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Cross Section for Formation of ^{7}Be by 20–155-MeV Proton-Induced Reactions in Carbon*

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The cross section for the reaction ^{12}C$(p,x)^7$Be was measured as a function of energy from 20 to 155 MeV. A sharp rise above the neighboring thresholds for ^{12}C$(p,{}^6$Li$)$, ^{12}C$(p,\alpha d)$, and ^{12}C$(p,\alpha pn)$ reactions was observed. The excitation function peaks with a cross section of ~20 mb at 40 MeV and then decreases slowly with increasing energy. No structure is observed at the thresholds for the ^{12}C(p,tdp), ^{12}C$(p,3d)$, or other reactions of higher threshold energy.

INTRODUCTION

The excitation function for the reaction ^{12}C$(p,x)^7$Be was measured from the threshold to 155 MeV. The interest in the production cross section of the 53-day ^{7}Be is threefold. This study was part of a general survey of residual radiation that will be produced in high-energy accelerator facilities.[1,2] Carbon is used in beam-handling systems of present-day accelerators, and will be used more extensively in proposed accelerators with very high beam intensity. For residual radiation considerations, ^{7}Be is the most important isotope produced by proton-induced reactions in carbon; thus a knowledge of the production cross section is needed. Inasmuch as ~90% of primary cosmic rays are protons, there is a need to know[3] the significance of their interaction with carbon which has a relatively large cosmic abundance. This is of particular interest in the present and projected study of induced radioactivity in meteorites and in lunar-surface material.[4] Thirdly, the excitation function for ^{12}C$(p,x)^7$Be should yield information about the reaction mechanism.[5]

Previous cross-section measurements have been made at proton energies from 80 to 150 MeV by Brun, LeFort, and Tarrago,[5] from 130 to 400 MeV by Rayudu,[3] and at 335 MeV by Marquez and Perlman.[6]

EXPERIMENTATION

Carbon in the form of rectangular graphite wafers was exposed to proton beams. Reactor-grade graphite with the following maximum impurity contents was employed: less than 300 parts per million by weight of oxygen or nitrogen, ~0.1 ppm boron, and no detectable quantities of beryllium. Exposures were made with incident beam energies of 40.0±0.25, 62.0±0.25, and 158.3±0.7 MeV. The 40- and 62-MeV irradiations were made at the Oak Ridge isochronous cyclotron (ORIC), and the 158-MeV bombardment was made at the Harvard University cyclotron. The thickness of the carbon wafers ranged from 124 mg/cm^2 for the lowest energy bombardment to 1090 mg/cm^2 for the highest energy exposure. The stack of wafers used in each bombardment was thick enough to stop the proton beam. The target stack was mounted on an insulated target holder. The charge collected on this beam stop was measured by an integrator circuit with an accuracy of ±1% for the 40- and 62-MeV bombardments and ±5% for the 158-MeV bombardment. In each bombardment the proton beam was ~1.25-cm in diameter. Subsequent scanning measurements of the induced radioactivity showed that the beam spot was near the center of the 2-in.-square wafers in all bombardments.

Four or more days after each irradiation the gamma spectra of the induced radioactivity were measured with a 3×3-in. NaI(Tl) crystal spectrometer. The area of the photo peak due to the ^{7}Be 478-keV gamma rays was integrated for each spectrum. From these data the source strength in each target was calculated; previously measured[7] absolute detection efficiencies were used. The gamma spectra of some targets were also measured with a high-resolution Ge(Li) gamma spectrometer[8] to verify that there were no 511-keV photons due to positron annihilation from radioactivity induced in possible impurity atoms; no 511-keV peaks were observed.

The data obtained from the measured spectra were used to compute the cross section for the production of ^{7}Be in each wafer of the target stack. The incident-beam intensity was attenuated, as it penetrated the target stack, by a geometric total reaction cross section. To correct for this effect, a nuclear radius parameter $r_0 = 1.25$ F was assumed. This correction was important for the 158-MeV bombardment only. One bombardment was made at each of the three incident-beam energies. The excitation-function data obtained from the 62- and 40-MeV bombardments overlapped from threshold to 40 MeV; also the data obtained from the 62- and

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158-MeV bombardments overlapped from 47 to 62 MeV. The agreement of the measured cross section in these regions was within 10%. The measured cross sections are given as a function of proton energy in Table I and plotted in Fig. 1. Previous measurements are shown also for comparison. The data above 80 MeV agree reasonably well with those obtained from previous measurements. The threshold energies for various reaction modes are indicated in the laboratory system.

