Excitation Function of the $C^{12}(p,pn)C^{11}$ Reaction in the Bev Region*

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The ratio of the cross section of the $C^{12}(p,pn)C^{11}$ reaction to the cross section of the $Al^{27}(p,3pn)Na^{24}$ reaction has been measured in the energy range 400 Mev to 3 Bev. This ratio as well as the excitation curve of the $C^{12}(p,pn)C^{11}$ reaction appear to be quite insensitive functions of the energy in the range studied. A possible interpretation is discussed.

THE excitation function of the $C^{12}(p,pn)C^{11}$ reaction between threshold and 390 Mev has previously been the subject of detailed studies.[1,2] In the present paper we report cross section measurements for this reaction in the energy range from 400 Mev to 3 Bev. The irradiations were carried out in the circulating proton beam of the Brookhaven Cosmotron.

Targets were made up of several layers of polythene of thicknesses varying from 5 mg/cm^2 to 10 mg/cm^2 and one or two layers of aluminum foil 1 mil or 3 mils thick. The Na^{24} induced in the aluminum served as the monitor of irradiation intensity. Multiple layers of foils were used to check the possibility of recoil losses and to obtain duplicate values. The total thickness of the sandwiches was in all cases less than 50 mg/cm^2, so that the contribution of secondary reactions to the measured activities would be negligible. The irradiations were carried out at the desired proton energy in the Cosmotron by means of the pulsed moving target technique described elsewhere.[3]

After irradiation identical sections of the foils in each sandwich were cut out and counted with end-window proportional counters. The polythene foils were counted immediately and showed a pure 20.5-min C^{11} decay and the aluminum foils were counted after the C^{11} and F^{18} activities had died out to leave the pure 15-hour decay of Na^{24}. Small corrections for self-absorption effects were applied to the data obtained.

TABLE I. Ratio of $C^{12}(p,pn)$ to $Al^{27}(p,3pn)$ cross sections.

Energy Bev	$\sigma_{C^{11}}/\sigma_{Na^{24}}$
2.95	2.38
2.2	2.24, 2.38
1.8	2.14
1.4	2.20
1.0	2.29
0.6	2.31
0.42	2.69, 2.85
0.44[a]	2.63
0.35[a]	2.88
0.35[b]	2.76
0.39[b]	2.84

[a] Determinations by A. Turkevich using Chicago synchrocyclotron (private communication).
[b] Determinations by J. Miller using Nevis synchrocyclotron (private communication).

The ratio of the $C^{12}(p,pn)C^{11}$ cross section to the $Al^{27}(p,3pn)Na^{24}$ cross section is given in Table I for each energy investigated. We consider these data to be reliable to ±5 percent. To convert these ratios to absolute cross sections for the $C^{12}(p,pn)C^{11}$ reaction we use the measured values of 10.8 mb at 420 Mev[4] and 9.0 mb at 2.2 Bev[5] for the $Al^{27}(p,3pn)Na^{24}$ reaction and assume the cross section for this reaction to vary linearly with energy between 400 Mev and 3 Bev. The values thus obtained for the $C^{12}(p,pn)C^{11}$ cross section are plotted in Fig. 1. Since the cross sections of the reference reaction $Al^{27}(p,3pn)$ above 400 Mev are tentative, the $C^{12}(p,pn)C^{11}$ excitation curve given in Fig. 1 may have to be revised somewhat when better absolute values for the $Al^{27}(p,3pn)Na^{24}$ reaction become available.

It should be noted that the excitation function reported here does not join smoothly with the lower-energy data (up to 390 Mev) of Aamodt *et al.*[1] and Warshaw *et al.*[2] The discrepancy may arise from an error in one of the absolute cross section measurements or an error in our cross section ratio in the 400-Mev region. To check on the latter possibility it seemed desirable to obtain independent checks of the ratio of $C^{12}(p,pn)$ to $Al^{27}(p,3pn)$ cross sections at ~400 Mev. J. M. Miller using the Nevis synchrocyclotron, and A. Turkevich using the Chicago synchrocyclotron, very kindly made such independent determinations of this ratio. Their results, shown in Table I, confirm the authors' work. The possibility that the measured ratios are too low because of production of Na^{24} by secondary neutrons [$Al^{27}(n,\alpha)$ reaction] was eliminated by experiments both by J. M. Miller at Nevis and by J. Hudis at the Cosmotron. In these experiments the cross section for Na^{24} production from aluminum was shown to be essentially independent of target thickness in the region of interest so that neutrons produced in the target itself cannot produce any significant fraction of the Na^{24} observed. Other experiments in the Cosmotron showed Na^{24} production from aluminum due to general neutron flux in the target region to be quite negligible. Accepting the validity of our ratio measurements, we

