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Energy dependence of deformation parameters in the $^{12}C(\vec{p},p')^{12}C$ reaction

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Values of deformation parameters have been extracted from macroscopic coupled-channels analyses of inelastic proton scattering to the first 2^+, 3^-, and 4^+ states of ^{12}C over the energy range from 200 to 700 MeV. The apparent deformations are almost unchanged over this energy interval; they agree also with nucleon scattering data at much lower energies and at 800 MeV and 1 GeV.

I. INTRODUCTION

Macroscopic analyses of inelastic-scattering experiments have been used to determine nuclear deformations for nuclei over the entire periodic table.[1–3] Large differences among the deformation parameters β_L or deformation lengths δ_L ($\delta_L = \beta_L R$, where R is an appropriately chosen nuclear radius) are often observed with different probes, or when the same probe is used at different energies. The discrepancies are particularly significant for light nuclei, where analyses of proton[4–8] or neutron[9] scattering often yield deformations at least 25% larger than similar analyses of the scattering of composite particles.[10,11] It has also been demonstrated that coupled-channel effects are important in the analysis of inelastic pion scattering to low-lying levels in ^{12}C.[12] At low energies, a strong energy dependence has been observed recently in the $^{28}Si(p,p')^{28}Si$ reaction by Leo *et al.*[13] Few analyses are available at energies above 100 MeV, but it is noteworthy that the nuclear deformation parameters extracted from the analyses of the $^{208}Pb(p,p')^{208}Pb$ reaction at 200 MeV are generally about 30% smaller than lower energy values.[14] Even larger discrepancies have recently been obtained for proton scattering from ^{92}Zr, ^{120}Sn, and ^{208}Pb at 100 MeV.[15] On the other hand, results of proton scattering experiments at 800 MeV generally agree quite well with the results of proton experiments at energies in the 20—50 MeV range. Osterfeld *et al.*[16] have pointed out that the shape of the effective transition operator for proton scattering changes with energy, so that an energy variation in the deformation parameters should be expected.

II. EXPERIMENTAL DETAILS

With this in mind, we have analyzed data obtained at the Clinton P. Anderson Meson Physics Facility (LAMPF) with the high resolution proton spectrometer (HRS) for the $^{12}C(\vec{p},p')^{12}C$ reaction at 398, 597, and 698 MeV, as well as previous data at 200 MeV taken at Indiana. Cross sections and analyzing powers were measured at LAMPF over the momentum transfer range from 0.3 to 2.1 fm^{-1} up to an excitation energy of 21 MeV. The particle detection system consisted of the standard HRS focal plane wire chambers and trigger scintillators. The overall energy resolution varied between 100 and 150 keV (FWHM). Absolute normalization of the data was accomplished by measuring cross sections for p-p scattering from a CH_2 target of known thickness. Such data were taken at angles where previous data exist and nucleon-nucleon scattering phase shift solutions provide a reasonable description of the cross section.

At 398 MeV, the absolute elastic scattering cross sections determined in this way could be very well fitted by the optical model without any renormalization of the data; at 597 and 698 MeV, however, a much better fit could be obtained to the elastic data if the data were renormalized upward by a factor of 1.25—1.30. Reexamination of our p-p data at these energies brought to light some previously unnoticed problems. Consequently, elastic and inelastic scattering data for low-lying transitions in ^{12}C and normalization data were taken at incident proton energies of 647 and 733 MeV with the same targets as in the original experiment. In addition, elastic scattering from ^{208}Pb was measured at 647 MeV for comparison with previous data.[17] Scheduling considerations prevented data from being acquired at the original incident energies. Analysis of these new data confirmed that the original normalizations at 597 and 698 MeV were indeed incorrect. The data at 597 and 698 MeV have been renormalized according to the best extrapolations possible by using the reliable normalization data at 398, 647, 733, and 800 MeV. The best optical model fits to the elastic data at 597 and 698 MeV are now obtained with renormalization factors very close to 1.0.