The probable errors in the cross section are ±20%. These are principally due to uncertainties in gamma counting geometry and efficiency.

The energy of the beam after it traversed half the thickness of each target wafer was computed from range-energy tables.[9] The uncertainty of the proton energy for each datum point is due to energy spread of the incident beam and to energy-loss straggling. The 40.0- and 62.0-MeV beams had an energy spread of 0.5 MeV full width at half-maximum (FWHM)[10] and the 158-MeV beam had an energy spread of 1 MeV FWHM.[11] The energy-loss straggling was obtained from tabulated Vavilov distributions.[12] This effect for a particular wafer depends on the depth of that wafer in the stack. The energy-loss straggling for monoenergetic 40-MeV protons that are slowed to 24 MeV in carbon is 0.6 MeV FWHM; for 158-MeV protons slowed to 50 MeV it is 2.6 MeV. Thus, the energy uncertainties for the data obtained at ORIC range from ±0.25 to ±0.4 MeV; for the Harvard cyclotron data the energy uncertainties range from ±0.7 to ±1.5 MeV.

TABLE I. Experimentally determined cross sections as a function of proton energy in the laboratory system.

Proton energy (MeV)	Cross section (mb)
155.0	9.5
150.3	9.4
145.3	8.9
139.6	9.9
134.0	10.3
128.2	10.8
122.3	10.8
116.0	10.8
109.6	11.6
102.9	11.4
95.7	11.6
88.0	11.7
80.0	12.7
71.2	13.9
61.5	14.6
60.0	15.5
59.0	16.0
56.0	16.3
53.3	18.5
53.1	16.9
50.5	17.3
47.0	19.1
47.0	18.0
44.6	18.5
41.5	18.9
39.5	19.2
37.5	19.3
35.8	18.2
34.0	16.3
31.9	11.1
29.8	3.4
27.4	0.42
24.5	0.05

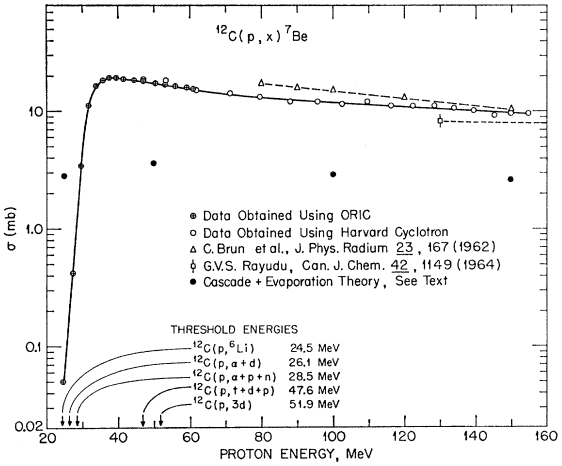

FIG. 1. Excitation function for the production of ^7Be by bombardment of carbon with protons. A cross-section determination by Marquez and Perlman (Ref. 6) at 335 MeV yielded 11 mb. For comparison, the calculations by the method of Ref. 13 are shown (•).

DISCUSSION

The excitation function exhibits a steep increase above the threshold energies for the reactions $^{12}C(p,^6Li)$, $^{12}C(p,\alpha d)$, and $^{12}C(p,\alpha pn)$, but shows no discontinuities at the threshold energies for $^{12}C(p,tdp)$ and $^{12}C(p,3d)$ reactions. This indicates that one or more of the three reactions with the lowest threshold energies is the dominant mode.

Possible contribution to the production of ^7Be by secondary neutrons produced in proton-induced reactions is discounted by the following argument. The stack exposed to 158-MeV protons (which had a thickness greater than the range of the protons) and carbon wafers on the backside (which were beyond the range of incident protons) exhibited no measurable ^7Be activity.

