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Elastic and Inelastic Scattering of Polarized Protons from Carbon-12 at 400, 600, and 700 MeV

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ABSTRACT OF THE THESIS

Elastic and Inelastic Scattering of

Polarized Protons from Carbon- 12

at 400, 600, and 700 MeV

by KEVIN WYNDHAM JONES

Thesis Director: Professor Charles Glashauser

Good resolution cross section and analyzing power ($\vec{p}, p'$) data for many states in ^{12}C up to an excitation energy of 21 MeV and spanning a momentum transfer range of 0.3 to 2.1 fm^{-1} were obtained using the High Resolution Spectrometer at the Clinton P. Anderson Meson Physics Facility at incident beam energies of 398, 597, and 698 MeV. Optical model potentials were obtained from the elastic scattering data. Inelastic data were analyzed in the Distorted Wave Impulse Approximation using the Love-Franey effective nucleon-nucleon interaction. The energy dependent isoscalar natural parity cross sections were underestimated, while phase difficulties were encountered in fitting analyzing powers. The energy independent isovector natural parity cross sections were reasonably reproduced, but analyzing powers were not, the calculations yielding positive trends whereas the data are of opposite sign. The energy independent isoscalar and isovector unnatural parity cross sections were quite well reproduced up to moderate momentum transfers, and striking successes were observed for some analyzing power data. An example is the success achieved in

reproducing the strong negative low momentum transfer dependence of the analyzing power for the $E_x=12.71$ MeV $1^+;0$ state at 398 MeV. The strengths of the dominant terms in the 425 MeV force were found to be qualitatively and quantitatively well determined. A systematic lack of strength of some 20 - 30% in all dominant components of the 650 MeV force was observed. Nevertheless, the Love-Franey parameterization of the nucleon-nucleon interaction is shown to provide a useful description of inelastic intermediate energy proton scattering from the ^{12}C nucleus, although some refinement is needed. Knock-on exchange contributions were found to be essential, generally interfering destructively with direct amplitudes, and optical model distortions influenced both cross sections and analyzing powers of some states. Systematics of energy dependence together with the results of the DWIA calculations permitted the assignment of spin, parity and isospin quantum numbers to states in the 18-21 MeV excitation region.

I. INTRODUCTION

In recent years there has been much interest in the scattering of a variety of intermediate energy probes from different nuclei. Particles such as electrons, protons, neutrons and pions provide a rich and comprehensive testing ground for nuclear effective interactions, nuclear structure, and nuclear reaction theories.

Electrons, which interact with the nucleus through the well-known electromagnetic and weak interactions, provide information on charge density distributions in nuclear matter. In addition, harmonic oscillator parameters used in describing the radial distribution of different nuclear states may be well determined by fitting the measured electron scattering form factors for the states in question. Such well-determined information can then be used to fix parameters in the analysis of the scattering of more complex probes, such as nucleons. Furthermore, inelastic 180° electron scattering is sensitive only to the transverse electromagnetic form factor, and hence can be used to selectively excite nuclear states requiring a transfer of one unit of spin and isospin. In this way electron scattering tests the distribution of magnetism in nuclei.

Pions, which are intrinsic isovector particles, can, through charge exchange reactions and inelastic scattering, provide differing sensitivities to neutron and proton distri-

butions within the nucleus. Such experiments yield important information concerning the dominant isospin components in the structure of some nuclear states, particularly isospin mixing between states of the same spin and parity.

Protons are an especially desirable but complex probe of the nucleus. The proton can excite a wide variety of states in a given nucleus which may or may not be accessible by other modes of excitation. For example, elastic scattering measurements, which leave the target nucleus in a residual state without excitation, provide determinations of neutron and matter distributions which cannot be made with other probes. A study of differential cross sections and analyzing powers for inelastic transitions, in which the residual nucleus is left in a well-defined state of finite excitation energy, provides a means for extracting transition densities, particularly neutron transition densities, for transitions from the ground state to the excited state. Both elastic and inelastic scattering data test the validity of microscopic models of reaction theory such as Glauber¹⁾ or KMT (Kerman, McManus and Thaler)²⁾ theories. It is also possible to test available parameterizations of the free nucleon-nucleon interaction, such as that proposed by Love and Franey³⁾. Contributions of multi-step processes to the excitation of inelastic states can be investigated through coupled-channels calculations.

Information gained from the three probes mentioned

Provides interlocking pieces in the puzzles of nuclear structure and nuclear reaction theory. Each set of measurements serves as a guide to the interpretation of the physical processes involved in nuclear excitations, and the complementarity of the information so gained allows reliable deductions to be made concerning nuclear structure and reaction theory.

The ^{12}C nucleus, like all even-even nuclei, has a ground state spin and parity of 0^+ , which provides useful simplifications in computations. This nucleus also exhibits a richness in discrete states of particle-hole character with reasonable excitation energies⁴⁾. For excitation energies below 18 MeV a wide variety of states of small width, of order 100 keV, are easily resolved from broader states of width greater than 1 MeV which form an underlying background. In addition to isoscalar ($\Delta T=0$) states of 'natural' parity ($\pi=(-1)^J$), there exist both isoscalar and isovector ($\Delta T=1$) states of 'unnatural' parity ($\pi=(-1)^{J+1}$); for example the $(J^\pi; T) = 1^+; 0$ states at $E_x = 12.71$ MeV and the $1^+; 1$ state at $E_x = 15.11$ MeV. Also, an isovector state of 'natural' parity ($2^+; 1$) is readily seen at $E_x = 16.11$ MeV. A level diagram of this nucleus is shown in Figure I-1, and a tabulation of known states together with their intrinsic widths is given in Table I-1. The wide variety of states requiring different modes of excitation provides a considerable degree of sensitivity to the various components of the

Energy Levels of ^{12}C

Figure I-1.

Energy Levels of ^{12}C

E_x (MeV)	$J^\pi; T$	Γ (keV) [†]
0.00	$0^+; 0$	
4.44	$2^+; 0$	10.8 ± 0.6 meV
7.65	$0^+; 0$	8.7 ± 2.7 eV
9.64	$3^-; 0$	34 ± 5 keV
10.3	$(0^+); 0$	3000 ± 700
10.84	$1^-; 0$	315 ± 25
11.83	$2^-; 0$	260 ± 25
12.71	$1^+; 0$	14.6 ± 2.6 eV
13.35	$(2^-); 0$	375 ± 40 keV
14.08	$4^+; 0$	258 ± 15
15.11	$1^+; 1$	42 ± 7 eV
16.11	$2^+; 1$	6.5 ± 0.6 keV
16.58	$2^-; 1$	300
17.23	$1^-; 1$	1150
17.78	$0^+; 1$	80 ± 20
18.13	$(1^+; 0)$	600 ± 100
(18.27)	$(4^-; 0)$	275 ± 40
18.36	$(3^-; 1)$	210 ± 40
18.40	$0^-; (1)$	43
(18.6)	$(3^-); ?$	300
18.71	$? ; (1)$	100
18.80	$2^+; 1$	80 ± 30
19.25	$(1^-; 1)$	1100
19.40	$(2^+; 0)$	45
19.57	$(4^-; 1)$	400 ± 60
20.0	$(2^+); ?$	90
20.24		170
20.5	$(3^+; 1)$	250
20.6	$(3^-; 1)$	200 ± 40

Table I-1.

[†]Unless otherwise noted

nucleon-nucleus effective interaction which excites them.

We present in this work data for, and discussion of, elastic and inelastic scattering of polarized protons from ^{12}C at incident proton beam energies of 398, 597, and 698 MeV. The range of excitation energy spanned in the residual ^{12}C nucleus is from 0.0 to 21.0 MeV. We discuss the elastic scattering data briefly within the framework of the standard nuclear optical model. The data for a wide range of inelastic states is discussed within the framework of the Love-Franey nucleon-nucleon interaction and the Distorted Wave Impulse Approximation (DWIA)²⁾.

Data at incident beam energies of 120, 155, 180, 200, 402, 600, and 800 MeV have recently been acquired⁵⁻¹⁶⁾, using both polarized and unpolarized beams. The data at 402 and 600 MeV in particular were taken with unpolarized beam and yielded only differential cross sections for a few states. Our extension of the measurements to beam energies between 200 and 800 MeV with polarized beam thus provide an almost complete set of differential cross section and analyzing power data spanning an incident beam energy range of some 800 MeV. The analyzing power measurements provide spin-dependent data which exhibit particular sensitivity to spin-dependent terms in the nucleon-nucleon effective interaction. Such sensitivity may impose further constraints on interactions used in theoretical descriptions of the data.

The benefits of obtaining data over such a wide range of incident beam energy are as follows. First, the energy dependence of the data will provide useful systematics for states of differing modes of excitation. Second, the energy dependence of effective nucleon-nucleon interactions, especially the Love-Franey force, can be studied in some detail. Third, the effects of such phenomena as Pauli blocking and knock-on exchange can be investigated as a function of incident beam energy. These effects are of importance in the practical computation of observables in the DWIA, and may also provide information on the applicability of the impulse approximation itself.

From a nuclear structure point of view, several sets of shell-model wavefunctions for lp-shell nuclei, of which ^{12}C is one, are available. Some such p-shell wavefunctions calculated by Cohen and Kurath¹⁷⁾ have received extensive examination. Millener¹⁸⁾ has recently derived an extensive set of wavefunctions for negative parity states in ^{12}C . These wavefunctions include components involving the 1d and 2s-shells. Figure I-2 shows a schematic representation of the shell structure of ^{12}C applicable to such wavefunctions. The data obtained in this work provide a useful test of the validity of these wavefunctions.

Previous studies of the 'unnatural' parity states have been suggestive of various phenomena which were deemed to warrant further study in this work. The $1^+;0$ state was

Shell Model Orbitals used
for ^{12}C Wavefunctions

Figure I-2.

observed to have a negative analyzing power at low momentum transfer for an incident beam energy of 900 MeV¹⁸⁾. Such a property has been suggested as a signature for states excited by $\Delta S=1$, $\Delta T=0$ mechanisms. We investigate this assertion in this work. Furthermore, several authors²⁰⁻²³⁾ proposed the $1^+;1$ state as a suitable candidate for the observation of precritical phenomena related to pion condensation. Current data available at lower energies^{8,9,12)} and at 800 MeV¹⁵⁾ are not supportive of this assertion; the data obtained in this work also show no discernible evidence.

The excitation energy region from 18 to 21 MeV has also been the subject of considerable recent investigation through the use of inelastic scattering of electrons²⁴⁾, protons⁹⁾, and pions^{25,26)}, as well as nucleon transfer reactions²⁸⁾. This region is difficult to analyze because the states existing there are broad and overlapping. The data obtained in our work, taken with other available information and the results of DWIA calculations, provide information on spin, parity and isospin assignments in this region.

II. THEORETICAL MODELS

A) Optical Model Analysis of Elastic Scattering

We treat the optical model analysis of the elastic scattering in a phenomenological way. In this approach the complex reaction of an incident projectile with a many-body nuclear system is reduced to the simpler problem of the interaction of the incident projectile and the target nucleus as a whole in the presence of an average potential. The absorption of particles due to the existence of non-elastic channels is accounted for by the inclusion of imaginary components in the average potentials. In addition, the scattering of a proton from a ^{12}C nucleus is a case of the scattering of a spin $\frac{1}{2}$ projectile from a spin 0 target. Spin-orbit effects are therefore important and a complex spin-orbit potential of the Thomas form is included in the description of the interaction.

The strategy of a phenomenological optical analysis is as follows. A guess is made at a potential, and the Schrödinger equation for the scattering process is solved in a partial wave expansion. The physical observables are then computed from this solution and compared with data. The potential parameters are then varied to optimize the quality of the fit of the calculated observables to the data.

Adopting a standard partial wave expansion for the wave function of the scattered spin $\frac{1}{2}$ particle, we may write

this wavefunction as

$$\psi = i^{2\ell} [4\pi(2\ell+1)]^{1/2} (\ell\ell s s | j m) (\ell\lambda s v | j m) f_{\ell j}(kr) Y_{\ell}^{\lambda}(\theta, \phi) \chi_s^u e^{i\sigma_{\ell}} \quad \text{II-1}$$

where $(\ell\ell s s | j m)$ is a Clebsch-Gordan coefficient coupling angular momenta ℓ and s to a state of definite j and projection m . The $f_{\ell j}$ is a partial scattering amplitude from state ℓ to state j , χ_s^u is the spin wave function, $Y_{\ell}^{\lambda}(\theta, \phi)$ is a spherical harmonic and $e^{i\sigma_{\ell}}$ is the Coulomb Phase Factor.

We now define the radial functions $u_{\ell j}(kr)$ such that

$$u_{\ell j}(kr) = kr[f_{\ell j}(kr)] \quad \text{II-2}$$

This transformation results in a simplification of the radial Schrödinger equation. The spin-orbit component requires the expectation values of the operator $\vec{L} \cdot \vec{S}$, which are given by

$$\langle \vec{L} \cdot \vec{S} \rangle = \frac{1}{2} [j(j+1) - \ell(\ell+1) - s(s+1)] \quad \text{II-3}$$

Since the projectile has half integral spin, $j = \ell \pm \frac{1}{2}$ and the eigenvalues of $\langle \vec{L} \cdot \vec{S} \rangle$ are simply ℓ and $-(\ell+1)$ respectively. The radial part of the Schrödinger equation may then be written as

$$\left[\frac{d^2}{dr^2} + k^2 - \frac{\ell(\ell+1)}{r^2} + V_f(r) + iW_g(r) - V_c(r) + (V_{so} + iW_{so})h(r) \left\{ \begin{matrix} \ell \\ -(\ell+1) \end{matrix} \right\} \right] u_{\ell j}(kr) = 0 \quad \text{II-4}$$

The $u_{\ell j}(kr)$ are solutions corresponding to $j = \ell \pm \frac{1}{2}$. The $u_{\ell j}$ functions are linear combinations of the irregular Coulomb functions F and G because of the presence of the Coulomb

potential required to describe proton scattering. The shape functions are of the Woods-Saxon form appropriate for a spherical nucleus and are given by

$$f(r) = [1 + \exp(\frac{r-R}{a})]^{-1} \quad \text{II-5(a)}$$

$$Wg(r) = [W - 4W_s \frac{d}{dx},] (1 + e^{x'})^{-1} \quad \text{II-5(b)}$$

$$x' = \frac{r-R'}{a'} \quad \text{II-5(c)}$$

$$h(r) = [1 + \exp(\frac{r-R_s}{a_s})]^{-1} \quad \text{II-5(d)}$$

The Coulomb potential is defined as

$$V_c(r) = \frac{Z_1 Z_2 e^2}{2R_c} \left(3 - \frac{r^2}{R_c^2}\right) \quad r < R_c \quad \text{II-6(a)}$$

$$V_c(r) = \frac{Z_1 Z_2 e^2}{r} \quad r > R_c \quad \text{II-6(b)}$$

and the spin-orbit potential of the Thomas form is given by

$$V_{so}(r) = (V_{so} + iW_{so}) \left(\frac{\hbar}{m_\pi c^2}\right)^2 \frac{1}{r} \frac{d}{dr} [h(r)] \vec{\tau} \cdot \vec{\sigma} \quad \text{II-7}$$

We note that Equation II-5(b) provides for an absorptive term strongly peaked near the nuclear surface.

The solution of Equation II-4 yields the u_{lj} , from which the f_{lj} are easily computed. The f_{lj} may then be used to compute observables such as the differential cross-section

$$\frac{d\sigma}{d\Omega} = \frac{1}{w} \sum_{\nu\mu} |f_{\nu\mu}|^2 \quad \text{II-8}$$

where w is the total number of spin states. Comparison of the calculated differential cross section with data yields a chi-squared parameter which may be minimized by successive

repetitions of the same calculation while varying components of the potentials and/or shape functions. The results of such calculations are presented in Chapter VI of this work.

Since we are performing calculations for incident kinetic energies of 400 MeV and higher, corresponding to a value for v/c of 0.713, it is appropriate to use relativistic kinematics. At such high bombarding energies it is reasonable to expect a large number of inelastic channels to be open, and thus for the imaginary part of the potential to dominate the scattering, indicating strong absorption. We might also expect the imaginary potential to increase in strength as the bombarding energy increases, reflecting the opening of more inelastic channels and an increase in the strength of some existing channels relative to the elastic channel. Several authors^{28,29)} have noted that the relatively weak real central potential should change from attractive to repulsive at an incident energy of about 400 MeV. Such an observation is consistent with the behaviour of the nucleon-nucleon force as a function of energy, and is indeed observed. An excellent summary of the optical model may be found in Jackson³⁰⁾ and references therein.

B) The Distorted Wave Impulse Approximation

The analysis of inelastic transitions presented in Chapter VI of this work has its basis in the Distorted Wave Impulse Approximation (DWIA). We endeavour to present here

a description of the salient features of the DWIA in order that the results of calculations presented in Chapter VI may be more meaningful.

The impulse approximation²⁾ may be understood as follows. The many-body transition operator T may, following KMT, be successively approximated by

$$T = \sum_j t(j) \approx \sum_j \tau(j) \quad \text{II-9}$$

where $t(j)$ is the effective two-nucleon operator within the nuclear medium and $\tau(j)$ is the free two-nucleon operator describing the scattering of the incident particle from the j 'th nucleon. The basic assumption, then, is that the complex interaction may successfully be approximated by the free nucleon-nucleon t -matrix.

Furthermore, for $E_p \geq 400$ MeV the energy of the incident projectile is much greater than that of the nucleons confined within the nucleus, and the interaction time with a target nucleon is small compared with the characteristic period of a bound nucleon. These conditions comprise the basis for the Impulse Approximation. It should be pointed out that since the energy-momentum conditions for nucleon-nucleus scattering are different from free nucleon-nucleon scattering the impulse approximation matrix elements are necessarily off the energy shell for free scattering.

The distorted waves representing the incident and scattered particles are plane waves which are distorted in

the entrance and exit channels by the effect of the elastic scattering optical potential. In this work, both the incoming and outgoing projectiles are protons. In addition, the energy loss in the target is small with respect to the particle energy and consequently the incident and exit channel optical potentials must be the same, except for the small differences in energies. Since potentials change slowly with energy, this may be neglected. This potential, then, is a prerequisite for a distorted wave analysis of inelastic scattering.

The formalism of the DWIA has been well-documented^{2,29)}. The transition matrix element for inelastic scattering from an initial state i to a definite final state f is given by

$$T_{fi}(\vec{k}', \vec{k}) = \langle \phi_f \chi_f^- | \sum_j \tau(j) | \phi_i \chi_i^+ \rangle \quad \text{II-10}$$

where $\chi^\pm$ are the distorted waves for the projectile. As in the optical model, the distorted waves may be expanded in a partial wave expansion with appropriate angular momentum couplings and the transition matrix element may be evaluated using the effective interaction derived in the next section.

C) An Effective Nucleon-Nucleon interaction for Intermediate Energy Scattering

As we have seen, the DWIA requires the evaluation of a matrix element based on a realistic nucleon-nucleon in-

teraction, which is also assumed to be able to describe with some degree of success nucleon-nucleus scattering. The effective interaction used in the DWIA calculations presented in this work is that which has recently been developed by Love and Franey³⁾. We present here a summary of the important features of this interaction, following the formalism as developed in their paper.

The starting point of the analysis is the free nucleon-nucleon scattering amplitude M , which may be obtained from a phase shift analysis as described by MacGregor et. al.³¹⁾. Amplitudes at 425 and 515 MeV were obtained from the phase shift analysis of Bugg et. al.³²⁾, while at 650 and 800 MeV the analysis of Arndt et. al.^{33,34)} was used. Following KMT²⁾, the nucleon-nucleon amplitudes may be expressed as

$$M(E, q) = A + B \vec{\sigma}_1 \cdot \hat{n} \vec{\sigma}_2 \cdot \hat{n} + C (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n} + E \vec{\sigma}_1 \cdot \vec{q} \vec{\sigma}_2 \cdot \vec{q} + F \vec{\sigma}_1 \cdot \vec{Q} \vec{\sigma}_2 \cdot \vec{Q} \quad \text{II-11}$$

where the coefficients A , B , C , E and F are functions of E , q , and T , the centre-of-mass energy, momentum transfer, and total two-body isospin respectively. The spinors $\sigma_{1,2}$ and represent the spins of the incident and scattered particles respectively. If $\vec{k}$, $\vec{k}'$ are the initial and final momenta of either particle in the centre-of-mass system, then the unit vectors $[\hat{q}, \hat{Q}, \hat{n}]$ form a right-handed coordinate system such that

$$\vec{q} = \vec{k} - \vec{k}' \quad \vec{Q} = \vec{k} + \vec{k}' \quad \text{II-12(a)}$$

$$q = 2k \sin \frac{\theta}{2} \quad Q = 2k \cos \frac{\theta}{2} \quad \text{II-12(b)}$$

To make the isospin dependence explicit it is customary to express each coefficient as, for example,

$$A = A_1 + A_3 \vec{t}_o \cdot \vec{t}_j \quad \text{II-13}$$

where $\vec{t}_o$, $\vec{t}_j$ are isospin operators for nucleons o and j respectively. In order to better understand the expression for M it is convenient to reduce it using the identity

$$\vec{\sigma}_1 \cdot \hat{Q} \vec{\sigma}_2 \cdot \hat{Q} = \frac{1}{3} [S_{12}(\hat{Q}) + \vec{\sigma}_1 \cdot \vec{\sigma}_2] \quad \text{II-14}$$

and the completeness condition on $[q, Q, n]$. The result is

$$M(E, q) = A' P_S + B' P_T + C(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n} + E' S_{12}(\hat{q}) + F' S_{12}(\hat{Q}) \quad \text{II-15}$$

where S_{12} is the standard tensor operator, P_S and P_T are the spin singlet and triplet projection operators respectively, and

$$A' = A - B - E - F \quad B' = A + [(B + E + F)/3] \quad \text{II-16(a)}$$

$$E' = (E - B)/3 \quad F' = (F - B)/3 \quad \text{II-16(b)}$$

The expression has thus been reduced to central singlet and triplet terms, a spin-orbit term and two tensor terms. The amplitudes may be converted into the nucleon-nucleon t -matrix by

$$t_{NN}(E, q) = \frac{-4\pi(\hbar c)^2}{E} M(E, q) \quad E^2 = m^2 c^4 + (\hbar c k)^2 \quad \text{II-17}$$

The point now is to relate the free nucleon-nucleon t -matrix so derived to an effective interaction capable of describing a nucleon-nucleus interaction. It is convenient to begin this analysis by defining an effective nucleon-nucleon in-

teraction which may then be multiplied by an appropriate kinematic factor to yield an effective nucleon-nucleus interaction. In each nucleon-nucleon channel the effective nucleon-nucleon interaction V_{12} is represented by

$$V_{12} = V^C(r_{12}) + V^{LS}(r_{12}) \vec{L} \cdot \vec{S} + V^T(r_{12}) S_{12} \quad \text{II-18}$$

where $\vec{L} \cdot \vec{S}$ and S_{12} are the standard spin-orbit and tensor operators. The parameters of V_{12} are then adjusted to optimize the representation

$$t_{NN}(E, q) = \int d^3r e^{-i\vec{k}' \cdot \vec{r}} V_{12} [1 + (-)^l P^X] e^{i\vec{k} \cdot \vec{r}} \quad \text{II-19}$$

where P^X is the spatial coordinate exchange operator operating to the right and $(-)^l$ ensures antisymmetrization. The angular momentum is the relative angular momentum in the nucleon-nucleon system. To provide some physical insight into the structure of the coefficients in the expression for V_{12} , and to ensure compatibility with the computer code DWBA70, the radial parts of V^C and V^{LS} may be represented by a sum of Yukawa terms while the radial shape of V^T is taken to be r^2 times a sum of Yukawa terms. Consequently

$$V^C(r) = \sum_i V_i^C Y(\frac{r}{R_i}) \quad \text{II-20(a)}$$

$$V^{LS}(r) = \sum_i V_i^{LS} Y(\frac{r}{R_i}) \quad \text{II-20(b)}$$

$$V^T(r) = \sum_i V_i^T r^2 Y(\frac{r}{R_i}) \quad \text{II-20(c)}$$

$$Y(x) = [e^{-x}]/x \quad \text{II-20(d)}$$

For the real part of V^C the longest range is chosen to be representative of the long-range part of the one-pion exchange potential (OPEP). The maximum range of 0.7 fm for V^T

was chosen so as to emulate the small q Fourier components of the tensor part of the OPEP. The range parameter of 0.4 fm was chosen to roughly represent the effects of multiple pion-exchange processes. The remaining range parameters were chosen for flexibility.

Recalling that t_{NN} is related to V_{12} by a Fourier transform (see Eq. II-19), some algebra yields the following relations between the t -matrix components and the amplitudes:

$$t_S^C = \tilde{V}_S^C(q) + (-)^L \tilde{V}_S^C(Q) = \eta A' \quad \text{II-21(a)}$$

$$t_T^C = \tilde{V}_T^C(q) + (-)^L \tilde{V}_T^C(Q) = \eta B' \quad \text{II-21(b)}$$

$$4t^{LS} = Q\tilde{V}^{LS}(q) - (-)^L q\tilde{V}^{LS}(Q) = -4i\eta C \quad \text{II-21(c)}$$

$$t^T = \tilde{V}^T(q) = -\eta F' \quad \text{II-21(d)}$$

$$\tilde{V}^T(Q) = (-)^{L+1} \eta F' \quad \text{II-21(e)}$$

Symmetry requires

$$E'(\pi-\theta) = (-)^L F'(\theta) = (-)^T F'(\theta) \quad \text{II-22}$$

The nucleon-nucleus t -matrix is then given by t_{NA} where

$$t_{NA} = \frac{\epsilon_0^2}{\epsilon_p \epsilon_t} t_{NN} \quad \text{II-23}$$

In this expression ϵ_c, ϵ_p and ϵ_t are energies representing the total energy of the incident nucleon in the nucleon-nucleon system, the total energy of the incident nucleon in the nucleon-nucleus system and the total energy of the target nucleon in the nucleon-nucleus system respectively.

It is instructive to examine the dependence of the

t-matrix on the exchange term in the nucleon-nucleus system. For a given nucleon-nucleon channel the t-matrix may be written in a Fourier transform representation as the sum of a direct term and an exchange term,

$$t_{NN} = \tilde{V}(q) + \tilde{V}(Q) ; Q^2 = 4k^2 - q^2 \quad \text{II-24}$$

Petrovich et. al.³⁵⁾ and Love³⁶⁾ have shown that for the nucleon-nucleus system it is reasonable to approximate the exchange term as

$$t_{NN} = \tilde{V}(q) + \tilde{V}(k_A) \quad \text{II-25}$$

where k_A is the momentum of the incident nucleon in the centre-of-mass. Physically, the exchange term represents the ejection of a proton which is not the proton which collided with the nucleus in the first instance. Consequently, the momentum transfer required for this term is that associated with stopping the incident nucleon. The exchange terms are evaluated in a short-range approximation described by Petrovich et.³⁵⁾ al. and Raynal³⁷⁾. The exchange terms are included explicitly in the components of the t-matrix.

Having thus determined the effective interaction, it is now appropriate to relate the elements of the interaction and amplitudes to physical observables. Such relations will allow investigation of the dependences of observables on components of the interaction for different classes of nuclear transitions. It is these dependences we investigate in more detail in Chapter VI.

For natural parity excitations ($\Delta\pi = (-)^J$, $\Delta S=0$) in the Plane Wave Impulse Approximation, Kerman, McManus and Thaler²⁾ have shown that the differential cross-section for excitation of a state of definite J in terms of the nucleon-nucleon amplitudes is

$$\frac{d\sigma}{d\Omega} = [|A|^2 + |C|^2] * SF \quad \text{II-26}$$

where SF is a nuclear structure factor. For unnatural parity excitations ($\Delta\pi = (-)^{J+1}$, $\Delta S=1$ dominant) they find

$$\frac{d\sigma}{d\Omega} = [|B|^2 + |C|^2 + |F|^2 + \eta|E|^2] * SF \quad \text{II-27}$$

where η is a structure factor dependent on the relative importance of allowed orbital angular momentum transfers in the generation of J, and is defined by $2J/(J+1)$ for $L = J-1$.