Absolute uncertainties in the measured cross sections due to this method of normalization are ±7% at 398 MeV, ±13% at 597 MeV, and ±21% at 698 MeV. A complete description of the experiment and a microscopic analysis of the results are in preparation; results for the 18.30- and 19.40-MeV states have been published previously.[18] Inelastic cross sections are less affected by the renormalization, but it should be noted that the cross sections presented in Ref. 18 should be increased by a factor of 1.11 at both 597 and 698 MeV. The data are shown in Figs. 1—4.

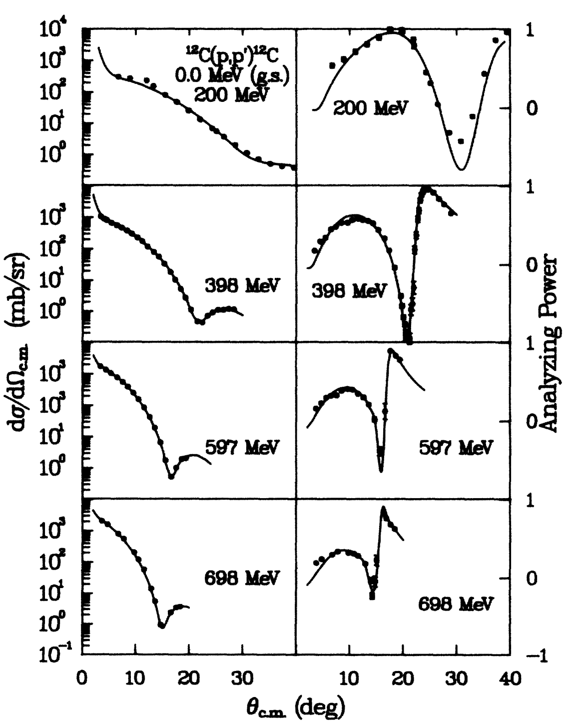

FIG. 1. Elastic scattering cross section and analyzing-power data for scattering of 200—698-MeV polarized protons from ^{12}C. The curves are described in the text.

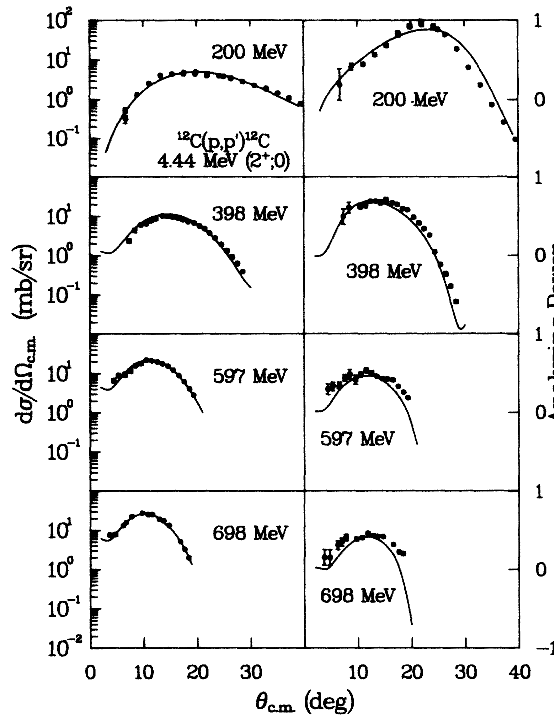

FIG. 2. Cross section and analyzing-power data for excitation of the 2$^+$;0 level at $E_x = 4.44$ MeV in ^{12}C by scattering of 200—698-MeV polarized protons. The curves are described in the text.

