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Backward production of high energy protons in the $(p,2p)$ reaction in ^{6}Li

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Two magnetic spectrometers have been utilized to measure the momentum spectra and angular distributions of forwardly produced protons in coincidence with backwardly emitted protons (105°) of momenta $q = 0.35$, 0.4, and 0.55 GeV/c in the reaction $p(0.8\text{ GeV}) + {}^6\text{Li} \rightarrow p + p + X$. The data demonstrates an unexpected new feature: the angular independence of the ratio of coincidence to forward singles spectra.

[NUCLEAR REACTIONS ^{6}Li$(p,2p)$, ^{9}Be$(p,2p)$, "cumulative" region; deduced excitation spectrum, test of single particle approximation.]

The backward production of high energy protons in p-nucleus interactions cannot take place without the presence of high nuclear recoil momenta. An important question has been whether these recoils preexist in the nucleus, so that the incident particle interacts with a high momentum nucleon (recoiling against the residual nucleons) and ejects it, or whether, in another extreme view, multistep nuclear collisions with low momentum nucleons in the nucleus build up the high momentum nuclear recoil. In the former case one would hope from such studies to extract information on the high momentum components of the wave function of the struck nucleon and of the outgoing nucleon. Unfortunately, inclusive measurements, which depend on sums over the recoil momenta (k) and excitation energies (ϵ) of the undetected nuclear configurations, can be shown, for a large variety of models, to depend mainly on the minimum momentum of the nuclear recoil.[1] Thus while single nucleon interaction models, using an *effective* long-tailed momentum distribution, appear to have had good success,[2–5] other models, statistical in nature or involving cluster structure, while not as widely tested, also are said to reproduce the main features of the data.[6–8]

The virtue of a $(p,2p)$ experiment, as seen from Fig. 1(a), is that measurement of both the momentum of the backward proton $\vec{q}$ and of the forward proton $\vec{p}\,'$ allows the experimental determination of the unique recoil momentum and excitation energy in *each* interaction and is thus richer in information about the reaction mechanism. To this end we have used the high resolution spectrometer (HRS) at LAMPF and a low resolution spectrometer (LRS) of our own design to investigate backward proton production, mainly in ^{6}Li, over a range of recoil momenta extending to 0.9 GeV/c and excitation energies ϵ ranging from 0 to 400 MeV.

It is important to keep in mind that the purpose of this experiment was to obtain data on a very special part of the phase space of a $(p,2p)$ reaction, namely for kinematic regions not accessible in p-p reactions.

Only one experiment studying this kinematic regime has been previously reported.[9] That experiment used scintillation counters, range telescopes, and dE/dx to select out $(p,2p)$ events. It was set up to study a special kinematic region, the region in which the scattering of the incoming proton from a two-body cluster at rest inside the nucleus