In terms of the isospin and exchange dependent representations of the nucleon-nucleon t-matrix, these expressions become

$$\frac{d\sigma}{d\Omega} = [|t^C|^2 + |t^{LS}|^2] * SF \quad \text{II-28}$$

for natural parity states and

$$\frac{d\sigma}{d\Omega} = [|t^{LS}|^2 + |t^C + t^{T\alpha}|^2 + |t^C + t^{TS}|^2 + \eta |t^C + t^{TY}|^2] * SF \quad \text{II-29}$$

for unnatural parity states where

$$t^{T\alpha} = t^T(q) + (-)^J t^T(k_A) \quad \text{II-30 (a)}$$

$$t^{TS} = -2t^T(q) + (-)^J t^T(k_A) \quad \text{II-30 (b)}$$

$$t^{TY} = t^T(q) - 2(-)^J t^T(k_A) \quad \text{II-30 (c)}$$

represent the tensor contributions to B, F and E respectively.

Now it must be pointed out that these equations are still not representative of the nucleon-nucleus scattering since the components refer to states of definite spin and isospin in the nucleon-nucleon system. In nucleon-nucleus scattering, transfer of definite units of spin and isospin are appropriate and Love and Franey have derived expressions for such t-matrix elements in terms of the components of the nucleon-nucleon t-matrix. The final expressions are then

$$t_O^C = \frac{1}{16}[3t^{SE} + 3t^{TE} + t^{SO} + 9t^{TO}] \quad \text{II-31(a)}$$

$$t_\sigma^C = \frac{1}{16}[-3t^{SE} + t^{TE} - t^{SO} + 3t^{TO}] \quad \text{II-31(b)}$$

$$t_\tau^C = \frac{1}{16}[t^{SE} - 3t^{TE} - t^{SO} + 3t^{TO}] \quad \text{II-31(c)}$$

$$t_{\sigma\tau}^C = \frac{1}{16}[-t^{SE} - t^{TE} + t^{SO} + t^{TO}] \quad \text{II-31(d)}$$

$$t_O^{LS} = \frac{1}{4}[t^{LSE} + 3t^{LSO}]; \quad t_\tau^{LS} = \frac{1}{4}[-t^{LSE} + t^{LSO}] \quad \text{II-31(e)}$$

$$t_O^T = \frac{1}{4}[t^{TNE} + 3t^{TNO}]; \quad t_\tau^T = \frac{1}{4}[-t^{TNE} + t^{TNO}] \quad \text{II-31(f)}$$

and for example

$$t_\tau^{T\alpha} = \frac{1}{4}\{-[t^{TNE}(q) + t^{TNE}(k_A)] + [t^{TNO}(q) - t^{TNO}(k_A)]\} \quad \text{II-32}$$

In terms of these components, states of natural parity depend upon t_O^C , and t_O^{LS} . For unnatural parity transitions only the spin-transfer dependent parts of the central terms contribute, together with t^{LS} and t^T where

$$|\bar{E}^T| = [|t^{T\alpha}|^2 + |t^{T\beta}|^2 + n|t^{T\gamma}|^2]^{1/2} \quad \text{II-33}$$

The analyzing powers may in turn be expressed as

$$A_y = \frac{2\text{Re}[A^*C]}{[|A|^2 + |C|^2]} \quad \text{II-34}$$

for natural parity transitions and

$$A_Y = \frac{2\text{Re}[B^*C]}{[|B|^2 + |C|^2 + |F|^2 + \eta|E|^2]} \quad \text{II-35}$$

for unnatural parity transitions. Rewriting these expressions in terms of the appropriate nucleon-nucleus t-matrix elements we find

$$A_Y = \frac{2[t_R^{LS} t_I^C - t_I^{LS} t_R^C]}{|t^C|^2 + |t^{LS}|^2} \quad \text{II-36}$$

for natural parity transitions and

$$A_Y = \frac{2[t_R^{LS}(t_I^C + t_I^{T\alpha}) - t_I^{LS}(t_R^C + t_R^{T\alpha})]}{|t^{LS}|^2 + |t^C + t^{T\alpha}|^2 + |t^C + t^{TS}|^2 + \eta|t^C + t^{TY}|^2} \quad \text{II-37}$$

for unnatural parity transitions.

Note that if the product of $\frac{d\sigma}{d\Omega}$ and A_Y is taken, then the denominators in the expressions for A_Y reduce to unity and we simply find for natural and unnatural parity transitions respectively,

$$\frac{d\sigma}{d\Omega} * A_Y = 2\text{Re}[A^*C] = 2[t_R^{LS} t_I^C - t_I^{LS} t_R^C] \quad \text{II-38(a)}$$

$$\frac{d\sigma}{d\Omega} * A_Y = 2\text{Re}[B^*C] = 2[t_R^{LS}(t_I^C + t_I^{T\alpha}) - t_I^{LS}(t_R^C + t_R^{T\alpha})] \quad \text{II-38(b)}$$

Note that these expressions as derived by KMT and Love and Franey are valid only in the Plane Wave Impulse Approximation. The effect of distortions must then be taken into account, and these will be discussed in Chapter VI. Nevertheless, these expressions may be used as a guide to the sys-

tematic dependence of the observables on either the amplitudes or the components of the t -matrix.

In order to better appreciate the relative significance of the components of the nucleon-nucleus t -matrix, (including exchange), Figures II-1 to II-12 present the dependence of each component in Equations II-31 on incident nucleon energy and momentum transfer. Several general observations are in order.

The strongest energy dependence is seen for the scalar-isoscalar term t_0^C , which is also seen to dominate for all energies, especially for $q < 1 \text{ fm}^{-1}$. For $q > 1 \text{ fm}^{-1}$ the strengths of t_0 , t_0^{LS} , t_0^T and t_T^T become comparable for $E_p < 400 \text{ MeV}$, while t_0^C continues to dominate for $E_p > 400 \text{ MeV}$. One might then expect that scalar-isoscalar excitations should dominate the nucleon-nucleus spectrum for small values of q . A notable exception is the strong excitation of 1^+ states for small q , a point which will be discussed later. The scalar-isoscalar spin-orbit term grows in relative importance as q increases and should thus contribute significantly to the excitation of isoscalar natural parity states in regions of larger momentum transfer. The isovector spin-orbit term is the weakest of all terms in general, and may only contribute to the analyzing powers for some excitations. The central isoscalar spin-flip term t_0^C is generally weak for all q and E_p . The isoscalar tensor term t_0^T , which is dominated by exchange terms, is significant for all

Strength of N-N Interaction Components
 $q = 0.5 \text{ fm}^{-1}$

Figure II-1.

Strength of N-N Interaction Components
 $q = 1.0 \text{ fm}^{-1}$

Figure II-2.

Strength of N-N Interaction Components
 $q = 1.5 \text{ fm}^{-1}$

Figure II-3.

Strength of N-N Interaction Components
 $q = 2.0 \text{ fm}^{-1}$

Figure II-4.

Figure II-5.

Figure II-6.

Figure II-7.

Figure II-8.

Figure II-9.

Figure II-10.

Figure II-11.

Figure II-12.

q and E_p , as is the isovector part t_{τ}^T . The spin and isospin-flip component of the central part, $t_{\sigma\tau}^C$ is uniform as a function of incident particle energy, reflecting the dependence of the one-pion exchange potential which dominates this term. This term also is much stronger for small momentum transfers than for large q .

The excitation of unnatural parity isovector states is expected to be dominated by $t_{\sigma\tau}^C$ for low q , and by t_{τ}^T for large q . The relative strength of the spin and isospin-flip term mentioned previously would then account for the strong excitation of 1^+ states at low momentum transfer. For isoscalar unnatural parity states several terms are involved, namely the t_{σ}^C , t_{σ}^{LS} and t_{σ}^T terms, with the tensor term dominating through exchange processes for small q .

The estimations of the behaviour of analyzing powers are somewhat more complex because of the dependence on real and imaginary parts of the t -matrix elements. For natural parity isoscalar transitions the dominant terms are t_I^C and t_R^{LS} which are both large and negative, resulting in positive analyzing powers (see Eq. II-36). Natural parity isovector excitations are found to have moderate positive values at all energies. Isovector states of unnatural parity are predicted to have very small analyzing powers. This reflects the fact that t^C and t^T are predominantly real, and also that t^{LS} is very weak, especially in the imaginary part. Isoscalar transitions of unnatural parity are found

to be negative for small q , changing to positive values as q increases. This is dominated by the behaviour of t_0^{LS} and t^C , and provides a potential unique signature for such transitions.

III. EXPERIMENTAL METHOD

A) Accelerator

The data presented in this work were taken at the High Resolution Spectrometer (HRS) facility at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF). Polarized negative hydrogen ions are produced in a Lamb-shift type polarized ion source, and are injected into the linear accelerator at an energy of 750 keV. This injection energy is provided by a Cockroft-Walton accelerator. The polarized negative hydrogen beam (P-) is then accelerated to an energy of 100 MeV in a four-sector Alvarez-type drift-tube linear accelerator operating at 201.25 Hz. Further energy is provided by up to 48 sectors of a resonantly-side-coupled standing-wave linear accelerator operating at 805 MHz.

Since the accelerator is primarily a pion production facility, a proton beam (H+) is accelerated through all radiofrequency sectors to a maximum energy of 800 MeV. The negative beam, P-, is accelerated on the opposite phase portion of the radiofrequency oscillation. In normal single energy, dual beam operation at 800 MeV, both H+ and P- beams are pulsed at a frequency of 120 Hz with a pulse length of 500 microseconds, resulting in a duty factor of 6%.

It is possible, however, to reduce the energy of the P- beam while maintaining that of the H+ beam at 800 MeV. The experiments described here were among the first to util-

ize the dual energy beam capability of the LAMPF linear accelerator. This is accomplished in the following manner.

Two thirds of the 120 Hz macropulses are devoted exclusively to acceleration of the H⁺ beam with an extended pulse length of approximately 750 microseconds. The precise pulse length varies from one experimental cycle to another, depending upon optimum accelerator operation conditions. The resulting duty factor for the H⁺ beam is then close to 6%, as it is in full dual-beam operation at 800 MeV. The remaining third of the pulses are devoted exclusively to acceleration of the P⁻ beam on the appropriate phase of the radiofrequency oscillation. Two pulses of H⁺ beam are followed by one pulse of P⁻ beam.

Since the P⁻ beam is now accelerated independently of the H⁺ beam, it is possible to control the energy of the negative beam by reducing the number of radiofrequency modules operating in the 805 MHz portion of the accelerator during the acceleration of the P⁻ beam. By selectively turning off some klystrons it is possible to obtain the beam energies of 398, 597 and 698 MeV used in this work. The pulse frequency and duration of 40 Hz and about 750 microseconds result in a duty factor of close to 3% for the P⁻ beam in the dual-energy mode of operation.

Upon exiting the accelerator the P⁻ beam is magnetically separated from the H⁺ beam and deflected into line X,

as shown in Figure III-1 and III-2. The beam in line X may be tailored by a series of strippers of various geometries and collimator jaws to provide acceptable momentum and spatial dispersion for lines B and C. Electrons are removed from that portion of the P- beam which passes through the strippers, creating a mixture of H+ and P- beam. The stripped and unstripped beams are then magnetically separated and the stripped H+ beam enters line C. The beam is then transported through the line C quadrupole-dipole system to the HRS target. The beam transport properties of line C together with the beam dispersion matching conditions at the HRS target have been described in detail previously^{38,39}).

The beam spot on target was approximately 3 mm wide and 2 cm high. The vertical dispersion of the beam is required for proper momentum dispersion matching with the spectrometer acceptance. The final beam on target was polarized normal to the scattering plane with an average polarization of 0.80 as measured by the line C polarimeter. The beam polarization was reversed every 3 minutes at the ion source to eliminate errors which may have resulted from systematic drifts in the beam polarization.

Beam currents were adjusted by selected collimating jaws in line C to provide reasonable event rates in the focal plane detector array of the HRS. Typical beam currents ranges from tens of picoamperes at forward angles where large count rates exist due to dominant elastic scattering,

Experimental Areas
Los Alamos Meson Physics Facility

Figure III-1.

Experimental Area 'C'

Figure III-2.

to several (about 10) nanoamperes at larger spectrometer angles (> 12 degrees) where both lower background and reduced elastic scattering cross-sections permit increased beam currents. Large backgrounds at forward angles (< 12 degrees) are caused by interactions of the unscattered beam with the magnet pole-faces of the spectrometer and the air between the scattering chamber and the beam-dump tunnel. For angles greater than 12 degrees, the beam misses the spectrometer structure and an evacuated beam pipe may be inserted between the exit window of the scattering chamber and the beam-dump tunnel to reduce scattering from air.

B. The High Resolution Spectrometer

A section view of the HRS facility is shown in Figure III-3. The spectrometer consists of a quadrupole and two dipole magnets. We define a spectrometer co-ordinate system as follows: let z be in the beam momentum direction, let x be perpendicular to z and in the direction of the momentum dispersion of the beam, then y represents the transverse angular direction in such a way that x , y and z represent a right-handed system of axes.

The quadrupole magnet provides focussing in the y -direction and defocussing in the x -direction. Momentum analysis is accomplished by the dipole magnets. The optical properties of the system as a whole provide parallel-to-point focussing in the y -direction and point-to-point

SECTION HRS FACILITY

focussing in the x-direction, allowing precise angular and energy-loss measurement. Details of the operation of and beam transport through the spectrometer have been described previously³⁸⁾.

C. Targets

Four targets were used in this work. These, together with a variety of other targets, were mounted on a wheel within the scattering chamber to facilitate target changing during the course of the experiments. The size of each aperture within which the targets were suspended was sufficiently large to essentially eliminate target frame-beam interactions.

The primary target was a natural spectroscopic grade graphite strip of isotopic composition 98.9% ^{12}C and 1.1% ^{13}C , and of thickness 44.7 mg/cm². A 65 mg/cm² $^{12}\text{CH}_2$ foil was used for primary normalization purposes. Two ^{208}Pb strip targets of thickness 19.8 mg/cm² and 50 mg/cm² were used for secondary normalization purposes, resolution checks and setup runs. Details of the measurement of the thickness of the graphite target will be discussed in Chapter IV.

Of concern in choosing the thickness of the target for this work was the desire to optimize the experimental resolution. There are three basic components contributing to the observed resolution of 90 to 150 keV FWHM for narrow states with intrinsic widths much less than this value.

These are energy straggling induced by the target thickness and isotopic composition, a kinematic shift contribution $\frac{dT}{d\theta}$ which increases for larger scattering angles, and focussing aberrations in the spectrometer.

Examination of a dotplot of Missing Mass as a function of θ_{fp} determined that the spectrometer focussing was optimized since no detectable systematic correlations between these two variables could be seen. It is impossible to remove the kinematic broadening factor, and so the remaining adjustable parameter is the target thickness.

Thicknesses of less than 50 mg/cm^2 , while improving the resolution by reducing straggling, did not provide sufficient count rates for rapid data acquisition. Targets with thickness greater than 50 mg/cm^2 caused deterioration of the resolution to some 200 keV FWHM . It was therefore optimal in terms of both data rates and resolution to use a target of thickness about 50 mg/cm^2 . The overall experimental resolution was then approximately 110 keV FWHM .

D. Beam Monitors

The HRS facility is not yet equipped with a Faraday Cup for beam current monitoring. Relative beam currents are monitored by two ionization chambers which can be placed in a position so as to intercept the unscattered beam within the scattering chamber after the target.

The ionization chambers are gas-filled containers of rectangular construction with aluminized mylar windows of areal dimensions $3\frac{1}{2}" \times 4\frac{1}{2}"$ designed to accomodate dispersion of the beam by the target. Each chamber contains three parallel foils of aluminized mylar of thickness 0.25 mil. The outer foils are maintained at a potential of -300 V relative to the central foil. The chambers are filled with a mixture of 90% Argon and 10% CO_2 . One (ER03) is maintained at an absolute pressure of 50 mm Hg while the other (ER04) is maintained at an absolute pressure of 200 mm Hg.

Ionization current generated by the passage of the energetic proton beam is collected at the central foil and passed through a LRS TTL-NIM converter and then into an ORTEC 439 current digitizer. The chambers are each linear to within 3% for beam currents ranging from 1 pA to 10 nA, and relative yields monitored during the course of the experiments were constant to within 0.8% .

During acquisition of data at 3 degrees (laboratory) it was necessary to carefully adjust the location of the ionization chambers in order to minimize edge scattering from the chambers into the spectrometer acceptance. Nevertheless, such edge scattering did result in high backgrounds in the first third of the spectrometer at this most forward angle setting.

E. Focal Plane Detection System

Elastically and inelastically scattered protons passing through the spectrometer are detected in an array of multi-wire drift chambers and scintillators mounted near the focal plane of the spectrometer. A diagram of the detector system is shown in Figure III-4.

The scintillators S2, S3 and S4 provide pulses which are used in the event trigger, and also energy-loss and time-of-flight information for particle identification. The multi-wire drift chambers D1 and D2 are of the delay-line readout type developed at LAMPF by Atencio et. al.⁴⁰⁾. Each chamber consists of two perpendicular sets of planes, or four planes each. Anode wires in each plane are of the alternating gradient design with wire spacing of 8 mm. Parallel planes CX1, CX2 for example, are offset by 4 mm, or one half wire spacing. The anode wires, biased at +2150 V with respect to the grounded cathode planes, are connected directly into fast (2.5 ns/cm) delay lines which provide two anode outputs per plane. The active area of the chambers is 10 cm (y) by 60 cm (x).

The chambers are filled with a gas mixture of 65% Argon, 35% Iso-butane and 0.10% Freon and operate at a pressure of 650 mm Hg. The anode signals are passed through 100 Ohm terminators into LRS LD604 fast amplifier-discriminators, converted to NIM fast logic and transmitted to the

HRS Focal Plane Detector Array

All dimensions in inches.

Figure III-4.

data acquisition area over some 200 m of 50 Ohm coaxial cable.

The chambers provide x and y position information for protons passing through the focal plane. From these data, the trajectory of the proton through the spectrometer may be reconstructed to determine scattering angle and missing mass information, for example.

F. Electronics and Data Acquisition

Raw data is acquired by a multi-level system consisting of (i) CAMAC crates housing ADC's (Analog to digital converters), TDC's (Time to digital converters), Scalars and other devices; (ii) A MBD (Microprogrammable branch driver) and (iii) a pdp 11/45 computer with 124k of fast memory, display terminals and a 1600 bpi Kennedy 9100 tape drive. A schematic representation of this system is shown in Figure III-5.

Fast NIM logic signals from the focal plane devices (wire chambers and scintillators) are regenerated in NIM leading edge discriminators in the counting house. An event pulse is generated using the fast signals from the coincidence $S2 \cdot S3 \cdot S4$. A Trigger pulse is then generated by demanding the coincidence $EVENT \cdot RUN \cdot BEAM \cdot \overline{BUSY}$; i.e. Event detected, run in progress, beam on and CAMAC not busy. Details of the electronic module system used to generate the trigger pulse, together with relevant timing information,

are shown in Figure III-6. This Trigger pulse issues a start signal to the TDC's and opens gates for ADC's, scalars and so on, while simultaneously triggering a 15 microsecond BUSY signal which disables the generation of new trigger pulses for its duration. During this 15 microsecond interval the signals from the wire chambers and scintillators are digitized and stored in a 9 x 32 bit storage buffer at each CAMAC address.

The 9 bit size provides a resolution of 512 channels per address, while the 32 bit dimension provides a buffered storage capacity for 32 digitized events at each CAMAC address. The completion of event digitization and re-enabling of the trigger generates a LAM (look-at-me) which is sent by the CAMAC crate to the MBD, and the MBD responds by reading the event from all CAMAC addresses into a circular buffer on a first-in, first-out basis. The MBD is then capable of applying tests to various words of the event to determine whether the event should be kept for further processing or rejected. This process will be described in more detail in the next section. Suffice it to say that if the event fails the test the buffer does not rotate and the next event overwrites the event which failed the test. If the test was passed, the buffer rotates and the new event is read into an empty location. Events passing the MBD tests are designated as taped triggers.

The "Q" data acquisition system⁴¹⁾ monitors the

DATA ACQUISITION SYSTEM
SCHEMATIC.

Figure III-5.

operation of the MBD and reads every ten taped triggers into the memory of the pdp 11/45, whence they are transferred to tape. Depending upon the rate at which taped triggers are being read and written, time is available for some fraction of the events to pass through an event analyzer for on-line display. Typically some 10% of the events were analyzed on-line.

The capability of the buffered CAMAC system to store 32 events per beam burst gives a maximum time-averaged data rate of 1280 events/sec, which is considerably superior to single event transfer to the MBD.

G. MBD Event Rejection

The experiments described here were the first to utilize the capability of the MBD to selectively reject events prior to processing for transfer to tape. The motivation for this is as follows.

The 60 cm active area of the focal plane in the momentum dispersion direction x corresponds to an excitation energy bite of some 18-30 MeV depending upon the incident beam energy. The primary focus of the experiments was to study the 1^+ , $T=0,1$ states at $E_x = 12.71$ and 15.11 MeV, and it was therefore desirable to place these states as close to the center of the focal plane as possible so as to optimize the resolution in this region. Consequently, states of lower excitation, such as the 2^+ state at $E_x = 4.44$ MeV,

HRS FAST TRIGGER

Figure III-6.

were constrained to lie on the active area of the focal plane. At angles greater than 10 degrees, the natural parity states such as the 2^+ dominate the spectrum and hence the yield of scattered particles. In addition, the peak-to-background ratio in the region of interest becomes smaller as the scattering angle increases. It was therefore desirable to increase the efficiency of data taping of taped triggers in the region of interest.

The MBD was programmed to examine the raw x position of the event in chamber 1 prior to processing. If the x-value of the event fell outside of predetermined limits the event was flagged for rejection. Not all such events were rejected. Depending upon the relative intensity of the states being rejected it was possible to specify, together with the rejection limits, a certain fraction of events falling outside those limits which was to be retained. Typically some 10% of the events in the rejection region were retained for relative normalization purposes.

A sample MBD test program is given in the Appendix. The cut limits were determined by examining a dotplot of Missing Mass vs ClX(N-P) (Raw x position in chamber 1). Recalling that the x-direction corresponds to the momentum dispersion direction of the spectrometer, the x position is in first order related to Missing Mass, or excitation energy of the nucleus in the case of these experiments. The largest excitation energies are located at the smallest values

of x and vice versa. A typical dotplot of these variables exhibiting this phenomenon is shown in Figure III-7.

The dotplot was the used to determine the rejection limits on the variable $X1(N-P)$ as shown in Figure III-7. These variables, together with the fraction of events to be retained were edited into the file MBDTST.DAT which loaded the tests into the MBD at the start of a run.

It is evident from the dotplot that a clean cut in x is not a clean cut in Missing Mass, but rather introduces a cut of non-negligible width in Missing Mass. A typical spectrum of Missing Mass at $E_p = 398$ MeV showing an MBD cut in the $E_x = 10$ MeV region is shown in Figure III-8. Typical cut widths in the Missing Mass spectrum were 700 keV full width. Consequently some care had to be taken when extracting peak sums near these cuts to ensure that the cut was in no way interfering with the peak under consideration.

Unfortunately, placing the cut at an excitation energy of about 10 MeV necessarily prevented measurement of complete angular distributions of the $1^-;0$ state at $E_x = 10.84$ MeV for some beam energies. Nevertheless, the gains in improved statistics per tape for unnatural parity states of interest clearly outweigh this rather minimal loss.

Raw X Position (1) vs. Missing Mass

234 * QEXACT * MISSING MASS

TST=0
RUN=26

Figure III-7.

Spectrum Showing MBD Cut

D41 234 * QEXACT * MISSING MASS TEST= 86 15-MAR-82
 10400<X<11051 0.<Y< 1000. (LIN.) BIN= 2 RUN= 20 15:10:14

Figure III-8.

IV. DATA ANALYSIS AND REDUCTION

A) Event Processing and Testing

Events successfully passing the MBD tests outlined previously and written to tape were analyzed both on- and off-line. The on-line analysis provided a rough estimate of yields during the running of the experiments, together with the means by which the satisfactory operation of the data acquisition system could be monitored. Only a small fraction (5-10%) of the taped triggers were analyzed and histogrammed on-line. Consequently the primary data reduction was performed off-line on various computers at LAMPF.

Typically, events were read from tape into a pdp 11/60 computer for processing by the analyzer HRSBUF running under the data acquisition and analysis system Q.2. The analyzer applies a sequence of tests to selected words associated with each event, the tests being specified in a user-defined file. An example of such a file used in the reduction of these data is given in the Appendix. Events successfully passing tests which specify a "good event" are then tested to determine into which histograms the analyzer should place them.

A total of 24 histograms were defined in the replay of the data. Eighteen of the histograms were of missing mass and six were of true scattering angle gated on various states in the observed spectra. A sample THETASCAT histo-

gram is shown in Figure IV-1. The lower and upper limits of the THETASCAT variable were determined from such a histogram gated on a well-populated state in the spectrum, such as the elastic scattering at forward angles. These bounds were used to determine the correct angular binning values for THETASCAT in order to subdivide the spectrometer acceptance into two and three equal bins, and these values were edited into the test file. Events passing these tests could then be used to construct Missing Mass histograms for the various angular acceptance bins. The full acceptance, together with the two and three bin subdivisions provided six sets of missing mass histograms. Each set consisted of three separate histograms, one requiring beam polarization 'normal', one requiring beam polarization 'reverse' and one requiring 'normal or reverse', thereby creating the eighteen Missing Mass histograms.

The utility of subdividing the acceptance into varying degrees of fineness is evident from some of the more complex spectra. Some states are very weakly excited while others are more strongly excited. Those with sufficient statistics in the background-subtracted peak may be extracted from the spectra subdivided into three bins without significant loss of information, while those for which statistics are poor could simultaneously be extracted from the full acceptance spectra without necessitating a time-consuming second replay of the data. A sample histogramming

Spectrometer Angular Acceptance

D44 293 * THTSCT * TRUE SCATTERING ANGLE
0500<X<10500 0.<Y< 1000. (LIN.)

TEST= 05 10-MAY-02
BIN= 10 RUN= 00 07.20.02

Figure IV-1.

file used in the data replay is given in the Appendix.

Histograms from various runs (tapes) at the same laboratory scattering angle were added together to form a final composite set of histograms useful for peak fitting. Associated with the final set of histograms was a test file enumerating the numbers of events which had passed the various tests defined in the file while the histograms were being generated, together with a scalar file containing the cumulative information recorded by the scalars, such as digitized beam currents, normal and reverse beam gates and so on.

Three classes of histograms were finally generated:

(a) A class comprising the excitation region 0.0-10.0 MeV, with and without MBD cuts, for study of elastic scattering and excited states up to $E_x = 9.64$ MeV.

(b) A class comprising the excitation region 4.0-16.5 MeV, with and without MBD cuts, for study of inelastic scattering in this excitation region.

(c) A class comprising the excitation region 12.0-25.0 MeV, with and without MBD cuts, for analysis of the excitation region 18.0-21.0 MeV.

The overlap states from class to class were used to provide relative normalization information.

B) Peak fitting

Differential cross-sections and analyzing powers for the elastic scattering and the first excited state ($2^+, 0$; $E_x = 4.44$ MeV) were extracted from the program SHT applied to the replayed histograms. This program enables fine binning of the angular acceptance for well-populated, clean states with no appreciable background. As is evidenced by the spectrum shown in Figure IV-2 these two states clearly satisfy these criteria.

