Large angle scattering of 0.8 GeV protons from ^{12}C

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Experimental elastic and inelastic angular distributions for 0.8 GeV $p + {}^{12}C$ are reported for momentum transfers up to $q = 7.1$ fm^{-1}. At the largest angle the elastic cross section is $\sim 2.0 \times 10^{-8}$ mb/sr. The data are analyzed using the distorted-wave Born approximation and the coupled-channels formalism, where phenomenologically deformed optical potentials are used in the latter analysis. The multipole moments extracted from the optical potentials are found to be in fair agreement with those of the charge densities as obtained from electron scattering.

NUCLEAR REACTIONS $^{12}C(p,p')$, $E = 0.8$ GeV; measured $\sigma(\theta)$; natural targets; resolution 100 to 650 keV, $\theta_{c.m.} = 3.9°-67.2°$, $q_{max} = 7.1$ fm^{-1}. Optical model potential, DWBA and coupled channels analyses, rotational model, coupling parameters, multipole moments, inelastic deformation lengths $\beta_l R$.

I. INTRODUCTION

During the past year a concerted effort has been undertaken to examine the high momentum transfer nature of 800 MeV proton-nucleus elastic and inelastic scattering.[1-3] As a result of the theoretical analysis of these data using the multiple scattering theory of Kerman, McManus, and Thaler (KMT),[4] a hitherto unsuspected inadequacy with the treatment of the Coulomb interaction in multiple scattering theory was detected and appropriate improvements in the theoretical calculations implemented.[2] In addition, it has been observed that the simple diffractive pattern of the data and the theoretical calculation gradually become out-of-phase with each other at large momentum transfer, $q \geq 3$ fm^{-1}.[1-3] In order to provide experimental data for further high momentum transfer tests of multiple scattering calculations for ~1 GeV proton-light nucleus scattering the elastic and inelastic angular distributions for $p + {}^{12}C$ at 800 MeV of Ref. 5 have been extended to 7 fm^{-1}. The ^{12}C nucleus is appropriate for such study since thick targets are readily available and because the overall exponentially declining diffractive pattern decreases with q (momentum transfer) less rapidly than for heavier nuclei, thus permitting data at higher momentum transfer to be obtained.

Meaningful evaluation of the ability of KMT calculations to describe these high q data should incorporate deformation and multistep effects which are known to be important in these reactions.[6] Rather than carry out the numerically difficult coupled-channels KMT calculations, the analysis here will be a phenomenological one, thus deferring the coupled-channels KMT analysis to the future.

In addition to providing new data for further theoretical tests, the data have been analyzed both with the distorted wave Born approximation (DWBA) (Ref. 7) and in the coupled-channels (CC) formalism[8] using phenomenological potentials. As pointed out in previous work,[9] coupled-channels analysis of 800 MeV p + deformed nucleus ground state rotational band angular distribution data can provide information about the multipole moments of the intrinsically deformed ground state matter density. Such analyses rely on the well known sensitivity of proton-nucleus scattering to details of the nuclear surface and to the well proven applicability of the folding model of the ~1 GeV proton-nucleus optical potential.[10] As in previous analyses of ~1 GeV proton inelastic scattering from deformed nuclei, important multistep processes must and will be included in the calculations.

Therefore in this work we report new data for the scattering of 0.8 GeV protons from ^{12}C which extend to about 7 fm^{-1}. Angular distributions corresponding to the residual ^{12}C nucleus being left in the (0.0 MeV, 0^+), (4.439 MeV, 2^+), (7.66 MeV, 0^+), (9.64 MeV, 3^-), and (14.1 MeV, 4^+) states have been remeasured over the angular range of previous data[5] and extended out to 67° c.m. (7.1 fm^{-1}). A complete tabulation of the data is on deposit in PAPS.[11]