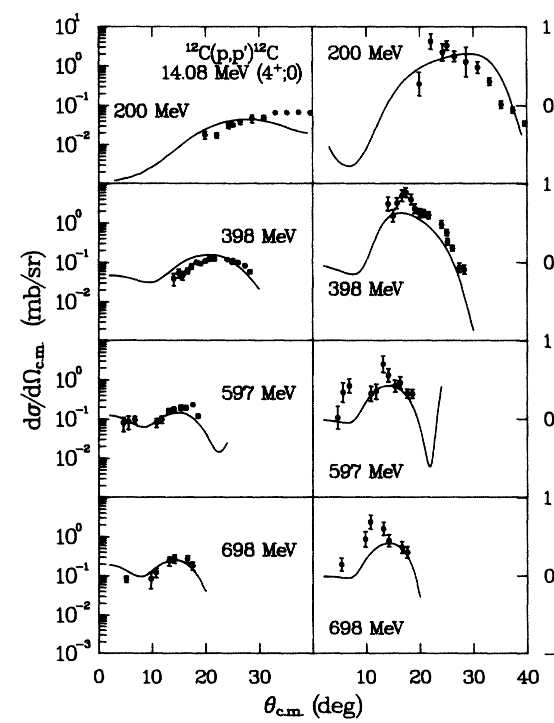

FIG. 3. Cross section and analyzing-power data for excitation of the 4$^+$;0 level at $E_x = 14.08$ MeV in ^{12}C by scattering of 200—698-MeV polarized protons. The curves are described in the text.

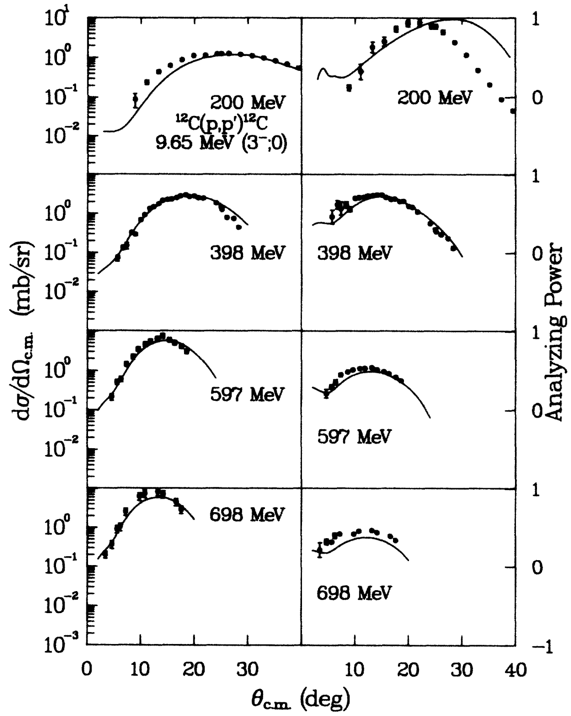

FIG. 4. Cross section and analyzing-power data for excitation of the $3^-;0$ level at $E_x=9.65$ MeV in ^{12}C by scattering of 200–698-MeV polarized proton. The curves are described in the text.

III. RESULTS AND DISCUSSION

In this paper we will concentrate on a coupled-channels (CC) macroscopic analysis of the states belonging to the ground state rotational band, the 0^+, 2^+ (4.44 MeV), and 4^+ (14.08 MeV) states, as well as the 3^- vibrational state at 9.65 MeV.

The theoretical calculations were performed with the code ECIS of Raynal.[19] This code uses relativistic kinematics and permits the large number of partial waves ($l>100$) required at these energies. The deformed spin-orbit term (DSO) was of the full Thomas form. The calculations were carried out as follows. Optical model (OM) parameters were obtained from ECIS by searching on all parameters and fitting the elastic cross section and analyzing-power data. The best-fit optical model potentials are listed in Table I. They include negative real potentials V and negative imaginary spin-orbit potentials W_{SO} at the three energies. Large volume absorption W_V increasing with energy was required. The resulting fits are very good.