Yields for all remaining observed states up to an excitation energy of $E_x = 20.6$ MeV were extracted at Rutgers using the line-oriented peak fitting program LOAF⁴²⁾. This program enables backgrounds to be fitted with polynomials of up to order 7, and peaks above such backgrounds to be fitted either to a reference peak shape defined in the spectrum or to a user-defined peak shape such as a gaussian. For narrow peaks (width approximately 100 keV, which approximately corresponds to the overall experimental resolution) the peak for a given state in the Missing Mass (Normal or Reverse) Histogram was used as a reference peak for fitting subsequent Missing Mass Histograms in that run. For peaks of greater width, such as those in the 18-19 MeV region, synthetically generated gaussian peak shapes of the appropriate width were used.

States identified in the spectra are listed in Table

Sample Low Excitation Energy
Missing Mass Histogram

D41 234 * QEXACT * MISSING MASS

8800<X<11101 0.<Y< 1500. (LIN.)

TEST= 88 19-MAY-82

BIN= 2 RUN= 94 07:35:09

Figure IV-2.

IV-1, together with observed widths where applicable. With the exception of the three states in the 19 MeV complex, all are clearly resolved and well-established. Identification and fitting of the three overlapping states in the 19 MeV region was accomplished by a systematic analysis of spectra at all angles for all three energies.

For each energy it was found that this region was dominated by a single gaussian peak at 19.4 MeV for small values of the momentum transfer q . As the value of q increased a centroid shift to 19.65 MeV together with a slight change in width was observed. This was interpreted as follows. The state at 19.4 MeV is dominant at low q , while the state at 19.65 MeV is dominant at high q , there being an intermediate region of q where the diminishing 19.4 MeV and rising 19.65 MeV states are of comparable magnitude. In this intermediate region, peaks were fitted in a consistent way at both locations. In the large q spectra it is quite evident that a third, broader state at 19.28 MeV is present, and large q fits were performed which included this state. Widths and centroids were fitted consistently from angle to angle and from beam energy to beam energy. Widths were primarily established by fitting the isolated peaks at low and high q with various gaussian shapes, holding the centroid and background fixed. The widths tabulated were taken to be those which optimized the chi-squared fitting procedure. In subsequent fits, especially in overlapping regions, the

Excitation energies and widths
 extracted from peak-fitting
 in the 18 - 21 MeV region

E_x (MeV)	Γ (keV)
18.30 ± 0.03	380 ± 30
19.28 ± 0.03	580 ± 50
19.40 ± 0.02	480 ± 40
19.65 ± 0.03	440 ± 40
20.60 ± 0.02	280 ± 20

Table IV-1.

widths were held constant, as were the centroids. The errors in the centroid locations were determined by fixing the width and allowing the centroid of the peak to vary during a peak-fitting minimization on the isolated peak. Similar tests were performed on overlapping peaks and resulted in no significant increase in the assigned uncertainties in peak location. Sample fits for this region are shown in Figures IV-3 and IV-4.

On the basis of the procedure outlined above, it was concluded that no fewer than three states could be clearly identified in the 19 MeV region. It is conceivable that the state at 19.65 MeV could be a composite of two or more closely overlapping states. However, since consistent fits could be made with a single gaussian shape there was no basis upon which such a decomposition could be made, and we therefore treat the peak observed at 19.65 MeV as a single state in subsequent analysis.

C) Differential Cross-sections and Absolute Normalization

Differential cross-sections and analyzing powers were computed from the yields obtained from peak fitting by use of the program APOWR. Appropriate corrections for beam polarization, chamber efficiency, live times and so on are made by the program through data obtained from the scalar and test result output from the analysis program. The most

Low q High Excitation Energy Spectrum

D41 234 * QEXACT * MISSING MASS

11700<X<12105 0.<Y< 1000. (LIN.)

TEST= 72 25-JUL-82

BIN= 2 RUN= 112 00:24:53

Figure IV-3.

High q High Excitation Energy Spectrum

70

D41 234 * QEXACT * MISSING MASS
11666<X<12025 0.<Y< 6000. (LIN.)

TEST= 72 25-JUL-82
BIN= 2 RUN= 161 00:19:31

Figure IV-4.

critical factor affecting the differential cross-section in these computations was that used to convert the relative corss-sections into absolute units.

The cross-section is computed using the formula

$$\frac{d\sigma}{d\Omega} = NF * G * \left[\frac{Y_N * CFN}{ER\emptyset 3N} * PN - \frac{Y_R * CFR}{ER\emptyset 3R} * PR \right] \quad IV-1$$

where $Y_{N(R)}$ is the normal (reverse) polarization yeild, $CFN(R)$ is the normal (reverse) polarization correction fac-
tor, $ER\emptyset 3N(R)$ is the normal (reverse) polarization beam
current monitor digitized value, $PN(R)$ is the normal (re-
verse) beam polarization, G is the Jacobean for transforma-
tion from laboratory to center-of-mass co-ordinates and NF
is an absolute normalization factor which is dependent on
beam energy.

The analyzing power is computed using the formula

$$A_Y = \frac{2 * EPS}{PN - PR - EPS * (PN + PR)} \quad IV-2$$

where

$$EPS = \frac{Y_N - Y_R}{Y_N + Y_R} \quad IV-3$$

If $PN = -PR = P_B$, then this expression reduces to the fami-
liar

$$A_Y = \frac{1}{P_B} \left[\frac{Y_N - Y_R}{Y_N + Y_R} \right] \quad IV-4$$

Since $PN \neq -PR$ in most cases, the additional term in the
denominator adjusts for this effect so that A_Y maybe comput-
ed correctly.

In general, all parameters used in the above formulae have uncertainties associated with them. Uncertainties in $PN(R)$ are determined by statistical means from counts accumulated in the line C polarimeter. Uncertainties in beam current monitoring have been discussed previously, and result in uncertainties in the values of the $ER03N(R)$ scalars of about 3%. The correction factors are determined by scalar counts that are typically of the order of 10^5 or greater. Assuming the errors in these numbers to be purely statistical, the uncertainty in the correction factors is less than 0.1% and may be neglected.

Uncertainties for $PN(R)$ and $ER03N(R)$ are included in the computation of errors in the relative differential cross-sections and also the analyzing powers, as are the uncertainties in the yields $Y_{N(R)}$. The uncertainties in the yields are twofold: there are statistical uncertainties in the peaksums, and also, for states for which the peak-to-background ratio is small there are associated background subtraction errors. These two sources of uncertainty have been combined where applicable to provide conservative estimates for uncertainties in the measured yields, and, in general, the uncertainties in the yields dominate the computed uncertainties in the relative differential cross-sections and the analyzing powers.

At the time this work was performed, lack of accurately calibrated beam monitors at the HRS precluded abso-

lute normalization of the data by measurement of the incident beam charge. Since these experiments were among the first conducted at beam energies below 800 MeV at LAMPF, few data exist for comparative purposes. Although some elastic and inelastic proton scattering differential cross-section data from ^{12}C exist at incident beam energies of 402 and 600 MeV^{13,14)}, it would not be wise to normalize to these data because the results of the current work should be viewed as complementary to such existing data.

Absolute normalization was accomplished by utilizing available nucleon-nucleon elastic scattering data. At each incident beam energy the yield for the scattering process $^1\text{H}(p,p)^1\text{H}$ was measured. Comparison with tabulated data and phase shift calculations yielded a normalization factor which could then be applied to the ^{12}C data.

The graphite target used for data acquisition was weighed and the ^{12}C thickness was determined to be 44.7 ± 1.0 mg/cm². The uncertainty results from the deposit of small amounts of glue on the upper and lower edges from the mounting system used to suspend the foil in the target frame. The glue was not in the region of the target intercepted by the proton beam during the experiments. The full foil $^{12}\text{CH}_2$ target used for normalization purposes was found to have a thickness of 65.0 ± 0.5 mg/cm². The carbon content of this target is then 55.7 ± 0.43 mg/cm², while the hydrogen content is 9.3 ± 0.07 mg/cm².

The ratio of carbon Thickness for the two targets was verified at a single angle for each beam energy by measuring the yield of elastically scattered protons from the ^{12}C nuclei. Results are given in Table IV-2. The ratios so measured were self-consistent to within 2%, but showed a mean systematic deviation of some 4% from the value obtained by weighing. The fact that the mean measured ratio reflects a slightly smaller thickness may be understood in terms of the glue deposits visible on the target and discussed previously. In subsequent discussions a mean ^{12}C target thickness for the graphite target of 43.7 ± 1.0 mg/cm^2 will be used.

For a given arbitrary normalization factor NF, let the relative APOWR differential cross sections for $^1\text{H}(p,p)^1\text{H}$ be σ_{AP} and for $^{12}\text{C}(p,p)^{12}\text{C}$ be σ_{AC} . If an absolute differential cross section for $^1\text{H}(p,p)^1\text{H}$, σ_p , is known at a given angle θ_n , then absolute normalization of the measured carbon differential cross sections may be accomplished by computing

$$\sigma_{\text{C}}(\theta) = \sigma_{\text{AC}} * \frac{N_{\text{P}}}{N_{\text{C}}} \left[\frac{\sigma_p(\theta_n)}{\sigma_{\text{AP}}(\theta_n)} \right] \quad \text{IV-5}$$

where the factor $N_{\text{P}}/N_{\text{C}}$ expresses the ratio of the number of ^1H nuclei per unit area to the number of ^{12}C nuclei per unit area in the CH_2 and graphite targets respectively.

The quantity $N_{\text{P}}/N_{\text{C}}$ may be written as

$$\frac{N_{\text{P}}}{N_{\text{C}}} = \frac{2M_{\text{CH}_2} T_{\text{C}}}{M_{\text{C}} T_{\text{CH}_2}} \quad \text{IV-6}$$

where T is the thickness of the appropriate target (in mg/cm^2) and M_C , M_{CH_2} are the atomic and molecular masses of ^{12}C and $^{12}\text{CH}_2$ respectively. This factor is found to be 2.54 ± 0.06 .

The measured relative differential cross-sections and corresponding absolute cross-sections σ_{AP} and σ_p are given in Table IV-3. Errors in the relative cross-sections are purely statistical, there being minimal background under the elastic scattering peaks. A possible source of uncertainty in the hydrogen scattering peak sums is as follows. The incident protons can excite the carbon nuclei in the CH_2 target. Although the dipole and quadrupole fields of the spectrometer are set to focus protons elastically scattered from ^1H nuclei in the CH_2 foil, the energy loss for protons leaving the ^{12}C nucleus in the 9.64 MeV excited state is so as to generate outgoing protons with the same momentum as those scattered from the ^1H nuclei. However, because of kinematic differences in the scattering from ^{12}C and ^1H , these protons are not optimally focussed on the focal plane of the spectrometer, and are skewed as shown in Figure IV-11. It may be seen that it is possible for some of the particles inelastically scattered from the carbon nuclei to contribute to the ^1H peak sum. However, at the laboratory angles at which the normalization data were taken, the excitation of the 9.64 MeV state was so weak as to make no significant systematic contribution to the sources of error in

Target Weight Ratios

E_p (MeV)	θ_{cm} (deg)	$\frac{T_c(C)}{T_c(CH_2)}$	$\frac{T_c(C)}{T_c(CH_2)}$
		Scattering	Weighing
398	12.84	0.754	0.803
597	14.90	0.769	0.803
698	13.73	0.774	0.803

Table IV-2.

Relative and Absolute Cross-sections and Normalization Factors by Bin

E_p (MeV)	θ_{cm} (deg)	$\sigma_{AP} \times 10^4$	σ_P ($\frac{mb}{sr}$)	$\frac{N_P \sigma_P}{N_C \sigma_{AP}}$ ($\frac{mb}{sr}$)
		(rel. units)		
398	10.83	6.018 ± 0.263	4.58 ± 0.07	1.94 ± 0.10
398	12.08	5.829 ± 0.268	4.43 ± 0.07	1.93 ± 0.11
398	13.33	5.494 ± 0.265	4.42 ± 0.07	2.05 ± 0.12
398	18.62	5.961 ± 0.189	4.25 ± 0.15	1.81 ± 0.10
398	19.85	5.880 ± 0.212	4.24 ± 0.15	1.83 ± 0.10
597	13.57	9.005 ± 0.325	7.52 ± 0.90	2.12 ± 0.27
597	14.87	9.113 ± 0.336	7.56 ± 0.90	2.11 ± 0.27
597	16.17	8.633 ± 0.325	7.49 ± 0.90	2.21 ± 0.28
698	12.40	11.46 ± 0.409	11.0 ± 1.7	2.44 ± 0.39
698	13.73	14.28 ± 0.444	10.6 ± 1.7	1.89 ± 0.31
698	15.06	14.35 ± 0.467	10.5 ± 1.7	1.86 ± 0.31

Table IV-3.

the normalization.

Absolute ${}^1\text{H}(p,p){}^1\text{H}$ differential cross-sections were determined from tabulated data and phase shift calculations from a phase shift analysis program provided by Arndt³²⁾ and references therein. At 398 MeV, agreement between such calculations and available data is good. The situation was found to be less clear at 597 and 698 MeV, where data are not available at the exact energy or angle, and discrepancies between calculation and data are observed. The value of σ_p at 597 MeV was determined by linear interpolation between data at the same momentum transfer at 572 and 648 MeV. The resulting interpolated value was then averaged with a mean calculated value from different phase shift solutions at 597 MeV. The error quoted contains contributions from experimental uncertainty, computational uncertainty and interpolation uncertainty.

At 698 MeV the value for σ_p was determined by averaging various phase shift solutions, since no data were available at the angle in question. For consistency, phase shift solutions used were compared with other available data at the same energy not too far from the normalization angle, and agreement was found to be reasonable. The large uncertainty in σ_p is due mainly to averaging procedures and deviations of calculated solutions from measured values.

$$\text{The normalization factors } NF = \frac{N_p}{N_c} \cdot \frac{\sigma_p}{\sigma_{AP}}$$

determined using the procedures described above are given in Table IV-4. Uncertainties are the result of the application of standard error propagation techniques, and range from 7% to 21%. These factors have been applied to all relative ^{12}C differential cross-sections to yield absolute differential cross-sections.

Differential cross-sections and analyzing powers for all states extracted at each beam energy are tabulated in the Appendix.

Absolute Normalization Factors

$$E_p \text{ (MeV)} \quad \frac{N_P}{N_C} \star \frac{C_P}{\sigma_{AP}} \times 10^{-8} \left(\frac{\text{mb}}{\text{sr}} \right)$$

398	1.912 ± 0.134
597	2.147 ± 0.277
698	2.063 ± 0.431

Table IV-4.

V. THE DATA

In this chapter we present and discuss the main qualitative features of the data. General observations concerning raw spectra are made, followed by a more detailed discussion of observed differential cross sections and analyzing powers.

A) Spectra

A large number of spectra covering different regions of excitation energy were obtained at each beam energy. The criteria for the construction of these spectra have already been presented. The qualitative features of the spectra are relatively independent of incident beam energy, so we choose to present and discuss a selection of spectra taken at a beam energy of 398 MeV. These spectra are presented in Figures V-1 to V-3. Each of these figures consists of three spectra taken at representative values of the momentum transfer variable q (0.34 , 0.97 and 1.75 fm^{-1}) for a given range of excitation energy.

Figure V-1 shows spectra for an excitation region of 0.0 to 11.0 MeV. The spectrum for $q = 0.34 \text{ fm}^{-1}$ is dominated by elastic scattering, with little or no strength seen in the 2_1^+ ($E_x = 4.44 \text{ MeV}$), 0_2^+ ($E_x = 7.65 \text{ MeV}$) or 3_1^- ($E_x = 9.64 \text{ MeV}$) states. The spectrum at $q = 0.97 \text{ fm}^{-1}$ shows the continued dominance of the elastic peak, but the 2_1^+ , 0_2^+ and 3_1^- states are now also strongly excited. Note also that back-

Low Excitation Spectra

041 234 * DEFACT * MISSING MASS TEST= 00 10-MAY-68
 000000000000 0. CYC 1000. (LIN.) SIN= 2 RUN= 104 07:00:14

041 234 * DEFACT * MISSING MASS TEST= 00 10-MAY-68
 000000000000 0. CYC 1000. (LIN.) SIN= 2 RUN= 104 07:00:00

041 234 * DEFACT * MISSING MASS TEST= 00 10-MAY-68
 000000000000 0. CYC 1000. (LIN.) SIN= 2 RUN= 00 07:01:00

Figure V-1.

ground is negligible up to an excitation energy of some 7-8 MeV, but starts to rise smoothly above this energy. The spectrum at $q = 1.75 \text{ fm}^{-1}$ shows a marked decrease in strength for both elastic scattering and the 0_2^+ state while the 2_1^+ state is now dominant. The background is similar to that observed at $q = 0.97 \text{ fm}^{-1}$.

Figure V-2(a) show an excitation range from 7.0 to 18.0 MeV at $q = 0.34 \text{ fm}^{-1}$. It is apparent that the dominant inelastic states in this region are the unnatural parity $1^+; 0, 1$ states at $E_x = 12.71 \text{ MeV}$ and $E_x = 15.11 \text{ MeV}$ respectively. The 0_2^+ state is also seen. The background shows no significant structure, and at this small laboratory angle (4°) the uniform background is attributable to edge scattering of particles entering the spectrometer acceptance. It should be noted that these states observed here require no angular momentum transfer to the nucleus ($\Delta L=0$), and it is therefore not surprising that they should dominate the low momentum transfer inelastic scattering.

The spectrum in Figure V-2(b), at $q = 0.97 \text{ fm}^{-1}$, shows considerably more structure than that at in Figure V-2(a). Isoscalar states of natural parity are now dominant, especially the 0_2^+ , 3_1^- and 1_1^- states ($E_x = 7.65, 9.64$ and 10.84 MeV respectively). The 4_1^+ state ($E_x = 14.08 \text{ MeV}$) is weakly excited and the very broad ($\sim 1 \text{ MeV}$) collective quadrupole state at 15.3 MeV is clearly evident. The 1^+ states

Medium Excitation Spectra

D41 254 - DELACT - FUSIONING PAGE TEST= 00 21-APR-68
10788-0111001 0.074 5000. (LIN.) SCN= 2 RUN= 187 22:17:58

D41 254 - DELACT - FUSIONING PAGE TEST= 00 21-APR-68
10788-0111001 0.074 5000. (LIN.) SCN= 2 RUN= 20 21:58:01

D41 254 - DELACT - FUSIONING PAGE TEST= 00 21-APR-68
10788-0111001 0.074 5000. (LIN.) SCN= 2 RUN= 04 21:40:12

Figure V-2.

remain visible although it is clear that their strength is diminishing. Also, the relative strength of the isoscalar 1^+ state is approximately the same as the isovector 1^+ state, whereas at small q the isovector state is much stronger (See Figure V-2(a)). The isovector 2_1^+ state at $E_x = 16.11$ MeV is now visible, and a state at 11.83 MeV is also seen.

Note that the background at 7 MeV of excitation is small, and that the small peak to the left of the 0_2^+ state is evidence of the excitation of a $\frac{3}{2}^+$ state in ^{13}C at $E_x = 7.68$ MeV due to the presence of this isotope in the natural graphite target.

Figure V-2(c) shows a spectrum for the same excitation region at $q = 1.75 \text{ fm}^{-1}$. The MBD cut discussed in the preceding chapters can easily be seen at an excitation energy of about 10 MeV, interfering directly with the 1_1^- state at $E_x = 10.84$ MeV. The spectrum is again dominated by natural parity isoscalar states, most notably the 3_1^- and 4_1^+ states, while the 1^+ states are depressed relative to previous spectra at smaller q . The lowest 2^- isovector state at $E_x = 16.58$ MeV is now visible. The 7.68 MeV state in ^{13}C has kinematically shifted to lower excitation energy, while an apparent doublet has developed in the 11-12 MeV excitation energy region. We interpret this doublet as consisting of the isoscalar 2^- state in ^{12}C at 11.83 MeV and a kinemat-

ically shifted state of ^{13}C at 11.46 MeV which itself is an unresolved doublet of spins $\frac{5}{2}^+$ and $\frac{7}{2}^+$. This identification is made upon observation of the kinematic shift of the 'state' as a function of q , and the fact that considerable strength in the region has been observed in 550 MeV inelastic proton scattering from ^{13}C as shown in Figure V-4⁴³⁾. We also note that the giant quadrupole state at 15.3 MeV, although still seen, is much weaker. It appears that some broad strength is present at ~13.5 MeV of excitation. There is an isoscalar 2^- state of ^{12}C at 13.35 MeV with a width of some 400 keV. This is much narrower than the broad structure observed in the spectrum, and cannot account for this strength. The apparent shift in collective strength from 15.3 MeV to a lower excitation energy is observed at all beam energies, and appears to be a real effect.

Nuclear data tables⁴⁴⁾ show there to be a very broad state in ^{13}C at about 13.4 MeV, but examination of Figure V-4, which is representative of a roughly equivalent momentum transfer to that of Figure V-2(b), shows insufficient strength in the region to warrant identification of the broad state seen in this work with an inelastic excitation of a broad state in ^{13}C . A further point against such an identification is the small fraction of ^{13}C present in the target, as well as the relative strength of the 13.4 MeV region compared to the other states of ^{13}C visible in our spectra.

Figure V-3 shows spectra for the excitation energy range from 17.0 to 21.0 Mev. The 18.0 to 21.0 MeV region is seen to contain several broad states. There is a state at 18.3 MeV of width 380 ± 30 keV which is seen in all spectra from smallest to largest values of q . The various states in the 19 MeV region which have been described previously are clearly seen. A state at $E_x = 20.6$ MeV of width 280 ± 20 keV is seen for values of q greater than -0.85 fm^{-1} .

B) Differential Cross-sections and Analyzing Powers

1) Isoscalar states of natural parity

We discuss here the data for states with $\pi = (-1)^J$ which are predominantly excited by mechanisms which do not involve spin or isospin transfer to the nucleus ($\Delta S = 0$; $\Delta T = 0$). The states of interest in this class are 0_1^+ (0.00), 2_1^+ (4.44), 0_2^+ (7.65), 3_1^- (9.64), 1_1^- (10.84) and 4_1^+ (14.08) where the number in parentheses indicates the excitation energy of the residual nucleus.

(a) Elastic scattering (0_1^+ ; $0 - E_x = 0.00$ MeV)

The data are presented in Figures V-5 to V-7. The differential cross sections at all beam energies show the characteristic opaque disc diffraction pattern associated with elastic scattering. Also, the magnitude of the cross section generally increases as an increasing function of incident beam energy. The value of momentum transfer q at

High Excitation Spectra

D-1 254 = DETACT = MISSING MASS
11700-CLC12858 8.474 2000. (LIN.)

TEST= 00 21-APR-68
RUN= 2 RUN= 127 22:24:04

D-1 254 = DETACT = MISSING MASS
11700-CLC12857 8.474 4000. (LIN.)

TEST= 00 21-APR-68
RUN= 2 RUN= 30 22:27:11

D-1 254 = DETACT = MISSING MASS
11700-CLC12857 8.474 6000. (LIN.)

TEST= 00 21-APR-68
RUN= 2 RUN= 04 22:30:28

Figure V-3.

Figure V-4.

which the first minimum in the cross section is located decreases slightly as the incident proton energy increases, and the shape of the minimum becomes somewhat narrower.

Similar phenomena are seen in the analyzing power data, in which the value of q for which the sharp rise corresponding to the cross section minimum has $A_y = 0$ decreases as the incident proton energy increases. In general, the positive region of A_y for $q \leq 1.2 \text{ fm}^{-1}$ decreases in magnitude as the beam energy increases, while also showing less pronounced curvature. The depth of the minimum decreases as E_p increases, consistent with the previously known fact that A_y is strictly positive in the measured range of q for $E_p = 800 \text{ MeV}$ ⁴⁵. Of interest is the observation that, at 398 MeV, the value of A_y oscillates from -1 to +1 while passing through the position of the minimum in the cross section. Such extreme oscillation may have application as an energy calibration point.

On first appearance it seems as though the 'width' of the minimum in A_y is increasing as the beam energy increases. We believe this to be illusory, resulting from the decrease in positive values for low q , and the shift to lower q of the crossover point from negative to positive values of A_y . If all three minima are aligned, the fall-off to the most negative value of A_y occurs with the same slope for all three beam energies.

Elastic Differential Cross Sections

Figure V-5.

Elastic Analyzing Powers

Figure V-6.

Elastic - Comparative Observables

Figure V-7.

Simple optical model theory in which the nucleus is treated as a sharp opaque disc of radius R predicts, to first order, a minimum in the observed differential cross section for a value of qR such that

$$\frac{J_1(qR)}{qR} = 0 \quad \text{V-1}$$

where $J_1(qR)$ is a Bessel function of the first kind. The value $qR = 3.8$ gives this condition. Noting that q is about 1.55 fm^{-1} on average for the location of the first minimum in the elastic differential cross section, we find a value $r_0 = 1.08 \text{ fm}^{-1}$, where $R = r_0 A^{(1/3)}$. This rough value is consistent with parameters obtained in full optical model search calculations described in the next chapter. We do not believe it to be appropriate to attempt to explain the small shift in the minimum as a function of q in terms of this simple approximation, because diffuseness effects and the well-known energy dependence of the optical model parameters have not been taken into account.

It is instructive to consider the behaviour of the product of the differential cross section and the analyzing power as a function of the incident beam energy, as shown in Figure V-7(c). We note that for $q \geq 1.3 \text{ fm}^{-1}$ this product is constant for all beam energies, and that each curve peaks at $q \approx 0.5 \text{ fm}^{-1}$. The peak ratios, normalized to that at $E_p = 398 \text{ MeV}$, are 2.1:1.6:1.0.

We should note that our data for the differential cross sections at $E_p = 398$ and 597 MeV respectively are in good agreement with those obtained by others at 402 and 600 MeV. These other experiments were performed with unpolarized beam, and consequently analyzing powers were not available for comparison.

(b) The $2^+_{1/2}$ state at $E_x = 4.44$ MeV

The differential cross sections data are presented in Figure V-8, and the analyzing power data are presented in Figure V-9. In addition, Figure V-10 shows the data for all beam energies plotted simultaneously, as well as the product $*A_y$ for all beam energies.

We notice that the differential cross sections for incident beam energies of 597 and 698 MeV are larger than that at 398 MeV by factors of 2.8 and 3.5 in the region of the maximum. The location of the maximum also exhibits a shift to smaller q for increasing beam energy in the same fashion as the minimum in the elastic data. Of interest is the shape of the measured differential cross section for $q \geq 1.5 \text{ fm}^{-1}$. While the shape below this value is roughly constant for all beam energies, the data at 398 MeV fall off less rapidly in this region of momentum transfer than those at 597 or 698 MeV; in fact, the values are seen to coincide at $q = 1.75 \text{ fm}^{-1}$.

The analyzing powers are always positive in the meas-

$E_X = 4.44 \text{ MeV } 2_1^+; 0 - \text{Differential Cross Sections}$

Figure V-8.

$E_{\bar{x}} = 4.44 \text{ MeV } 2_1^+; 0 - \text{Analyzing Powers}$

Figure V-9.

Figure V-10.

ured region for the two higher beam energies, while that at 398 MeV becomes strongly negative in the $q = 2.0 \text{ fm}^{-1}$ region. We note that the magnitude of the analyzing power decreases for increasing beam energy in the region $0.5 \text{ fm}^{-1} \leq q \leq 1.5 \text{ fm}^{-1}$, with the difference between the data at 597 and 698 MeV being much less pronounced than that between these data and those at 398 MeV.

Study of the data for $\sigma * A_y$ shows strong peaking in the $q = 1.05 \text{ fm}^{-1}$ region for all beam energies. The large q values for this quantity at $E_p = 398 \text{ MeV}$ are slightly negative, reflecting the change of sign of the analyzing power in this region. In keeping with the behaviour of the two observables, the product exhibits almost similar values for $E_p = 597$ and 698 MeV , which are much enhanced over those for $E_p = 398 \text{ MeV}$. Examination of these data yield the following ratios at the peak normalized to that for $E_p = 398 \text{ MeV}$; 2.13:1.95:1.

