Proton + nucleus inclusive (p,p′) scattering at 800 MeV

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(Received 28 July 1983)

800 MeV inclusive (p,p′) data, spanning the momentum range from that of the quasi-elastic peak to outgoing proton momenta of about 350 MeV/c, are reported for the target nuclei ^{1}H, ^{2}H, ^{12}C, ^{40}Ca, and ^{208}Pb. The data are consistent with simple ideas concerning quasi-free π production, and an angle and momentum integration of $d^2\sigma/d\Omega\, dp$ across the entire quasi-free region accounts for most of the p + nucleus total reaction cross section.

[NUCLEAR REACTIONS (p,p′) on ^{1}H, ^{2}H, ^{12}C, ^{40}Ca, ^{208}Pb; $E_p=800$ MeV, $\theta_L=5°-30°$; measured $d^2\sigma/d\Omega\, dp$ for quasi-elastic and quasi-free pion production.]

I. INTRODUCTION

The 800 MeV (p,p′) inclusive data[1] for a variety of target nuclei suggest that nucleon-nucleon quasi-free processes account for the prominent features of the p′ spectra. The available data clearly and graphically illustrate the important contribution from proton (p) + nucleon (N) quasi-elastic scattering (p + N→ p + N) and also imply significant quasi-free inelastic p + N pion production (p + N→ p + N + π). In fact, a plane wave impulse approximation calculation[2] for ^{12}C (p,p′) which includes these two processes is found to be in qualitative agreement with the available data at excitations above pion production threshold, when normalized to the quasi-elastic peak. This calculation also gives a total reaction cross section consistent with experiment. Quantitative success of this picture would be significant, for it would imply that the impulse approximation is a good starting point for the microscopic treatment of ~ 1 GeV proton + nucleus elastic and inelastic scattering.[2,3]

Clearly, before detailed quantitative statements can be made, additional data are needed to map out the region of the spectra most sensitive to pion production. More detailed and realistic theoretical calculations are also required for comparison with experiment. Here we report data for 800 MeV (p,p′) on the targets ^{1}H, ^{2}H, ^{12}C, ^{40}Ca, and ^{208}Pb. After a brief experimental discussion, we show that these data are consistent with simple ideas concerning quasi-free π production, and that an angle and momentum integration of $d^2\sigma/d\Omega\, dp$ across the entire quasi-free region accounts for most of the p + nucleus total reaction cross section.

II. EXPERIMENTAL

The data, shown in Figs. 1—5, were obtai high resolution spectrometer (HRS) at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). Details of the HRS system have been reported in recent publications[4,5] and will not be repeated here. The measurements were made at HRS laboratory angles of 5°, 11°, 15°, 20°, 25° (^{1}H only), and 30°, and the HRS fields were stepped to provide momentum increments of $\sim 50-100$ MeV/c in order to span the p′ momentum range from that of the quasi-elastic (elastic for ^{1}H) peak to outgoing proton momenta (p′) of about 350 MeV/c. The focal plane proton detection efficiency was measured to be uniform to $\pm 1\%$ for the p′ energy range covered during the course of the experiment. A single data point was obtained for each target at each angle and field setting. The spectrometer momentum acceptance is $\simeq \pm 1\%$. Absolute normalization was obtained through comparison of relative p + p elastic cross sections measured here with the 800 MeV p + p elastic data of Ref. 5, and is believed accurate to $\sim \pm 5\%$. The ^{1}H and ^{2}H data were obtained using CH_2 and CD_2 targets, necessitating careful background subtraction of the ^{12}C contributions; all other targets were self-supporting foils of thicknesses between 50 and 100 mg/cm^2 and isotopic enrichments $>97\%$. Errors resulting from statistics and background subtraction are typically 5—10%. Other experimental details may be found elsewhere.[6] Also shown in Figs. 1—5 are renormalized