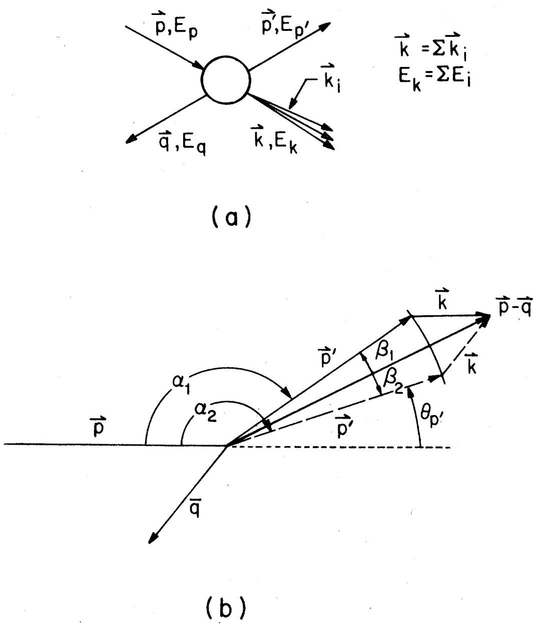

FIG. 1. (a) Kinematics of a $(p,2p)$ reaction: The nuclear excitation energy ϵ can be calculated for each measurement of $\vec{q}$ and $\vec{p}'$. The excitation energy is defined as $(k^2+M_{\text{inv}}^2)^{1/2}-(k^2+M_{A-1}^2)^{1/2}$ with $k \equiv \Sigma \vec{k}$, and $(k^2+M_{\text{inv}}^2)^{1/2} \equiv \Sigma E_i$. (b) Symmetric kinematic configurations: Vector diagrams shown for equal magnitudes of p' at equal angles ($\beta_1=\beta_2$) relative to the $\vec{p}$-$\vec{q}$ axis. The values of k for the two configurations are identical while the p-p scattering angles ($\alpha_1 > \alpha_2$) are different.

would be optimized. Therefore the experimental conditions were set to have good efficiency to detect protons with one half the momentum of an elastically forward scattered two-body cluster. Thus that experiment centered about a region in phase space where the difference in the kinetic energy of the incoming proton and the sum of the kinetic energies of the two detected outgoing protons was large; that is, the region of high excitation of the undetected $A-1$ nucleons. In our experiment we have used two magnetic spectrometers of better resolution than those employed in Ref. 9 to search the region from zero excitation energy (quasifree scattering) up to missing energies of about 400 MeV. Thus the two experiments are quite complementary. In addition we reproduced the kinematic configuration used in this prior experiment to study p-two body cluster contributions for one of our runs.

It is important to keep in mind that the cross sections for backward proton production represent a very small part of the inclusive cross section and that these cross sections fall rapidly with both angle and backward momentum. Thus in order to obtain sufficiently high coincidence rates free of accidental coincidences one must pick the backward angles, momenta, and spectrometer phase-space acceptances judiciously. In this sense the experiment is quite different from the usual $(p,2p)$ experiment which examines two forward protons and where the two proton coincidence efficiency is high.

The plan of the experiment was, first to measure for a fixed backward angle and several backward momenta the momentum spectra in the forward spectrometer set at a fixed angle. Second, the coincidence angular distribution was measured by varying the forward spectrometer angle at fixed forward momentum. The first set of data provides information on the variation of cross section with excitation energy of the recoiling $A-1$ nucleons. The second set of data provides information on the validity of single scattering models, since it allows one to determine whether the p-nuclear angular distribution reflects the p-constituent angular distribution.

In this experiment the backward spectrometer (LRS) was fixed at 105° relative to the incident 0.8 GeV beam; it had a momentum resolution of $\pm 3.5\%$ and an acceptance of 3.3 msr. The forward rotatable spectrometer (HRS) was used as a low resolution spectrometer with a resolution of $\pm 1.4\%$ and an acceptance of 3.0 msr.[10]

A goal of the experiment was to study the spectrum of nuclear excitation following the production of a backward proton. The momentum of the backward proton was fixed, the angle of the forward proton chosen to be the $\vec{p}$-$\vec{q}$ direction (that expected in a free p-p collision), and the coincidence momentum spectrum of the forward proton measured. Figure 2 shows these data for the momenta $q=0.35$, 0.4, and 0.55 GeV/c. The data on ^{6}Li appear as closed circles. (To call attention to a special configuration in the $q=0.55$ GeV/c spectrum, three of the data points are plotted as open circles.) Be data, obtained only for $q=0.35$ GeV/c, are plotted as $\times$'s along with the Li data. The right side of this figure shows the observed coincidences *per backward proton* versus the momentum of the forward proton.[11] The arrow marked "LIM" shows the kinematic limit, i.e., the maximum possible p' corresponding to an unexcited $A-1$ residual nucleus. For each value of q a peak in the excitation energy appears at a p' corresponding to an $\epsilon = 18-20$ MeV, so there is a clear contribution from "coherent" recoil. The invariant cross sections per nucleon at each peak,

