(p,pn) Reactions on Light Nuclei at 46 MeV*

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The reactions ^{6}Li(p,pn)^{5}Li, ^{9}Be(p,pn)^{8}Be, and ^{13}C(p,pn)^{12}C, as well as the reaction ^{6}Li(p, 2p)^{5}He, have been studied at 46 MeV. The plane-wave impulse approximation (PWIA) has been used for a preliminary analysis. The ^{9}Be and ^{13}C cross sections show a pronounced p-state minimum near zero recoil momentum as expected in the PWIA. No such minimum is seen for either reaction on ^{6}Li. The angular dependence of the three (p,pn) reactions departs strongly from PWIA predictions.

Quasifree (p, 2p) reactions at bombarding energies of 150–600 MeV have been used extensively[1] to extract separation energies and momentum distributions of proton single-particle states. Similar experiments have been undertaken at lower energies where data can be accumulated with relative ease and precision. Unfortunately, the latter experiments often require a more refined theoretical analysis, since multiple scatterings among all particles increase as their relative kinetic energies decrease. Nevertheless, it has been possible at these lower energies to discuss momentum distributions for weakly bound proton states in light nuclei using a simple normalized plane-wave impulse approximation (PWIA). It is evident that such a model should be applied to a whole range of data, so as to test it under varying conditions.

By way of extending the general results of (p, 2p) experiments in the energy range 20–100 MeV we have performed the first systematic study ever made of (p,pn) reactions on 1p-shell nuclei. The bombarding energy was 46 MeV, and at this energy the PWIA predicts no essential differences between (p, 2p) and (p,pn) reactions. The targets chosen were ^{6}Li, ^{9}Be, and ^{13}C, which have neutron separation energies of 5.66, 1.67, and 4.95 MeV respectively.

Using PWIA, the cross section for the (p,pn) or (p, 2p) knockout reaction may be written as

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = N_j F\left(\frac{d\sigma}{d\Omega}\right)_{12} |\varphi(q)|^2, \qquad (1)$$

where $(d\sigma/d\Omega)_{12}$ is the free p-n (or p-p) cross section resulting from replacement of the half-off-shell t matrix for p-n (or p-p) scattering with the on-shell t matrix; $\varphi(q)$ is the momentum wave function, in the target, of the knocked-out nucleon; N_j is the number of neutrons or protons available in a given subshell; and the kinematic factor F contains phase space.

The principal detector arrangement chosen for this experiment restricted the behavior of $(d\sigma/d\Omega)_{12}$. The separation angle between the two detectors was kept approximately constant so that $q = 0$ was always kinematically accessible; $(d\sigma/d\Omega)_{12}$ is then effectively constant for a given q. $(d\sigma/d\Omega)_{12}$ was always evaluated at the p-n (or p-p) final-state energy. We shall multiply formula (1) by an arbitrary normalization factor for each spectrum. In this way, we examine the shape of $|\varphi(q)|^2$ independent of the variation of absorption with angle. We then examine the dependence of the (p,pn) data upon the angles at which particles were detected.

Self-supporting targets of ^{6}Li, ^{9}Be, and ^{13}C were bombarded with 46-MeV protons. Detectors were always coplanar with the proton beam. For the (p,pn) experiments protons were detected with a counter telescope consisting of a 750-μm Si surface-barrier ΔE detector and either a 5-mm Si(Li) or a NaI(Tl) E detector. For the ^{13}C experiment a 200-μm Si surface-barrier detector was placed before the 750-μm detector, allowing particle identification to lower energies. A fast voltage-sensitive preamplifier[2] was used with the 750-μm detector to derive a timing signal for measuring neutron times of flight. The solid-state detectors were cooled to 77°K to improve time resolution by reducing noise and charge collection time. The neutron detector was an 11.43-cm-diam × 12.70-cm-long cylindrical capsule of NE213. Neutron–γ-ray discrimination was used to reduce random coincidences. Typical flight paths were 3 to 5 m. The efficiency of the detector was calculated using a Monte Carlo code.[3] To permit large counting rates, pulse-pileup rejection was imposed on the signal from the 750-μm detector. For the (p, 2p) experiment two ΔE-E veto telescopes were used with 200-μm ΔE de-