II. EXPERIMENT

The data were obtained using the high resolution spectrometer (HRS) at LAMPF. Details of the experimental system have been reported elsewhere.[5,12,13] Natural graphite targets of 174 and 360 mg/cm^2 and a CH target (pilot *B* scintillator) with 81 mg/cm^2 of ^{12}C were used. The energy resolution was about 100 keV for the smaller angles, but increased at the larger angles. The resolution for the 2^+ state at the largest angle was 650 keV. The spectra were similar to those previously reported.[5] The overall experimental angular resolution $(\Delta\theta)$ was determined to be ≤ 1.6 mrad full width at half maximum (FWHM) from the observed energy resolution for $p+p$ scattering, since for this case, the resolution is dominated by the kinematic term $(dE/d\theta)\Delta\theta$. For example at $15°_{lab}$, $dE/d\theta = 9.4$ MeV/degree while $\delta E_{measured}$ was 840 keV. Data was also acquired on ^{208}Pb and compared to the data of Hoffmann *et al.*[1] The absolute scattering angle for their data was determined to $\pm 0.02°$. From this comparison, the absolute angle for the ^{12}C data should be known to $\pm 0.05°$.

A clean particle identification (PID) system was very important in order to obtain the small cross sections ($< 10^{-7}$ mb) measured here. Four scintillators spaced over a two meter interval provided pulse height and time-of-flight information for the PID. A fourfold coincidence among these scintillators provided the event trigger. The fraction of protons to the total number of events was found to be about 0.3 at 30°, 0.1 at 40°, and 0.01 at $55°_{lab}$. Most of the events at the back angles are low energy deuterons and tritons. The overall efficiency of the delay-line and drift chambers used to record, for each event, trajectory position and angle information at the focal plane of the HRS was determined for each run by evaluating the quantity: (good proton PID and good chamber time-sum checks)/(good proton PID).[13] The chambers occupied a region in space which was larger than the region occupied by the scintillators. The overall chamber efficiency was greater than 90% for runs at $\theta_{lab} < 40°$ and about 85% for $\theta_{lab} > 40°$. The instantaneous singles rate (due mainly to room background) in the scintillators was held to $< 0.5\times10^6$/s. This limited the proton beam to ≤ 40 nA on target. Thus the data acquired at the larger angles required runs of up to 24 h.

In order to minimize the relative errors in the data, the measurement of proton angular distributions over the entire angular range previously reported[5] was repeated, and extended to larger angles. The new data, shown in Figs. 1 and 2 cover the range from 3.9° to 67.2° c.m.

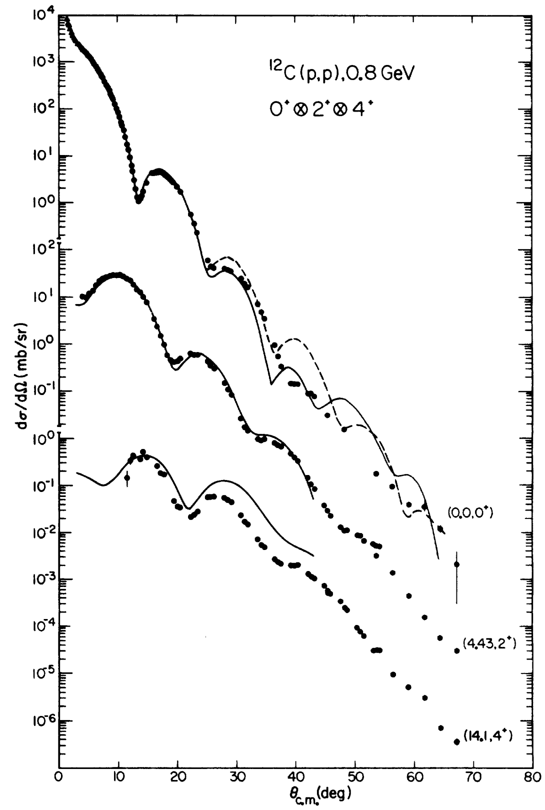

FIG. 1. The angular distributions for excitation of the $0^+, 2^+, 4^+$ ground state rotational band in ^{12}C. Shown as solid curves are CC predictions using the deformed symmetric rotator collective model, coupling the 0^+, 2^+, and 4^+ with $\beta_2 R = -1.91$ fm and $\beta_4 R = +0.002$ fm.