(c) The $0_2^+; 0$ state at $E_x = 7.65 \text{ MeV}$

The differential cross section data are presented in Figure V-11, the analyzing power data in Figure V-12 and Figure V-13 shows these data plotted together as well as the product $\sigma * A_y$ for all beam energies.

The differential cross section shows a strong peak for all beam energies at $q = 1.0 \text{ fm}^{-1}$. The maximum values for σ rise as the beam energy increases, yielding ratios at

$E_x = 7.65 \text{ MeV } 0_2^+; 0$ - Differential Cross Sections

Figure V-11.

$E_x = 7.65 \text{ MeV } 0_2^+; 0 - \text{Analyzing Powers}$

Figure V-12.

$E_x = 7.65 \text{ MeV } 0_2^+ : 0 - \text{Comparative Observables}$

Figure V-13.

the peak normalized to that for $E_p = 398$ MeV of 2.8:2.1:1.0. At $E_p = 398$ MeV we note a minimum in the differential cross section at $q = 1.9 \text{ fm}^{-1}$, after which the value of the cross section is seen to rise once more. The data at $E_p = 597$ and 698 MeV do not extend sufficiently far in q to show this effect.

The analyzing powers are negative for all beam energies from the smallest value of q for which data were taken out to $q = 0.55 \text{ fm}^{-1}$. Thereafter, A_y rises smoothly to a positive maximum value at $q = 1.15 \text{ fm}^{-1}$ for all values of E_p . The data at $E_p = 398$ MeV change sign at $q = 1.55 \text{ fm}^{-1}$, dropping to -0.9 at $q = 1.9 \text{ fm}^{-1}$. For $1.9 \text{ fm}^{-1} \leq q \leq 2.05 \text{ fm}^{-1}$ there is a sharp rise in A_y to $+0.94$ reminiscent of the behaviour of the elastic analyzing power in the region of the minimum in the differential cross section. We note that this sharp rise occurs at the same value of q as the observed minimum in the differential cross section, in keeping with the elastic scattering data. The data at $E_p = 597$ MeV also change sign at $q = 1.55 \text{ fm}^{-1}$, although the region in which the sharp rise might be seen was not examined. For $E_p = 698$ MeV a small negative value is seen for $q = 1.7 \text{ fm}^{-1}$, and the last data point shows a sharp change in sign to $+0.4$. This would indicate a shift to a slightly smaller value of q for this sharp rise in the analyzing power at this beam energy. We note that the basic structure of the for the elastic scattering data. The depth of the minimum decreases as

beam energy increases, while the cross-over point from negative to positive values of A_y in the sharp rise apparently shifts to lower q for increasing beam energies. Further comparison with the elastic data indicate that the minimum in $\frac{d\sigma}{d\Omega}$, together with the 'oscillation' in A_y occur at a larger value of q for this state than that for which the effect is seen in the elastic data.

As has been seen for the other state examined this far, the maximum value of A_y in the smoothly positive region is seen to decrease as a function of increasing beam energy, the maximum occurring at $q \sim 1.05 \text{ fm}^{-1}$. Again, the difference between values for $E_p = 398 \text{ MeV}$ and 597 MeV is much larger than that between values for $E_p = 597$ and 698 MeV .

The data for $\sigma * A_y$ show a behaviour very similar to that for the $2_1^+; 0$ state. A sharp peak is seen at $q = 1.0 \text{ fm}^{-1}$, with the maximum value ratios being $1.8:1.6:1.0$. Negative values are observed for $q \leq 0.5 \text{ fm}^{-1}$ and $q \geq 1.5 \text{ fm}^{-1}$, in keeping with the behaviour of the analyzing power in these regions of momentum transfer.

(d) The $3_1^-; 0$ state at $E_x = 9.64 \text{ MeV}$

Differential cross section data are presented in Figure V-14, and analyzing power data in Figure V-15. Figure V-16 shows the data at all beam energies plotted together, as well as the product $\sigma * A_y$.

$E_x = 9.64 \text{ MeV } 3_1^-; 0$ - Differential Cross Sections

Figure V-14.

$E_x = 9.64 \text{ MeV } 3_1^-; 0 - \text{Analyzing Powers}$

Figure V-15.

$E_x = 9.64 \text{ MeV } 3_1^-; 0 - \text{Comparative Observables}$

Figure V-16.

The data for σ show a smooth rise from ~ 0.1 mb/sr at $q = 0.5 \text{ fm}^{-1}$ to a maximum value between 3 and 10 mb/sr at $q \sim 1.2 \text{ fm}^{-1}$ to $q \sim 1.3 \text{ fm}^{-1}$. We see that the value of q for which the differential cross section attains its greatest magnitude shows slight variation from one beam energy to another. The maximum value of σ for the three beam energies are in the ratio 3.1:2.8:1.0. The shape of the differential cross section is consistent from beam energy to beam energy in the region of measurement.

The analyzing power data show little structure. In the measured region these data are always positive, rising smoothly at low values of momentum transfer to maximum values at $q \sim 1.1$ - 1.2 fm^{-1} , the location of the maximum shifting to slightly larger values of q as the beam energy increases. As was seen in the data for the $2^+_{1/2}$ state, the analyzing power at $E_p = 398 \text{ MeV}$ is dropping more rapidly than the data at $E_p = 597$ or 698 MeV . Indeed, A_y is seen to have the same value at $q \sim 1.8 \text{ fm}^{-1}$ for all beam energies.

The larger error bars on the data points for smaller values of q reflect poor statistics. In this region this state is relatively weakly excited with respect to other states in the spectrum, and consequently obtaining satisfactory statistics for the more prominent states demanded that the statistics for more weakly excited states be necessarily poorer.

The data for σ^*A_y show behaviour similar to that for the $2_1^+;0$ and $0_2^+;0$ states discussed previously. There is a strong peak at $q=1.3 \text{ fm}^{-1}$ for all energies; the small shifts in opposite directions for maxima in σ and

A_y as a function of E_p appear to compensate when the product is taken. The data for $E_p = 597$ and 698 MeV are almost identical, and much larger than those for $E_p = 398 \text{ MeV}$. The ratios taken at the value of q for which the data is a maximum are $2.2:2.2:1.0$, normalized to the value for $E_p = 398 \text{ MeV}$. We note that the absence of difference between data for the two higher beam energies is not in agreement with what is seen for the $2_1^+;0$ and $0_2^+;0$ states.

(e) The $1_1^-;0$ state at $E_x = 10.84 \text{ MeV}$.

The differential cross section data are presented in Figure V-16, the analyzing power data in Figure V-17, and the σ^*A_y data, together with common plots of $\frac{d\sigma}{d\Omega}$ and A_y in Figure V-18.

The data for this state at $E_p = 597$ and 698 MeV are truncated because of interference from the MBD cut as described in Chapter III. The problem is especially severe for $E_p = 698 \text{ MeV}$ where only two low momentum transfer data points are available. Consequently, meaningful comparisons can only be made for the data at $E_p = 398$ and 597 MeV .

We find that the differential cross section data ex-

$E_x = 10.84 \text{ MeV } 1_1^-; 0 - \text{Differential Cross Sections}$

Figure V-17.

$E = 10.84 \text{ MeV } l_1^-; 0 - \text{Analyzing Powers}$

Figure V-18.

$E_x = 10.34 \text{ MeV } 1_1^-; 0 - \text{Comparative Observables}$

Figure V-19.

hibit a smooth rise to a maximum value at $q = 1.2 \text{ fm}^{-1}$ for both these beam energies. The ratio of the maxima at this value of q is 2.0:1.0. No other significant observations can be made.

The analyzing powers are uniformly positive at all energies and exhibit little structure. The data for $E_p = 398 \text{ MeV}$ start to fall off towards 0 at $q = 1.4 \text{ fm}^{-1}$, corresponding to the decrease in σ from its maximum. The values of A_y for $E_p = 597 \text{ MeV}$ are uniformly smaller than those for $E_p = 398 \text{ MeV}$.

The product $\sigma * A_y$ exhibits a structure similar to other states in this group already discussed. A sharp rise from 0 at $q = 0.5 \text{ fm}^{-1}$ peaks at $q = 1.2 \text{ fm}^{-1}$, the data for $E_p = 597 \text{ MeV}$ being greater than those for $E_p = 398 \text{ MeV}$ at the maximum by a factor of 1.4.

(f) The $4_1^+; 0$ state at $E_x = 14.08 \text{ MeV}$

This is the last of the well-known states in this category visible in the spectra. It is a broad state, having an intrinsic width of some 260 keV FWHM. In addition, it lies on top of the large background due to the wide collective quadrupole state at $E_x = 15.3 \text{ MeV}$. These considerations require careful fitting of the background, and the large error bars for the high q data primarily reflect errors in background subtraction. The errors assigned to the

$E_x = 14.03 \text{ MeV } 4_1^+; 0 - \text{Differential Cross Sections}$

Figure V-20.

$E_x = 14.08 \text{ MeV } 4_1^+; 0 - \text{Analyzing Powers}$

Figure V-21.

$E_x = 14.08 \text{ MeV } 4_1^+; 0 - \text{Comparative Observables}$

Figure V-22.

data at low q are primarily statistical, the background being smoother in this region and the peaks being less well-defined than in the high q region.

The data are presented in Figures V-20 to V-22. The differential cross sections are seen to peak in the region $q = 1.5-1.7 \text{ fm}^{-1}$, with a shift to lower q being evident as the beam energy rises. The data exhibit a minimum in the $q = 1.0 \text{ fm}^{-1}$ region, and in some cases it was possible to extract data in the $q = 0.5 \text{ fm}^{-1}$ region. We note that this could not be done at $E_p = 398 \text{ MeV}$ where statistics were very poor. The ratio of differential cross sections at the main peak to the data at $q = 0.5 \text{ fm}^{-1}$ for the two higher beam energies is approximately 3.0. The ratio of the values of at the primary maximum are 2.6:1.8:1.0.

The analyzing powers are generally positive and attain the largest values observed for this category of states. The general trend of larger values for lower beam energies is apparent, as is the more rapid fall-off at larger q for $E_p = 398 \text{ MeV}$ where some negative values are found.

The product $\sigma \cdot A_y$ shows strong peaking in the $q = 1.4 \text{ fm}^{-1}$ region, with the ratios of the maxima being 2.0:1.6:1.0.

2) Isovector states of natural parity

Only one well-known state with $\pi = (-1)^L$ and isospin transfer $\Delta T = 1$ is present in the spectrum. This is the $2^+_{1;1}$ state at $E_x = 16.11$ MeV. Data for this transition are presented in Figures V-23 to V-25.

In general, statistics for this state were poor at forward angles (small q) because it is weakly excited in a spectrum dominated by strong natural parity isoscalar transitions and low ΔL unnatural parity states. For large values of q the differential cross section is seen to drop to the 1 microbarn range, and again poor statistics dominate the uncertainties.

Examination of the differential cross section data as presented in Figure V-23 reveals some interesting phenomena. A maximum in the cross-section is seen at a momentum transfer of $q = 0.95 \text{ fm}^{-1}$ at all beam energies. The shape of the cross section is not as symmetric as those observed for the isoscalar states discussed previously (e.g. the $0^+_{2;0}$ and $3^-_{1;0}$). Rather, the rate of decrease for $q > 1.0 \text{ fm}^{-1}$ is less pronounced than the rise to the maximum at low q . Clearly the most interesting feature of the data is not the shape nor magnitude of the differential cross section for a given beam energy, but rather the independence of the shape and magnitude of the data as a function of the incident beam energy. This is most clearly seen in Figure V-25 where the three curves representing the data are seen to lie on top of one another. Such behaviour is markedly dif-

$E_x = 16.11 \text{ MeV } 2_1^+; 1 - \text{Differential Cross Sections}$

Figure V-23.

Figure V-24.

$E_{\gamma} = 16.11 \text{ MeV } 2_{1}^{+}; 1 - \text{Comparative Observables}$

Figure V-25.

ferent from the previously discussed isoscalar transitions.

The analyzing power data, presented in Figure V-24, show reasonable consistency of structure for all incident particle energies. For momentum transfers up to $q = 1.5 \text{ fm}^{-1}$ there is a scatter of points around $A_y = 0$, showing a trend from slightly positive values for small q to slightly negative values for larger q . For $E_p = 398 \text{ MeV}$ the data, after dropping to slightly negative values for $1.5 \text{ fm}^{-1} \leq q \leq 1.75 \text{ fm}^{-1}$ return to values consistent with zero for $q > 1.75 \text{ fm}^{-1}$. The data for $E_p = 698 \text{ MeV}$ show a continuing trend to negative values at $q = 1.75 \text{ fm}^{-1}$ as do the data for $E_p = 597 \text{ MeV}$.

The product $\sigma * A_y$ shows large oscillations around zero for values of q less than 1 fm^{-1} . The oscillations decrease as q increases, all curves converging to zero. This behaviour is an artifact of the oscillations of sign for A_y for low momentum transfers, coupled with the drop to small values of the differential cross section for large values of q .

3) Isoscalar states of unnatural parity

We present in this section data for states having no isospin transfer ($\Delta T = 0$) which are primarily populated through spin transfer mechanisms ($\Delta S = 1$) resulting in parities $\pi = (-1)^{L+1}$. Several such states are known to exist in

^{12}C , the most well-known being the $1^+_{1/2}$ at $E_x = 12.71$ MeV. In addition, $2^-_{1/2}$ states are known to exist at $E_x = 11.83$ and 13.35 MeV.

(a) The $1^+_{1/2}$ state at $E_x = 12.71$ MeV

The differential cross section data are presented in Figure V-26, the analyzing power data in Figure V-27 and the product $\sigma \cdot A_y$ together with common plots of the data in Figure V-28.

The differential cross section is seen to attain a maximum value of 0.26 mb/sr for $E_p = 398$ MeV, 0.38 mb/sr for $E_p = 597$ MeV and 0.33 mb/sr for $E_p = 698$ MeV at the smallest values of q for which data were taken. It appears that the data are flattening out as q is extrapolated to zero, and it may be appropriate therefore to interpret the zero momentum transfer cross sections as being very close to these values. The data are seen to drop smoothly by an order of magnitude to a momentum transfer of about 1.4 fm^{-1} , where a small shoulder in the data is evident. This shoulder is seen at all beam energies. At $E_p = 398$ MeV, where data exist for q up to 2.2 fm^{-1} , the data are seen to continue to drop after passing through the shoulder, but not as steeply as is observed in the lower momentum transfer region. Of special interest is the observation that the cross section is, in general, almost constant in shape and magnitude as a function of incident beam energy. This is most easily seen in

$E_x = 12.71 \text{ MeV } 1_{1/2}^+$; 0 - Differential Cross Sections

Figure V-26.

$E_x = 12.71 \text{ MeV } 1_1^+; 0 - \text{Analyzing Powers}$

Figure V-27.

$E_x = 21.71 \text{ MeV } 1_1^+; 0 - \text{Comparative Observables}$

Figure V-28.

Figure V-28.

Examination of Figure V-27 yields interesting observations for the analyzing power. In contrast with all data presented thus far, large negative analyzing powers (-0.3 to -0.4) are seen for small values of q . For $q \leq 0.5 \text{ fm}^{-1}$ the data for all beam energies are remarkably consistent, as are the data for $q \geq 1.5 \text{ fm}^{-1}$ where A_y is strongly positive.

The intermediate region of $0.5 \text{ fm}^{-1} \leq q \leq 1.5 \text{ fm}^{-1}$ shows some differences from beam energy to beam energy. For $E_p = 398 \text{ MeV}$, where the quality of the data is best, the value of q for which the sign of A_y changes from negative to positive is about 1.4 fm^{-1} , coinciding with that at which the shoulder is observed in the differential cross section. For $E_p = 597 \text{ MeV}$, the cross-over point has shifted to about 1 fm^{-1} , as has that for $E_p = 698 \text{ MeV}$. As such, these data then do not coincide with the shoulder seen in the differential cross section data.

The product $\sigma * A_y$ shows interesting features. For $q < 0.5 \text{ fm}^{-1}$ it is sharply negative reflecting the sign of A_y . Differences in magnitude in this region are attributable to slightly different magnitudes for the cross section. The product then rises smoothly to small positive values and then falls to zero as q increases, the rise for $E_p = 398 \text{ MeV}$ being less pronounced than that for the higher beam energies. This is evidence for the shift to lower q of the

change in sign of A_y for the higher beam energies together with the rapid decrease in the magnitude of the differential cross section.

The form of A_y and $\sigma * A_y$ are so characteristic as to warrant the postulate that such behaviour could be a signature for isoscalar unnatural parity transitions. This postulate will be examined in more detail in succeeding sections and the next chapter.

(b) The $2^-_2;0$ state at $E_x = 13.35$ MeV

The data for this state are presented in Figures V-29 to V-31. This transition is very weakly excited and is only visible in the spectra for values of q greater than 1.4 fm^{-1} . Consequently, very few data points are available and little detailed information may be obtained.

The differential cross sections shown in Figure V-29 are seen to be of the order of 0.01 mb/sr , and almost constant in magnitude as a function of beam energy. The analyzing powers are positive in the region where data exist. The product $\sigma * A_y$ does not yield any useful information.

4) Isovector states of unnatural parity.

This class of states is populated by transitions involving transfer of one unit of both spin and isospin ($\Delta S =$

$E_x = 13.35 \text{ MeV } 2^-_{2;0} - \text{Differential Cross Sections}$

Figure V-29.

$E_x = 13.35 \text{ MeV } 2_2^-; 0 - \text{Analyzing Powers}$

Figure V-30.

$E_x = 13.35 \text{ MeV } 2_2^-; 0 - \text{Comparative Observables}$

Figure V-31.

1, $T = 1$). The best example of such a transition is the $1^+_{1/2}; 1$ state at $E_x = 15.11$ MeV. Also of interest is the $2^-_{1/2}; 1$ state at $E_x = 16.58$ MeV, the spin, parity and isospin assignments of these states being well-established.

(a) The $1^+_{1/2}; 1$ state at $E_x = 15.11$ MeV

The differential cross section data are presented in Figure V-32, the analyzing power data in Figure V-33 and combined plots together with σ^*A_y in Figure V-34.

The differential cross section data show an almost exponential decrease over two orders of magnitude for the range $0.3 \text{ fm}^{-1} < q < 1.3 \text{ fm}^{-1}$. Some minor structure is seen for $q \sim 0.6 \text{ fm}^{-1}$ at all beam energies. The magnitude of the cross section for the different beam energies at $q \sim 0.35 \text{ fm}^{-1}$ is constant and about 1.3 mb/sr . A small maximum, or 'shoulder' is clearly evident in the $E_p = 398 \text{ MeV}$ data at $q = 1.6 \text{ fm}^{-1}$, and although the data for the higher beam energies is less complete, evidence for this structure is also present there. The increase in uncertainty in the data points as an increasing function of q reflects poorer statistics coupled with a decreasing peak-to-background ratio. Uncertainties at low q are small because this state, apart from the elastic scattering, is dominant in the spectra.

Again, the most remarkable feature of these data is the independence of the magnitude and shape of the cross

$E_x = 15.11 \text{ MeV } 1^+_1; 1 - \text{Differential Cross Sections}$

Figure V-32.

$E_x = 15.11 \text{ MeV } 1_1^+; 1 - \text{Analyzing Powers}$

Figure V-33.

$E_x = 15.11 \text{ MeV } 1_1^+; 1 - \text{Comparative Observables}$

Figure V-34.

section as a function of incident particle energy. There is some slight discrepancy in the $q = 1.3 \text{ fm}^{-1}$ region where the $E_p = 398 \text{ MeV}$ data are slightly lower than the data at $E_p = 597$ or 698 MeV , but up to this point the equivalence is almost exact.

The analyzing power data in Figure V-33 show systematic features. For values of q up to about 0.6 fm^{-1} , A_y is consistent with zero. In the $q = 0.7 \text{ fm}^{-1}$ region a rise to small positive values is seen, followed by a drop back to zero in the $q = 1 \text{ fm}^{-1}$ region. Small positive values are attained in the $1.2 \text{ fm}^{-1} \leq q \leq 1.5 \text{ fm}^{-1}$ region, after which a consistent trend toward negative values is seen. These features are most evident for the $E_p = 398 \text{ MeV}$ data, and are consistent with the data at $E_p = 597$ and 698 MeV . The zero value for A_y at low q should be contrasted with the strongly negative values seen for this observable for the isoscalar state with the same spin and parity. It would appear that the behaviour of the analyzing power as a function of q for unnatural parity states may therefore be a sensitive probe of the isospin transfer nature of different modes of excitation in the nucleus.

The product $\sigma * A_y$ shows strong fluctuations in the low q region, representative of the fluctuations of A_y about zero. This quantity converges rapidly to zero as q increases, this being an artifact of the exponentially decreasing differential cross section.

(b) The $2_1^-;1$ state at $E_x = 16.58$ MeV

This state, with an intrinsic width of some 300 keV FWHM, is found to be populated at larger momentum transfers ($q \geq 1.0 \text{ fm}^{-1}$). The data for this transition are presented in Figures V-35 to V-37.

The differential cross section has a maximum for $q \approx 1.35 \text{ fm}^{-1}$, and we note from the superposed data in Figure V-37 and also the data points with error bars in Figure V-35 that, to within uncertainties, the magnitude and shape of the cross section are invariant with respect to incident projectile energy. The maximum value attained by the cross section is 0.035 mb/sr .

The analyzing powers shown in Figure V-36 are uniformly positive, and the data for the lower two beam energies are falling off slowly as q increases. For these lower beam energies there appears to be some structure in A_y for values of q close to the maximum in the differential cross section. Such an observation cannot be made for the data at $E_p = 698 \text{ MeV}$ because of the large interval in q between data points.

The product $\sigma * A_y$ shows structure somewhat resembling the peaks seen for natural parity states. However, if the uncertainties in this quantity are taken into account, such structure is washed out and the curves plotted in Figure V-37 are not inconsistent with one another as might

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{Differential Cross Sections}$

Figure V-35.

$E_X = 16.58 \text{ MeV } 2_1^-; 1 - \text{Analyzing Powers}$

Figure V-36.

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{Comparative Observables}$

Figure V-37.

first appear. No significant deductions can be made from these data.

5) States of indefinite quantum numbers for $E_x > 18.0$ MeV

We present here data for five states in the excitation energy region $18.0 \text{ MeV} \leq E_x \leq 21.0 \text{ MeV}$. The exact spin, parity and isospin assignments for these states are open to question, and the discussion of the DWIA analysis in the next chapter will address such assignments directly. In this section we endeavour to discuss the systematics of these states and the similarity or dissimilarity of these systematics with those discussed previously for more well known states.

(a) The state at $E_x = 18.30$ MeV

Data for this state are presented in Figures V-38 to V-40. One of the more striking features of the data is the significant strength observed for $q \leq 0.5 \text{ fm}^{-1}$. The shape of the differential cross section is seen to resemble that of the $T = 0 \text{ } 1^+$ transition, although the behaviour for small values of q is different. These data show a well-defined rise to a maximum value for $q \sim 0.8 \text{ fm}^{-1}$, while the $E_x = 12.71$ MeV data are constant for small values of q . The data for $E_p = 398$ MeV show a definite minimum in the $q = 2.0 \text{ fm}^{-1}$ region which is unfortunately not observable at the higher

$E_X = 18.30 \text{ MeV}$

- Differential Cross Sections

Figure V-38.

$E_x = 18.30 \text{ MeV}$ - Analyzing Powers

Figure V-39.

$E_x = 18.30 \text{ MeV}$ - Comparative Observables

Figure V-40.

energies because the data do not extend this far. Examination of Figure V-40 shows evidence for the unnatural parity character of this state. The comparative plot of the differential cross sections for the different beam energies shown in Figure V-40 exhibits the same independence of incident projectile energy as is seen for isoscalar or isovector unnatural parity states and isovector states of natural parity of lower excitation energy.

The analyzing power data of Figure V-39 provide some evidence for assignment of an isoscalar nature to this transition. The analyzing power for all incident proton energies is clearly negative for small values of q , rising to positive values as q increases. The crossover point from negative to positive values decreases as E_p increases. These observations are entirely consistent with the systematic behaviour of A_y for the isoscalar 1^+ state at $E_x = 12.71$ MeV, thereby providing some motivation for assigning isoscalar properties to this transition.

The product of the differential cross section and the analyzing power as shown in Figure V-40 show features remarkably similar to those observed for the isoscalar 1^+ transition. Strongly negative values are seen for small values of q , rising to values consistent with zero as q increases.

The systematics of the observables measured for this

transition thus suggest that it is an isoscalar transition of either natural or unnatural parity. The data, though, provide no basis for a spin or parity assignment. Possible assignment of spin and parity, together with more restrictive tests of the deductions made here require the results of DWIA calculations which are presented in the next chapter.

(b) The state at $E_x = 19.28$ MeV

The data for this state are presented in Figures V-41 to V-43. This state is not populated at all for values of q less than 1.2 fm^{-1} . For q larger than this value, it is seen for all incident beam energies. This particular state is one of the broadest particle-hole states seen in the spectra, having a width of $580 \pm 50 \text{ keV}$. The fact that no strength is observed for small values of q suggests that the spin of this state must be large, possibly 3 or 4. The measured differential cross sections are of the order of 0.1 mb/sr or less, and as can be seen from Figure V-41 it is not possible to make definite observations concerning the structure of the cross section.

The analyzing powers are generally negative for values of the momentum transfer less than 1.8 fm^{-1} , rising to values near zero for larger q . The product of the differential cross section and A_y does not yield any significant information.

$E_x = 19.23 \text{ MeV}$ - Differential Cross Sections

Figure V-41.

$E_X = 19.28 \text{ MeV}$ - Analyzing Powers

Figure V-42.

$E_X = 19.28 \text{ MeV}$ - Comparative Observables

Figure V-43.

Other than the natural parity 3^- and 4^+ isoscalar states discussed previously, no other 'high' spin states have been seen in the spectra up to this excitation energy. The negative character of the analyzing power differs from that observed for the isoscalar natural parity states suggesting that this transition may be of unnatural parity, but no deductions may be made concerning the isospin nature of this states.

(c) The state at $E_x = 19.40$ MeV

The data for this transition are presented in Figures V-44 to V-46. The differential cross section data presented in Figure V-44 show strong peaking for small values of q . Furthermore, the strength associated with this transition at the smallest values of q is of the order of 1 mb/sr, only a factor of about 2.5 smaller than that observed for the $1^+;1$ state in the same region of q . The data fall off rapidly as q increases, and for values of q greater than about 1.2 fm^{-1} , no strength could be extracted. Examination of Figure V-46 shows that the measured cross section is independent of incident particle energy, which has been shown to be representative of isoscalar and isovector transitions of unnatural parity, or isovector transitions of natural parity. The strong forward peaking of the cross section is suggestive of a state of low spin (2 or less) of unnatural parity, but previous systematics cannot preclude the pres-

$E_x = 19.40 \text{ MeV}$ - Differential Cross Sections

Figure V-44.

$E_x = 19.40 \text{ MeV}$ - Analyzing Powers

Figure V-45.

$E_X = 19.40 \text{ MeV}$ - Comparative Observables

Figure V-46.

ence of isovector components of natural parity.

The analyzing powers, presented in Figure V-45, provide some useful information when compared with previously discussed data. For small values of q , A_y is generally consistent with zero, showing a trend toward negative values for $q \geq 0.8 \text{ fm}^{-1}$. Comparison with the analyzing power data for the $1^+;1$ transition show remarkable similarities, suggesting that this transition has a dominant unnatural parity isovector component.

The data for the product of the observables is in general positive for small values of q , decreasing to zero as q increases, reflecting the rapid decrease in magnitude of the differential cross section. The behaviour of this product is somewhat similar to that for the $1^+;1$ state, although there are considerably fewer data points for this transition.

It is therefore possible to conclude on the basis of the systematics of the data that this transition should be dominated by a low spin isovector unnatural parity component, although the presence of a low spin isovector natural parity component cannot be ruled out.