* Research performed under the auspices of the U. S. Atomic Energy Commission.
[1] Aamodt, Peterson, and Phillips, Phys. Rev. 88, 739 (1952). This paper gives references to earlier work.
[2] Warshaw, Swanson, and Rosenfeld, Phys. Rev. 95, 649 (1954).
[3] Friedlander, Miller, Wolfgang, Hudis, and Baker, Phys. Rev. 94, 727 (1954).
[4] L. Marquez, Phys. Rev. 86, 405 (1952).
[5] A. Turkevich, Phys. Rev. 94, 775 (1954).

must then consider either the absolute value of the $C^{12}(p,pn)$ cross section or that of the $Al^{27}(p,3pn)$ cross section (or both) to be in error. We have rather arbitrarily chosen to base our data on the 10.8-mb value for the $Al^{27}(p,3pn)$ cross section at 420 Mev.

Figure 1 shows that the cross section of the $C^{12}(p,pn)C^{11}$ reaction is a fairly insensitive function of the energy of the incident proton in the energy range studied here. Since similar results were found for the production of Na^{24}, Na^{22}, and F^{18} from aluminum and for Be^7 formation from carbon,[6] it appears to be generally true that the probability of ejecting a small number of nucleons from a small nucleus remains substantially constant over a range of bombarding energies from a few hundred Mev to at least 3 Bev. This implies that the probability that the incident particle leaves behind a relatively small amount of energy ($\lesssim$100 Mev) in the *initial* interaction with the nucleus is relatively constant over the wide energy range studied. However within this energy range meson production increases very markedly with energy and becomes a probable process. If the nucleus is large these mesons would have a good chance of being reabsorbed in the nucleus in which they were produced. This would result in a shift of the maximum in the total energy deposition spectrum to higher values, and reactions in which only a small number of particles are ejected would become less likely. Such an effect has been observed in our studies on heavier nuclei.[3] However, in a small nucleus reabsorption of mesons would be a much less important mode of depositing excitation energy because of their greater escape probability. Thus it becomes plausible that while the increasing dominance of meson processes decreases the cross sections for relatively simple reactions in heavy target nuclei, the cross sections for similar reactions of light nuclei remain almost unchanged.

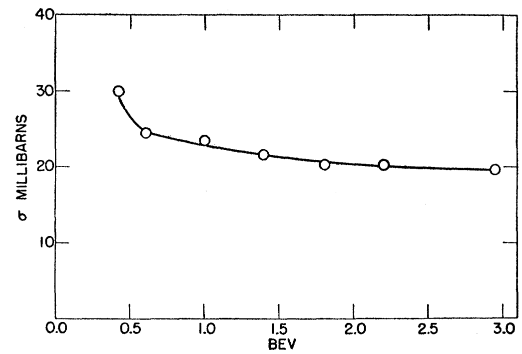

FIG. 1. Excitation function of the $C^{12}(p,pn)C^{11}$ reaction.

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[6] Hudis, Wolfgang, and Friedlander (unpublished).

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Conservation of Isotopic Spin and Isotopic Gauge Invariance*

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It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

INTRODUCTION

THE conservation of isotopic spin is a much discussed concept in recent years. Historically an isotopic spin parameter was first introduced by Heisenberg[1] in 1932 to describe the two charge states (namely neutron and proton) of a nucleon. The idea that the neutron and proton correspond to two states of the same particle was suggested at that time by the fact that their masses are nearly equal, and that the light stable even nuclei contain equal numbers of them. Then in 1937 Breit, Condon, and Present pointed out the approximate equality of $p-p$ and $n-p$ interactions in the ^1S state.[2] It seemed natural to assume that this equality holds also in the other states available to both the $n-p$ and $p-p$ systems. Under such an assumption one arrives at the concept of a total isotopic spin[3] which is conserved in nucleon-nucleon interactions. Experi-

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[1] W. Heisenberg, Z. Physik **77**, 1 (1932).

[2] Breit, Condon, and Present, Phys. Rev. **50**, 825 (1936). J. Schwinger pointed out that the small difference may be attributed to magnetic interactions [Phys. Rev. **78**, 135 (1950)].

[3] The total isotopic spin **T** was first introduced by E. Wigner, Phys. Rev. **51**, 106 (1937); B. Cassen and E. U. Condon, Phys. Rev. **50**, 846 (1936).