Additional relative measurements of $p+p$ scattering using a CH target were made at angles of 15, 20, 25, and $30°_{lab}$, and compared to the data of Willard *et al.*[14] As previously discussed,[5] their point at 15° is believed to be low. When the other three points are used to compute an absolute normalization of the $p+p$ cross sections, we find agreement within $\pm 4\%$ except for the 15° point which is 6% larger than their point. When the new cross sections for elastic scattering from ^{12}C are then normalized and compared to the data of Ref. 5, which were also normalized in this manner, we find agreement to 2% in the region of the first two maxima located at ~17° and 29° c.m.

The small angle cross sections can be compared to the elastic $p+{}^{12}C$ data of Wriekat *et al.*[15] which were measured with small absolute error, over the angular range 0.5 to 3.7° c.m. These data were fit with $d\sigma/d\Omega = a\cdot \exp^{(b\alpha)}$ and extrapolated

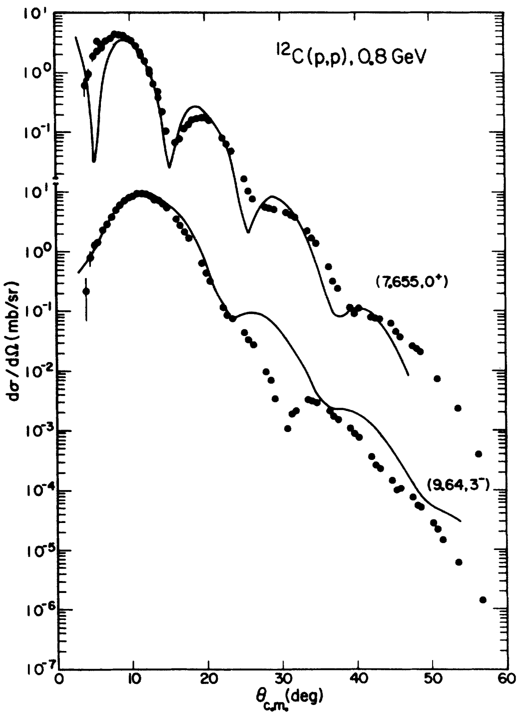

FIG. 2. The angular distributions for the $(0^+, 7.66)$ and $(3^-, 9.64)$ states in ^{12}C. Shown as solid curves are DWBA predictions as discussed in the text.

to larger angles. The ratio of the data from this experiment matched to that from Wriekat *et al.* is 0.97 ± 0.01. Some of their elastic data from 1.7° to 3.7°, rebinned into larger angular steps is given as triangles in Fig. 1. When the ^{208}Pb cross sections obtained here are compared to those of Ref. 1 (absolute error ± 5%) one finds a ratio of 1.05 ± 0.05. Thus the absolute error of ±10% assigned to the elastic data of Ref. 5 seems to be conservative.

III. RESULTS

The new experimental angular distributions for 800 MeV proton excitation of the (0^+, ground state), (2^+, 4.439 MeV), and (4^+, 14.1 MeV) states are given in Fig. 1, while that for the (0^+, 7.66 MeV) and (3^-, 9.64 MeV) states are given in Fig. 2. As seen in Fig. 1, beyond 45° c.m. the diffraction patterns for the 0^+, 2^+, and 4^+ states are damped out, fall monotonically, and have similar slopes. This is even more evident when the data are plotted as a function of the momentum transfer, $q(\text{fm}^{-1})$. If the back angle data are parametrized as $d\sigma(q) = a \cdot \exp(bq)$, then for the 0^+, 2^+, and 4^+ states the values of b are -3.03, -3.13, and -3.08 fm, while $a = 230$, 4359, and 4024 mb/(GeV/c)^2, for data in the range $4.5 \leq q \leq 7.1$ fm^{-1}. A similar monotonic falloff can be seen in the 0.8 GeV $p + {}^4$He data of Fong *et al.*[16] The cross section for $p + {}^4$He decreases smoothly from 5.1 to 6.4 fm^{-1}, where it changes slope and again declines monotonically out to about 9.4 fm^{-1}, where a back angle diffraction pattern begins. Using the same parametrization for the $p + {}^4$He data one finds $b = -1.60$ fm, $a = 60.3$ mb/(GeV/c)^2 for $5.1 < q < 6.4$ fm^{-1}, $b = -1.90$ fm, $a = 337$ mb/(GeV/c)^2 for $6.4 < q < 9.4$ fm^{-1} and $b = -1.83$, $a = 206$ mb/(GeV/c)^2 for $5.1 < q < 9.4$ fm^{-1}. One would like to connect this monotonic decrease in cross section to the diffusivity of the nucleus. The complexity of the reaction mechanism, especially the importance of various correlations, makes it difficult to interpret the monotonic decrease in cross section with a simple geometric model.