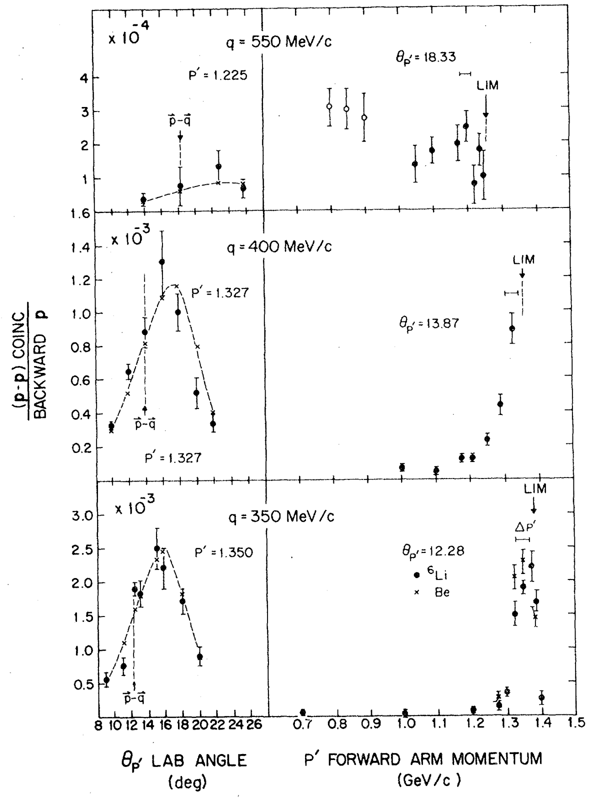

FIG. 2. The p-p coincidence rate per backward proton (q) vs momentum (p') in the forward arm is plotted to the right. The HRS momentum bite is shown by the horizontal bar. The spectra "peaks" occur at 18 ± 2 MeV below the appropriate end point energies. The left plot shows the coincidence per backward proton versus the angle ($\theta_{p'}$) of the forward spectrometer with p' kept fixed in the bar region. The $\vec{p}$-$\vec{q}$ axis is shown by the vertical line. The dashed curve is the forward spectrometer singles rate alone ($\times$) normalized to the coincidence rate. LIM shows the elastic limit for ^{6}Li.

$E_qE_{p'}d^4\sigma/q^2dq\,d\Omega_qp'^2dp'd\Omega_{p'}$, in millibarns (GeV)^2/(GeV/ c)^6 (sr)^2, for ^{6}Li are the following: $q=0.35$, $p'=1.350{:}158$; $q=0.40$, $p'=1.227{:}48$; $q=0.55$, $p'=1.255{:}2.6$.

The left side of Fig. 2 shows the coincidences *per backward proton* when the forward spectrometer is set near the peak energy (shown by the bracket on the right side of the figure) and its laboratory angle is varied. The solid circles are the ^{6}Li data. Superimposed on this figure are the singles rates in the forward spectrometer (shown as $\times$'s and arbitrarily normalized to the same area). The dashed line through the $\times$'s is to guide the eye. The vertical dashed line shows the two body scattering angle ($\vec{p}$-$\vec{q}$ direction).

The data we have presented on the angular distribution and excitation spectra in the $p,2p$ reaction for backwardly produced protons are unique and it is hoped that they will stimulate theoretical activity. It is our goal in this section to look only at conclusions that stand out in these new data and that without detailed investigation rule out previously proposed mechanisms or suggest new ones.

The first important fact to notice from Fig. 2 is that the yields appear to peak at momenta just below the elastic limit and show a rapid falloff as p' decreases. These data were taken with the forward spectrometer set in the $\vec{p}$-$\vec{q}$ direction. Furthermore, the momentum at the peak yield corresponds with an excitation of the recoiling $A-1$ nucleus (taking into account the recoil kinetic energy) of only about 18 MeV. At first sight it might seem that the main contribution to the cross section comes from the idealized configuration of "coherent recoil." However, we shall see that only about 2% of the *inclusive* cross section appears in this peak for $q=0.35$ GeV/c. Even smaller fractions appear in the peaks in the 0.40 and 0.55 GeV/c data.