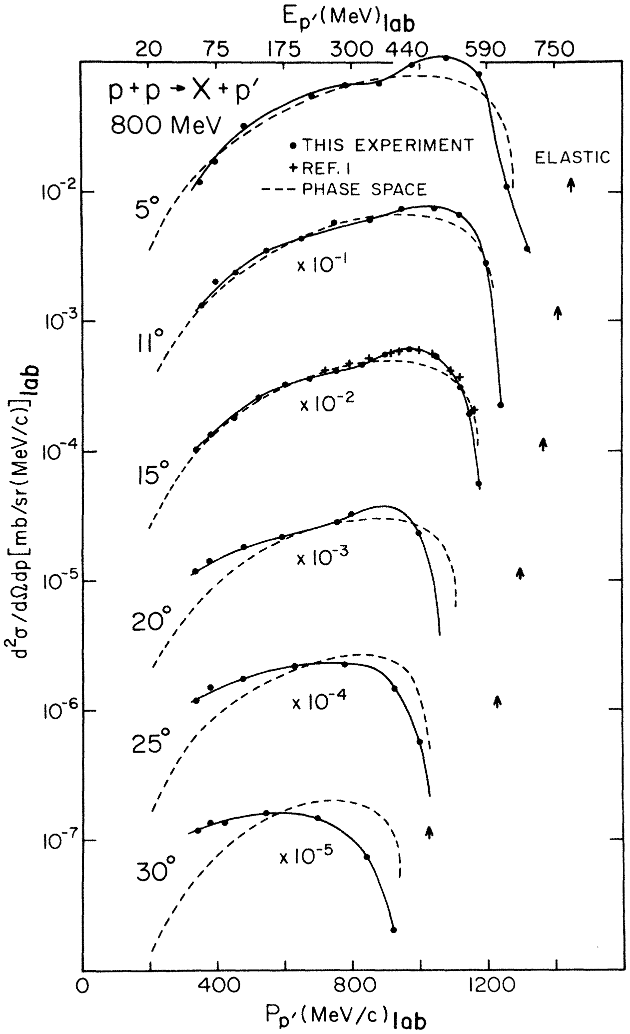

FIG. 1. Inclusive proton spectra for 800 MeV p + p. The solid curves are drawn to guide the eye. The dashed curves correspond to the proton phase space for p + N→ p+N+π (arbitrary normalization).

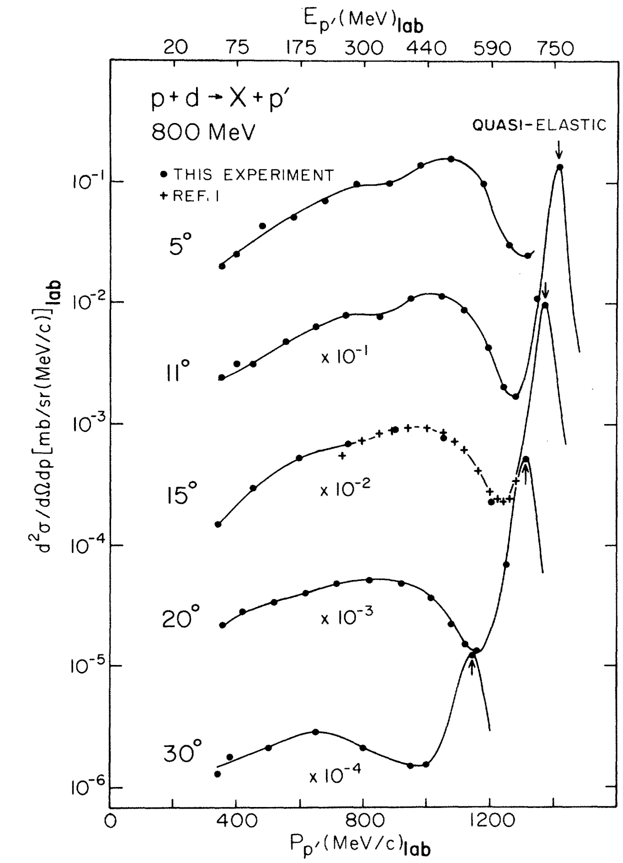

FIG. 2. Inclusive proton spectra for 800 MeV p+^{2}H. The curves are drawn to guide the eye.

data from Ref. 1; the renormalization factors vary from 1.1 to 1.25, depending upon angle. The discrepancy has been shown[5] to originate in the use of inaccurate p + p data, in Ref. 1, to obtain absolute normalization.