IV. THEORY

As discussed in Ref. 6, the deformation of the ^{12}C ground state and multistep inelastic processes must be included in any calculation that attempts to reproduce the data for the 4^+ state. Nuclear deformation and multistep processes are most naturally treated in the coupled-channels (CC) formulation of inelastic scattering theory.[8]

The theoretical description of nucleon-nucleus scattering at intermediate energies is generally given in the framework of the Kerman, McManus, and Thaler (KMT) optical potential formalism.[4] In the impulse approximation the first order optical potential is most simply obtained by folding the free nucleon-nucleon t matrix with the uncorrelated, one-body nuclear density. Many examples can be found in the literature of applications of this folding model to ~1 GeV proton scattering from spherical nuclei.[1,5,17,18] The results indicate that folding models in general provide a good description of the data. In fact, the lowest order KMT microscopic optical potential gives a very good description of these data, and corrections are small for nuclei $A \geq 12$.[19] Similar folding model calculations, using the CC formalism and deformed densities, have not been attempted thus far. Therefore, we will assume that the p + deformed nucleus optical potential can be obtained in principle by folding a spherically symmetric proton-nucleon effective interaction, $\bar{t}(\vec{r})$, with the deformed nuclear ground state matter density as in

$$V(\vec{r}) = \int \rho_m(\vec{r}\,')\bar{t}(\vec{r} - \vec{r}\,')d^3r' . \tag{1}$$

Instead of obtaining this potential from a microscopic calculation, we will determine a deformed optical potential $V(\vec{r})$, by fitting the elastic and inelastic scattering data using the CC formalism, in which multistep processes are included. Then from the assumed applicability of the folding model and Satchler's theorem,[20] the multipole moments of the matter density[21] are obtained from those of the optical potential. Satchler's theorem states that in units for which $\int \bar{t}\, d^3r = 1$ the $(E\lambda)$ multipole moment of $V(\vec{r})$ obtained in the folding process is equal to the same $(E\lambda)$ moment of the matter density. Such a comparison has been made for 0.8 GeV $p + {}^{154}$Sm and ^{176}Yb.[22] The results agreed well with those obtained from electron scattering, Coulomb excitation, and theory.[22] The multipole moments of the dominant imaginary part of the optical potential, $V(r,\theta')$ (axially symmetric in the body fixed system[8]) quoted below are defined as[20]

$$M(E\lambda) = \frac{Ze\int r^\lambda Y_{\lambda 0}(\Omega')\mathrm{Im}[V(r,\theta')]\, r^2 dr\, d\Omega'}{\int \mathrm{Im}[V(r,\theta')]\, r^2 dr\, d\Omega'}. \quad (2)$$

The charge of the target nucleus Ze is included to allow direct comparison between the optical potential quantities and the charge distribution moments.