These OM parameters were thereafter used in the CC calculations as starting parameters when the 0^+, 2^+, and 4^+ states or the 0^+ and 3^- states were coupled together. When these parameters were used in the CC calculations for the ground state band, several had to vary from their initial values in order to obtain a good fit to all the data. The most significant of these were the real diffuseness a_0 which typically increased by 50–100%, and W_V which consistently decreased by about 10%. Much smaller increases in a_0 produced almost equally good fits. The final results of the parameter searches are listed in the lower part of Table I. The deformation parameters obtained from the CC search on a_0, W_V, β_2, and β_4 are listed in the upper part of Table II. For the 0^+-3^- calculations, the search parameters were simply W_V and β_3. These deformation parameters are also given in the upper part of Table II.

The rotational model with an oblate shape was used in the CC calculations for the ground state band in ^{12}C; this is well established. Calculations for the 3^- state assumed a one-phonon vibrational model description. The solid lines in Figs. 1–4 show the results of the CC calculations. Good fits were obtained for all states at all three energies with almost identical deformation parameters. These values are very close to those obtained in proton scattering both at low energies and at 800 MeV and 1 GeV.[8] The values of δ_2 are constant to ±0.04 over the entire energy

TABLE I. (a) Optical parameters (in the convention of Ref. 20) which provide the best fit to the elastic data in the absence of channel coupling. All distances are in fm and all potential strengths are in MeV. (b) Final optical parameters (in the convention of Ref. 20) yielding best fits with channel coupling. All distances are in fm and all potential strengths are in MeV.

(a)

T_p	V	R_0	a_0	W_V	R_I	a_I	V_{LS}	R_{LS}	a_{LS}	W_{LS}	R_{WLS}	a_{WLS}	R_c
200	4.87	1.41	0.34	16.5	1.05	0.68	2.67	0.91	0.52	−2.95	0.91	0.52	1.05
398	−2.51	1.08	0.48	21.6	1.13	0.64	3.21	0.93	0.57	−2.79	1.00	0.53	1.05
597	−2.38	1.12	0.55	35.4	1.13	0.62	1.99	0.95	0.57	−4.23	0.95	0.55	1.05
698	−9.87	1.11	0.64	37.7	1.12	0.64	2.61	0.93	0.57	−3.83	0.99	0.53	1.05

(b)

T_p	Coupling	V	a_0	W_V
200	0-2-4	4.87	0.34	13.3
200	0-3	4.87	0.34	17.1
398	0-2-4	−2.51	0.73	18.8
398	0-3	−2.51	0.48	21.6
597	0-2-4	−2.24	1.11	32.0
597	0-3	−2.38	0.55	35.8
698	0-2-4	−7.78	1.14	37.8
698	0-3	−9.87	0.64	38.3

TABLE II. Deformation parameters deduced from coupled-channels analyses of ^{12}C data at various energies with protons and other projectiles.

Protons							
E (MeV)	β_2	δ_2	β_4	δ_4	β_3	δ_3	Ref.
30.4	−0.66	−1.61					4
30–40	−0.66	−1.62	0.00	0.00	0.33	0.80	5
200	−0.67	−1.63	−0.02	−0.04	0.40	0.95	22,This work
398	−0.65	−1.68	0.01	0.03	0.36	0.91	This work
597	−0.66	−1.70	−0.04	−0.10	0.36	0.92	This work
698	−0.62	−1.60	−0.03	−0.08	0.34	0.88	This work
800	−0.78	−1.70	0.00	0.00	0.33	0.75	8
1040	−0.81	−1.73	0.00	0.00			8

Other projectiles								
Particle	E (MeV)	β_2	δ_2	β_4	δ_4	β_3	δ_3	Ref.
n	14.7	−0.60	−1.72			0.33	0.94	9
$\bar{p}$	46.8	−0.66	−1.60					6
α	60–90	−0.48	−1.37			0.20	0.57	10
α	65	−0.40	−1.37	0.16	0.54			11

range; also, δ_4 is consistent with zero over this range. The values of δ_3 are constant from 200 to 700 MeV, but the values at the lowest and highest energies in the upper part of Table II are somewhat lower.