To get the total contribution to the inclusive cross section at any fixed excitation energy ϵ, i.e., at a fixed value of p', we must integrate the p-$2p$ cross section over all the angles θ and ϕ'. We have, however, only measured the p-$2p$ cross section in the p,q plane. However, if we assume ϕ symmetry about the $\vec{p}$-$\vec{q}$ axis, for the purpose of our estimate, we can find the fraction of events with excitation energy ϵ observed with our spectrometer fixed in the $\vec{p}$-$\vec{q}$ direction. This can be carried out by integrating our angular distributions numerically. A more useful way is to parametrize the β dependence and then carry out the calculation analytically. [See Fig. 1(b).] Since each value of β corresponds to a value of k we can fit our coincidence rate per backward proton, using k rather than θ. We find from our data, and also from the data of Komarov, that this rate is well parametrized by the function $\exp(-k/K)$. For all three of our angular distributions, at low excitation energy, we find $K=25$ MeV/c. Aside from any theoretical interest in such a parametrization, it is a useful one because it allows one to obtain a simple analytic expression for the fraction of all events of excitation energy ϵ that are detected by the spectrometer of acceptance $d\Omega_{p'}$ oriented along the $\vec{p}$-$\vec{q}$ axis. This fraction f is $p'\,|\vec{p}-\vec{q}\,|\,d\Omega_{p'}/2\pi K(\,|\vec{p}-\vec{q}\,|-|\vec{p}'\,|\,)$. Thus a plot of f vs p' gives the expected number of coincidences per

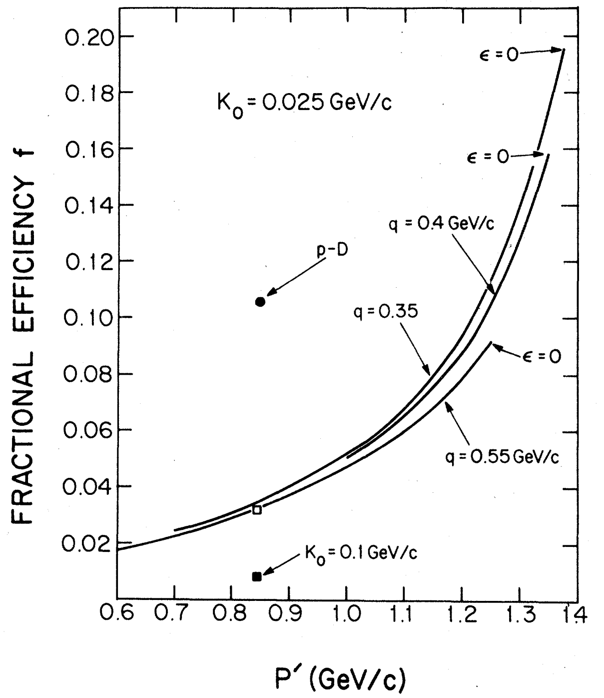

FIG. 3. The fraction of the inclusive cross section f at fixed p', detected by the forward spectrometer set in the $\vec{p}$-$\vec{q}$ direction, as a function of p' for each q. The fractions for $K_0 = 0.025$ GeV/c (open square) and for $K_0 = 0.1$ GeV/c (filled square) at $p' = 0.86$ GeV/c, $q = 0.55$ GeV/c are also compared. The fraction of all events due to deuteron breakup that would be detected in this configuration (filled circle) is also shown.

backward proton that would be expected *if* the excitation spectrum were completely flat. Such a plot is shown for our three spectra in Fig. 3 for our value of $K = 25$ MeV/c. We have analyzed the angular distributions of Komarov and find that K increases with excitation energy so that at an excitation of about 300 MeV, $K = 100$ MeV/c. This variation would result in a faster falloff. This is illustrated by the filled square in Fig. 3. (Since it is known that the inclusive cross section, which sums over all excitation energies, falls off with an average K of about 70 MeV/c,[12] the small value of 25 MeV/c at low excitation had to be accompanied by a large value of K for high excitation.)