(d) The state at $E_x = 19.65 \text{ MeV}$

The data for this state are presented in Figures V-47 to V-49. The differential cross section data shown in

$E_x = 19.65 \text{ MeV}$ - Differential Cross Sections

Figure V-47.

$E_x = 19.65 \text{ MeV}$ - Analyzing Powers

Figure V-49.

$E_x = 19.65 \text{ MeV}$ - Comparative Observables

Figure V-49.

Figure V-47 show a distinct maximum for $q \sim 1.4 \text{ fm}^{-1}$. The shape of the data is consistent with a spin assignment of 3 or 4. As has become common for states in this excitation energy region, the differential cross section show almost no dependence on the incident proton energy, thus suggesting a state of unnatural parity, or an isovector state of natural parity. The maximum value attained by the differential cross section is of the order of 0.25 mb/sr .

The analyzing power does not exhibit much structure, being near zero for $0.8 \text{ fm}^{-1} \leq q \leq 1.1 \text{ fm}^{-1}$. For $q > 1.1 \text{ fm}^{-1}$ A_y is consistently positive, and about 0.2. The absence of significant structure in the analyzing power data does not allow any further conclusions concerning the isospin nature of the transition.

The product of the differential cross section and A_y shows a reasonable constancy as a function of E_p , and its structure is dominated by the structure of the cross section as A_y is almost constant. Further information on the quantum number assignments for this state requires the results of the DWIA computations presented in the next chapter.

(e) The state at $E_x = 20.60 \text{ MeV}$

The data for this state are presented in Figures V-50 to V-52. The data for the differential cross section show a maximum for $q \sim 0.9 \text{ fm}^{-1}$. The shape of the data is

$E_x = 20.60 \text{ MeV}$ - Differential Cross Sections

Figure V-50.

$E_X = 20.60 \text{ MeV} - \text{Analyzing Powers}$

Figure V-51.

$E_x = 20.60 \text{ MeV}$ - Comparative Observables

Figure V-52.

consistent with a spin of 2 or 3, as is evidenced by comparison with the data for isoscalar states of natural parity. Examination of Figure V-52 shows, however, that the magnitude of the differential cross section is independent of incident beam energy, and that consequently this transition is of unnatural parity or possibly an isovector transition of natural parity.

The analyzing power data are, in general, small in magnitude and positive over the range of q for which data were taken. Such behaviour is consistent with that observed for the state at $E_x = 19.65$ MeV, so it might be expected that the isospin properties of this transition could be the same as that of the 19.65 MeV state. This deduction is of use when comparisons with DWIA calculations are made.

The structure of the product of the cross section and A_y provides little additional information, other than to exhibit a dependence on q similar to that for the 19.65 MeV state. The positive nature of the analyzing power would seem to suggest a transition of isovector nature, although this cannot be taken as strong evidence for such an assignment.

VI. THEORETICAL INTERPRETATIONS OF THE DATA

We present here the results of theoretical calculations performed to aid in the interpretation of the data presented in the preceding chapter. Optical model computations for the elastic scattering data are presented first, together with a summary of the potentials resulting from these computations. Results of Distorted Wave Impulse Approximation calculations for a variety of transitions are then presented, and their validity and consequences discussed.

A) Optical Model Calculations - Elastic Scattering

A prerequisite for DWIA calculations is knowledge of an average potential capable of describing the incident and exit channel elastic scattering. Such optical model parameters were not readily available for the incident beam energies used in this work. The optical model search program CUPID⁴⁶⁾ was used to determine an optimal set of potential parameters which best reproduced the measured elastic scattering differential cross section and analyzing power at each incident beam energy.

The code accepts, as input, data for both the differential cross section and the analyzing power, together with initial estimates for the strengths, radii, and diffusenesses of real and imaginary central and spin-orbit potentials. The shape of the potential well used in the com-

putations is the standard Woods-Saxon form, and relativistic kinematics was used throughout.

The data for $E_p = 398$ MeV were fitted first. A set of previously determined parameters⁴⁷⁾ was used as an initial estimate. Both cross sections and analyzing powers were fitted simultaneously, and the full set of twelve adjustable parameters (four potentials, four radii and four diffusenesses) were varied to minimize chi-squared. An adjustable normalization factor was held fixed at 1.0 throughout. The best fits to the data obtained in this way are presented in Figures VI-1 and VI-2.

The potential parameters derived in the fitting procedure outlined above are presented in Table VI-1, together with the resulting normalized chi-squared values indicating the overall quality of the fit to the data for the tabulated parameters. The overall chi-squared parameter is dominated by contributions from the analyzing power.

We note that the quality of the fit to the differential cross section data is in general good. Some deviations are seen for the smallest scattering angles measured, as well as in the region of the minimum and the second maximum. For the angular region 8° to 16° CM, the fit is seen to slightly underestimate the magnitude of the cross section data. The fit to the analyzing power is not as good as that to the cross section. While the minimum in A_y is well

Figure VI-1.

Optical Model Potential Parameters

	400 MeV	600 MeV	700 MeV
V	-2.62 MeV	1.10 MeV	1.84 MeV
W	-25.9	-78.8	-93.5
V _{ls}	-7.88	-4.89	-4.67
W _{ls}	-11.3	-14.3	-18.4
W _s	-	-2.37	-2.58
r _V	1.25 fm	2.53 fm	0.912 fm
r _W	1.08	0.859	0.875
r _{Vls}	0.995	1.01	0.908
r _{Wls}	0.971	0.897	0.879
r _s	-	1.94	1.59
a _V	0.474 fm	0.474 fm	0.474 fm
a _W	0.594	0.594	0.594
a _{Vls}	0.496	0.496	0.496
a _{Wls}	0.507	0.507	0.507
a _s	-	0.500	0.500
χ ²	4.3	12.7	24.3

Table VI-1.

reproduced, the data for angles larger than 23° CM are underestimated. Furthermore the shape for the calculated quantity differs significantly from the data from 3° to 17° CM. For the more forward angles in this region the calculation overestimates the data, while underestimating the data for $10^\circ < \theta_{\text{cm}} < 17^\circ$.

The data for $E_p = 597$ and 698 MeV were fitted using the same procedure. For consistency, the diffuseness parameters determined in the fit to the data for $E_p = 398$ MeV were held constant in all calculations for the two higher beam energies. Normalization factors were also fixed at 1.0 to eliminate arbitrary renormalization of the fits. Reasonable fits to the data at these energies could not be obtained for searches on the standard central and spin-orbit potentials. The fits could not reproduce the depth of the minimum in the differential cross section, and also produced a much deeper oscillation in the analyzing power than is seen in the data.

It was noted that a set of optical parameters for proton scattering from ^{12}C at $E_p = 800$ MeV⁴⁷⁾ contained an imaginary surface absorptive term, the form of which is the first derivative of the Woods-Saxon shape. This term was included in further searches and was found to considerably improve the quality of the fits obtained. The diffuseness parameter for this term was held fixed at 0.5 fm. Fits to the data for $E_p = 597$ and 698 MeV so obtained are shown in

Figures VI-3 to VI-6.

The fit to the cross section data for $E_p = 597$ MeV is excellent. The fit to the cross section data for $E_p = 698$ MeV is not as good, underestimating the data at forward angles and not reproducing the minimum as well. The fits to the analyzing power are not as good as that for $E_p = 398$ MeV. The minimum is reasonably well reproduced in both cases. The sharp drop after the rise from the minimum is not well reproduced, and the differences in shape up to the drop off to the minimum noted for $E_p = 398$ MeV are seen to worsen as the beam energy increases. The data are overestimated at the most forward angles measured, and are badly underestimated for larger angles, convergence finally being reached in the region of the dip to the minimum.

It should be pointed out that the simple phenomenological approach adopted in the analysis presented here is not necessarily the most fundamental analysis possible, but it is very useful for DWBA calculations. Glauber theory and the theory of Kerman, McManus and Thaler may provide a better understanding of the behaviour of the phenomenological potentials derived in this analysis. The fitting procedure was directed primarily to optimizing the fit to the data, and consequently rather loose physical constraints were imposed on the parameters used in the search. The potential strengths were found to be reasonable, as were the values for the diffuseness of the Woods-Saxon wells,

Figure VI-3.

ELASTIC SCATTERING ANALYZING POWER $E(\text{BEAM})=597 \text{ MeV}$

Figure VI-4.

Figure VI-5.

although the central imaginary strengths for 597 and 698 MeV were greater than that for 800 MeV⁴⁷⁾. Of more concern were the radius parameters of the wells, especially that of the real central and surface imaginary terms. The real central radius exhibited wide variation from beam energy to beam energy, the value of 2.53 fm for $E_p = 597$ MeV being rather unphysical; the surface imaginary radius was of the order of 1.7 fm. It is reasonable to expect the real central radius to be representative of the physical size of the nucleus when multiplied by $A^{(1/3)}$. The adjusted radius for $E_p = 597$ MeV is then too large by a factor of two. Nevertheless, attempts to constrain this parameter to a more reasonable value such as 1.2 fm while adjusting the potential strength to maintain the volume integral of the real central term at a constant value were unsuccessful. Such a procedure caused a significant deterioration in the quality of the fit to the differential cross section. This is surprising since the strength of this potential is so small. We also note that the central imaginary radii for 597 and 698 MeV were smaller than that for 800 MeV by about 7%. This results in about a 22% decrease in volume which is consistent with the fact that the potentials are stronger. Since these parameters were to be used solely as entrance and exit average potentials for the DWIA computations for inelastic transitions, it was decided to retain the optimal fit parameters, and to run test DWIA calculations for a more physically realistic potential. Independent elimination of

the imaginary surface term and the real central term was found to have no significant effect on the results of the DWIA calculations. The reliability of the normalization of the data indicates that misdetermination of the imaginary central term is also unlikely.

It is interesting to note that while the real spin-orbit potential is always attractive (negative in the CUPID convention), the real central potential changes from being attractive at $E_p = 398$ MeV to repulsive for $E_p = 597$ and 698 MeV. This is consistent with the fact that this term is repulsive at 800 MeV incident proton energy, and also with the observations noted in Chapter II. The largest variation in strength is seen for the imaginary central term, which increases by almost a factor of four from $E_p = 398$ MeV to $E_p = 698$ MeV. The imaginary spin-orbit potential increases in strength by about a factor of 1.6 , while the real spin-orbit potential decreases in magnitude by a factor of 1.7 . The absolute value is then about constant. Note that this is also approximately true of the t_0^{LS} term in the Love-Franey interaction.

B) Distorted Wave Impulse Approximation Calculations

The microscopic DWIA calculations were performed using a modified version of the code DWBA70⁴⁸⁾, known as DW81⁴⁹⁾. Since it is expected that the impulse approximation is valid for incident beam energies greater than 400

MeV⁵⁰⁾, the use of this approach for study of the inelastic transitions was deemed appropriate. Furthermore, reactions were assumed to be single-step, and multiple scattering corrections were assumed to be adequately described by the distorted waves. Knock-on exchange calculations, which are of importance for some transitions, were performed exactly, and relativistic kinematics was used throughout. The optical potentials used have been discussed in the preceding section of this chapter.

Harmonic oscillator radial wavefunctions were used in all computations. The $1p$ shell transition densities of Cohen and Kurath¹⁷⁾ were used to describe states of positive parity. States of negative parity were described by the $1p-1d$, $1p-1s$ and $1p-2s$ shell transition densities of Millener¹⁸⁾. The harmonic oscillator length parameters for given transitions were chosen to match prominent maxima of the longitudinal and transverse form factors measured in inelastic electron scattering. Where such measurements do not exist, a length parameter of 1.681 fm consistent with elastic scattering has been adopted. The transition densities used in the DWIA calculations, together with oscillator length parameters appropriate to each transition and corrected for centre-of-mass effects as described by Comfort⁶⁾, are given in Table VI-2. The effective interactions of Love and Franey³⁾ appropriate to nucleon-nucleus collisions at different energies were used throughout. The de-

Reduced Matrix Elements

$J^\pi; T$	$b(\text{fm})$	$p_1 s_1$	$p_3 s_1$	$\sigma_1 p_1$	$d_3 p_1$	$d_5 p_1$	$\sigma_1 p_3$	$d_3 p_3$	$d_5 p_3$	$p_1 p_1$	$p_1 p_3$	$p_3 p_1$	$p_3 p_3$
$1^+; 0$	1.572												
$2^+; 0$	1.681												
$1^+; 1$	1.866												
$2^+; 1$	1.570												
$2^+; 1Q$	1.570												
$1^-; 0$	1.681	.0543	-.0436	.2701	.0999		.6306	-.1219	.3195				
$2^-; 0$	"		-.0199		-.0710	-.1216	-.3956	.1639	-.3875				
$2^-; 0$	"		.0107		-.0144	.0924	.2783	.1189	-.6988				
$2^-; 0$	"		-.0440		.1160	.1309	-.5969	-.1459	-.0594				
$3^-; 0$	"					.2654		-.3145	.5099				
$4^-; 0$	"								.3390				
$1^-; 1$	"	-.0842	.0235	.1073	.0031		-.7172	.1199	-.1773				
$1^-; 1$	"	-.0283	-.0216	-.5280	.0021		-.0947	-.0150	-.0652				
$2^-; 1$	"		.0133		-.0332	.0047	.7079	-.0050	.3474				
$2^-; 1$	"		-.0074		-.0678	-.2973	-.3213	-.0904	.5521				
$3^-; 1$	"					-.0384		-.1322	-.7510				
$4^-; 1$	"								-.8069				

Table VI-2.

tails of the force have been summarized in Chapter II of this work. The 425 MeV interaction was used for calculations to be compared with the 398 MeV data, while the 650 MeV interaction was used for calculations to be compared with the 597 and 698 MeV data. On occasion the 515 MeV force was used for comparisons with the 597 MeV data, as was the 800 MeV force for comparisons with the 698 MeV data. All calculations were performed including exchange. The results are presented in the form of six sets of curves for each transition. These curves are generated by sequential addition of the results for real and imaginary components of the force with appropriate phases. A key which may be used in the interpretation of the various curves is given in Figure VI-7. The symbols C, LS and T denote the central, spin-orbit and tensor components of the force, while the symbols R and I denote real and imaginary parts.

In order to provide a broader setting for both the data and results of the computations, we discuss for each transition not only the results of our work, but those obtained by other authors at other incident proton energies. It is hoped that such a systematic study will provide a broader understanding of the transitions investigated. Where applicable, results of studies using probes other than protons are discussed. Comparison with electron scattering is very useful. Even if the transition densities are not well determined, useful information concerning the nucleon-

Key for Curves in Figures VI-8 to VI-56

Comparisons with Data

.....	CR
.	CR+CI = C
-----	C+LSR
- - - - -	C+LSR+LSI = C+L
— — — — —	C+L+TR
—————	C+L+TR+TI = C+L+T

Comparison of Calculations at different Energies

.....	E_p Force
	398 MeV (425 MeV)
-----	597 MeV (515 MeV)
— — — — —	597 MeV (650 MeV)
—————	698 MeV (650 MeV)
— — — — —	698 MeV (800 MeV)

Figure VI-7.

nucleon interaction and reaction dynamics may be extracted by comparing normalization factors necessary to bring inelastic electron and proton scattering calculations into agreement with the data. If these renormalization factors are comparable, then it is appropriate to say that the description of the (p,p') interaction and reaction dynamics is reasonable and the difficulties lie with the transition densities.

1) Isoscalar states of natural parity

(a) The $2_1^+;0$ state at $E_x = 4.44$ MeV

The dominant configuration for the excitation of this state is $(p_{1/2}p_{3/2}^{-1})$. The $(p_{3/2}p_{1/2}^{-1})$ configuration yields an almost comparable contribution of opposite phasing, and the $(p_{3/2}p_{3/2}^{-1})$ term is half as strong as the $(p_{1/2}p_{3/2}^{-1})$ term and also of opposite phase. The oscillator parameter used was 1.681 fm.

The results of the calculations are presented in Figures VI-8 to VI-11. The calculations are seen to significantly underestimate the data for all beam energies. This is not unusual for natural parity collective states where effective charges are needed to explain $B(EL)$ values. Renormalization factors of 2.10, 3.25, and 3.74 are required to produce the agreement shown in Figure VI-11. With this

$E_x = 4.44 \text{ MeV } 2_1^+; 0 - \text{Differential Cross Section Calculations}$

Figure VI-8.

$E_x = 4.44 \text{ MeV } 2_1^+; 0 - \text{Analyzing Power Calculations}$

Figure VI-9.

$E_x = 4.44 \text{ MeV } 2_1^+; 0$ - Comparative Calculations for Observables

Figure VI-10.

$E_x = 4.44 \text{ MeV } 2_1^+; 0$ - Renormalized Differential Cross Sections

Figure VI-11.

correction the quality of the fit is good but not perfect. The calculated cross section overestimates the data over the region encompassing the rise to the maximum, while underestimating the data in the region of fall-off for $q > 1 \text{ fm}^{-1}$. The problem of understanding the large momentum transfer data has been reported by Comfort et. al.^{5-7,9)} for incident energies from 122 MeV to 200 MeV where large momentum transfer fits are much worse than shown here. Density-dependent modifications to the interaction determined by Kelly et. al.⁵¹⁾ for isoscalar natural parity transitions yielded considerable improvement in the shape of the differential cross sections and the absolute cross section scale for fits to the 122 MeV data⁵²⁾. Such effects are expected to be much smaller at our energies. From Figure VI-11 it is apparent that a small adjustment to the oscillator parameter would give a very good fit of the renormalized calculation to the data. Coupled channels effects have been seen to contribute to enhancements of calculated cross sections for large q . Such investigations are currently being conducted and will be reported elsewhere.

The renormalization factors are of considerable interest. The electromagnetic excitation of this transition in inelastic electron scattering indicates that core polarization effects result in an enhancement of the pure Cohen-Kurath results by a factor of two^{53,54)}. Also, the experimental $B(E2)$ value exceeds the predicted value by about 2.0.

Consequently, it is reasonable to require that the results of the DWIA calculations be multiplied by 2.0 for comparison with the data. The calculation at 398 MeV after renormalization to account for such effects differs from the data only by some 10%. From Table VI-3 we see that additional enhancement factors of 1.55 and 1.75 are required after renormalization to bring the calculations for 597 MeV and 698 MeV into agreement with the data. Comfort et. al.⁵⁻⁹⁾ have seen that suitably renormalized fits to data at 122, 185 and 200 MeV consistently overestimate the data by factors of 1.15 to 1.9. Haji-Saied et. al.¹⁵⁾ report reasonable agreement with the data of Blanpied at 800 MeV after appropriate renormalization. They observe an overestimation for small angles and an underestimation for q between 1 and 2 fm⁻¹, as is found in the current work. It is not clear why the progression from overestimation at low incident energies to underestimation at 698 MeV is broken for the 800 MeV data. Medium corrections have not been applied to any computations for energies greater than 122 MeV, and while these corrections are very successful at 122 MeV⁵²⁾, it would be interesting to see if such successes can be repeated for higher energies where deficiencies are seen to exist at large momentum transfer.

Careful observation of the curves in Figure VI-8 show the primary dependence of the cross section on the imaginary central part of the force. This is different from

the observations of Comfort et. al.⁹⁾ who find that at 200 MeV the transition is dominated by the real part of the central interaction. Removal of the imaginary term for these lower energy calculations is seen to make a small difference and results in an improvement in the quality of the fit to the cross section, but results in a degradation of the fit to the analyzing power. The difference in dependence on real and imaginary parts of the central interaction is understood in terms of the energy dependence of the real and imaginary strengths of the central optical potential described previously. Enhancement due to the spin-orbit component of the force is significant, especially at large momentum transfers, while the tensor terms play essentially no role. Such observations are in keeping with the expectations outlined at the end of Chapter II. Calculations with the 515 MeV force required an increase of 1.4 in the renormalization factor required to reproduce the 597 MeV data, showing poorer agreement. The calculation with the 800 MeV force reduced the renormalization factor for the 698 MeV data by 1.4, resulting in better agreement with the data.

Turning to the analyzing powers, we see from Figure VI-9 that the shapes of A_y for the different beam energies are reasonably well reproduced, but a phase difference between calculation and data is clearly evident. Forward angle data are generally underestimated, while larger angle data are overestimated. A similar phase difference has been

observed by Comfort et. al. at 200 MeV⁹⁾, while calculations at 120 MeV are found to overestimate the data uniformly⁶⁾. The microscopic spin-orbit interaction is seen to be primarily responsible for reproducing the shape of the analyzing powers. The mismatch between data and calculation for the analyzing power discussed here does not mirror that seen for the elastic analyzing power.

It is appropriate to consider the role played by spin-orbit distortions in the incoming and outgoing channels. Computations were performed with the spin-orbit optical potential terms set to zero. The central force yields zero analyzing power, but the microscopic spin-orbit force was found to reasonably reproduce the shape of A_y for $q < 1 \text{ fm}^{-1}$. The analyzing power so calculated was in general larger than that computed with distortions, and the structure seen between 2 and 2.5 fm^{-1} was removed. The calculated cross section was reduced by about 12%, resulting in a comparable increase in the renormalization factor. Spin-orbit distortion effects are therefore seen to play a relatively minor role for low momentum transfers, but are significant for $q > 1.0 \text{ fm}^{-1}$.

The effect of including knock-on exchange in the calculation is to significantly reduce the calculated cross sections, and to enhance the analyzing powers. The interference of the direct and exchange terms in the central imaginary calculation results in a reduction of the direct

cross section by a factor of almost 3.5, while enhancing the analyzing power computed in the spin-orbit terms by a factor of 2.

The qualitative features of σ^*A_y are reproduced by the calculations. However, the 698 MeV result is enhanced above that for 597 MeV, contrary to the behaviour of the data.

(b) The $3_1^-; 0$ state at $E_x = 9.64$ MeV

The dominant configuration for the excitation of this state is $(d_{5/2}p_{3/2}^{-1})$, with significant contributions from $(d_{5/2}p_{1/2}^{-1})$ with the same phasing and $(d_{3/2}p_{1/2}^{-1})$ with opposite phasing. The oscillator parameter used was 1.681 fm.

The results of the calculations are presented in Figures VI-12 to VI-15. As was the case for the $2_1^+; 0$ state, the calculations significantly underestimate the data. Renormalization factors of 1.85, 2.93 and 3.00 are required to produce the good agreements shown in Figure VI-15. Some over-estimation by the calculations for low q after renormalization is seen for 597 and 698 MeV, but agreement for 398 MeV is excellent. Table VI-3 shows that the enhancement factors for 597 and 698 MeV relative to 398 MeV are 1.58 and 1.62 respectively, in reasonable agreement with those determined for the $2_1^+; 0$ state. Comfort et. al. find that little renormalization is required for this transition for $E_p = 200$

$E_x = 9.64 \text{ MeV } 3_1^-; 0$ - Differential Cross Section Calculations

Figure VI-12.

$E_x = 9.64 \text{ MeV } 3_1^-; 0$ - Analyzing Power Calculations

Figure VI-13.

$E_x = 9.64 \text{ MeV } 3_1^-; 0$ - Comparative Calculations for Observables

Figure VI-14.

$E_x = 9.64 \text{ MeV } 3_1^-; 0$ - Renormalized Differential Cross Sections

Figure VI-15.

MeV⁹⁾.

The dominant longitudinal electron scattering form factor is well reproduced when renormalized by a factor of two out to a momentum transfer of about 1.7 fm^{-1} , and the weaker transverse form factor is underestimated by about a factor of 0.6^{9,54)}. A renormalization by about two of our calculations is therefore justified, and so agreement at 398 MeV is reasonable. Comfort et. al. also found little sensitivity to the $S = 1$ amplitudes in the wavefunctions⁹⁾.

Study of the curves in Figure VI-12 show the primary contributions to the cross section to come from the central imaginary and real spin-orbit terms in the interaction, the spin-orbit term providing enhancement primarily in the high q region and at 398 MeV. The relative enhancement due to this term is seen to decrease for increasing incident energy. The strong dependence on the imaginary part of the interaction is again opposite to that observed by Comfort et. al. who find the primary contribution to come from the real central term⁹⁾. Medium corrections have not been considered for this transition, and coupled channels effects are currently under investigation.

The analyzing powers, as seen in Figure VI-13, are reasonably well reproduced in shape, but exhibit a problem in phasing similar to that discussed in the previous section. Forward angle data are underestimated while large

momentum transfer data are overestimated. Again the dominant contribution to this observable is the real spin-orbit term in the interaction. A slight phase difference in the sense observed in this work is found to exist for the data at 200 MeV⁹⁾.

Removing spin-orbit distortion effects in the optical potential results in effects almost identical to those reported in the previous section. Knock-on exchange amplitudes again reduce the direct amplitude cross sections by a factor of 3.2, and in this instance the analyzing powers are also enhanced by the exchange effects. The qualitative features of the energy dependence of the calculated cross sections are consistent with the energy dependence of the measured cross sections. The shape of the product $\sigma \cdot A_y$ is consistent with the data, but the difference in A_y yields a greater difference between the calculated values for 597 and 698 MeV than is seen for the data.

(c) The $1_1^-; 0$ state at $E_x = 10.84$ MeV

The dominant configuration in the transition density is $(2s_{12}1p_{3/2}^{-1})$ with additional significant contributions from the $(d_{5/2}p_{3/2}^{-1})$ and $(2s_{1/2}1p_{1/2}^{-1})$ terms, which are of the same phase as the dominant component. Small contributions from a variety of other configurations are present, and may be found in Table VI-2. The oscillator parameter used was 1.681 fm.

The results of the calculations are presented in Figures VI-16 to VI-19. The fit to the cross section data for an incident energy of 398 MeV is remarkably good, while the data for 597 MeV are underestimated by a factor of 1.83, somewhat larger than the 2^+ and 3^- states. The fact that the shape of the data is so well fitted is especially interesting in view of the fact that it is very similar to the shape of the 3^- data. A collective model would thus give a very poor fit. The paucity of data for 698 MeV precludes any statement concerning the relationship between data and theory.

We note once more the strong contributions from the imaginary central component of the interaction, as well as the enhancement due to the spin-orbit term. It is of interest to note that the spin-orbit enhancement is now almost uniform as a function of q , rather than simply being most significant for large momentum transfer as observed for the two states discussed previously. It is surprising that the calculated cross sections do not exhibit a clear systematic increasing trend as a function of incident projectile energy as seen in Figure VI-18. Indeed, the values for the differential cross section at the peak are almost identical for all beam energies. Some structure is seen at both very small and large momentum transfers.

The calculated analyzing powers exhibit some of the same qualitative features as those for the 4.44 and 9.64 MeV

$E_X = 10.84 \text{ MeV } 1_1^-; 0 - \text{Differential Cross Section Calculations}$

Figure VI-16.

$E_x = 10.94 \text{ MeV } 1_1^-; 0$ - Analyzing Power Calculations

Figure VI-17.

$E_x = 10.84 \text{ MeV } 1_1^-; 0$ - Comparative Calculations for Observables

Figure VI-18.

$E_x = 10.84 \text{ MeV } 1_1^-; 0 - \text{Renormalized Cross Section}$

Figure VI-19.

states which have been discussed previously. There are some notable differences, however, particularly in the low momentum transfer region from 0.0 to 0.6 fm⁻¹. While the $2^+_{11};0$ and $3^-_{11};0$ states exhibit little structure in this region, the calculations for the $1^-_{11};0$ state show pronounced negative minima. The depth of the minimum decreases with increasing projectile energy and at 597 MeV two small minima are seen to emerge. In addition, the tensor term is seen to play a significant role in this region, while intermediate and high momentum transfer data are dominated by the spin-orbit component of the interaction as for other isoscalar natural parity states. However, the small cross section at low q precludes observation of this effect.