III. DISCUSSION

As seen in Figs. 3—5, the gross structure in the data at each angle for the targets ^{12}C, ^{40}Ca, and ^{208}Pb is similar to that seen in Figs. 1 and 2 at the corresponding angles for ^{1}H and ^{2}H. For all targets a quasi-free nucleon knockout peak (except ^{1}H) is followed by a second, broader peak at an additional momentum loss of about 500 MeV/c. These similarities suggest that elementary quasi-free processes are the main contributors to the (p,p′) spectra for the heavier nuclei. A natural interpretation of these data can be made in terms of the quasi-free doorway model[2,3] in which quasi-free elastic and inelastic scattering processes form doorway states through which all subsequent reactions evolve. Clearly there are important differences between the various spectra at each angle, such as the widths of the quasi-elastic peaks and the degree of flatness of the second peaks. However, these differences are presumably owing to Fermi motion effects, multiple scattering of the detected protons, final state interactions, etc., and do not invalidate the quasi-free doorway model to be discussed.

At 800 MeV laboratory energy, the p + p total cross section is about 47 mb; about half (25 mb) of this is in the elastic channel, while the other half (22 mb) is associated with pion production (p + p→ N + N + π). For p + n the same two processes compete (total cross section =38 mb, elastic cross section =26 mb, pion production =12 mb).[3,7] The predominant mechanism for π production in p + N collisions at laboratory energies near 1 GeV is excitation to the delta resonance $\Delta(3/2,3/2)$.[2,3]

The Born terms describing π production through the Δ (isobar production model[2,3]) are schematically shown in Figs. 6 and 7. For both p + p and p + n, three processes can lead to at least one proton in the outgoing channel. The last columns in Figs. 6 and 7 indicate the source(s) of protons that would be detected in a single-arm inclusive (p,p′) experiment. The "recoil" proton is the proton not associated with the Δ, and the "decay proton" is the proton resulting from Δ decay. Assuming charge indepen-

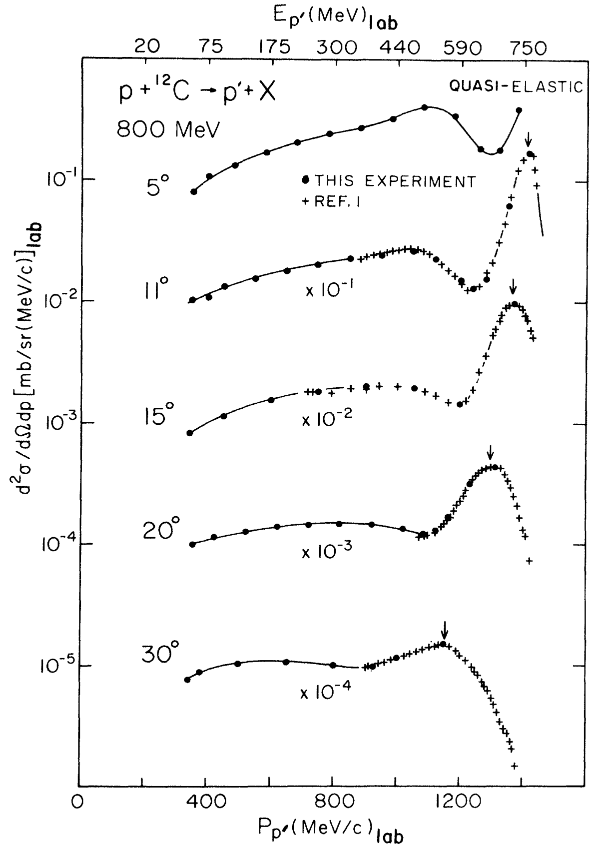

FIG. 3. Inclusive proton spectra for 800 MeV p+^{12}C. The curves are drawn to guide the eye.

