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RADIOACTIVE PRODUCTS FROM BORON CTR REACTIONS*

R. J. PETERSON, C. S. ZAIDINS,† and M. J. FRITTS
Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado
N. A. ROUGHTON
Regis College, Denver, Colorado and Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado
and
C. J. HANSEN
Joint Institute for Laboratory Astrophysics and Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado

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Abstract—The nuclear reaction rates for $^{10}B(p, \alpha)^7Be$ and $^{10}B(p, \gamma)^{11}C$ have been measured by a thick target technique using proton energies from 75 keV to 3·0 MeV. The results are valid for proton temperatures near 3×10^9 K where the $^{11}B(p, 3\alpha)$ reaction has been suggested for power generation. At this temperature, the rates $N_A\langle\sigma v\rangle$ are $2{\cdot}66 \times 10^7$ and $8{\cdot}3 \times 10^2$ cm^3 g^{-1} s^{-1} for ^7Be and ^{11}C, respectively. As such, these rates suggest the possibility of serious radioactive contamination in using natural boron as a fuel in CTR devices.

Use of the exotic CTR reaction $^{11}B(p, 3\alpha)$ has been suggested for power generation (Weaver *et al.*, 1972, 1973). A number of advantages result from this reaction, but the chief one is the lack of radioactive byproducts, either direct or from neutron induced reactions. Since, however, natural boron contains 19·78% ^{10}B, two radioactive byproducts will be present from reactions on this isotope. Enrichment procedures are of course feasible, but for a full evaluation of this problem the detailed nuclear reaction rates are needed for

$$^{10}B(p, \alpha)^7Be(\beta^+)^7Li, \tag{1}$$

$$^{10}B(p, \gamma)^{11}C(\beta^+)^{11}B. \tag{2}$$

The nuclide ^{11}C is a positron emitter with a 20·4 min half-life, so the longer-lived ^7Be (53·3 day half-life) is the main problem. The ^7Li daughter of this decay has a 477 keV gamma ray with a 10·42% branch (Poenitz and Devolpi, 1973).

Most previous studies of the ^7Be yield from proton bombardment of ^{10}B have been at energies too high to be of interest to the CTR program (Bernstein, 1964; Jenkin *et al.*, 1964; Ophel *et al.*, 1962; Segel *et al.*, 1966). The only data at sufficiently low beam energy are those of Overly and Whaling (1962), from 0·2 to 3·0 MeV. These data, however, were not of the total yield, but only for the excitation function at one angle to study resonances in the compound ^{11}C system.

The object of the present investigation is to measure the total cross sections for low energy protons on ^{10}B, and to evaluate the thermonuclear reaction rate for the total production of radioactive ^7Be and ^{11}C.

The method used is described in detail by Roughton *et al.* (1974). Basically, a thick natural boron target is bombarded with protons and the resulting radioactivity is then counted with a calibrated Ge(Li) detector. All beam energies were below threshold for the $^{11}B(p, n)^{11}C$ reaction. The 10 min activity of ^{13}N from carbon contamination of the target was separated by multiscaling the counts into eight successive spectra totaling 42 min 40 s. A least-squares analysis of the decay allowed the clear subtraction of this small contamination. The yield curves for ^{11}C and ^7Be are shown in Fig. 1, on the basis of a pure ^{10}B target, and with the branching ratio for ^7Be already included. (The yield as shown in the figure is defined to be "radioactive nuclei produced per incident proton.") The variable energy cyclotron of the Nuclear Physics Laboratory of the University of Colorado was used for the data points at 0·245 MeV (c.m.) and above. (This machine is normally used for proton beams of up to 27 MeV, but was operated in harmonic modes for these energies.) The point at 0·069 MeV (c.m.) was taken with the positive ion linear accelerator of the Electrical Engineering Department of the University of Colorado.

An analytic form was fitted to these yield curves,

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† Also at University of Colorado, Denver Campus.

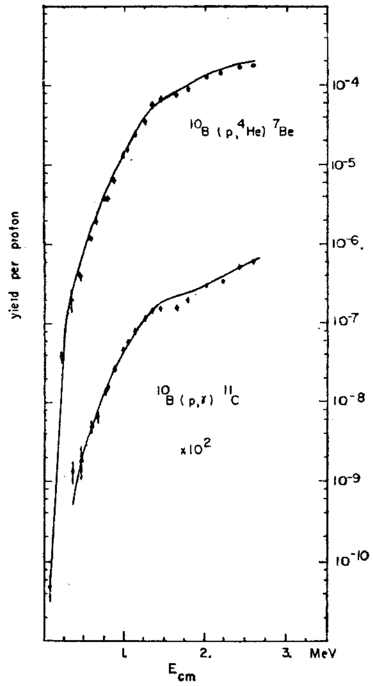

Fig. 1. The thick target yields for ^{7}Be and ^{11}C production for protons incident on pure ^{10}B are displayed. The curves are the numerical fits used for further analysis, as described in the text. The 10·3 % branching ratio to the excited state of Li has been included for the ^{7}Be yield.

embodying the energy loss rate for the protons, and is given by

$$\text{Yield} = \frac{N_A}{M}\int_0^E \frac{\sigma(E')}{\dfrac{\mathrm{d}E'}{\mathrm{d}\rho x}(E')}\,\mathrm{d}E',$$

where

N_A = Avogadro's number
M = molecular weight of the target
E = beam energy in MeV.