The product of the differential cross section and analyzing power, while exhibiting the sharp peak characteristic of the natural parity isoscalar transitions, shows an unusual trend. Whereas the $2^+_{11};0$ and $3^-_{11};0$ states show an increase in this quantity as a function of energy, this state shows a decrease, largely due to the sharp decrease in A_y from an incident energy of 398 MeV to 597 MeV, given that the differential cross section is roughly constant. In this context it is unfortunate that little data was extracted at 597 and 698 MeV, but as was seen in Figure V-18 indications are that the experimentally observed energy dependence of this quantity is not consistent with the calculations. Experiments at other energies have not reported data for this

transition, nor have studies of this nucleus with other probes.

The substantive difference between this transition and the $2\frac{1}{2}^+;0$ and $3\frac{1}{2}^-;0$ transitions may be found in the transition densities. While the preceding two transitions involve particle-hole configurations exclusively within the lowest (1) principal quantum number harmonic oscillator shell, the excitation of the $1\frac{1}{2}^-;0$ transition is dominated by configurations requiring the promotion of a particle from the lowest to the second (2) shell. The $2s_{1/2}$ harmonic oscillator wave function then necessarily has a node at about $r = 2 \text{ fm}^{-1}$ and is negative for values of r smaller than this because the DW81 code requires the radial wave function to be positive at infinity. This then can result in differing sensitivities of the spin-orbit and tensor components of the interaction to the transition densities. Additional data for this transition would be most useful in examining this phenomenon.

Once again, little dependence is seen on the distortion terms in the optical potentials; the low momentum transfer dependence being relatively independent of these effects. Knock-on exchange results in a reduction in the magnitude of the direct differential cross section by a factor of 3.5, consistent with the other transitions of this kind.

(d) Summary

We have determined several systematic trends for isoscalar states of natural parity. The excitation of these states is dominated by the imaginary central and real spin-orbit components of the effective interaction. The dependence on the imaginary part of the central term is different from the observations of Comfort et. al. at lower energies. The differential cross sections were in general underestimated by the calculations. Spin-orbit distortion effects in the optical potentials were found to play a minor role for low momentum transfers, but contributed significantly to a reduction in A_y for moderate values of q . Knock-on exchange effects, which were included in all cases, were found to consistently interfere destructively with the direct processes, resulting in a reduction in the magnitudes of the calculated cross sections by a consistent factor of 3.5, independent of energy. The analyzing power and differential cross section for the 10.84 MeV state were found to exhibit deviations from the systematic behaviour seen for the 4.44 and 9.64 MeV states. These deviations are probably attributable to the $2s_{1/2}$ transition density components.

2) Isovector states of natural parity

The $2^+ T = 1$ State at $E_x = 16.11$ MeV

The Cohen-Kurath transition density for this state

is dominated by the $(p_{1/2}p_{3/2}^{-1})$ configuration, like the $1^+;1$ state at 15.11 MeV. There is an admixture of the $(p_{3/2}p_{1/2}^{-1})$ configuration, but this is much weaker. The $S = 0$ and $S = 1$ amplitudes in the Cohen-Kurath wavefunctions are of comparable magnitude, and the relative importance of these amplitudes is then determined by the importance of the parts of the force which dominate the interaction. Relative to this wavefunction, electron scattering data show a suppression of the longitudinal and transverse form factors associated with this state^{53,55}). Consequently the $S = 0$ and $S = 1$ amplitudes can be renormalized to accommodate this suppression. The normalization factors used in the LS representation⁵⁶) were 0.50 and 0.84 for the $S = 0$ and $S = 1$ components respectively. The resulting transition density is still dominated by the $(p_{1/2}p_{3/2}^{-1})$ configuration, but the $(p_{3/2}p_{1/2}^{-1})$ term is suppressed, being replaced by a contribution of opposite phase from the $(p_{3/2}p_{3/2}^{-1})$ configuration.

The excitation of this state can be mediated by the t_{τ}^C , $t_{\sigma\tau}^C$, t_{τ}^{LS} and t_{τ}^T components of the interaction. The isovector spin-orbit component is generally very small and may be neglected. The dominance of the $S = 0$ or $S = 1$ amplitudes for the central component of the interaction may be determined by evaluating the ratio $\left| \frac{t_{\sigma\tau}}{t_{\tau}} \right|^2$ as a function of q and E_p . For the 425 MeV force this quantity is greater than 1 and the $S = 1$ amplitude is more significant for all q . This is true for lower energies also, as has been pointed

out by Comfort et. al.⁹⁾. For the 650 MeV force, the ratio is unity for $q = 0.5 \text{ fm}^{-1}$, but for larger q it is less than unity, and the $S = 0$ amplitude is more significant.

The results of the calculations using standard CKWF are presented in Figures VI-20 to VI-22. The renormalized transition densities were used in the computations presented in Figures VI-23 to VI-25.

The DWIA calculations affirm the dominance of the real isovector tensor exchange part of the interaction, t_{τ}^T , together with contributions from the real central terms. The spin-orbit terms play almost no role. We discuss first the features of the fits using the standard CKWF.

For $E_p = 398 \text{ MeV}$ the calculated differential cross section is seen to overestimate the data by a factor of 1.85. Similar factors for $E_p = 597$ and 698 MeV are 1.2 and 1.5 respectively. Rescaled plots are shown by the solid curves in Figure VI-26. The data for the higher beam energies are well reproduced after rescaling. This is not true for 398 MeV where the calculation is seen to peak at $q = 1.10 \text{ fm}^{-1}$ while the data peak at $q = 0.95 \text{ fm}^{-1}$. This phase difference results in the calculation's over-estimating the data for $q > 1 \text{ fm}^{-1}$ even after scaling. For this particular set of transition densities it is clear that the dominant effect of the isovector tensor part of the force is decreasing for increasing beam energies. The enhancement due to

$E_x = 16.11 \text{ MeV } 2_1^+; 1 - \text{Differential Cross Section Calculations (Unquenched)}$

Figure VI-20.

$E_x = 16.11 \text{ MeV } 2_{11}^+; 1 - \text{Analyzing Power Calculations}$
(Unquenched)

Figure VI-21.

$E_x = 16.11 \text{ MeV } 2_1^+; 1$ - Comparative Calculations for Observables (Unquenched)

Figure VI-22.

$E_x = 16.11 \text{ MeV } 2_1^+; 1 - \text{Differential Cross Section Calculations (Quenched)}$

Figure VI-23.

$E_x = 16.11 \text{ MeV } 2_1^+; 1 - \text{Analyzing Power Calculations}$
(Quenched)

Figure VI-24.

$E_x = 16.11 \text{ MeV } 2_1^+; 1$ - Comparative Calculations for Observables (Quenched)

Figure VI-25.

$E_x = 16.11 \text{ MeV } 2_1^+; 1 - \text{Renormalized Differential Cross Sections (Both)}$

Figure VI-26.

this component at $q = 1.5 \text{ fm}^{-1}$ is reduced from 3.3 at 398 MeV to 2.3 at 597 MeV to 2.1 at 698 MeV. Also, the central term shows a decrease of some 30% from 398 MeV to 597 MeV, then rising again to a value at the maximum for 698 MeV which is comparable to that for 398 MeV. The low momentum transfer behaviour also changes significantly from 398 MeV to 597 MeV. The cross section for the smallest values of q is enhanced relative to that for 398 MeV by a factor of three for 597 MeV and five for 698 MeV. Also, a pronounced minimum is seen at $q = 0.4 \text{ fm}^{-1}$ for 597 and 698 MeV. Such a minimum is absent in the 398 MeV calculation, as well as in the lower energy calculations of Comfort et. al.⁹⁾. Examination of the q and E_p dependence of t_r^T as determined by Love and Franey shows the shape of the low momentum transfer region to be largely determined by this part of the force.

Renormalization of the transition densities results in only minor differences in the overall shape of the calculated cross sections, as is seen from the dashed lines in Figure VI-26. Some small differences for $q \leq 0.5 \text{ fm}^{-1}$ and $q \geq 1.5 \text{ fm}^{-1}$ are seen; the renormalized transition densities yielded slightly lower values than the standard CKWF. Renormalization provides a very good fit to the data for $E_p = 698 \text{ MeV}$, an improved fit to the data for $E_p = 398 \text{ MeV}$, and a poorer fit to the data for $E_p = 597 \text{ MeV}$. The calculation continues to overestimate the 398 MeV data, but now only by a factor of 1.2. This renormalization factor is consistent

with those noted by Comfort et. al.⁹⁾ and Haji-Saied et. al.¹⁵⁾ and with that required for electron scattering⁵³⁾. The 597 MeV data are now underestimated by a factor of 1.6.

The enhancement factors for the t_T^T term at $q = 1.5 \text{ fm}^{-1}$ are 4.0, 3.7 and 3.2 for the energies 398, 597 and 698 MeV respectively. The central term retains the same behaviour as seen without transition density renormalization. At the smallest values of q , the t_T^T term contributes an enhancement in the cross section relative to that at 398 MeV of a factor of 2.8 for 597 MeV and 4.3 for 698 MeV. It is also evident that the contribution of t_T^T to the cross section for small q is more significant by a factor of two than for the standard CKWF.

In summary, the renormalization of the transition densities results in an overall reduction in the strength of the cross section. Furthermore, the contribution from the isovector tensor term is enhanced for all beam energies, particularly for the 650 MeV force.

The fits to the analyzing power data are poor at large momentum transfer. No significant difference is observed between standard and renormalized transition density calculations for A_y . Whereas the measured analyzing powers become negative for $q > 1.4 \text{ fm}^{-1}$, the calculations give monotonically increasing positive values from $q > 1 \text{ fm}^{-1}$. Some modicum of agreement is seen for small q , but calcula-

tion and data clearly diverge for large q . The source of the divergence is not readily obvious because of complicated interferences which occur between contributions from various parts of the force.

Analyzing power data for this transition have been reported by Comfort et. al. for energies of 122⁷⁾ and 200⁹⁾ MeV. The data at these energies are different in structure from the data reported here, being in general positive but showing some structure for large momentum transfer (2-2.5 fm⁻¹). DWIA calculations at these energies give results not completely consistent with the data, but quite dissimilar to those reported here, the A_y becoming negative in the large q region.

It is remarkable that this state should show a very small dependence on incident beam energy as compared with the $2^+_{1/2}$ state. The calculations presented here, together with those of Comfort and Haji-Saied, show a slight decrease in magnitude as incident energy increases, consistent with the data. It should also be pointed out that the data at 398 MeV are consistent with those of Escudie et. al. at 402 MeV. The dominance of the isovector tensor term makes it difficult to examine the q and E_p dependence of the central isovector terms, but the central contribution to the full cross section is roughly consistent with the dependences predicted by Love and Franey.

The fits to the cross section data out to about 2 fm^{-1} suggests that the isovector tensor and central components of the interaction, and their energy dependence, appear to be correct over this range of momentum transfer to within a factor of about 1.2. Furthermore, the renormalization of the calculation based on electron scattering data appears to be correct.

The serious difficulties with the analyzing power calculations are not easily understood. Knock-on exchange terms are found to reduce the cross sections as has been noted for isoscalar natural parity states, but the effect is somewhat reduced from a factor of 3.5 to about 2.

3) Isoscalar states of unnatural parity

The $1^+ T = 0$ state at $E_x = 12.71 \text{ MeV}$

The dominant transition densities associated with this state are $(p_{1/2}p_{3/2}^{-1})$ and $(p_{3/2}p_{1/2}^{-1})$, the former being twice as strong as the latter. Small contributions from the rearrangement configurations within the $p_{1/2}$ and $p_{3/2}$ subshells are also present, and these were included in the calculations. The harmonic oscillator parameter used in the computations was 1.572 fm .

The comparison of the results of the DWIA calculations with the experimental data are presented in Figures

VI-27 and VI-28. The full curves for a variety of forces at different energies are presented in Figure VI-29.

An excellent fit to the differential cross section data for q up to 1.4 fm^{-1} is obtained for $E_p = 398 \text{ MeV}$. For $q > 1.4 \text{ fm}^{-1}$, the full calculation is seen to underestimate the data, and also to show less structure than is evident in the data. We note the constancy of the cross section projected back to $q = 0$ at this beam energy. The fit to the cross section data for $E_p = 597 \text{ MeV}$ is poor. A serious discrepancy occurs for small values of q where the calculated curve underestimates the measured cross section, and falls off as q goes to zero, contrary to what is observed for $E_p = 398 \text{ MeV}$. For $0.8 \text{ fm}^{-1} < q < 1.2 \text{ fm}^{-1}$ agreement with the data is reasonable, but as for the 398 MeV data the calculation underestimates the data for $q > 1.2 \text{ fm}^{-1}$. A more pronounced structure in the calculation for the 597 MeV case is observed in the 1.6 to 1.8 fm^{-1} region of q , which appears to better reproduce the shape of the data in this region. The fit to the cross section data for $E_p = 698 \text{ MeV}$ is seen to exhibit some of the same characteristics as that for the 597 MeV data. Agreement for small q is poor, the calculation also falling off as q tends to zero. Agreement in the intermediate range of q is good, and while the data for $q > 1.4 \text{ fm}^{-1}$ are again underestimated, agreement is much closer than for the lower energies. The shape in the large momentum transfer region is reasonably reproduced, partly

$E_x = 12.71 \text{ MeV } 1_1^+; 0$ - Differential Cross Section Calculations

Figure VI-27.

$E_x = 12.71 \text{ MeV } 1_1^+; 0$ - Analyzing Power Calculations

Figure VI-28.

$E_x = 12.71 \text{ MeV } 1_{\frac{1}{2}}^+; 0$ - Comparative Calculations for Observables

Figure VI-29.

because error bars are large.

Comparison of the calculations with the analyzing power data show a remarkable degree of success for $E_p = 398$ MeV at all momentum transfers. Unfortunately, agreement for the higher beam energies is not as good. The higher energy calculations do not exhibit the same distinctive negative values for low q seen in the data, and a clear difference in phase between calculations and data is apparent. The phase difference between the calculations for the three different beam energies is most clearly evident in Figure VI-29.

The calculations show that the dominant mechanism for the excitation of this state is the imaginary tensor exchange part of the force, especially at low q and 398 MeV. The spin-flip part of the central force is weak, while the real isoscalar spin-orbit component plays a significant role. Of interest is the change in shape for low q of the calculated cross section in going from the 425 MeV force to the 650 MeV force, as well as the marked difference in shape for A_y yielded by these two descriptions of the force. The tensor exchange contribution is decreasing as a function of energy in the intermediate momentum transfer region, but is roughly constant for the smallest values of q , and does not explain the observed differences. It appears that a reduction in the spin-orbit strength in the low q region results in the reduction of the forward angle calculated cross section for the 650 MeV force. Since both the 597 and 698 MeV

calculations were done with the 650 MeV force, it is reasonable to suspect a deficiency in the force at this energy to explain the observed behaviour.

To further investigate this problem, computations were performed using the 597 MeV optical potentials with the 515 MeV force to attempt to reproduce the 597 MeV data, and using the 698 MeV optical potentials and the 800 MeV force to attempt to reproduce the 698 MeV data. The 800 MeV force showed the same behaviour as the 650 MeV force, and produced no significant improvement. The 515 MeV force, however, generated a small momentum transfer dependence in the observables which fit the data better, and also were more consistent with the results at 398 MeV. This force has about the same spin-orbit strength as the 425 MeV force, but less tensor strength.

We recall that the 597 MeV optical potential was somewhat suspect. Several calculations were performed to deduce the sensitivity of the low momentum transfer dependence of the calculations to various terms in the optical potential. Removing either the real central or surface imaginary terms resulted in no significant change in the cross sections. The calculated analyzing powers were also insensitive to these changes. The effects of removing the spin-orbit distortions from the entrance and exit channels at both 597 and 698 MeV are minimal. A small change in the overall slope of the cross section is observed, and the

analyzing powers showed little change.

This insensitivity of the calculated observables to the optical parameters and spin-orbit distortions indicates that the poor fits to the data, especially at low q , are an artifact of the force rather than adjustable parameters. The difficulty seems to lie with the real isovector component of the spin-orbit force, especially for $q < 0.5 \text{ fm}^{-1}$. The fact that this discrepancy occurs for both the 597 and 698 MeV data when both are described by the 650 MeV force is also an indication. This is more obvious when the 515 MeV force removes a substantial part of the discrepancy when used to describe the 597 MeV data. The weak negative analyzing power for low q calculated from the 650 MeV force is a further indication of a deficiency in the description of the spin-orbit force at this energy.

Extensive studies of this transition have also been made by several authors at a variety of incident proton energies, as well as with other probes. Escudie et. al. measured the differential cross section for this transition at $E_p = 402 \text{ MeV}$, and while forward angle agreement with the data presented here is reasonable, the 402 MeV data drop slightly more rapidly for $q > 1.5 \text{ fm}^{-1}$ than the 398 MeV data. The source of this difference remains unclear. Comfort et. al. have reported differential cross section data for $E_p = 122, 185$ and 200 MeV , and analyzing power data for $E_p = 122$ and 200 MeV (5-7,9). Haji-Saied et. al. have report-

ed data for $E_p = 800$ MeV together with DWIA calculations¹⁵⁾. What is striking about these data is the significant degree of insensitivity of both the magnitude and shape of the cross section as a function of incident particle energy. There is some energy dependence for the smallest momentum transfers, the cross section rising gradually in this region as the incident energy rises. The shoulder at $q = 1.4 \text{ fm}^{-1}$ is clearly evident in all the data, and appears to retain its shape over the entire energy range.

Agreement with calculations, though, exhibits a definite energy dependence. Fits to the differential cross sections for $E_p \leq 200$ MeV badly overestimate the data for the smallest momentum transfers, while underestimating at larger momentum transfers^{5-7,9)}. At 800 MeV there is a slight underestimation of the data at smallest angles, agreement at intermediate angles and underestimation for large angles¹⁵⁾. The calculated cross sections are almost invariant as a function of energy with the exception of those involving the 650 MeV force and 597 MeV optical potential. The slight energy dependence of the data for low q consequently results in better fits to the data in the 400 to 800 MeV range; at large q the data and the calculations are about the same as a function of energy.

Electron scattering is not of much assistance in understanding the behaviour of this state. There is a large degree of interference and consequent cancellation between

spin and orbital contributions, and also high sensitivity to isovector admixtures. While small isospin admixing has been proposed^{57,58)}, the effects on (p,p') scattering are negligible. The Cohen-Kurath wave functions are found to underestimate the measured transverse form-factors by about a factor of four⁵³⁾.

The analyzing powers reported by Comfort et. al. are in marked disagreement with calculations at 122 MeV⁷⁾ while agreement is much improved at 200 MeV⁹⁾. The calculations yield strongly negative values for low q , crossing to positive values in the 1 fm^{-1} region as we have seen for the calculations performed in this work. The data at 122 MeV are not negative for low q , but this disagreement is an exception to the systematics observed from 200 MeV to 700 MeV.

As has been mentioned, the knock-on exchange terms are essential for the description of the tensor term. Interference between direct and exchange amplitudes results in a reduction in the differential cross section by a factor of 2 from the direct calculation only.

4) Isovector states of unnatural parity.

(a) The $1^+ T = 1$ state at $E_x = 15.11 \text{ MeV}$

The dominant transition densities are $(p_{1/2}p_{3/2}^{-1})$ and $(p_{3/2}p_{1/2}^{-1})$, the ratio of the strengths being 2:1. Small contributions from rearrangement configurations within the

$P_{1/2}$ and $p_{3/2}$ subshells are also present, and were included in the calculations. The harmonic oscillator parameter used for this state was 1.866 fm, the largest for any state and required to fit the electron scattering form factor⁵⁴⁾.

This transition is primarily mediated at small q by the central spin-isospin flip part of the nucleon-nucleon amplitude, which is dominated by one pion exchange. The tensor isovector term t_{τ}^T plays a dominant role for larger momentum transfers. The Cohen-Kurath transition densities used in the computations are believed to be reliable for $q \leq 1 \text{ fm}^{-1}$, but not for values of q larger than this^{53,54)}. The Cohen-Kurath wave functions are successful in reproducing the shape of the inelastic electron scattering transverse form-factor out to about 1.5 fm^{-1} , but fail to reproduce a second maximum near $q = 2 \text{ fm}^{-1}$. The quality of the fit to the data for $q \leq 1.0 \text{ fm}^{-1}$ would then furnish information concerning the validity of the force, assuming the transition density in this region to be well-defined.

Comparison of the calculations with the data are presented in Figures VI-30 and VI-31, and the calculations are compared with each other in Figure VI-32.

The DWIA calculations show the forward angle cross section to be dominated by the real component of $t_{\sigma\tau}^C$, while the real isovector tensor term plays an important role in enhancing the cross section for $q > 0.5 \text{ fm}^{-1}$. The spin-

$E_x = 15.11 \text{ MeV } 1_1^+; 1 - \text{Differential Cross Section Calculations}$

Figure VI-30.

$E_x = 15.11 \text{ MeV } 1_1^+; 1$ - Analyzing Power Calculations

Figure VI-31.

$E_x = 15.11 \text{ MeV } 1_1^+; 1 - \text{Comparative Calculations for Observables}$

Figure VI-32.

orbit components are seen to have an almost negligible effect. The fit to the cross section data for $E_p = 398$ MeV up to $q \sim 0.6 \text{ fm}^{-1}$ is excellent. Agreement is reasonable for $E_p = 698$ MeV over the same region of q , while the fit to the data at $E_p = 597$ MeV is poor in this range. The calculation for this latter beam energy underestimates the data by a factor of about 1.6.

The calculations for the analyzing powers show a consistency in shape and phase as a function of incident particle energy. This is in contrast to the more significant energy dependence seen for the isoscalar 1^+ state discussed previously. The analyzing power for $q > 0.5 \text{ fm}^{-1}$ appears to be strongly influenced by the tensor exchange component of the interaction. In general the small q data are reasonably fit by the calculation. The shapes of the data and the calculations are consistent, but a definite phase difference between data and calculation at each beam energy is seen, although the relative phases of the calculations are constant. The first minimum in the calculated analyzing power occurs at a larger value of q than in the data, becoming progressively worse as the beam energy increases. The location of the minimum is coincident with the location of the dip in the calculated cross section.

This transition, because of the reliability of the Cohen-Kurath wave functions for low q , provides a good test of the components of the effective interaction in this re-

gion. Since we find excellent agreement for the low momentum transfer region at 398 MeV and reasonable agreement at 697 MeV, the spin-isospin flip component of the interaction describing this transition appear to be well-defined. The discrepancy at 597 MeV may to some extent be removed by use of the 515 MeV parameterization which gives a slightly larger cross section than the 650 MeV force at this energy.

This particular state has been the subject of much recent interest in the search for evidence of precritical phenomena related to pion condensation in the nucleus. Calculations using the Landau fermi-liquid theory by Toki and Weise and others predict a significant peak (about a factor of three) in the differential cross section for $q \sim 1.6-2.0 \text{ fm}^{-1}$ (20-23). No evidence for such an enhancement is seen in the data, and this, together with the fact that the shape of the data is reasonably reproduced by a standard DWIA calculation, allow us to conclude that such evidence for precritical phenomena is not seen for this state at these beam energies. The discrepancies seen here between theory and experiment are comparable to those observed for other states, specifically the 12.71 MeV 1^+_{π} state for which no precritical phenomena should exist. This conclusion is compatible with similar observations made by Comfort et. al.^{6,9,52)} and Haji-Saeid et. al.¹⁴⁾ at lower and higher beam energies.

The disagreements between calculation and experiment in the high momentum region have proved to be rather in-

tractable. Comfort⁵²⁾ has studied this transition at lower energies in great detail, and concluded that reasonable variations of available parameters could not account for the observed discrepancies. Similar difficulties have been noted at 800 MeV by Haji-Saied et. al.¹⁴⁾. Comfort has noted that for lower energies removal of the $[LSJ] = [111]$ amplitude from the transition density, or alternatively the use of the empirical amplitudes of Dubach and Haxton⁵⁹⁾, resulted in some improvements. This constant problem, though, does not yet have a satisfactory explanation. The calculations presented here do not, unfortunately, aid in the resolution of this difficulty.

The analyzing powers at lower energies show much more structure than is seen in the results of this work. The calculations at 122 MeV reasonably reproduce the forward angle data, but exhibit much the same phase difficulties for larger angles as seen in this work. The situation at 200 MeV is much worse, the calculation and data being completely out of phase. This situation may be remedied to a certain extent by the removal of the $[111]$ amplitude.

The effects of spin-orbit distortions on this transition are rather interesting. While having little effect on the low momentum transfer cross section and analyzing power, removal of the spin-orbit distortions causes a significant deepening of the minimum in the region of the shoulder in the differential cross section at $q = 1.2 \text{ fm}^{-1}$. Also,

the first minimum in the analyzing power, corresponding to the cross section minimum, is much sharper in the absence of such distortions. The distortions are thus essential to smooth out the calculation in this region, thus bringing the results into better qualitative agreement with the data.

Over the momentum transfer region encompassing the data, the knock-on exchange terms are seen to reduce the direct differential cross sections by an almost uniform factor of two. While such a reduction is generally favourable for low momentum transfers, it possibly contributes to deficiencies at higher values of q .

We finally note the remarkable independence of the calculated differential cross sections as a function of incident particle energy. Although small deviations are seen for low q and also in the region of the shoulder, it is clear that the $t_{\sigma\tau}^C$ and t_{τ}^T terms which mediate the excitation of this state should be approximately constant as a function of E_p for different values of q . The figures presented in Chapter II attest to the validity of this observation.

(b) The $2^- T = 1$ state at $E_x = 16.58$ MeV

The transition density for this excitation is dominated by the $(2s_{1/2}1p_{3/2}^{-1})$ configuration with a significant contribution from the $(d_{5/2}p_{3/2}^{-1})$ configuration. Several other configurations are present but are negligibly small. The oscillator parameter used in the computations was 1.681

fm, which is the same as used by Comfort et. al.^{6,9)} but larger than that of 1.55 used by Haji-Saeid et. al.¹⁵⁾.

The comparisons of the calculations with data are presented in Figures VI-33, 34 and 36, while the calculations for various energies are presented together in Figure VI-35.

We note that the differential cross sections, while being reasonably well-reproduced in shape are badly overestimated by the calculations. Renormalization factors of 0.33, 0.50 and 0.57 are required for 398, 597 and 698 MeV respectively to generate the fits in Figure VI-36. Comfort et. al. report factors of 0.2 and 0.25 needed to renormalize the calculations at 122 and 200 MeV^{6,9)}. Haji-Saeid et. al. require no scaling to fit the data at 800 MeV¹⁵⁾, and so the trend is clear. The measured cross sections are almost independent of energy, while the calculated cross sections are monotonically decreasing as the beam energy increases, finally converging with the data at 800 MeV. As is the case for the 15.11 MeV state, this transition is mediated by the isovector tensor component of the effective interaction. While it is clear from the fits to the cross section data that the real tensor component dominates, it is interesting to note the relative strength of these components vis-a-vis that observed for the 15.11 MeV state. Whereas the central term dominated almost completely except for large momentum transfer in the case of the 15.11 MeV state, we find here

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{ Differential Cross Section Calculations}$

Figure VI-33.

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{Analyzing Power Calculations}$

Figure VI-34.

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{Comparative Calculations for Observables}$

Figure VI-35.

$E_x = 16.58 \text{ MeV } 2_1^-; 1 - \text{Renormalized Differential Cross Sections}$

Figure VI-36.

that the contributions from the tensor term, especially the real direct tensor component, are much more significant. Furthermore, while the first maximum is always dominated by the real central term, the second maximum is dominated by the tensor term as was observed for the 15.11 MeV state. Also, the 650 MeV force gives a much reduced contribution from the real central term to the second maximum, and requires less renormalization to reproduce the data. We note that the 800 MeV data, while requiring no renormalization, show an offset in the maximum which is attributable to the different oscillator parameter used at that energy. Our oscillator parameter would give a much improved fit to the data.