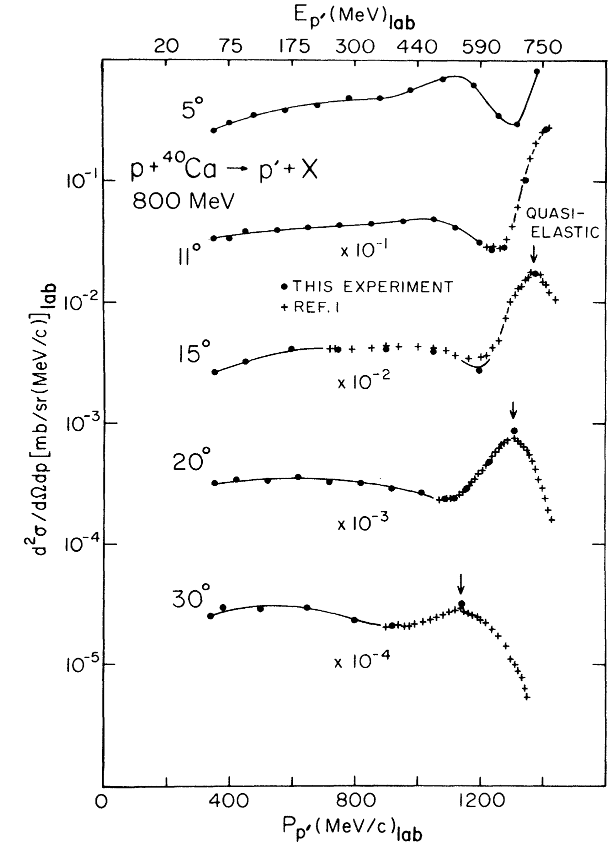

FIG. 4. Inclusive proton spectra for 800 MeV p+^{40}Ca. The curves are drawn to guide the eye.

dence, the cross sections for the various channels are related via isospin Clebsch-Gordan coefficients (as shown in Figs. 6 and 7). Neglecting distortion effects and considering targets with $A \geq 1$, an examination of the diagrams in Figs. 6 and 7 suggests that an inclusive (p,p′) experiment will over count quasi-free p + p π production by 17% and count quasi-free p + n π production properly. For an $N \simeq Z$ nucleus, by weighting by the appropriate cross sections, it follows that the (p,p′) inclusive measurement will over count quasi-free π production by about 12%. However, the effect of this over counting on the measured integrated total (p,p′) cross section will be less because of the quasi-elastic contributions (counted exactly). For an $N \simeq Z$ nucleus it is easy to show that the (p,p′) total inclusive angle-integrated cross section will be in error by only 5% because of this double counting. Since the cross section for the process $p+p \to (\pi^+ p)n$ is significantly larger than those for the other p + p and p + n pion production processes (see Figs. 6 and 7), the inclusive (p,p′) spectra for *any target* in the region above the pion production threshold should be dominated by decay protons. Since the decay protons are associated with a three-body final state, the spectra should resemble the proton phase space for $p+N \to p+N+\pi$. The recoil protons arise from quasi-two-body processes, and so should cause structure in the spectra which follows $p+N \to p+\Delta$ kinematics.

The data shown for ^{1}H (Fig. 1) extend from the pion production threshold to outgoing proton laboratory momenta of 350 MeV/c and represent the single-arm signature of proton + proton pion production. The dashed curves in Fig. 1 correspond to the three-body phase space mentioned above. For laboratory angles less than 15°, the phase space curves track the general shape of the data, while this agreement deteriorates at larger angles. However, it can be shown that decay protons detected for $\theta_{lab} \leq 15°$ originate primarily from small momentum transfer pion production, while for $\theta_{lab} \geq 15°$ a broad range of larger momentum transfers is involved, so that the momentum transfer dependence of the pion production processes may explain this observation. A comparison of the ^{2}H data (Fig. 2) with the ^{1}H data indicates that for a given angle, the shapes of the spectra in the pion production region are remarkably similar. This same general structure is also seen in the inclusive spectra for ^{12}C, ^{40}Ca, and ^{208}Pb (Figs. 3–5). For angles greater than 5°, the broad quasi-elastic peak is also observed; this peak, for each nucleus, follows quasi-elastic kinematics.