The sensitivity of the extracted deformation parameters and lengths to various optical-model parameter sets was investigated. These parameter sets typically differed in potential strength and radius parameters by small amounts. Cross sections for the ground state and 2^+ state were insensitive to these parameter changes. The calculated cross sections for the 3^- state varied in magnitude by up to 10%. The magnitudes of the cross sections for the 4^+ state are most sensitive to changes, varying by as much as a factor of 2 at 698 MeV, and up to 10% at other energies. The shapes of the cross sections and analyzing powers were not sensitive to changes in the optical model parameters. Variations in β_2 and β_3 for differing sets of parameters yielding similar quality fits were typically ± 0.02. It is worthwhile noting that β_4 is, in general, close to zero and consequently small variations in β_4 result in apparently large fluctuations in δ_4. Uncertainties in β_4 are of the order of ± 0.03.

Several interesting features emerge from these CC calculations. The spin-orbit potential, particularly W_{SO}, plays a crucial role in obtaining good fits even for cross section data. Secondly, the fits to the analyzing powers were improved by allowing the ratio of spin-orbit and central deformation parameters to deviate slightly from 1.0 up to values of 1.1 or 1.2; this is contrary to a recent analysis of the $^{18}O(\vec{p},p')^{18}O$ reaction at 800 MeV.[20] At lower energies this ratio can be as large as 1.5 (Refs. 1 and 21).

In order to extend this study to 200 MeV, the energy where analyses of the $^{208}Pb(p,p')$ data revealed deviations of the deformation parameters from low energy values, we have also analyzed the published data from Indiana on the $^{12}C(\vec{p},p')^{12}C$ reaction up to 40° (c.m.) using similar methods.[22] These results are also shown in Figs. 1–4 and in Tables I and II. It was not necessary to introduce unusual shapes for the optical potentials in order to obtain good fits to the elastic cross sections or analyzing powers; the total reaction cross section is predicted to be within 5% of the experimental value. The fits to the inelastic states are also almost as good as those obtained at the higher energies. The deformation parameters derived at 200 MeV are very close to those obtained at the higher energies.

The deformation parameters obtained with low-energy protons[4,5] and neutrons,[9] with antiprotons,[6] and with composite projectiles,[10,11] are listed in the lower part of Table II. The values of β_2 and β_3 obtained here are in good agreement with the values shown there for nucleons and antinucleons. The β values obtained with composite projectiles tend to be about 25% lower. For β_4, information is scarce. A recent analysis of proton scattering between 30 and 40 MeV determined that β_4 was very close to zero,[5] in agreement with the present results and with the 800-MeV results.[7,8] However, the value obtained from a recent alpha scattering experiment at 65 MeV was $\beta_4 = 0.16 \pm 0.03$ (Ref. 11).

From electron scattering it is known that the equidensity charge density surfaces in ^{12}C have β_2 and β_4 deformations which depend on the radius.[23] The deformations become larger toward the interior of the nucleus, and β_4 is, in fact, close to zero at the edge of the nucleus. Now, as noted in the Introduction, Osterfeld *et al.*[16] have shown that the shape of the effective transition operator changes with bombarding energy, partly as a result of the change in transparency of the nucleus. It would be useful to determine whether a consistent calculation of all these effects can explain the surprisingly constant values of the deformation parameters observed in ^{12}C over such a large range of proton bombarding energies.

IV. CONCLUSIONS

We have analyzed elastic and selected inelastic cross section and analyzing-power data for polarized proton scattering from ^{12}C at intermediate energies within the coupled channels framework. Deformation parameters β_2, β_3, and β_4 have been extracted and compared with those obtained for proton scattering at other energies, and also with values obtained from other probes. Contrary to the expectations of Osterfeld *et al.*,[16] the deformation parameters show remarkably little dependence on incident proton energy over the incident energy range from 30 to 1040 MeV.

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