coincidence by two 7.6×7.6-cm-plastic scintillators placed at 180° respective to each other and coupled to fast EMI 9821 B photomultipliers, which were powered by home-developed transistorized voltage divider networks.[4] A very constant amplitude versus counting rate and versus time was indeed requested all along the measurements [which lasted for at least four lifetimes of the isotope of interest, i.e., for 10 h for the $^{18}O(p,n)^{18}F$ reaction]. The detection efficiency problem was already explored in I, as well as the fitting procedure of the number of coincidence-versus-time spectra which were recorded in the multiscaling mode and fitted with the MINUIT code.[5] Measured cross sections are affected by a 9% error, of which less than 1% is statistical, the rest coming from uncertainties in the current integration, the detector's efficiency, and the target homogeneity. The energy was calculated from the range-energy tables.[6] The total energy width induced by the target thickness was of the same order as in I (see Table I therein), namely ±0.2 MeV above 15 MeV and ±0.1 MeV above 25 MeV.

Only for the $p+{}^{14}N$ reaction, we had to follow a different strategy to obtain the cross section for ^{14}O production which was very low compared with the nearby nuclei (^{13}N,^{11}C) produced in the same reaction; we detected, as a stronger signature, the 2.3 MeV γ-ray from the $^{14}O(\beta^+)^{14}N$ decay, in a 7.6×7.6-cm NaI crystal, while recording at the same time its 70 sec half-life exponential decay. The absolute efficiency of the NaI detector at 2.3 MeV was obtained from Ref. 7 for a point source, and a correction was made for the target extension.[8]

III. RESULTS

Two kinds of results were obtained from our measurements, namely excitations functions $\sigma(E)$ for the production of radioactive nuclei, and thick target yields $Y(E_0)$, i.e., the integral from threshold T up to the energy E_0 of the excitation function times the target density;[6] Y is also the ratio of the number of produced nuclei to the number of incident protons.

A. The $p+{}^{14}N$ reaction

The cross section for ^{14}O ($T_{1/2}=70$ sec) production between 10 and 30 MeV is represented in Fig. 1(a); the agreement with previous data[9,10] is fair except in the 15–20 MeV region where the structure appearing in our data points is questionable. The data of Kuan,[11] which were about a factor of 10 higher and which are not drawn

here for clarity, are again contradicted by the present measurement.

On the other hand, cross sections for ^{13}N and ^{11}C production were obtained from a fit of a multiscaling spectrum, as described above. Only those two isotopes had to be included in the fit. Figure 1(b) shows the thick target yields for ^{14}O, ^{13}N, and ^{11}C production, calculated from the data of Fig. 1(a) for the former and from the data of Refs. 12 and 13 and our data for the last two nuclei. It appears that the $p+^{14}N$ reaction is a very weak source of ^{14}O nuclei; this point will be discussed later.