The CC calculations were performed using a version of the program JUPITER (Ref. 8) which was modified to include relativistic kinematics. The 0^+, 2^+, and 4^+ states are coupled assuming the strict rotational model.[23] The coupling parts of the optical potential are obtained using the Legendre polynomial expansion method discussed by Tamura.[8] The geometry of the optical potential is the usual Woods-Saxon form[8] where the radius parameter $R(\theta')$ is angle dependent according to

$$R(\theta') = R_0[1 + \beta_2 Y_{20}(\theta') + \beta_4 Y_{40}(\theta')]. \quad (3)$$

At energies near 1 GeV the spin orbit interaction is fairly weak compared to the central term and therefore is not important in describing elastic and inelastic angular distributions or in extracting the underlying matter density multipole moments. This is generally true for natural parity collective states which are populated either by direct or multistep processes as explicitly shown in a recent coupled-channels deformed spin-orbit analysis of 0.8 GeV $p + {}^{24}$Mg and ^{154}Sm inelastic scattering.[24] Therefore as in previous calculations the spin-orbit potential is omitted here.[6,22]

V. RESULTS OF THE ANALYSIS

A. Ground state rotational band

The results of CC calculations using the program JUPITER (Ref. 8) for the 0^+, 2^+, and 4^+ states in ^{12}C are shown in Fig. 1. The parameters of the deformed optical potential in the usual low-energy notation[25] V, W, W_D, r, a, r_W, a_W, r_D, a_D, and r_C are -8, 55, and 25 MeV, 0.975, 0.447, 0.925, 0.400, 0.60, 0.50, and 1.05 fm, respectively. The deformation parameters are $\beta_2 = -0.90$ and $\beta_4 = 0.001$. These values differ from those in Ref. 6 since the fit to the 2^+ data was allowed to deteriorate in order to optimize the fit to the 4^+ data in the previous analysis, while here the 0^+ and 2^+ fits are given priority in order to obtain an accurate $M(E2)$. The overall quality of the fits to the data <40° c.m. is quite good. The 0^+ and 2^+ transition data are well reproduced, while that for the 4^+ state is correct in the region of the first maximum, but is too large at the second maximum and beyond. The contribution of both the large quadrupole deformation of the optical potential, and the two-step transition via the 2^+ state, to the calculated 4^+ inelastic angular distribution is quite large as discussed in Ref. 6. The calculations for the 2^+ and 4^+ states are only shown out to ~ 45°. This is because the elastic data are poorly described by the CC calculation beyond 45°. The calculation is seen to develop an unrealistic oscillatory behavior in the differential cross sections at angles larger than 40°.

In order to investigate the origin of the breakdown in the CC description of the elastic back angle data the coupling to the excited states was omitted. In order to recover the fit to the elastic data at small angles, W was reduced to 48 MeV. The resulting fit is given by the dashed line in Fig. 1. In this calculation the oscillatory minima remain separated by about 11° throughout the angular distribution. Thus, the unrealistic structure seen in the above elastic calculation is due to the strong coupling between the 0^+ and 2^+ channels. This coupling has caused the minimum that occurs at about 48° in the uncoupled calculation to move to 44°, while the 59° minimum moved to 57°. The inability of this deformed Woods-Saxon potential to fit these data when full coupling is allowed, merely points out the not too surprising inappropriateness of this simple model for ^{12}C. DWBA calculations employing a spherically symmetric optical model potential yield results that follow the general trend of the data out to about 7 fm^{-1} for the 0^+ and 2^+ states, but fail to even qualitatively explain the data for the 4^+ state. Another restriction in the calculation is that all the $\Delta l = 2$ coupling potentials are kept fixed here, whether they couple the 0^+ and 2^+ or the 2^+ and 4^+ channels. There is evidence that the $\Delta l = 2$ coupling potential connecting states in light nuclei decreases for higher states in the band.[8,23] For light nuclei the shell-model configuration gives a maximum total angular momentum or endpoint of the band. The endpoint corresponds to an alignment of the angular momenta of the particles outside closed shells.