For each target the inclusive cross sections were integrated over momentum and angle. Similar measure-

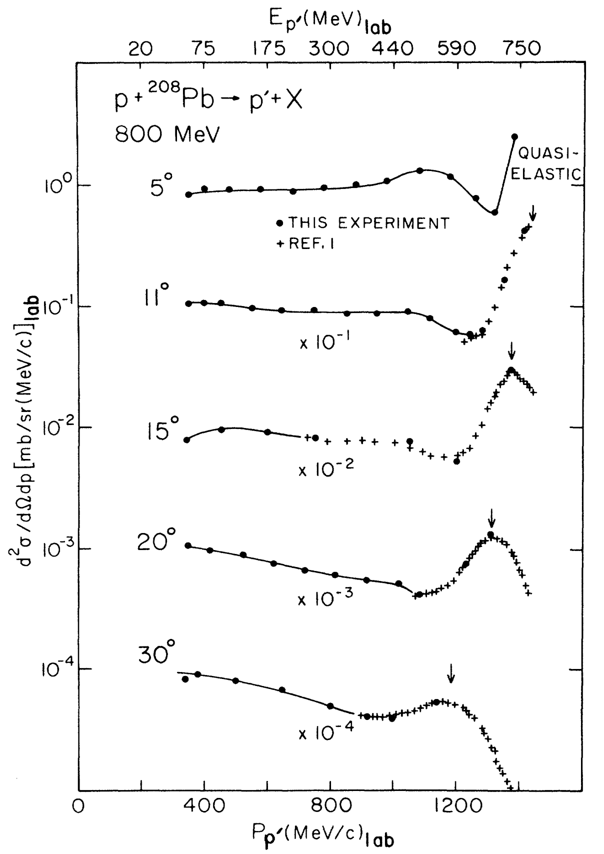

FIG. 5. Inclusive proton spectra for 800 MeV p+^{208}Pb. The curves are drawn to guide the eye.

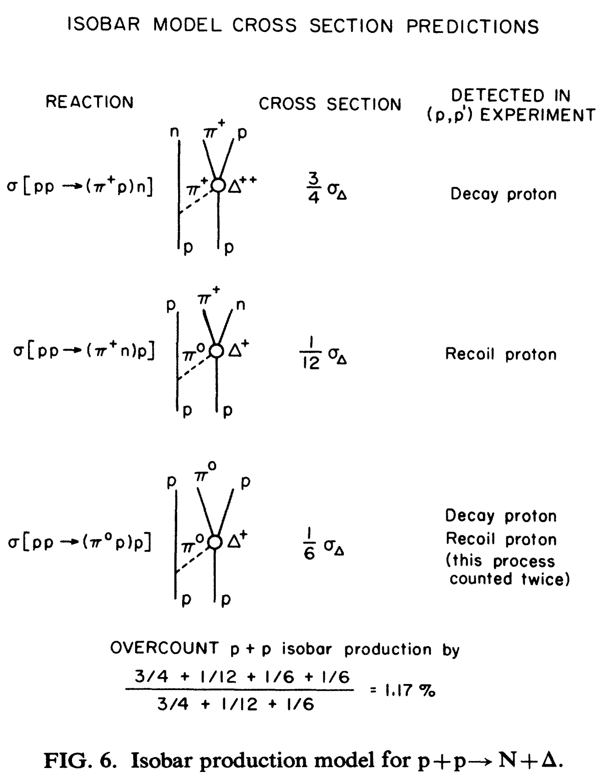

FIG. 6. Isobar production model for p+p→ N+Δ.

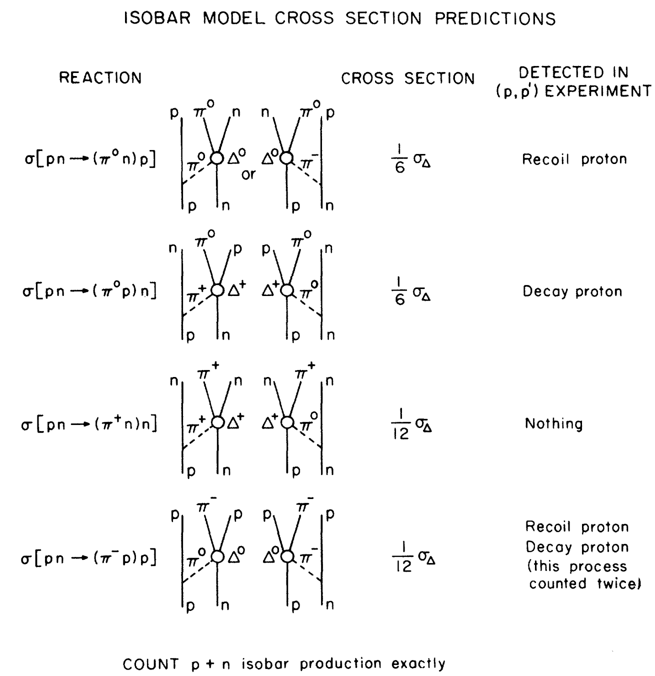

FIG. 7. Isobar production model for p+n→ N+Δ.