The forms for the cross section and energy loss are:

$$\sigma(E) = \frac{1}{E}\exp\left[a + \frac{b}{\sqrt{E}} + c\sqrt{E} + \mathrm{d}E\right]\mathrm{cm}^2,$$

$$\frac{\mathrm{d}E}{\mathrm{d}\rho x}(E) = \frac{219(1 - \mathrm{e}^{-10\cdot 2E})}{E^{3/4}}\ \mathrm{MeV\ g^{-1}\ cm^2}$$

where, in $\sigma(E)$, a, b, c and d are adjustable parameters. These parameters were varied freely to fit the yield curve which, for purposes of analysis, was broken up into several energy segments. A detailed physical interpretation does not seem possible for the final values of these parameters. The energy-loss expression is from Zaidins (1974). The resulting fits are shown on Fig. 1, with resulting values of χ^2 per degree of freedom equal to 5·0 for ^{11}C and 2·3 for ^{7}Be. The known resonances in the ^{11}C system are broad (Overly and Whaling, 1962), and were incorporated into the smooth fits.

The cross section result from the above analysis is integrated over a thermal distribution of proton energies to provide the nuclear reaction rates, $N_A \langle \sigma v \rangle$. The result of this method has been compared to earlier results for the ^{12}C(p, γ)^{13}N reaction (Roughton *et al.*, 1974), and found to be consistent. The reaction rates are shown in Fig. 2, and listed in Table 1.

Uncertainties in the reaction rates arise from the experimental uncertainties on each data point, from discrepancies between fitted and measured points on the yield curve, and from uncertainties in the extrapolation to proton energies below 75 keV. For strong activities, the yield data points were reproducible to better than 5%. An inexact fit by the parameterization of the yield has a minor

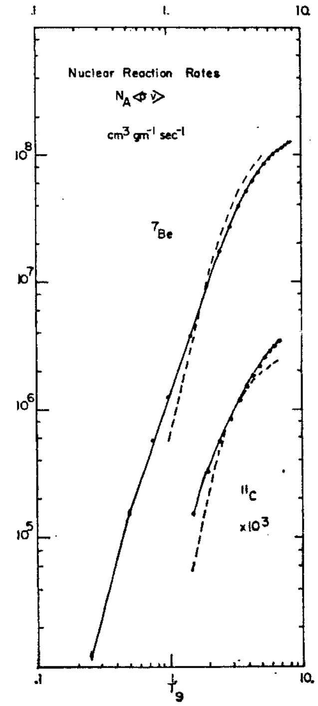

Fig. 2. The nuclear reaction rates $N_A\langle\sigma v\rangle$ are shown as a function of T_9, the temperature in 10^9 degrees of the proton distribution. The solid curves are fits to the data with the expression of Truran, and the parameters are listed in Table 2. These data are also listed as Table 1. The dashed line is the prediction of Fowler *et al.* (1967, 1974). The error bars reflect only the error in extrapolating the cross section data into the thermal distribution.

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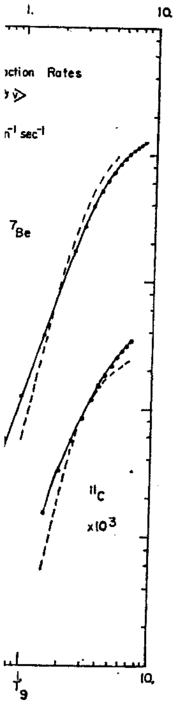

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Table 1. The reaction rates $N_A\langle\sigma v\rangle$ are given in cm^3 g^{-1} s^{-1} for the ^{7}Be and ^{11}C yields, for various vaues of T_9, the temperature in 10^9 K.

T_9	^{7}Be	^{11}C
0.25	0.0121 × 10^6	
0.50	0.156 × 10^6	
0.75	0.552 × 10^6	
1.0	1.271 × 10^6	
1.5	4.027 × 10^6	
2.0	9.16 × 10^6	320
2.5	16.86 × 10^6	551
3.0	26.63 × 10^6	834
3.5	37.65 × 10^6	1147
4.0	49.15 × 10^6	1475
4.5	60.50 × 10^6	1809
5.0	71.30 × 10^6	2143
5.5	81.28 × 10^6	2474
6.0	90.31 × 10^6	2799
6.5	98.35 × 10^6	3116
7.0	105.4 × 10^6	3423
7.5	111.5 × 10^6	
8.0	116.8 × 10^6	
8.5	121.2 × 10^6	

influence on the reaction rate results due to the average over many points. The uncertainties on the reaction rates shown in Fig. 2 are those due to uncertainties in extrapolation only. The value assumed in the initial studies of boron burning (Weaver *et al.*, 1972) was 36 × 10^6 cm^3 g^{-1} s^{-1} at $T_9 = 3$ ($\sim$260 keV), near our measured value of 26·6 × 10^6.