This alignment of the angular momenta of the particles has a large effect on the $E2$-matrix elements between members of the band.[23]

There have been some successful calculations of the p + light nucleus scattering in the region of high momentum transfer. Dirac equation optical model calculations of 0.8 GeV $p+{}^4$He elastic scattering are able to explain the data over the entire range out to $q \cong 10$ fm^{-1}.[26] However, second order KMT calculations of 0.8 GeV $p+{}^{208}$Pb elastic scattering are only able to explain the data out to $q \cong 3$ fm^{-1}, the calculation having a similar diffractive structure as the data, but being out-of-phase with it for $q > 3$ fm^{-1}.[1,2] The extension of these calculations to include deformed nuclei within a coupled-channels framework is the subject of future work.

The comparison between the parameters used in this analysis, and those for other reactions is interesting. The value of the deformation length $\beta_2 R = -1.91$ fm, where $R = r_W A^{1/3}$, agrees well with that obtained in the analysis of electron scattering[27] data for ^{12}C over the range of $0.5 \leq q \leq 2.1$ fm^{-1}. In Ref. 27 the experimental form factors are fitted with adjusted Nilsson orbitals. Density dependent deformation lengths are then extracted. Due to the large absorption encountered by 0.8 GeV protons, such data is primarily sensitive to the region of the nuclear surface, so that comparisons to the electron scattering results should be restricted to the surface region. The deformation parameters from the analysis of the electron data, as a function of the relative density, are $(\rho/\rho_{max}, \beta_2 R, \beta_4 R) = (0.7, -2.18, 0.50)$, $(0.5, -2.01, 0.29)$, $(0.3, -1.94, 0.17)$, and $(0.1, -1.90, 0.03)$. Thus the $\beta_2 R$ parameter averages about -1.95 fm, in the nuclear surface region in good agreement with the CC result (-1.91 fm) for 0.8 GeV proton scattering. The $\beta_4 R$ parameter rapidly varies in the region of the nuclear surface. A small value for $\beta_4 R = +0.002$ fm was obtained in the proton CC analysis, but the failure of the calculations to reproduce the correct slope for the 4^+ state makes it difficult to assign a realistic error to $\beta_4 R$. The electron scattering analysis indicates that the simple deformed optical model potential used herein may be too restricted for application to ^{12}C.

The comparison of the extracted multipole moments [Eq. (2)] of the dominant imaginary part of the 0.8 GeV optical potential with the moments from other measurements[27,28] and from theory,[29] are summarized in Table I. The moments determined in the present analysis agree fairly well with those of electron scattering[27] and 1 GeV $p+{}^{12}$C.[28] The agreement here is not as spectacular as that obtained for heavy deformed nuclei (1–2%),[22] but is encouraging. The Nilsson orbital description of the electron scattering data yielded a charge density whose deformation varied with relative density. The fact that the matter deformation length obtained from proton scattering agrees with that from the Nilsson analysis of the charge density in the surface region of the nucleus, but is lower than the charge density in the interior, might explain why the matter density $M(E2)$ moment is about 15% smaller than that from the electron scattering analysis. In other words, electron scattering probes the entire nucleus, and determines the deformation throughout the radial extent of the charge density whereas 800 MeV proton scattering from ^{12}C is less sensitive to the central region of the nucleus. The effect of surface localization on the measurement of a density dependent deformation has been pointed out for ^{238}U.[30] These results further indicate that analyses of 0.8 GeV p + nucleus inelastic scattering data appear to be an accurate method for studying surface matter distribution deformations.

B. Other inelastic transitions

In the previous analysis of 0.8 GeV $p+{}^{12}$C inelastic scattering,[5] the data for transitions to the (0^+, 7.66 MeV) and (3^-, 9.64 MeV) states were well reproduced by distorted wave Born approximation (DWBA) calculations, using the program VENUS.[31] These calculations are repeated using a macroscopic Woods-Saxon optical potential in place of the microscopic KMT potential of Ref. 5. The elastic cross section has been well described for

TABLE I. Optical potential and charge density multipole moments for ^{12}C, in $e\mathrm{b}^{\lambda/2}$.