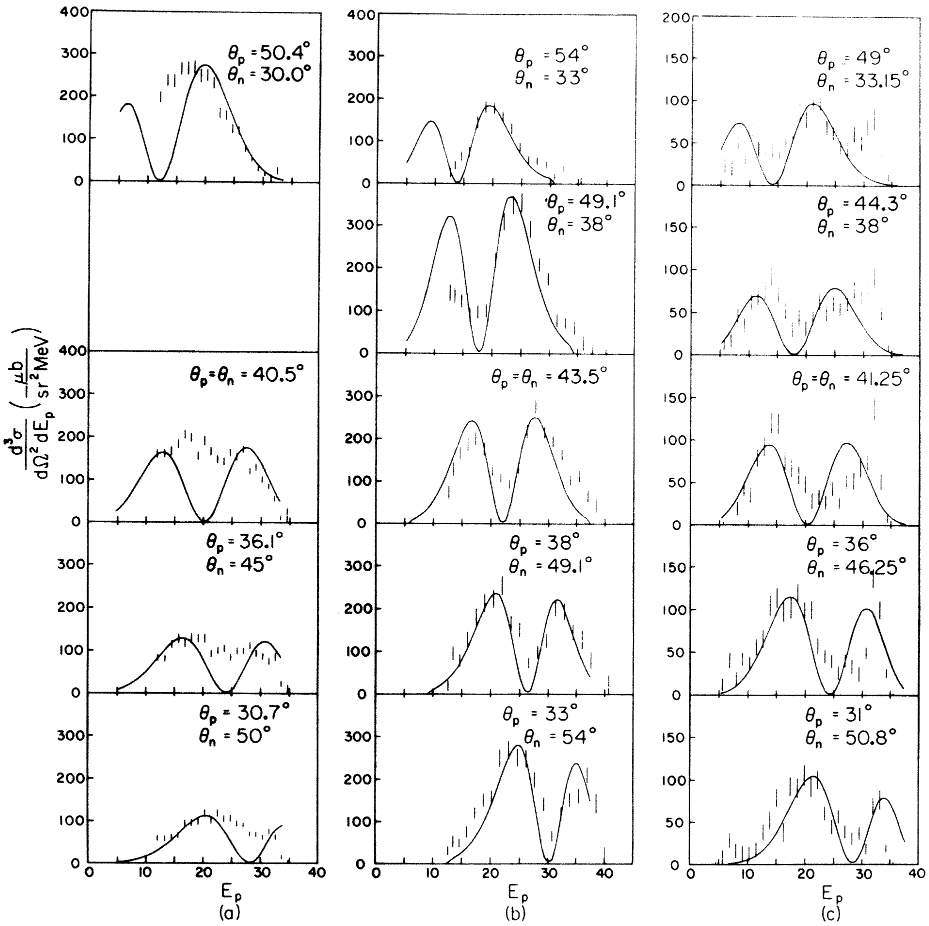

FIG. 1. Cross section for (p, pn) reactions on (a) ^6Li, (b) ^9Be, and (c) ^{13}C at 46 MeV. Zero recoil momentum is kinematically available for all angle pairs shown. The solid curves are arbitrarily normalized PWIA predictions, using optimized p-shell neutron wave functions.

tectors and 5-mm Si(Li) E detectors. Pulse-pile-up rejection was imposed on both ΔE signals.

Figure 1 shows the experimental results. The middle panel in each column is for the symmetric-angle pair. Moving up or down each column corresponds to moving the proton detector backward or forward in steps of roughly 5°. The solid curves are arbitrarily normalized PWIA calculations using $1p$-shell wave functions; hence $|\varphi(q)|^2$ goes to zero at $q = 0$.