For comparison, Fig. 2 also shows the reaction rates for ^{7}Be and ^{11}C production using the expression of Fowler *et al.* (1967, 1974). These curves agree fairly well with the presently measured values, suggesting the reliability of their expressions. The curves of $N_A\langle\sigma v\rangle$ *vs* T_9 have also been fitted to

Table 2. The parameters for the fit to the reaction rates are given using the form of Truran (1972).

	$^{10}B(p,\alpha)^7Be$	$^{10}B(p,\gamma)^{11}C$
A	−30.240 ± .104	19.372 ± .048
B	−17.188 ± .187	−15.977 ± .113
C	1.094 ± .062	0.218 ± .087

a convenient parameterization (Truran 1972):

$$N_A\langle\sigma v\rangle = \frac{1}{T_9^{3/2}} \exp\left[A + BT_9^{-1/3} + CT_9^{-1}\right].$$

The resulting parameters *A*, *B*, *C* are listed in Table 2.

With the reaction rates now measured for both $^{10}B(p, \alpha)$ and $^{11}B(p, 3\alpha)$ (quoted by Weaver *et al.*, 1973), the production rate of ^{7}Be may be computed for a given reactor. If we assume, for example, that the fuel is natural boron, at a reaction temperature of $T_9 = 3$ then, for a 1 MW unit reactor, the rates are $\langle\sigma v\rangle$ ^{10}B $= 4{\cdot}43 \times 10^{-17}$ and $4{\cdot}0 \times 10^{-16}$ cm^3 s^{-1} for ^{11}B. The energy release demands $5{\cdot}26 \times 10^{19}$ reactions/min for 1 MW. The ratios of rates and isotopic abundances then yield $\sim 10^{18}$ ^{7}Be produced per minute, or 4 Ci/min. For a ^{235}U fission reactor with the same power output, Table 13–1 of Wilson and Jones (1974) gives 3×10^{-3} Ci/min of fission products per 1 MW unit.

Although this residual radioactivity is large, several mitigating factors make the problem less serious than it might appear. First, it is possible to depete the fuel of ^{10}B. Also the chemical properties of beryllium make the ^{7}Be easier to contain, and the mean dose per Curie of ^{7}Be is less than most fission fragments. The half-life is one seventh of a year, compared to many years for some fission fragments. Finally there is also some chance to burn the ^{7}Be itself in the reactor. A detailed evaluation of all these factors should be made before boron can be considered seriously as a CTR fuel.

In summary, the results reported here make it possible to compute the yields of two residual radioactivities resulting from the burning of natural boron fuel. The ^{7}Be yield is shown to constitute a potential problem for power generation by such a reaction.

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REFERENCES

Bernstein E. M. (1964) *Nucl. Phys.* **59**, 525.

Fowler W. A., Caughlan G. R. and Zimmerman B. A. (1967) *Ann. Rev. Astron. Astrophys.* **5**, 525.

Fowler W. A., Caughlan G. R. and Zimmerman B. A. (1974) private communication.

Jenkin J G., Earwaker L. G. and Titterton E. W. (1964) *Nucl. Phys.* **50**, 516.

Opher T. R., Glover R. N. and Titterton E. W. (1962) *Nucl. Phys.* **33**, 198.

Overly J. C. and Whaling W. C. (1962) *Phys. Rev.* **128**, 315.

Poenitz W. P. and Devolpi A. (1973) *Int. J. appl Radiat. Isotopes* **24**, 471.

Roughton N. A., Fritts M. J. Peterson R. J., Zaidins C. S. and Hansen C. J. (1974) *Astrophys. J.* **188**, 595.

Segel R. E., Singh P. P., Hanna S. S. and Grace M. A. (1966) *Phys. Rev.* **145**, 736.

Truran J. W. (1972) *Astrophys. Space Sci.* **18**, 306.

Weaver T., Zimmerman G. and Wood L. (1972) Lawrence Livermore Laboratory, UCRL 74352.

Weaver T., Zimmerman G. and Wood L. (1973) Lawrence Livermore Laboratory, UCRL 74938.

Wilson R. and Jones W. J. (1974) *Energy, Ecology, and the Environment* Academic Press, New York.

Zaidins C. S. (1974) *Nucl. Instrum. Methods* **120**, 125.