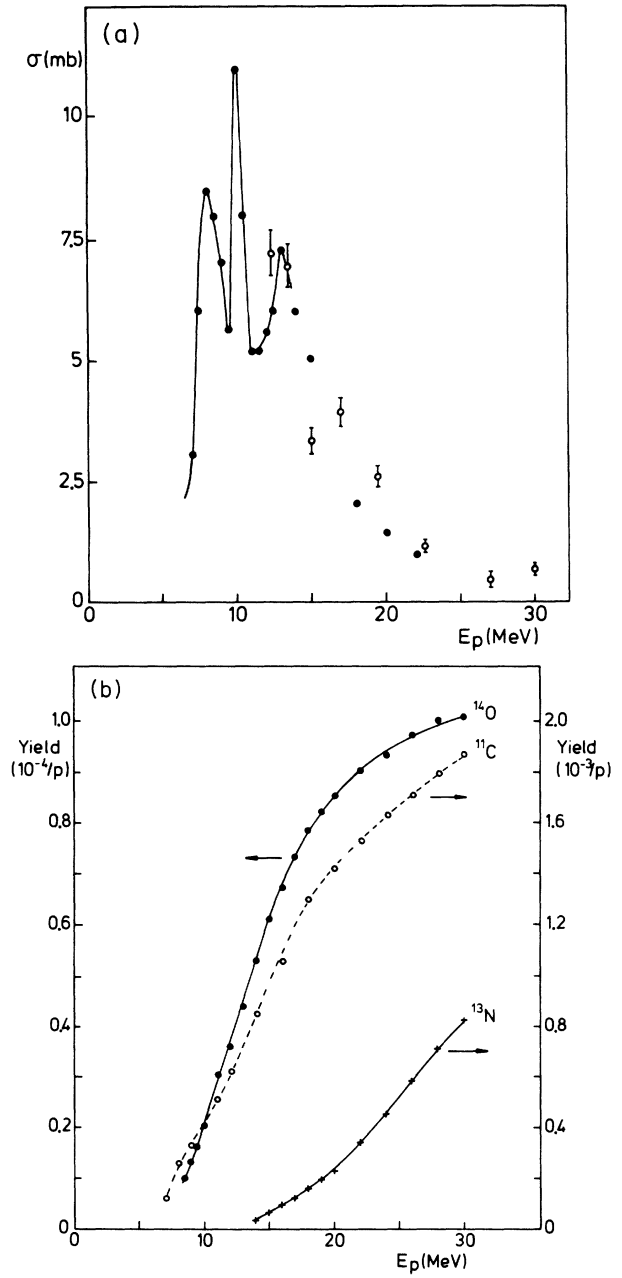

FIG. 1. (a) Total cross section σ (in mb) for the $^{14}N(p,n)^{14}O$ reaction versus the laboratory proton energy Ep (in MeV), from this work (open dots) and from Ref. 9 (up to 13 MeV) and Ref. 10 (above 13 MeV) (closed dots). Lines were drawn only to guide the eye, as in all the subsequent figures. Error bars on our data contain both the statistical and systematic uncertainties; the uncertainties on the data of Ref. 9 and 10 are 20% and 10%, respectively. (b) Thick target yields from the $p+^{14}N$ reaction, for the production of ^{14}O (left ordinate, 10^{-4} per incident proton) calculated from the cross section data of Refs. 9, 10, and from our data, and for the production of ^{11}C and ^{13}N (right ordinate, 10^{-3} per incident proton) calculated from the cross section data of Refs. 12, 13, and from our data.

B. The $p+^{15}N$ reaction

The $p+^{15}N$ cross section was measured between 15 and 28 MeV. The target was made of 99.8% ^{15}N. The irradiation time was 2 min. The lifetimes of ^{11}C, ^{13}N, and ^{15}O were included in the fit, while the production of ^{14}O was not observed. The cross section for ^{15}O production had been measured by Sajjad *et al.*[14] up to 16.6 MeV; at this energy, we are in excellent agreement, as shown in Fig. 2(a). As far as a conclusion can be drawn from one

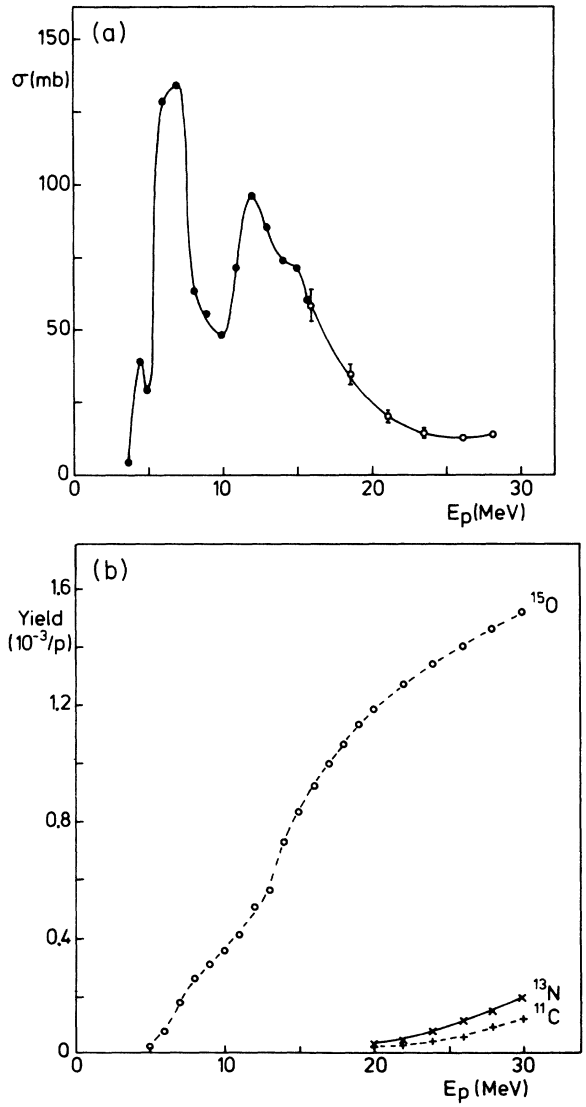

FIG. 2. (a) Total cross section for the $^{15}N(p,n)^{15}O$ reaction, from this work (open dots) and from Ref. 14 (closed dots); the uncertainty on the last data is 7%. (b) Thick target yields (in 10^{-3} per incident proton) from the $p+^{15}N$ reaction, for the production of ^{15}O calculated from the data of Ref. 14 and from our data, and for the production of ^{13}N and ^{11}C calculated from our data.

data point only, Barnett's results[15] which are twice as high as Sajjad's data from threshold to 12 MeV, should be disregarded. Figure 2(b) depicts the yields of ^{15}O as well as of two contaminants, namely ^{13}N and ^{11}C which are by far dominated by the ^{15}O yield.