The experimental data were compared with the calculated excitation function based on the compound-nucleus theory. The theory and computer program developed by Bertini[13] assumes a two-stage mechanism. It is assumed that after the projectile enters the target nucleus there is an internucleon cascade followed by nuclear evapora-

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[9] The *dE/dx* and range-energy computer program of Professor Hans Bichsel, which is described in University of Southern California Physics Department, Technical Report No. 3, 1961 (unpublished), was used to compute a range-energy table for protons in carbon.

[10] E. E. Gross (private communication).

[11] A. Koehler (private communication).

[12] S. M. Seltzer and M. J. Berger, Natl. Acad. Sci.–Natl. Res. Council Publ. **1133** (1964).

[13] H. W. Bertini, Phys. Rev. **131**, 1801 (1963); also see *ibid.* **138**, AB2 (E) (1965).

tion of any number of neutrons, hydrogen or helium isotopes; the latter process is calculated by an evaporation program,[14] modified to include the most recent semiempirical nuclear masses.[15] The theory does not include thresholds for cross sections nor does it simulate evaporation of ^{6}Li nuclei. The model is not anticipated to work well for a "liquid drop" with as few as 13 nucleons, particularly at low energies. However, good agreement between theory and similar types of experiments on carbon at energies above about 100 MeV has been obtained.[16] The computer-calculated excitation function is displayed in Fig. 1.

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[16] H. W. Bertini (private communication).

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Eigenstates of the $J=0$, $T=1$, Charge-Independent Pairing Hamiltonian. II. Seniority-One and -Two States*

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Exact equations for the seniority-one states of $2N+1$ nucleons in an arbitrary external potential well and interacting through a $J=0$, $T=1$, charge-independent pairing force are derived and, for a large class of states, solved exactly. The states in this class are characterized as having wave functions that are totally symmetric in the isospins of the paired particles. These states have total isospin $T=\frac{1}{2}, \frac{3}{2}\cdots, (2N+1)/2$. The states with the lowest energy consistent with the given values of N and T are contained in this class of states. All the states of $2N+1$ neutrons or protons belong to the charge multiplet with $T=(2N+1)/2$. Equations for the seniority-two states of $2N+2$ nucleons are also derived and the solutions to these equations that are totally symmetric in the isospins of the paired particles are considered. These solutions may be classified as charge-symmetric or charge-antisymmetric according to their parity under reflection in isospin space. The equations for the charge-symmetric state are solved exactly. These states have total isospin $T=1,3,\cdots,N+1$ for N even and $T=0,2,\cdots,N+1$ for N odd with each value of T not equal to zero occurring twice. The equations for the charge-antisymmetric states are solved in an approximation which conserves the isospin of the unpaired particles and which is exact when they occupy degenerate levels. These states have total isospin $T=0,2,\cdots,N$ for N even and $T=1,3,\cdots,N$ for N odd with each value of T not equal to zero occurring twice. The calculation of all these states is reduced to the diagonalization of a tridiagonal matrix, whose eigenvalue is given explicitly in terms of N and T, and the solution of N coupled, nonlinear, algebraic equations. The wave functions and energies of all the states of these systems having the indicated isospin symmetry and the given value of T are given in terms of the solutions of these equations. An explicit expression for the occupation probabilities of the levels of the single-particle potential (summed over the two charge states) is given. This expression may be evaluated by the solution of an $N\times N$ system of linear algebraic equations.

I. INTRODUCTION

THE charge-independent pairing Hamiltonian describes a system of nucleons that are contained in a potential well, e.g., a shell-model potential, and which interact through a pairing interaction that is effective between any two nucleons that are coupled to $J=0$ and $T=1$. The seniority-zero eigenstates of this Hamiltonian were considered in a previous paper[1] (to be referred to as I), where references to the previous work on the states of this Hamiltonian may be found. In this paper, the work of I is extended to include the seniority-one and -two states of the Hamiltonian.

In I, equations for all the seniority-zero states of the charge-independent pairing Hamiltonian were derived and, for a large class of states, solved exactly. The states of this class contain N pairs of nucleons, each pair being coupled to $J=0$ and $T=1$, and are such that their wave functions are totally symmetric functions of the z components of the isospins of the pairs. For this reason, these states are called isospin-symmetric states. The possible values of the total isospin of these isospin-symmetric states are $T=0, 2,\cdots, N$ for N even and $T=1, 3,\cdots, N$ for N odd. The wave function of one of

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