Thus we conclude, in agreement with Komarov, that there is a wide spread of excitation energies accompanying backwardly produced protons of high momentum.

We now remark on the large yields observed near $p' = 0.86$ GeV/c in the $q = 0.55$ GeV/c data (open circles). *Whatever* the mechanism for the reaction $p + A \rightarrow p + d + X$ there is no reason not to observe protons arising from "stripped deuterons" as well. Kinematically such protons could appear only in the $q = 0.55$ GeV/c data sine the other angles do not satisfy p-D kinematics. The efficiency f' for detecting such protons near $p' = p_d/2$ can be crudely estimated[13] and is shown plotted in Fig. 3. It is considerably larger than the efficiency f because it is essentially a two-body effect. Corrected for this effect the 0.55 data is quite similar in shape to the data at the other backward momenta.

Thus we conclude that by setting up spectrometers at the p-d elastic scattering angles one will always find a large yield of protons at approximately one half the deuteron momentum. It is better to avoid this configuration if one is to study the main part of the backward production mechanism.

We now turn to the main purpose of our experiment, to test the validity of a single scattering hypothesis, namely, to see whether the nuclear cross section follows the known p-p cross section. The cleanest test can be made by keeping k fixed, so that the dependence of the cross section on the wave function of the struck proton need not be known and only the angular dependence of the cross section studied at fixed k, to establish whether it tracks the nucleon cross section. We show, in Fig. 1(b), two configurations symmetric about the $\vec{p}$-$\vec{q}$ axis [i.e., $\beta_1 = \beta_2$, Fig. 1(b)]. While the values of k are identical the values of t differ. At these energies we expect the smaller momentum transfer scattering at angle α_2 to be enhanced relative to α_1, resulting in a shift of several degrees in the coincidence spectrum from the $\vec{p}$-$\vec{q}$ axis to *smaller* angles. From Fig. 2 we see that there is a clear shift of the data in the *opposite* direction, in contradiction to a single scattering model. Thus these new $(p,2p)$ data do not support a single scattering model for backward proton production.

We now wish to point out a remarkable feature of these new data which must serve as an important test for any viable production mechanism. As seen in Fig. 2 both the position of the angular maximum and the shapes of the coincidence and singles spectra are identical. This is not expected for a single scattering mechanism but could come about as the result of *rescatterings backward* of the low energy proton produced in an ordinary ("quasifree") p-p collision with a nucleon having no especially high momentum components in its wave function. However, in our kinematic configuration the excitation cannot exceed 18–20 MeV so that the rescatters cannot be incoherent scatterings from single nucleons, as in a single cascade, but must be coherent scatterings over at least several nucleons. Such a mechanism, to account for these $(p,2p)$ results and the results of analyzing power measurements for backward proton production[14] has recently been studied.[15]

While a statistical model for backward production would also predict these results one must recall that they would also predict zero analyzing power for the inclusive reaction. But large analyzing powers[14] have been observed experimentally at this angle for this reaction.

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[10] For both spectrometers, as employed, the momentum "acceptance" was the momentum "resolution." Actually the high resolution of the HRS was essential to the experiment; precise calibration of the proton orbits and momenta allowed the use of a tight coincidence requirement (±2 ns) necessary because of the poor LAMPF duty cycle.

[11] For each decrease $\Delta p' = 0.1$ GeV/c there is both an increase in k of 0.1 GeV/c and an increase in ϵ of ~ 70 MeV.

[12] S. Frankel, Phys. Rev. Lett. 38, 1338 (1977).

[13] A third of a century ago, R. Serber [Phys. Rev. 72, 1008 (1947)] studied deuteron breakup to be 45 MeV/c. We actually used our best fit to the data (43 MeV/c) of C. F. Perdrisat *et al.* [Phys. Rev. 167, 1201 (1969)] to calculate the efficiency f' for our spectrometer acceptance.

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