$M(E2)$	$\Delta(2)$[a]	$M(E4)$	$\Delta(4)$[a]	Reaction	Reference
−0.0552		+0.0019		0.8 GeV(p,p')	This work
−0.0536	3%	+0.0017	11%	1.0 GeV(p,p')	28[b]
−0.0634	15%	+0.0022	16%	(e,e')	27
−0.0686	24%	+0.0029	53%	Theory, Hartree-Fock	29[c]

[a] $\Delta(\lambda) = \mathrm{Abs.}\{[M(E\lambda) - M(E\lambda \text{ at } 800 \text{ MeV})]/M(E\lambda \text{ at } 800 \text{ MeV})\} \times 100\%$.
[b] Glauber formalism.
[c] Does not reproduce the known rms charge radius of ^{12}C.

$\theta < 40°$ c.m. assuming a spherically symmetric Woods-Saxon optical potential with the following parameters: V, W, W_D, r, a, r_W, a_W, r_D, a_D, and r_C = −7.55, 81, and 15 MeV, 1.028, 0.531, 0.903, 0.528, 0.455, 0.515, and 1.05 fm, respectively. The fit beyond $\theta = 40°$ could not be improved by further variation of parameters in this model. The inelastic transitions were then computed assuming a one-step mechanism and the derivative type collective model form factor with the above parameters.[7]

As seen in Fig. 2, the transition to the (3^-, 9.64 MeV) state is well reproduced by the DWBA prediction to about 25° c.m., with $\beta_3 R = 1.21$ fm. This value is obtained by normalizing to the small angle data $\theta < 10°$, which is not available in Ref. 5. The first maximum is better reproduced here with the larger value of $\beta_3 R$. As in Ref. 5, a coupled-channels prediction for the 3^- state using a deformed-vibrational model[8] gives results that are nearly identical to the DWBA prediction. Also calculations which use empirical inelastic transition densities obtained from inelastic scattering of electrons give a result very similar to that seen in Fig. 2.[32]

Both DWBA and CC calculations using a collective model (breathing mode) form factor for the (0^+, 7.66 MeV) state predict angular distributions that are out-of-phase with the data. As discussed in Ref. 5, Gustafsson and Lambert have shown that form factors based upon particle-hole excitations are able to reproduce both the electron and the 1 GeV proton inelastic scattering data.[32] The transition density used is

$$F_l(r) = V_0 r^l (a + br^2 + cr^4)\exp(-dr^2). \tag{4}$$

They find that $(1s)^{-1}$ $(2s)$ particle-hole excitations are not able to reproduce the data, whereas an assumed superposition of $(1s)^{-1}$ $(2s)$ and $(1p)^{-1}$ $(2p)$ excitations are able to reproduce the data.[32] The solid curve in Fig. 2 results from a calculation using $V = -113$ MeV fm^3, $W = 767$ MeV fm^3 ($V = 775$ MeV fm^3), $a = 0.0707$ fm^{-3}, $b = 0.02$ fm^{-5}, $c = -0.00447$ fm^{-7}, and $d = 0.321$ fm^{-2}. The a, b, c, and d parameters are the same as in Ref. 32, while V has been adjusted (from 710 MeV fm^3) to fit the magnitude of the 0.8 GeV data. The overall fit is good.

VI. SUMMARY AND CONCLUSIONS

New data for 0.8 GeV $p + {}^{12}C$ elastic and inelastic scattering, extending to $q = 7.1$ fm^{-1} have been presented and analyzed using the CC and DWBA formalisms. The DWBA calculations are able to reproduce the data for the 3^- and 0^+ excited state transitions. The CC calculations are able to reproduce the data for the transitions to the 0^+, 2^+, and 4^+ states for $q < 4$ fm^{-1}, but are poor at larger q.

The applicability of the folding model to 0.8 GeV proton-nucleus scattering, together with Satchler's theorem, suggests that the multipole moments of the 0.8 GeV proton-nucleus optical potential and those of the underlying matter density are nearly equal. As was shown earlier for heavy deformed nuclei, there is good agreement between the multipole moments of the optical potential and those of the charge distribution. These data should prove useful in future studies of deformed nuclear matter distributions and in tests of microscopic descriptions of collective states.

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