We note that whereas a deep mimimum is seen in the experimental ^9Be and ^{13}C spectra near $q = 0$, no such minimum is seen in the ^6Li spectra. Our $^6Li(p, 2p)^5He$ data[4,5] show the same feature. The absence of a p-state minimum has been previously noted[6,7] in the $^6Li(p, 2p)^5He$ reaction at 185 and 460 MeV. In those experiments resolution effects[8] could entirely explain the absence of a minimum; in the present experiment resolution effects cannot, especially since the minimum is clearly resolved for ^9Be and ^{13}C. Recent $^6Li(p, 2p)^5He$ data[9-11] with good resolution at 100 and 156 MeV also show the absence of a p-state mimimum.

The absence of the ^6Li p-state minimum has been explained[12] in the context of the nuclear cluster model. In essence the cluster model includes $(2s)^2$ as well as $(1p)^2$ components in the ^6Li wave function. If ^5He and ^5Li were pure $P_{3/2}$ states, this $(2s)^2$ component could not contribute to nucleon knockout reactions because the residual nucleus would have the wrong parity. Because ^5He and ^5Li are unbound, however, they contain some $S_{1/2}$ admixture and $2s$ knockout can then fill in the $1p$ knockout minimum. The shell model severely limits $(2s)^2$ admixtures in the ^6Li wave function and is therefore unable to explain this filling in.

For this analysis we have used analytic wave

TABLE I. Parameters for the p-shell wave functions used in the PWIA cross section in Fig. 1. Separation energies E_s are also tabulated.

Reaction	E_s (MeV)	$\beta=\gamma$	a_2
$^6Li(p,2p)^5He$[a]	4.655	0.740	0.736
$^6Li(p,pn)^5Li$	5.622	0.740	0.736
$^9Be(p,pn)^8Be$	1.665	1.200	0.700
$^{13}C(p,pn)^{12}C$	4.947	0.500	0.700

[a]Same as Ref. 7 for 460-MeV $^6Li(p,2p)^5He$.

TABLE II. PWIA normalization factors used in Fig. 1.

Reaction	θ_p (deg)	θ_n (deg)	Norm.
$^6Li(p,pn)^5Li$	30.7	50.0	0.063
	36.1	45.0	0.076
	40.5	40.5	0.103
	50.4	30.0	0.143
$^9Be(p,pn)^8Be$	33.0	54.0	0.0229
	38.0	49.1	0.0202
	43.5	43.5	0.0214
	49.1	38.0	0.0302
	54.0	33.0	0.0146
$^{13}C(p,pn)^{12}C$	31.0	50.8	0.0322
	36.0	46.25	0.0387
	41.25	41.25	0.0338
	44.3	38.0	0.0265
	49.0	33.15	0.0304

functions of a form used by Tyren *et al.*[7] for $(p, 2p)$ reactions at 460 MeV. The spatial wave functions (formulas 3.7 and 3.8 in Ref. 7) are a combination of exponentials multiplied by a Hankel function to provide correct asymptotic behavior. There are three free parameters called β, γ, and a_2. If $\beta=\gamma$, one has an approximately flat-bottomed potential with a rather large diffuseness; Tyren *et al.*[7] made this restriction, and we follow their choice. For ^6Li we have used the same parameters as Ref. 7. For ^9Be and ^{13}C, β $(=\gamma)$ and a_2 were adjusted to produce an optimum fit to our data. The parameters used are listed in Table I.

For our $^6Li(p,pn)^5Li$ data the parameters from Ref. 7 produce a good fit to the tail of the momentum distribution away from the filled-in minimum. With identical parameters we get an equally good fit to our $^6Li(p,2p)^5He$ data.[4,5] For ^9Be the agreement of the PWIA with the data is quite good. For ^{13}C the comparison of the PWIA with the data is complicated by strong sequential peaks in all spectra at proton energies of approximately 15 and 33 MeV and the quality of the fits is poorer.

The theoretical cross sections in Fig. 1 are normalized to fit the data. The normalization factor, which is listed in Table II, is different for each spectrum. Because the unnormalized PWIA predictions are essentially isotropic for our detector arrangement and angular range, variations of the normalization with angle simply reflect variations of the fitted parts of the experimental cross sections with angle.