The need for a (very expensive) enriched target is, of course, a severe drawback to the $p+^{15}N$ reaction. On the other hand, ^{15}O can be produced nearly as plentifully by the $p+^{16}O$ reaction, but with a larger relative contamination of ^{13}N and ^{11}C. (See I.)

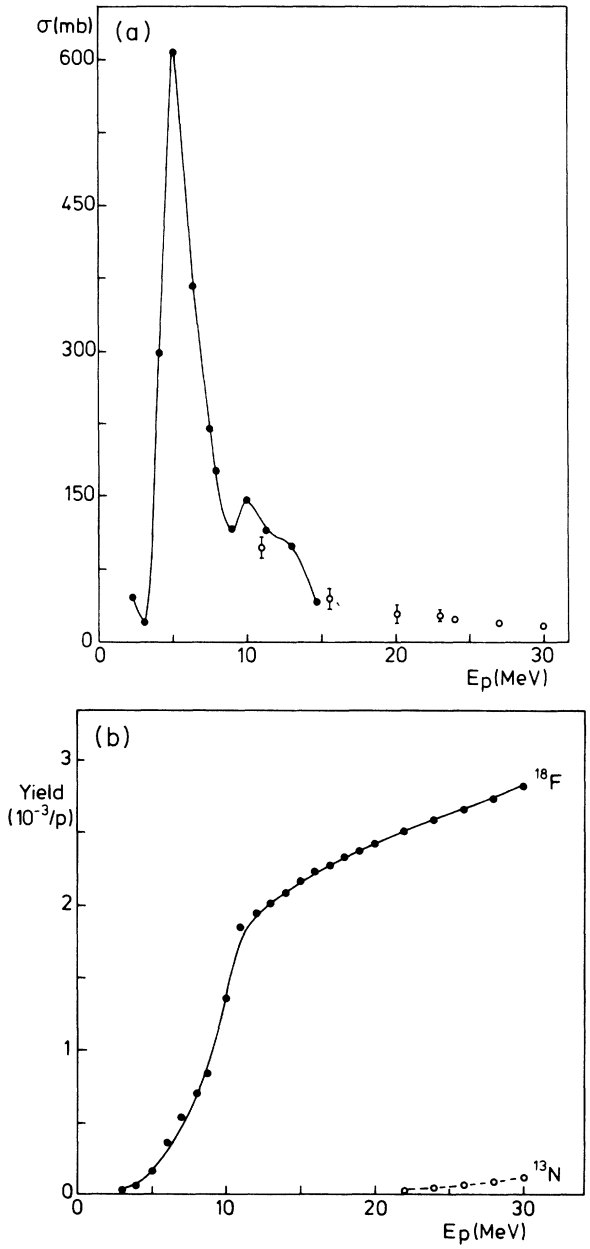

FIG. 3. (a) Total cross section for the $^{18}O(p,n)^{18}F$ reaction, from this work (open dots) and from Ref. 16 (closed dots); the data of Ref. 16 are affected by a 5% uncertainty. (b) Thick target yields from the $p+^{18}O$ reaction, for the production of ^{18}F calculated from the data of Ref. 16 and from our data, and for the production of ^{13}N calculated from our data.

C. The $p+^{18}O$ reaction

The $p+^{18}O$ reaction cross section was measured between 11.2 and 30 MeV. The enriched target contained 95% of ^{18}O and 5% of ^{16}O. The irradiation time was 30 min and the irradiated sample was counted for 10 h. The channel width of the recorded spectra was 1 min, which