ments[8] made at 165 MeV incident proton energy show a sharp rise in the proton yield for momenta ≤ 200 MeV/c, owing to evaporation from residual compound nuclei. To avoid double counting from such high multiplicity processes, the lower limit for the integration over momentum was taken as 300 MeV/c. The momentum integrals for each target were then plotted versus scattering angle and extrapolated to 90° in the N-N center-of-momentum system, and the integrations over angle were performed. This procedure does not yield the p + n quasi-elastic contribution for $\theta_{\text{c.m.}} > 90°$. However, the prescription

$$\sigma_R = 1.22\left[\frac{Z}{A}\sigma_{\text{pp,el}} + \frac{N}{A}\sigma_{\text{pn,el}} + \frac{Z}{A}\sigma_{\text{pp},\Delta} + \frac{N}{A}\sigma_{\text{pn},\Delta}\right]A^{2/3},$$

with $\sigma_{\text{pp,el}} = 25$ mb, $\sigma_{\text{pn,el}} = 26$ mb, $\sigma_{\text{pp},\Delta} = 22$ mb, and $\sigma_{\text{pn},\Delta} = 12$ mb gives an accurate ($\pm 2\%$) reproduction of 800 MeV reaction cross sections for nuclei from ^{12}C to ^{208}Pb obtained using a second order microscopic optical model.[9] Thus, since 30% of the p + n total elastic cross section is contained[7] between $90° \leq \theta_{\text{c.m.}} \leq 180°$, the *quasi-elastic* angle-integrated results were corrected by the factor $1.0 + 7.8N/(25Z + 26N)$. For $N = Z$ nuclei this correction is 15%, while for ^{208}Pb it is 18%. Table I presents numerical results for these angle-integrated cross sections and comparisons with (1) theoretical reaction cross sections obtained from second-order microscopic optical model calculations,[9] and (2) the experimental total reaction cross sections.[6] It is seen from Table I that the quasi-elastic and quasi-free pion production processes account for nearly all (88—93 %) of the reaction cross sections for the targets ^{12}C and ^{40}Ca. The reason that the integrated cross section is not larger for ^{208}Pb is most likely

TABLE I. The angle-integrated cross sections for the two quasi-free regions are shown in columns two and three. The total angle-integrated cross section in column four is compared to KMT predictions (column five) and measured total reaction cross sections (last column).

Target	Quasi-elastic[a]	π production[a]	Total	KMT[b]	Measured[c]
^{1}H	25.1±1.2[d]	19.7± 1.7	44.8± 2.1		47.3± 0.5[e]
^{2}H		34.9± 1.7			
^{12}C	100 ±5	137 ± 7	237 ± 9	269	278 ± 9
^{40}Ca	239 ±12	335 ±24	574 ±27	615	622 ± 32
^{208}Pb	347 ±12	825 ±49	1172 +52	1800	1836 ±212

[a]Errors owing to extrapolation included; see Ref. 6.
[b]Reference 9.
[c]Reference 6.
[d]Integrated p + p elastic differential cross section.
[e]Total cross section, Ref. 7.

owing to significant absorption in the outgoing channel for this large nucleus; note from Fig. 5 that the (p,p′) cross sections continue to rise with decreasing p_{out} for angles greater than 5°, suggesting a significant amount of rescattering and absorption of the outgoing protons.

The results shown in Table I and the discussion found in this section clearly suggest that the quasi-free picture of reactions is appropriate at energies near 1 GeV. Realistic theoretical predictions are clearly called for in order to test these ideas further.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy and the Robert A. Welch Foundation. We wish to thank Prof. S. J. Wallace and Prof. W. R. Coker for useful discussions.

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