The structure of the cross section is the result of a sensitive cancellation of the large p-s amplitude with the p-d amplitude at small momentum transfers, and $L = 1$ transfer to the nucleus dominates. From the location of the principal maximum, it might be expected that $L = 3$ transfer would be important, but Comfort⁹⁾ has shown that this is not the case. In comparing renormalization factors derived for (p,p') scattering with those for (e,e') scattering^{53,54)} we find that electron scattering requires a much small renormalization factor of 0.88, much more consistent with that for 800 MeV rather than those obtained in this work.

The shape of the calculated analyzing powers are in good agreement with similar calculations at 122⁷⁾ and 200

MeV⁹), and is somewhat reminiscent of that for the 1^+ state at 15.11 MeV. The data are not fitted at all, although the shape is consistent. The interference minimum is caused by the direct tensor term, which is generally responsible for the shape.

It is difficult to believe that the deviations from the data are an artifact of the force, since the dominant components in this transition do a reasonable job of describing the excitation of the 15.11 MeV state. Curiously, the shape at high q here is well described while that of the 15.11 MeV state is not. Also, the data are overestimated while the 15.11 MeV data are underestimated. Rather, the difficulty may lie with the wave function and the need for a very delicate balance between the two primary configurations contributing to the transition density.

The effects of distortions were not investigated for this transition, and the contributions from knock-on exchange were found to be small.

5) States for $E_x > 18.0$ MeV

(a) The state at $E_x = 18.30$ MeV

In Chapter V, it was postulated that the excitation of this state was isoscalar. Calculations were performed for the first three $2^-;0$ states derived by Millener, and also for the first and second $1^-;0$ state. The $1_1^-;0$, $2_1^-;0$

and $2_3^-;0$ states did not reproduce the shape of the differential cross section at all, showing peaking at larger momentum transfers reminiscent of the structure of the $2_1^-;1$ calculations for the 16.58 MeV state. A good fit to the data was found for the $2_2^-;0$ state, which is dominated by the $(d_{5/2}, p_{3/2}^{-1})$ configuration with non-negligible admixtures of the $(2s_{1/2}, 1p_{3/2}^{-1})$ and $(d_{3/2}, p_{3/2}^{-1})$ configurations. This is in contrast to the other $2^-;0$ states and the $2_1^-;1$ state which are primarily dominated by the $(2s_{1/2}, 1p_{3/2}^{-1})$ configuration.

The fits to the data are presented in Figures VI-37 and VI-38, while the comparative plots of the calculations are shown in Figure VI-39.

We note that the low q dependence, including the maximum at $q = 0.6 \text{ fm}^{-1}$, is well reproduced, but overestimated by a factor of about 1.7 to 2 for all three incident particle energies. The principal component of the effective interaction responsible for the excitation of this state is seen to be the real spin-orbit term, primarily through the direct interaction. Enhancements due to the tensor terms, especially at 597 and 698 MeV, are significant. Knock-on exchange processes provide some small cancellations resulting in an overall reduction of the cross section from the direct calculations.

We note from Figure VI-39 that the calculated cross sections are reasonably invariant with energy except in the

$E_x = 18.30 \text{ MeV } 2_2^-; 0$ - Differential Cross Section Calculations

Figure VI-37.

$E_x = 18.30 \text{ MeV } 2_2^-; 0 - \text{Analyzing Power Calculations}$

Figure VI-38.

$E_x = 13.30 \text{ MeV } 2_2^-; 0 - \text{Comparative Calculations for Observables}$

Figure VI-39.

region of the second maximum. Such behaviour is characteristic of the unnatural parity nature of the transition, and is also consistent with the energy independence of the data.

The fits to the analyzing powers show the characteristic negative values for low momentum transfer which we expect from the isoscalar nature of the excitation. The shape of the data for $E_p = 398$ MeV is very well reproduced, if somewhat off in magnitude. The fits for the higher beam energies are not as good, showing the same deficiencies as are seen for the $1^+;0$ state at 12.71 MeV. The tensor term again seems to be important in the generation of the shape of the calculated analyzing power. It should be kept in mind that interference effects make specific identification of dominant terms difficult. Significant deviations from beam energy to beam energy are seen for higher momentum transfers. The data and calculations presented here are in excellent agreement with the data obtained by Comford et. al. at 200 MeV for a state at $E_x = 18.40$ MeV⁹⁾.

Several states are thought to exist near this excitation energy. Karp²⁷⁾ has shown that a $3^-;1$ state dominates proton-transfer reactions to this excitation region, while Buenerd et. al.⁶⁰⁾ found weak evidence for a $2^+;0$ and $3^-;1$ state in (α, α') and (p, p') scattering. The shell-model calculations of Cohen and Kurath, Millener and Millener and Kurath⁶¹⁾ also predict many levels near this excitation.

Comfort et. al. have performed calculations for the third $2^+;0$ Cohen-Kurath wave function, the lowest $3^-;1$ Millener-Kurath wave function and the second $2^-;1$ Millener-Kurath wave function⁹⁾. None of these transitions were found to well reproduce either the differential cross sections or the analyzing powers. The $2^-;1$ was found to be reasonable in shape but overestimated the cross section by a factor of 10. It should be noted that at 200 MeV A_Y is not as discriminating concerning the isospin character of a transition as it is in this work. Comfort has since affirmed that the $2^-;0$ wave function used in this work yields an improved fit to the data at 200 MeV⁶²⁾.

As was mentioned in Chapter I, 180° electron inelastic scattering selects primarily spin- and isospin-flip transitions, and can thus be expected to be insensitive to states with $T = 0$. Flanz et. al.²⁴⁾ have studied this region in such scattering and observe no strength between 18 and 19 MeV of excitation, consistent with the absence of $T = 1$ states in this region.

In conclusion, on the basis of the systematics of the energy independence of the differential cross section, the shape of the analyzing power and the quality of the DWIA fits, together with the evidence from electron scattering, we propose that this transition is an unnatural parity isoscalar transition of spin and parity 2^- . We cannot, however, rule out the existence of other weakly excited states in

this same region that are difficult to observe.

(b) The states at $E_x = 19.28$ MeV and 19.65 MeV

These states are part of the complex set of overlapping states in the 19 MeV excitation region, and are very difficult to interpret. Inelastic pion scattering with both π^+ and π^- probes provides strong evidence for the existence of a strongly isospin-mixed pair of 4^- states at excitation energies of 19.25 and 19.65 MeV^{25,26}). The state at 19.25 MeV, which is thought to be dominantly $T = 0$ is strongly excited in inelastic π^+ scattering, while that at 19.65 MeV which is thought to be dominantly $T = 1$ is strongly excited in inelastic π^- scattering.

Inelastic electron scattering at 180° provides further information which seems only to cloud the issue. Fianz et. al.²⁴) claim to see three states in this region, at $E_x = 19.25$, 19.50 and 19.65 MeV. The interpretation of these states is as follows. The 19.65 MeV state form factor is well-reproduced by a $4_1^-;1$ transition density, while the weak 19.5 MeV state is consistent with a $4_1^-;0$ wave function. The form factor for the 19.28 MeV state is best described by a combination of $2_2^-;1$ and $1_2^-;1$ strength at low and high momentum transfer respectively. It is possible to observe $T = 0$ strength in electron backscattering if appreciable isospin mixing is present. It is clear that the inelastic pion and electron scattering results are not entirely

compatible.

How then might the inelastic proton scattering data presented here be interpreted? We have used the spin and isospin assignments of both (π, π') and (e, e') scattering as a guide, and computed the expected differential cross sections and analyzing powers for $4_1^-; 0$, $4_1^-; 1$, $2_2^-; 1$, $1_1^-; 1$ and $1_2^-; 1$ shell-model states derived by Millener. Several conclusions may be drawn. The angular distribution of the $2_2^-; 1$ state is quite incompatible with the data, and is consequently discarded. The $4_1^-; 0$ state is found to reasonably reproduce the magnitude of the differential cross section for the 19.28 MeV state, requiring a uniform downward renormalization of about 1.7, while the shape of the 19.65 MeV state was reasonably reproduced by the $4_1^-; 1$ calculation. The transition densities for these two states are pure $(d_{5/2} p_{3/2}^{-1})$ configurations. On the other hand, both the $1_1^-; 1$ and $1_2^-; 1$ states have a second maximum at $q = 1.5 \text{ fm}^{-1}$ which only underestimate the data for the 19.28 MeV state by factors of two to three. The strength for both these states that is predicted at $q = 0.6 \text{ fm}^{-1}$ is not seen in the data; if it is there, it is conceivable that it is masked by the strong excitation of the 19.40 MeV state, especially considering the width of the 19.28 MeV state. The $1_2^-; 1$ state is possibly more likely, based on its much reduced forward angle strength with respect to the first $1^-; 1$ state.

The calculations for the 4^- states are presented in

Figures VI-40 to VI-45, while those for the second $1^-;1$ state are shown in Figures VI-46,47. The calculated $4^-;1$ cross sections for the 19.65 MeV state require renormalization by factors of 0.33, 0.6 and 0.4 to reproduce the magnitudes of the data for incident energies of 398, 597 and 698 MeV respectively.

We note that the excitation of the $4_1^-;0$ state is dominated by the real direct part of the spin-orbit interaction, with some small enhancement due to the tensor exchange terms. This is in keeping with the effects observed for the $2^-;0$ state at 18.30 MeV discussed previously. The excitation of the 19.65 MeV state is dominated by the real direct tensor term with some high momentum transfer enhancements due to the spin-orbit and central terms. Knock-on exchange effects are found to be small. The large contributions from the tensor term is in keeping with the effects seen for the $2^-;1$ state at 16.58 MeV.

The fits to the analyzing power are very reasonable for the 19.65 MeV state. The shape is well-reproduced but the magnitude is generally underestimated. The structure of this observable is influenced by the tensor component of the force. The $4_1^-;0$ fits to the analyzing power data for the 19.28 MeV state are less successful, but the relative scarcity of data points makes interpretation difficult. The negative character is reproduced for the 398 MeV and 597 MeV data, but not for the 698 MeV data. The calculations show

$E_x = 19.28 \text{ MeV } 4_1^-; 0$ - Differential Cross Section Calculations

Figure VI-40.

$E_x = 19.28 \text{ MeV } 4_1^-; 0$ - Analyzing Power Calculations

Figure VI-41.

$E_X = 19.28 \text{ MeV } 4_1^-; 0$ - Comparative Calculations for Observables

Figure VI-42.

$E_x = 19.65 \text{ MeV } 4_1^-; 1 - \text{Differential Cross Section Calculations}$

Figure VI-43.

$E_x = 19.65 \text{ MeV } 4_1^-; 1 - \text{Analyzing Power Calculations}$

Figure VI-44.

$E_x = 19.65 \text{ MeV } 4_1^-; 1$ - Comparative Calculations for Observables

Figure VI-45.

$E_x = 19.28 \text{ MeV } 1_2^-$ - Differential Cross Section Calculations

Figure VI-46.

$E_x = 19.28 \text{ MeV } 1_2^-; 1 - \text{Analyzing Power Calculations}$

Figure VI-47.

less structure than other isoscalar unnatural parity transitions, especially at low q . In contrast, the $1^-;1$ states predict strong positive analyzing powers in the region where the data exist, so the $4^-;0$ computations are in somewhat better agreement with the data.

In summary, we find the 19.28 MeV state to be best represented by a $4^-;0$ transition and the 19.65 MeV state to be best represented by a $4^-;1$ transition, more in keeping with the results of inelastic pion scattering than inelastic electron scattering. It must be stressed, though, that those identifications should not be interpreted as absolute. The possibility of the existence of isovector 1^- strength cannot be discounted. More data, especially A_y for the two higher beam energies for $E_x = 19.28$ MeV, are required for better comparisons and understanding.

(c) The state at $E_x = 19.40$ MeV

This state, which is strongly excited at small momentum transfers has been observed in inelastic pion scattering. Although no state of this excitation energy has been seen in electron scattering, we will show that it appears consistent with the low q strength of the 19.28 MeV state observed by Flanz et. al.²⁴⁾. The inelastic pion scattering data are strongly suggestive of isospin mixing between states observed at 18.4 and 19.4 MeV. An assignment of 2^- for spin and parity was made, and this then suggested

that the 19.4 MeV state observed in this work might be a $2^-;1$ state.

Consequently, the calculation for such a transition using Millener's second $2^-;1$ shell-model state was made, and the results are presented in Figures VI-48 to VI-50. The dominant configurations for this transition are $(d_{5/2}p_{3/2}^{-1})$ and $(d_{5/2}p_{1/2}^{-1})$ of opposite phasing, together with a contribution from the $(2s_{1/2}1p_{3/2}^{-1})$ configuration. The $1_1^-;1$ calculations are shown in Figures VI-51 to VI-53.

The differential cross section is well-reproduced in shape, but is overestimated by a factor of 3 for the $2^-;1$ state. This is reasonable, however, because Millener⁶³⁾ has shown that in order to reproduce the transverse electron scattering form-factor for this excitation to the 19.28 MeV state observed in electron scattering, a reduction by a factor of 3 must be applied to the theoretical form-factor. Such renormalization yields almost perfect fits to the data reported here. On the other hand, if the transition is possibly a $1_1^-;1$ state, then a minimum renormalization by a factor of three upwards is required, while no low q strength is seen in electron scattering.

We note that, in keeping with the lower $2^-;1$ state and other isovector unnatural parity states, the transition is dominated by the real direct tensor term. The $1_1^-;1$ state also shows this dependence. Exchange effects result

$E_x = 19.40 \text{ MeV } 2_{2}^{-}; 1 - \text{Differential Cross Section Calculations}$

Figure VI-48.

$E_x = 19.40 \text{ MeV } 2_2^-; 1 - \text{Analyzing Power Calculations}$

Figure VI-49.

$E_x = 19.40 \text{ MeV } 2^-_{2;1} - \text{Comparative Calculations for Observables}$

Figure VI-50.

$E_x = 19.40 \text{ MeV } 1_1^-; 1 - \text{Differential Cross Section Calculations}$

Figure VI-51.

$E_x = 19.40 \text{ MeV } 1_{1/2}^+$ - Analyzing Power Calculations

Figure VI-52.

$E_x = 19.40 \text{ MeV } 1_1^-; 1 - \text{Comparative Calculations for Observables}$

Figure VI-53.

in some destructive interference and consequently a small reduction in the cross section as calculated by purely direct processes. Since the data do not extend beyond about 1 fm^{-1} it was not possible to investigate the effects of the contribution of the $1^-;1$ state at large momentum transfer. It would be interesting to do this to verify the electron scattering results, but the rapid decrease of the cross section in this region makes such experiments very difficult.

The analyzing power data are reasonably reproduced by the $2^-;1$ calculations. The structure of the calculations is influenced by the tensor component of the interaction, as we have grown to expect. The dependence of the analyzing power on momentum transfer is consistent with other unnatural parity isovector states, especially the $1^+;1$ states at $E_x = 15.11 \text{ MeV}$. However, the data are better reproduced by the $1_1^-;1$ analyzing power so discrimination on the basis of A_y is difficult. The energy independence of the differential cross section is further evidence for the isovector character of the state.

Returning to the question of isospin mixing, some questions become immediately obvious. Morris²⁶⁾ has shown that an off-diagonal mixing strength of 350 (40) keV is present for the 2^- states at 18.4 and 19.4 MeV in the inelastic pion spectra. This is almost three times the mixing strength of the 1^+ states in ^{12}C . Such mixing would then seem to indicate that the $T = 0$ state should be seen in

electron backscattering because of the appreciable isospin mixing, just as the $4^-;0$ is observed in (e,e') scattering, albeit weakly. However, as has been pointed out previously, no strength is seen in the inelastic electron scattering spectrum at this excitation energy. Some strength is seen at 18.80 MeV, and Buenerd⁶⁴⁾ has reported a state at this energy in 45 MeV (p,p') scattering, which is not seen at an incident proton energy of 155 MeV. These data also show significant strength at 18.35, 19.40 and 19.65 MeV, consistent with what is seen in this work. Unfortunately, (p,p') scattering is insensitive to the isospin mixing, and hence cannot serve as a tool for resolving this apparent discrepancy, which is nevertheless interesting.

In summary, then, a very tentative assignment of spin, parity and isospin of $2^-;1$ can be made for the state at $E_x = 19.40$ MeV, consistent with pion scattering, but not consistent with the excitation energy at which 2^- strength is seen in electron scattering. In order to better discriminate between the natural (1^-) and unnatural (2^-) parity states in question, spin-flip probabilities should be measured, but such measurements are especially difficult considering the broad nature and the excitation region of these states.

(d) The state at $E_x = 20.6$ MeV

This state has been observed by Comfort et. al. and

Buenerd et. al. in lower energy (p,p') scattering. There is much conflicting evidence for spin, parity and isospin assignments near this excitation energy. Deuteron stripping near this excitation energy indicates a state of $3^+;1$, while analogue states in ^{12}B indicate the presence of a $3^-;1$ states. Buenerd et. al. have observed strength in (p,p') scattering at 45 and 155 MeV, but not in (α,α') scattering at 60 MeV. Reasonable fits to the (p,p') data were obtained under the assumption that the state was $3^-;1$. Deuteron pick-up reactions indicate the presence of unnatural parity excitations as do the presence of strength for (d,d') and absence for (α,α') reactions. The cross section and analyzing power data of Comfort et. al. at 200 MeV are in agreement with those reported in this work. The independence of the data with energy are consistent with all the possibilities presented above.

We have calculated the observables for the lowest $3^-;1$ transition of Millener, the dominant configuration being $(d_{5/2}p_{3/2}^{-1})$ with a contribution from the $(d_{3/2}p_{3/2}^{-1})$ configuration. No calculations were made for a $3^+;1$ state for which we had no wavefunction, nor for any isoscalar states. The results of the calculations are compared with the data in Figures VI-54 to VI-56.

Since this is possibly only the second natural parity isovector state studied, it is gratifying to find the qualitative features of the calculated observables to be

$E_X = 20.60 \text{ MeV } 3\bar{1};1 - \text{ Differential Cross Section Calculations}$

Figure VI-54.

$E_x = 20.60 \text{ MeV } 3_1^-; 1 - \text{Analyzing Power Calculations}$

Figure VI-55.

$E_x = 20.60 \text{ MeV } 3_1^-; 1 - \text{Comparative Calculations for Observables}$

Figure VI-56.

consistent with those for the $2^+;1$ state at 16.11 MeV. The shapes of both the differential cross section and the analyzing power data are reasonably well reproduced. The calculated cross sections required renormalization by a factor of about two at 398 MeV to 1.4 at 698 MeV to bring them into agreement with the data. The real direct central and real direct tensor terms contribute to the excitation of this state, and knock-on exchange reduces the purely direct cross sections by a factor of two, consistent with the $2^+;1$ state.

Comfort et. al.⁹⁾ assumed a pure $P_{3/2}$ to $d_{3/2}$ transition as had been done by Buenerd et. al.⁶⁰⁾ In order to fit the data at 200 MeV the calculated cross section had to be rescaled by a factor of 0.1. It is apparent that the assumption of such a pure configuration is not good, especially in the light of the transition densities derived by Millener. The $3^+;1$ calculation at 200 MeV requires a renormalization of 0.6, but does not reproduce the analyzing power data as well as the $3^-;1$ transition for large angles.

Therefore, based on the results of the calculations for this work and the work of others, we may conclude that our data are consistent with an assignment of $3^-;1$ to this state, but the possibility of $3^+;1$ strength cannot be discounted.

Scale Factors for DWIA Computations

$J^\pi; T$	E_x (MeV)	398 MeV	597 MeV	698 MeV
$2^+; 0$	4.44	2.10	3.25(1.55)	3.74(1.75)
$3^-; 0$	9.64	1.85	2.93(1.58)	3.00(1.62)
$1^-; 0$	10.84	-	1.83	-
$2^+; 1$ Q	16.11	0.54	0.83(1.54)	0.67(1.24)
$2^+; 1$ NQ	16.11	0.83	1.56(1.88)	1.32(1.59)
$1^+; 0$	12.71	1.00	1.50(1.50)	1.40(1.40)
$2^-; 0$	18.30	1.50	1.60(1.05)	1.50(1.00)
$4^-; 0$	19.28	1.60	1.30(0.80)	1.60(1.00)
$1^+; 1$	15.11	1.00	1.50(1.50)	1.40(1.40)
$2^-; 1$	16.58	0.33	0.50(1.52)	0.57(1.73)
$2^-; 1$	19.40	0.33	0.33(1.00)	0.33(1.00)
$4^-; 1$	19.65	0.33	0.60(1.80)	0.55(1.70)

Number in parentheses indicates scaling required to fit data after renormalization to 398 MeV data.

Table VI-3.

VII. CONCLUSIONS

We have studied the excitation of the ^{12}C nucleus through the medium of good resolution elastic and inelastic polarized proton scattering at 400, 600, and 700 MeV. The data presented in this work, together with other data at both lower and higher energies, provide a comprehensive excitation function for this nucleus over an incident particle energy range of 800 MeV. This is the first systematic study of any nucleus over this energy range. No previous inelastic data exist at 700 MeV; the only previous data at 600 and 400 MeV were a few studies of strong natural parity collective states at 600 and 400 MeV and the 1^+ states at 400 MeV, all with unpolarized beam^{13,14}).

The efficiency of the Microprogrammable Branch Driver capability to reject events by software, resulting in improved taping efficiency for events of interest, was conclusively demonstrated. The increased data acquisition rate through the use of buffered electronics was most useful in completing the data-taking in the allotted time.

A detailed study of the inelastic transitions served a variety of purposes. Systematic trends in the analyzing power data were shown to be a signature of the isospin transfer for unnatural parity states. Specifically, negative values for low momentum transfers rising to positive values as q increases are strongly indicative of isoscalar

transitions of unnatural parity over the incident proton energy range studied in this work. This was amply illustrated for the $1^+;0$ and $2^-;0$ states. Analyzing powers close to zero for low momentum transfer were shown to be consistent with isovector states of both natural and unnatural parity. Spin-flip measurements are necessary to discriminate between natural and unnatural parity isovector states.

Perhaps the most interesting feature of the data themselves is the dependence on incident energy of the absolute cross sections. The independence of the magnitude of the absolute cross section as a function of energy has been shown to be indicative of isovector natural parity and all unnatural parity transitions. Monotonically increasing cross sections are identified with isoscalar natural parity states. The energy dependence of the natural parity states reflects the increase in elastic scattering cross sections and the strong increase in proton-proton scattering cross section over this energy range³⁾.

The phenomenological optical model was found to be reasonably adequate in describing the elastic scattering differential cross sections. Reasonable fits to the first minimum at 597 and 698 MeV required the introduction of a surface term with a large radius. The fit to the 597 MeV data also seems to require that the small real repulsive potential have an unphysically large radius. Expected trends for the energy dependence of the strengths of the potentials

were qualitatively reproduced. The model continues to show difficulty in reproducing the shape of the elastic scattering analyzing power.

The effective nucleon-nucleon interaction of Love and Franey³⁾ has been examined in considerable detail. The imaginary central scalar-isoscalar term dominates the excitation of natural parity isoscalar states. These states also require contributions from the real and imaginary isoscalar spin-orbit terms, especially for large momentum transfer. The real isoscalar spin-orbit term also drives isoscalar unnatural parity excitations for medium to large momentum transfers. The tensor force is the dominant component in the excitation of all isovector states; the exchange component being important also for isoscalar unnatural parity states at small momentum transfer. The real isovector tensor component dominates all classes of isovector transitions, especially at large momentum transfer. The central isovector term contributes to the high momentum transfer excitation of natural parity states, while the real spin-isospin flip central term drives the low momentum transfer excitation of unnatural parity isovector states.

The central scalar-isoscalar term is the only one to exhibit strong energy dependence, and this is reproduced approximately by the isoscalar natural parity data. The less dramatic energy dependence of the tensor interaction and various weaker components of the central and spin-orbit in-

interactions responsible for other transitions show remarkable cancellations which permit the overall cross sections for these transitions to be almost energy independent while the relative contributions of the individual components are varying as a function of q and E_p .

The analysis presented in Chapter VI allows us to draw some conclusions concerning how well the significant components of the interaction are determined. It must be pointed out that for most states several components are required to furnish a satisfactory description, and this necessarily means that information about individual components is difficult to extract.

We consider first the scalar-isoscalar central interaction t_0^C . The cross sections for natural parity isoscalar states increase at the maximum by 2.8 and 3.5 from 398 to 597 to 698 MeV. The magnitude of the ratio of the square of the scalar-isoscalar term for the 650 MeV force relative to the 425 MeV force is 2.6. However, Table VI-2 shows that additional renormalizations of about 1.6 are required for calculations done with the 650 MeV force relative to the 425 MeV force to bring the calculations into agreement with the data. Noting that inelastic electron scattering data require an upward renormalization by a factor of two^{53,54}), consistent with the 398 MeV inelastic proton scattering data, we may deduce that the strength of the scalar-isoscalar term at 425 MeV is essentially correct, while that

for 650 MeV is too small by a factor of 30%. This observation is consistent for all natural parity isoscalar states analyzed.

The central spin- and isospin-flip term $t_{\sigma\tau}^C$ dominates the low momentum transfer excitation of isovector unnatural parity states. Electron scattering data have shown that the wavefunction of the 15.11 MeV state is well determined to a momentum transfer of about 1.5 fm^{-1} without renormalization^{53,54}). The excellent fit to the low q data for this state indicates that this component is correct to within the uncertainties of the data, or 10%, at 425 MeV, but the renormalization of 1.5 required for the 650 MeV calculations indicates that this component is 30% too low for this force. The magnitude of this term in the Love-Franey interaction shows a slight decrease from 425 to 650 MeV which cannot be determined to within the error bars on the data.

The scalar spin-orbit component is predicted to be independent of energy and to be important for large momentum transfer. This is seen as an enhancement in the calculated cross sections for the natural parity isoscalar states at large q , more so for the calculations for the 650 MeV force than those for the 425 MeV force. This term dominates the excitation of the $2^-;0$ state at 18.30 MeV, and also the tentatively identified $4^-;0$ state at 19.28 MeV. The spin-orbit force adequately describes the data without enhancements due

to the tensor force, although the evidence is somewhat weaker for the $4^-;0$ state. Since electron scattering renormalization factors are not available, we cannot make a definite statement about the magnitude of this component, other than it may be correct to within the factor required to renormalize the calculations, or 30%. However, the energy independence (taking both real and imaginary parts) is clearly evident. This term is also primarily involved in the medium momentum transfer excitation of the $1^+;0$ state at 12.71 MeV. Comparisons with the data here affirm the independence with energy and indicate that the magnitude may be correct to within 20% in this region. The small momentum transfer strength is considerably reduced for the 650 MeV force, and significantly worsens the overall fit to the data.

The isoscalar tensor term, t_0^T , contributes only to the small momentum transfer dependence of the $1^+;0$ state at 12.71 MeV. The Love-Franey force predicts no discernible energy dependence for this term. We find the relative enhancement above the underlying spin-orbit contributions to be roughly constant for both the 425 and 650 MeV forces. The fit to the 398 MeV data shows this term to be accurate to about 15% for the 425 MeV force. The fits to the 597 and 698 MeV data indicate that this term may be no more accurate than 30%, and low. However, caution is advised because of the previously discussed problems with the spin-orbit force.

The last significant term is the isovector tensor

component, which dominates the excitation of several states at large momentum transfer. The medium momentum transfer contributions to the cross section for the 15.11 MeV state indicate a reasonable accuracy of about 20% given the validity of the wave functions in this region of q , the strength generally being low with respect to the data. It is not possible to make any statement for large momentum transfers because of structure uncertainties. The $2^-;1$ state at 16.58 MeV agrees with electron scattering results which overestimate the data by a factor of 1.5⁵⁴⁾, with the overestimation increasing monotonically from 800 MeV to lower beam energies. For the 650 MeV force this term is exclusively responsible for the strength, whereas the observed strength at 425 MeV is predicted solely by the $t_{0\tau}^C$ term, with the tensor component serving only to overestimate the data. Renormalization consistent with the electron scattering factor of 1.5 downward indicates that the strength of this term at 650 MeV may be low by about 15%. The strong contribution of $t_{0\tau}^C$ at 425 MeV precludes extracting a factor at that energy. The $2^+;1$ state at 16.11 MeV, having been renormalized to electron scattering data^{53,54)}, requires an enhancement by a factor of 1.6 for agreement between the 650 MeV force and 597 MeV data. This implies that the tensor part of the force being considered here is about 30% low at 597 MeV. The $4^-;1$ state at 19.65 MeV exhibits trends closely similar to those of the 16.58 MeV state, but the absence of an electron scattering renormalization factor precludes further

analysis.