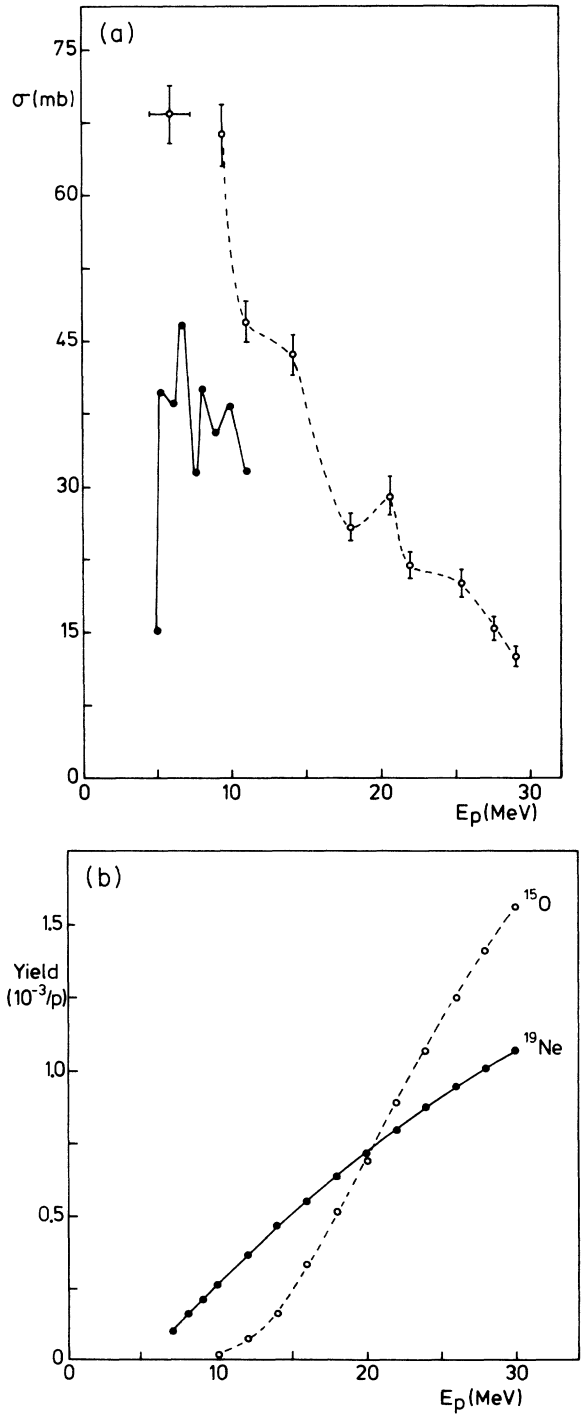

FIG. 4. (a) Total cross section for the $^{19}F(p,n)^{19}Ne$ reaction, from this work (open dots) and from Ref. 18 (closed dots). The uncertainty on the data of Ref. 18 is ±15%. (b) Thick target yields from the $p+^{19}F$ reaction from this work, for the production of ^{19}Ne (closed dots) and of ^{15}O (open dots).

prevented us from determining cross sections for the short-lived nuclei ^{15}O (2 min) and ^{17}F (64 sec). Only the lifetimes of ^{13}N and ^{18}F were needed to fit the spectra; the contribution of the $^{16}O(p,a)$ reaction to the ^{13}N production (see I) was subtracted to obtain the $^{18}O(p,x)^{13}N$ cross section. During the measurement of the $p+^{18}O$ reaction, a check of the gas density versus time stability was performed by doing two irradiations, of 3 min and 30 min, at the same proton energy (15.3 MeV). The two cross section values for ^{18}F production agreed well within the error bars (42.3 +/−4.3 mb and 44.5 +/−3.6 mb, respectively).

The cross section data are drawn in Fig. 3(a) and compared with data of Ruth and Wolf.[16] Yields for ^{18}F and ^{13}N production are pictured in Fig. 3(b).

D. The $p+^{19}F$ reaction

The $p+^{19}F$ cross section was measured from threshold (4.24 MeV) to 28 MeV. The target was made of LiF powder uniformly pressed between two 1 mm thick beryllium windows. To increase the detection efficiency, the target plane was located at 45° with respect to the beam direction. The irradiation time was 20 sec and the subsequent counting time was 60 min. The channel width of the multiscaler spectra was 1 sec. Besides ^{19}Ne, the production of ^{15}O was also observed. Owing to the fact that the channel width was very near the ^{18}Ne half-life (1.67 sec) and very far from the ^{18}F half-life (110 min), it was not possible to extract cross section values for those isotopes. The ^{17}F production was not observed; a previous measurement[17] of the $^{19}F(p,t)^{17}F$ reaction at 22.8 MeV had yielded a total cross section as low as 4 mb. The cross section of the $^{19}F(p,n)^{19}Ne$ reaction can be found in Fig. 4(a); an integral cross section measurement was done from threshold up to 7 MeV. It appears that our data are in strong disagreement with the previous data of Jenkin *et al.*;[18] those authors, however, quote a normalization uncertainty of ±15% and they indicate an agreement "better than a factor of two" between them and the older data.[19] The yield for ^{19}Ne production was calculated from our data and pictured in Fig. 4(b). An important production of ^{15}O was also obtained.