For ^6Li we note that the peak (p,pn) cross section increases roughly monotonically from ~100 $\mu b/sr^2$ MeV to ~300 $\mu b/sr^2$ MeV as the proton detector is moved from 30.7 to 50.4°. By contrast, our $^6Li(p,2p)^5He$ data[4,5] for the same energy, geometry, and angular range have a nearly constant peak cross section of ~40$\mu b/sr^2$ MeV. These results are very similar to the angular behavior of the reactions $^2H(p,2p)n$ and $^2H(p,pn)p$,[13] reinforcing our belief in a strong $\alpha+d$ cluster structure for ^6Li. In addition, the large ratio of the (p,pn) to the $(p,2p)$ cross sections for ^6Li at this energy (~5:1) is similar to that observed for deuterium.[14] We have one equal-angle $^{12}C(p,pn)^{11}C$ spectrum at 46 MeV which is relatively close in magnitude to the equivalent $^{12}C(p,2p)^{11}B$ data[15] at 50 MeV, which suggests that the large (p,pn)-to-$(p,2p)$ cross-section ratio observed for ^6Li is related to its $\alpha+d$ structure.

For ^9Be, although the PWIA fits the shapes of spectra rather well, we note that the PWIA normalization varies considerably with angle, as does the peak cross section. In addition, we note that where both peaks occur within the measured range of proton energies the PWIA may not fit them equally well (we chose always to fit the larger peak better). For smaller proton angles the higher-energy peak tends to be relatively low whereas at larger proton angles the higher-energy peak is relatively high. (This phenomenon is equivalent to one frequently observed in s-state knockout where the experimental peak may be shifted in energy from the PWIA prediction.)

The angular behavior of the ^{13}C is more difficult to discuss, because of the strong sequential peaks and poorer statistics. Note, however, that the change of relative peak heights with angle observed for ^9Be is also present in the ^{13}C data.

We can now draw some tentative conclusions about $(p,2p)$ and (p,pn) reactions in this energy range. (1) For our detector arrangement, $(p,2p)$ reactions are isotropic whereas (p,pn) reactions apparently are not. In addition to our data and Ref. 13 for ^{2}H, the reaction[16] ^{3}H$(p,2p)nn$ at 46 MeV is consistent with this pattern. (2) Target-dependent effects are evident in the angular behavior of the (p,pn) reaction: The angular behaviors of the reactions ^{6}Li(p,pn) and ^{2}H(p,pn) are very similar, and both are different from ^{13}C and ^{9}Be. (3) Nucleon knockout experiments with nonidentical particles at unequal angles reveal complexities in the reaction mechanism which are masked in symmetric $(p,2p)$ experiments.

A more sophisticated distorted-wave analysis of our data is in progress, and may be able to explain the behavior of the (p,pn) reaction at this energy. We plan to extend our study of (p,pn) reactions to other light nuclei; it will be interesting to see if the observed systematics persist.

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Resonance in the Reaction ^{12}C(^{12}C, p)^{23}Na at $E_{c.m.} = 19.3$ MeV*

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Excitation functions of the fifteen most strongly populated states ($9 < E_x < 17$ MeV) in the reaction ^{12}C(^{12}C,p)^{23}Na have been studied using a magnetic spectrograph. A resonance structure was observed for transitions to several final states at $E_{c.m.} = 19.3$ MeV with $\Gamma_{c.m.} \cong 500$ keV. Two particle-bound states in ^{23}Na at 9.08 and 9.84 MeV are particularly strongly populated in the reaction ^{12}C(^{12}C,p) at the resonant energy. The further study of the structure of these states may provide an important clue to the nature of the observed ^{12}C + ^{12}C resonance.

Intermediate structure was observed in the ^{12}C + ^{12}C system near and below the Coulomb barrier by the experiments of Almqvist, Bromley, and Kuehner[1] in 1960; they located correlated resonances in the total yield of p, n, α, and γ radiations from the ^{12}C + ^{12}C reaction. Somewhat less