IV. DISCUSSION

(A) As it was already remarked in I, it should be kept in mind that (i) the measured yields are upper limits in the sense that normal production targets are usually compounds and (ii) the quoted yields are somewhat dependent on the range-energy tables that were used [e.g., using the Ziegler[20] tables should have increased the $^{13}C(p,n)^{13}N$ yield at 30 MeV by 7%].[21]

(B) Large amounts of light radioactive nuclei (^{15}O, ^{18}F, and ^{19}Ne) can be produced by the (p,n) reaction; a marked exception is the $^{14}N(p,n)^{14}O$ reaction of which the yield is about a factor of 10 lower. One can remark in this case that the analog state of the final nucleus ground state is an *excited state of the target*, contrary to the other reactions, where either both the initial and final ground states are analog states (^{15}N and ^{15}O, ^{19}F and ^{19}Ne), or the initial ground state and an excited state of the final nucleus are analog states [^{18}O and $^{18}F^*$ (1.04 MeV)].

(C) For some nuclei, the large yields obtained from the (p,x) reaction on *natural* targets allow to bypass the use of the (p,n) reaction on an enriched target. Such are the ^{11}C production from ^{14}N or ^{11}B targets, or the ^{15}O production from ^{16}O and ^{19}F or from ^{15}N targets.

(D) The experimental method developed in the present paper consisted in using fast scintillation detectors coupled to stabilized voltage dividers; large counting rates could thus be sustained, and the counting of the sample could be started immediately after the end of the irradiation. Nuclei with a half-life as short as about 10 sec were easily measured. The difficulty, however, was to define, for a single irradiation, a channel time width of the multiscaling mode which was adapted to the very large range of half-lives.

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[1]W. A. Fowler, Rev. Mod. Phys. **56**, 119 (1984).
[2]M. Arnould *et al.*, Internal Report No. RIB-1988-01 of the Brussels, Leuven and Louvain-la-Neuve Universities, Louvain-la-Neuve, 1988 (unpublished).
[3]Sindano wa Kitwanga, P. Leleux, P. Lipnik, and J. Vanhorenbeeck, Phys. Rev. C **40**, 35 (1989).
[4]L. Bonnet, M. Frédéric, P. Leleux, I. Licot, and P. Lipnik, Nucl. Instrum. Methods A (to be published).
[5]F. James and M. Roos, CERN Report No. D506, 1983.
[6]C. F. Williamson, J. P. Boujot, and J. Picard, CEN Saclay, Report No. CEA-R-3042, 1966.
[7]*Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965).
[8]P. Oblozinsky and J. Ribansky, Nucl. Instrum. Methods **94**, 187 (1971).
[9]T. Nozaki and M. Iwamoto, Radiochim. Acta **29**, 57 (1981).
[10]P. Dyer, D. Bodansky, A. G. Seamster, E. B. Norman, and D. R. Maxson, Phys. Rev. C **23**, 1865 (1981).
[11]H.- S. Kuan and J. R. Risser, Nucl. Phys. **51**, 518 (1964).
[12]M. Sajjad, R. M. Lambrecht, and A. P. Wolf, Radiochim. Acta **39**, 165 (1986).
[13]G. T. Bida, T. J. Ruth, and A. P. Wolf, Radiochim. Acta **27**, 181 (1980); W. W. Jacobs, D. Bodansky, D. Chamberlin, and D. L. Oberg, Phys. Rev. C **9**, 2134 (1974).

[14]M. Sajjad, R. M. Lambrecht, and A. P. Wolf, Radiochim. Acta **36**, 159 (1984).
[15]A. R. Barnett, Nucl. Phys. **A120**, 342 (1968).
[16]T. J. Ruth and A. P. Wolf, Radiochim. Acta **26**, 26 (1979).
[17]H. D. Holmgren and C. B. Fulmer, Phys. Rev. **132**, 2644 (1963).
[18]J. G. Jenkin, L. G. Earwaker, and E. W. Titterton, Nucl. Phys. **44**, 453 (1963).
[19]J. H. Gibbons and R. L. Macklin, Phys. Rev. **114**, 571 (1959); J. P. Blaser, F. Boehm, P. Marmier, and P. Scherrer, Helv. Phys. Acta **24**, 465 (1961).
[20]*The Stopping and Ranges of Ions in Matter*, edited by J. F. Ziegler (Pergamon, New York, 1980).
[21]Th. Delbar and C. Michotte, private communication.