None of the other terms in the interaction contribute with sufficient strength to any state to warrant comment.

The preceding conclusions have centered around the magnitudes of the cross sections. The analyzing powers are particularly sensitive to interference between contributions from different parts of the force. The quality of fits to the analyzing powers varied widely, some being very good (e.g. 12.71 MeV state for 398 MeV) and some very poor (e.g. 16.11 MeV state at large q for all energies). Statements regarding the relative importance of different terms in the interaction are uncertain because of lack of knowledge of the phases involved, and must be treated with caution.

Fits to the analyzing powers which provide information about the Love-Franey force are as follows. Isoscalar natural parity states are reasonably well reproduced to within a phase. The combination of spin-orbit distortions and the spin-orbit component of the interaction results in approximately the correct magnitude for these analyzing powers. This is somewhat surprising since the cross section evidence points strongly to a spin-orbit force that is too weak at 650 MeV. This suggests a reasonably satisfactory phase between central and spin-orbit terms. The success achieved in fitting the analyzing powers of the isoscalar

unnatural parity states $1^+;0$ and $2^-;0$ at 398 MeV strongly suggests that the relative phase of the spin-orbit and imaginary isoscalar tensor components is reasonably well determined. The very small analyzing powers measured for small q in isovector natural and unnatural parity states points to the correctness of the weak isovector spin-orbit component. The large momentum transfer dependence of the $4^-;1$ state is also reasonably well reproduced.

The inability of the calculations to reproduce the 12.71 and 18.30 MeV data for the 650 MeV force is a strong indication of a deficiency in the isoscalar spin-orbit force, which supports assertions from cross section comparisons. Furthermore, the difference in sign for predicted and measured high momentum transfer analyzing powers for the isovector 2^+ state at 16.11 MeV, together with the phase problems apparent for large q for the 15.11 MeV state indicate that the relative phase of the spin-orbit and real isovector tensor terms is not well determined. This is also true for the $2^-;1$ state at 16.58 MeV.

Overall we find the strengths of the dominant terms in the 425 MeV force to be qualitatively and quantitatively well determined. Such a strong statement of agreement cannot be made for the 650 MeV force, where a systematic lack of strength of the order of 20 to 30% is found for the dominant components of the interaction, especially the scalar-isoscalar central term and the isoscalar spin-orbit term.

Nevertheless, the Love-Franey parameterization has been demonstrated to be a useful description for the study of inelastic proton scattering, and with further study and refinement may contribute significantly to the understanding of the systematics of intermediate energy proton-nucleus scattering.

The effects of knock-on exchange were found to be important. Exchange was found to reduce the calculated cross sections from purely direct values by a factor of 3.5 for isoscalar natural parity states. A reduction by a factor of 2 was noted for isovector natural parity states as well as for the better known unnatural parity transitions. Very small effects were observed for select states in the high excitation region.

The satisfactory performance of the Love-Franey interaction in describing the more well known states permitted the use of calculations to aid in the determination of the spins and parities of levels in the excitation region 18 to 21 MeV. We were able, on the basis of systematics of the data and the results of the DWIA calculations, to make suggested assignments of spin, parity and isospin to states in this region as listed in Table VII-1. These assignments are consistent with tentative pion scattering assignments²⁶⁾ for the 2^- and 4^- states, but they are different from tentative inelastic electron scattering assignments²⁴⁾.

High Excitation Energy
Spin, Parity, and Isospin Assignments
(Tentative)

E_x (MeV)	$J^\pi ; T$
18.30	$2^- ; 0$
19.28	$4^- ; 0 (1_2^- ; 1)$
19.40	$2^- ; 1 (1_1^- ; 1)$
19.65	$4^- ; 1$
20.60	$(3^- ; 1)$

Table VII-1.

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APPENDIX

Part I

Sample MBD Cut File used in conjunction with the
Q Analyzer HRSBUF for Software Event Rejection in the
Microprogrammable Branch Driver

Count 10
Sum 11
Reject Outside 107,360

Part II

Sample ALLTST File used in conjunction with the
Q Analyzer HRSBUF for replay event analysis

DISK ALJTEST RESULTS

RUN# 68 29-AUG-80 10:49:07 EVENT 07 FILE C.166,226HMS631POL.TST

314492.	= BOX 1,	11 P10 (PROTON)
0.	= BOX 2,	12
0.	= BOX 3,	13
124809.	= W0 65,60,	14 N0H1
196036.	= W0 66,50,	15 H0V
320043.	= FOR 1,-1,	16 LOOP 1 COUNTER
319640.	= GATE 131,10005,10110,	17 X-PLANE DRIFTTIME CH00R 1
314047.	= GATE 132,10005,10110,	18 X-PLANE DRIFTTIME CH00R 2
319619.	= GATE 133,10005,10110,	19 X-PLANE DRIFTTIME CH00R 3
319496.	= GATE 134,10005,10110,	100 X-PLANE DRIFTTIME CH00R 4
319416.	= GATE 171,10005,10110,	111 Y-PLANE DRIFTTIME CH00R 1
319446.	= GATE 172,10005,10110,	112 Y-PLANE DRIFTTIME CH00R 2
319507.	= GATE 173,10005,10110,	113 Y-PLANE DRIFTTIME CH00R 3
319440.	= GATE 174,10005,10110,	114 Y-PLANE DRIFTTIME CH00R 4
303033.	= GATE 241,9990,10010,	115 DIFF CORR POSIT X12 (+/- 1RM)
305115.	= GATE 242,9990,10010,	116 DIFF CORR POSIT X14 (+/- 1RM)
306736.	= GATE 245,9990,10010,	117 DIFF CORR POSIT Y12 (+/- 1RM)
300142.	= GATE 246,9990,10010,	118 DIFF CORR POSIT Y14 (+/- 1RM)
1010.	= 1GATE 1,	119 PEAK 1 GATE 1
41795.	= 1GATE 2,	120 PEAK 2 GATE 1
10906.	= 1GATE 3,	121 PEAK 3 GATE 1
0.	= 1GATE 4,	122 PEAK 4 GATE 1
0.	= 1GATE 5,	123 PEAK 5 GATE 1
98069.	= GATE 233,9020,9960,	124 SCAT ANGLE REGION 1
104165.	= GATE 233,9960,10100,	125 SCAT ANGLE REGION 2
101620.	= GATE 233,10100,10240,	126 SCAT ANGLE REGION 3
301662.	= GATE 233,9020,10240,	127 FULL SCAT ANGLE REGION
0.	= GATE 1,1,-1,	128 SPARE MICROTEST
220546.	= BOX 4,	129 BOX ON XANGL CUT
0.	= BOX 5,	130 BOX 5
0.	= BOX 6,	131 BOX 6
0.	= BOX 7,	132 BOX 7
146646.	= GATE 233,9020,10030,	133 SCAT ANGLE REGION A
165916.	= GATE 233,10030,10240,	134 SCAT ANGLE REGION B
43409.	= AND 1,4,29,	135 P10 * N0H * XANGL CUT
192473.	= AND 1,6,29,	136 F10 * H0V * XANGL CUT
317312.	= AND 7,0,	137 X12 DRIFT TIMES OK
310603.	= AND 9,10,	138 X04 DRIFT TIMES OK
310066.	= AND 11,12,	139 Y12 DRIFT TIMES OK
310663.	= AND 13,14,	140 Y14 DRIFT TIMES OK

61266. = 10R 73,74,
62173. = 10R 70,76,
62130. = 10R 77,70,
91714. = 10R 02,03,
93653. = 10R 04,05,
920856. = 10R 1,-1

187 GOOD EVENT SEAT REGION 1 N OR R
188 GOOD EVENT SEAT REGION 2 N OR R
189 GOOD EVENT SEAT REGION 3 N OR R
190 GOOD EVENT SEAT REGION A N OR R
191 GOOD EVENT SEAT REGION B N OR R
192 END OF LOOP COURTESY, LOOP 2

BOX CUTS FOR EVENT 7

BOX 1, X VAR=110, Y VAR=115	109320X(10077	100540Y(10063
BOX 2, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 3, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 4, X VAR=219, Y VAR=235	70080X(12910	63790Y(11626
BOX 5, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 6, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 7, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 8, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 9, X VAR= 1, Y VAR= 11	00X(0	00Y(0
BOX 10, X VAR= 1, Y VAR= 11	00X(0	00Y(0

INDIRECT GATES FOR EVENT 7

GATE 1, INDEX=234: 10736- 10795
GATE 2, INDEX=234: 10931- 11001
GATE 3, INDEX=234: 11241- 11395

Part III

Sample Histogram definition file used in conjunction with the Q Analyzer HRSBUF for replay histogramming of the data

```
FILE=HRS432POL.DSP
FREE ALL
;
H1=234,10400,11650,2
T1=86      !MM, GOOD EVENT, N OR R, FULL SCAT REGION
;
H2=233,9500,10500,10
T2=63      !THETASCAT, GOOD EVENT, PEAK 1, N
;
H3=233,9500,10500,10
T3=64      !THETASCAT, GOOD EVENT, PEAK 1, R
;
H4=233,9500,10500,10
T4=65      !THETASCAT, GOOD EVENT, PEAK 2, N
;
H5=233,9500,10500,10
T5=66      !THETASCAT, GOOD EVENT, PEAK 2, R
;
H6=233,9500,10500,10
T6=67      !THETASCAT, GOOD EVENT, PEAK 3, N
;
H7=233,9500,10500,10
T7=68      !THETASCAT, GOOD EVENT, PEAK 3, R
;
H8=234,10400,11650,2
T8=79      !MM, FULL SCAT REGION, NORM
;
H9=234,10400,11650,2
T9=80      !MM, FULL SCAT REGION, REV
;
H10=234,10400,11650,2
T10=73     !MM, SCAT REGION 1, NOR
;
H11=234,10400,11650,2
T11=74     !MM, SCAT REGION 1, REV
;
H12=234,10400,11650,2
T12=75     !MM, SCAT REGION 2, NORM
;
H13=234,10400,11650,2
T13=76     !MM, SCAT REGION 2, REV
;
H14=234,10400,11650,2
T14=77     !MM, SCAT REGION 3, NORM
```

```

;
H15=234,10400,11650,2
T15=78 !MM, SCAT REGION 3, REV
;
H16=234,10400,11650,2
T16=82 !MM, SCAT REGION A, NORM
;
H17=234,10400,11650,2
T17=83 !MM, SCAT REGION A, REV
;
H18=234,10400,11650,2
T18=84 !MM, SCAT REGION B, NORM
;
H19=234,10400,11650,2
T19=85 !MM, SCAT REGION B, REV
;
H20=234,10400,11650,2
T20=87 !MM, SCAT REGION 1, N OR R
;
H21=234,10400,11650,2
T21=88 !MM, SCAT REGION 2, N OR R
;
H22=234,10400,11650,2
T22=89 !MM, SCAT REGION 3, N OR R
;
H23=234,10400,11650,2
T23=90 !MM, SCAT REGION A, N OR R
;
H24=234,10400,11650,2
T24=91 !MM, SCAT REGION B, N OR R
;
CLEAR ALL
EXIT

```

Part IV

Tables of Experimental Differential Cross Sections
and Analyzing Powers, Tables A1-A3.

Experimental Angular Distributions
 $^{12}\text{C}(\vec{p}, p')^{12}\text{C}^* - 398 \text{ MeV}$

θ_{cm}	$q(\text{fm}^{-1})$	$\frac{d\sigma}{d\Omega}(\frac{\text{mb}}{\text{sr}}) \pm \Delta$	$A_y \pm \Delta$
3.39	0.254	1038.	15. .172 .013
3.64	0.269	967.	14. .203 .013
3.73	0.277	927.	13. .242. .011
3.90	0.290	898.	13. .242 .014
3.99	0.297	884.	12. .248 .011
4.15	0.307	842.	12. .236 .014
4.25	0.316	840.	12. .268 .011
4.41	0.328	765.	11. .291 .014
4.50	0.334	789.	11. .295 .012
4.76	0.355	745.	10. .319 .012
5.01	0.374	718.	10. .352 .012
5.27	0.392	686.	10. .361 .012
5.41	0.403	634.	9.0 .340 .019
5.66	0.419	597.	8.4 .388 .019
5.92	0.442	599.	8.4 .435 .019
6.17	0.459	570.	8.0 .392 .020
6.43	0.479	545.	7.6 .447 .020
6.69	0.499	524.	7.3 .478 .020
6.94	0.517	480.	6.7 .443 .022
7.08	0.529	470.	6.6 .460 .010
7.34	0.549	454.	6.5 .476 .010
7.59	0.567	434.	6.1 .481 .010
7.85	0.587	405.	5.7 .503 .010
8.10	0.608	376.	5.3 .517 .011
8.36	0.626	366.	5.1 .527 .011
8.61	0.644	343.	4.8 .521 .011
8.87	0.664	318.	4.5 .554 .011
9.01	0.674	309.	4.3 .529 .017
9.26	0.693	294.	4.1 .545 .017
9.52	0.713	274.	3.8 .528 .017
9.78	0.732	259.	3.6 .535 .018
10.03	0.751	242.	3.4 .559 .019
10.29	0.770	221.	3.1 .573 .020
10.43	0.781	210.	3.0 .564 .009
10.54	0.789	198.	2.8 .557 .021
10.68	0.800	197.	2.8 .575 .009
10.94	0.819	183.	2.6 .578 .009
11.19	0.838	169.	2.4 .595 .010
11.45	0.857	157.	2.2 .583 .010
11.70	0.876	143.	2.0 .563 .011
11.96	0.895	129.	1.8 .581 .011
12.10	0.908	125.	1.8 .552 .011
12.21	0.914	116.	1.6 .589 .012
12.35	0.926	113.	1.6 .564 .012
12.61	0.944	106.	1.5 .570 .012
12.86	0.962	94.6	1.3 .557 .013

13.12	0.980	86.9	1.2	.548	.014
13.37	1.001	77.9	1.1	.551	.013
13.63	1.021	70.3	.98	.520	.015
13.77	1.031	65.1	.91	.544	.013
13.88	1.039	61.0	.85	.545	.016
14.02	1.050	60.0	.84	.558	.016
14.28	1.069	55.4	.78	.522	.017
14.53	1.086	47.9	.67	.507	.018
14.79	1.107	43.8	.61	.499	.019
15.04	1.126	37.0	.52	.461	.021
15.30	1.145	32.8	.46	.436	.022
15.55	1.164	29.1	.42	.444	.024
15.69	1.173	26.7	.37	.431	.011
15.95	1.194	23.7	.33	.391	.012
16.20	1.212	20.7	.29	.385	.013
16.46	1.231	17.8	.25	.331	.015
16.71	1.250	15.2	.21	.286	.016
16.97	1.269	12.8	.18	.287	.017
17.11	1.279	11.8	.17	.221	.015
17.22	1.286	10.6	.15	.251	.019
17.36	1.299	10.3	.14	.177	.016
17.61	1.318	8.63	.12	.145	.018
17.87	1.337	7.27	.10	.054	.019
18.12	1.356	6.12	.095	-.006	.021
18.38	1.375	5.23	.072	-.041	.023
18.63	1.394	4.20	.059	-.102	.026
18.89	1.413	3.30	.046	-.230	.029
19.03	1.424	3.22	.045	-.245	.022
19.28	1.443	2.68	.038	-.317	.024
19.54	1.462	2.09	.029	-.406	.027
19.79	1.480	1.68	.024	-.534	.028
20.04	1.498	1.35	.019	-.680	.029
20.30	1.517	1.10	.015	-.771	.030
20.44	1.528	.985	.014	-.877	.038
20.55	1.536	.850	.012	-.952	.027
20.69	1.547	.745	.010	-.931	.041
20.95	1.566	.618	.009	-.927	.045
21.20	1.584	.545	.008	-.951	.046
21.46	1.603	.460	.008	-.578	.070
21.72	1.621	.484	.009	-.507	.071
21.96	1.640	.410	.008	-.294	.081
22.15	1.654	.442	.008	.188	.048
22.40	1.674	.431	.008	.373	.044
22.66	1.693	.520	.008	.576	.040
22.91	1.712	.572	.009	.684	.036
23.16	1.730	.646	.009	.817	.030
23.42	1.749	.712	.010	.890	.027
23.67	1.768	.814	.011	.923	.024
23.93	1.787	.829	.012	.912	.024
24.18	1.805	.887	.012	.937	.023
24.36	1.818	.905	.013	.992	.019
24.43	1.824	.935	.013	.967	.021
24.62	1.837	.943	.013	.953	.020

24.87	1.856	.972	.014	.985	.019
25.13	1.875	1.05	.015	.947	.020
25.38	1.893	1.09	.015	.939	.020
25.63	1.913	1.13	.016	.912	.020
25.89	1.931	1.10	.015	.926	.020
26.14	1.950	1.12	.016	.887	.020
26.37	1.968	1.09	.015	.874	.020
26.58	1.981	1.24	.017	.826	.014
26.65	1.986	1.11	.015	.833	.021
26.83	2.000	1.23	.017	.806	.014
27.08	2.019	1.23	.017	.791	.014
27.34	2.037	1.17	.016	.784	.014
27.59	2.056	1.18	.016	.764	.015
27.84	2.075	1.18	.016	.725	.015
28.10	2.094	1.18	.016	.704	.015
28.35	2.112	1.15	.016	.683	.016
28.60	2.131	1.11	.016	.671	.017
28.86	2.150	1.07	.015	.647	.017

$2^+; 0 - 4.44 \text{ MeV}$

7.08	0.529	3.14	.40	.591	.088
7.34	0.549	2.36	.28	.494	.098
7.59	0.567	3.32	.40	.392	.089
7.85	0.587	3.77	.45	.524	.079
8.10	0.608	3.50	.42	.532	.079
8.36	0.626	4.39	.52	.608	.071
8.61	0.644	4.20	.42	.614	.067
8.87	0.664	4.61	.46	.571	.068
9.01	0.674	3.97	.40		
9.26	0.693	5.35	.54		
9.52	0.713	6.01	.55		
9.78	0.732	5.55	.51		
10.03	0.751	6.34	.55		
10.29	0.770	7.53	.60		
10.43	0.781	7.32	.55	.621	.030
10.54	0.789	6.34	.50	.647	.050
10.68	0.800	7.86	.45	.629	.035
10.94	0.819	8.04	.65	.613	.029
11.19	0.838	8.17	.65	.667	.027
11.45	0.857	7.68	.60	.635	.027
11.70	0.876	8.60	.60	.669	.026
11.96	0.895	8.61	.60	.679	.026
12.10	0.908	7.67	.50	.637	.020
12.21	0.914	8.32	.50	.644	.026
12.35	0.926	8.69	.50	.691	.022
12.61	0.944	9.22	.55	.650	.018
12.86	0.962	8.81	.55	.663	.018
13.12	0.980	9.29	.55	.665	.018
13.37	1.001	9.86	.55	.691	.018
13.63	1.021	10.2	.60	.688	.017
13.77	1.031	10.2	.60	.708	.035

13.88	1.039	9.83	.55	.676	.018
14.02	1.050	10.25	.40	.675	.035
14.28	1.069	10.4	.50	.673	.032
14.53	1.086	10.0	.50	.689	.036
14.79	1.107	10.0	.50	.719	.035
15.04	1.126	10.1	.50	.681	.036
15.30	1.145	10.7	.50	.703	.034
15.55	1.164	9.54	.40	.692	.037
15.69	1.173	9.57	.40	.721	.016
15.95	1.194	9.20	.38	.691	.017
16.20	1.212	9.15	.37	.692	.017
16.46	1.231	8.99	.35	.669	.017
16.71	1.250	8.99	.32	.685	.017
16.97	1.269	8.51	.30	.690	.017
17.11	1.279	8.24	.29	.646	.015
17.22	1.286	8.27	.29	.632	.018
17.36	1.299	8.20	.28	.651	.015
17.61	1.318	8.24	.28	.641	.015
17.87	1.337	7.85	.28	.612	.016
18.12	1.356	7.56	.26	.652	.016
18.38	1.375	7.37	.26	.595	.016
18.63	1.394	7.09	.26	.602	.016
18.89	1.413	6.78	.25	.579	.017
19.03	1.424	7.00	.25	.582	.013
19.28	1.443	7.01	.25	.580	.013
19.54	1.462	6.73	.24	.551	.013
19.79	1.480	6.46	.24	.528	.014
20.04	1.498	6.27	.24	.533	.014
20.30	1.517	6.02	.23	.496	.014
20.44	1.528	5.70	.22	.483	.020
20.55	1.536	5.57	.22	.496	.015
20.69	1.547	5.34	.21	.448	.021
20.95	1.566	5.14	.21	.440	.022
21.20	1.584	4.96	.21	.429	.022
21.46	1.603	4.83	.20	.412	.023
21.71	1.621	4.51	.20	.322	.023
21.96	1.640	4.37	.20	.377	.024
22.15	1.654	3.97	.19	.340	.016
22.40	1.674	3.70	.19	.338	.016
22.66	1.693	3.50	.20	.324	.017
22.91	1.712	3.26	.19	.284	.017
23.16	1.730	3.11	.19	.227	.018
23.42	1.749	2.79	.18	.256	.019
23.67	1.768	2.62	.18	.150	.020
23.93	1.787	2.37	.18	.199	.021
24.18	1.805	2.27	.17	.119	.021
24.36	1.818	2.07	.17	.041	.021
24.43	1.824	2.09	.17	.097	.022
24.62	1.837	1.89	.16	.026	.021
24.87	1.856	1.76	.15	-.024	.022
25.13	1.875	1.56	.15	-.171	.023
25.38	1.893	1.43	.15	-.120	.025
25.63	1.912	1.32	.15	-.130	.026

25.89	1.931	1.22	.15	-.183	.027
26.14	1.950	1.09	.14	-.205	.028
26.47	1.968	.991	.14	-.238	.029
26.58	1.981	.910	.12	-.255	.021
26.65	1.986	.851	.11	-.294	.031
26.83	2.000	.833	.10	-.292	.022
27.08	2.019	.760	.09	-.352	.022
27.34	2.037	.671	.08	-.391	.024
27.59	2.056	.617	.07	-.429	.024
27.84	2.075	.557	.07	-.462	.025
28.10	2.094	.501	.06	-.581	.026
28.35	2.112	.442	.05	-.588	.027
28.60	2.131	.392	.03	-.630	.028
28.86	2.150	.362	.02	-.622	.030

$0_2^+; 0 - 7.65 \text{ MeV}$

2.87	0.218	.097	.033	.240	.196
3.99	0.297	.148	.026	.136	.060
4.94	0.368	.175	.018	.112	.040
5.66	0.419	.227	.022	.161	.040
6.62	0.494	.388	.032	.052	.028
7.33	0.548	.497	.046	.057	.037
8.29	0.619	.832	.068	.272	.026
9.01	0.674	.976	.060	.331	.019
9.96	0.745	1.32	.097	.375	.014
10.68	0.800	1.59	.11	.409	.011
11.63	0.870	1.66	.12	.461	.011
12.35	0.926	1.66	.12	.451	.010
13.31	0.998	1.59	.11	.468	.010
14.02	1.050	1.65	.12	.484	.010
14.98	1.122	1.27	.090	.472	.010
15.69	1.173	1.08	.083	.431	.018
16.64	1.242	.930	.073	.433	.019
17.36	1.299	.869	.074	.427	.016
18.31	1.368	.601	.047	.323	.020
19.03	1.424	.512	.038	.295	.016
19.98	1.494	.307	.024	.118	.021
20.69	1.547	.205	.024	.064	.024
21.64	1.617	.125	.012	-.180	.038
24.02	1.795	.075	.007	-.470	.040
24.97	1.863	.028	.005	-.857	.051
25.12	1.875	.021	.003	-.611	.070
26.07	1.942	.023	.003	.500	.057
27.34	2.037	.034	.007	.869	.060
28.28	2.098	.040	.008	.858	.037

$3_1^-; 0 - 9.64 \text{ MeV}$

5.66	0.419	.071	.013	.459	.091
6.62	0.494	.134	.018	.613	.055
7.33	0.548	.149	.029	.564	.087
8.29	0.619	.327	.036	.613	.041
9.01	0.674	.291	.029	.555	.035
9.96	0.745	.685	.056	.698	.021
10.68	0.800	.923	.069	.708	.017
11.63	0.870	1.34	.099	.713	.015
12.35	0.926	1.49	.108	.730	.014
13.31	0.998	1.78	.13	.736	.014
14.02	1.050	2.15	.15	.743	.014
14.98	1.122	2.28	.16	.739	.014
15.69	1.173	2.34	.16	.709	.017
16.64	1.242	2.55	.20	.684	.016
17.36	1.299	2.82	.21	.689	.014
18.31	1.368	3.01	.23	.655	.013
19.03	1.424	2.71	.19	.660	.013
19.98	1.494	2.82	.13	.595	.010
20.69	1.547	2.53	.18	.582	.012
21.64	1.617	2.46	.18	.524	.012
24.02	1.795	1.87	.14	.373	.010
24.97	1.863	1.44	.11	.295	.012
25.12	1.875	1.26	.090	.270	.009
26.07	1.942	.792	.057	.231	.012
27.34	2.037	.740	.056	.182	.018
28.28	2.098	.443	.035	.060	.024

 $1_1^-; 0 - 10.84 \text{ MeV}$

7.81	0.588	.042	.019	.523	.217
9.49	0.714	.095	.014	.422	.072
11.16	0.840	.180	.015	.498	.026
12.83	0.965	.267	.020	.500	.015
14.50	1.090	.354	.026	.500	.013
16.17	1.215	.326	.024	.552	.013
17.84	1.339	.367	.026	.570	.012
19.50	1.464	.295	.021	.500	.010
21.17	1.587	.222	.016	.328	.010

$4_1^+; 0 - 14.08 \text{ MeV}$

14.02	1.050	.039	.015	.743	.090
14.93	1.122	.054	.014	.530	.080
15.69	1.173	.047	.012	.752	.070
16.64	1.242	.062	.010	.849	.075
17.36	1.299	.080	.013	.891	.062
18.31	1.368	.101	.011	.800	.069
19.03	1.424	.094	.009	.682	.062
19.98	1.494	.110	.011	.626	.058
20.69	1.547	.122	.013	.620	.051
21.64	1.617	.122	.013	.596	.048
24.02	1.795	.119	.011	.482	.051
24.97	1.863	.101	.010	.377	.042
25.12	1.875	.113	.008	.261	.044
26.07	1.942	.100	.010	.178	.039
27.34	2.037	.083	.007	-.069	.062
28.28	2.098	.058	.007	-.091	.058

 $1_1^+; 0 - 12.71 \text{ MeV}$

3.35	0.252	.241	.043	-.383	.092
3.83	0.290	.265	.033	-.245	.060
3.99	0.299	.187	.039	-.244	.118
4.46	0.337	.248	.027	-.251	.050
10	0.380	.230	.026	-.219	.051
5.50	0.413	.271	.027	-.273	.044
6.14	0.463	.236	.025	-.313	.047
6.78	0.510	.224	.024	-.369	.048
7.17	0.538	.193	.037	-.410	.102
7.81	0.588	.194	.027	-.361	.070
8.45	0.638	.181	.025	-.258	.071
8.85	0.665	.118	.022	-.410	.102
9.49	0.714	.165	.020	-.328	.056
10.12	0.763	.123	.018	-.449	.070
10.52	0.791	.163	.017	-.276	.044
11.16	0.840	.132	.014	-.353	.045
11.79	0.888	.109	.012	-.236	.050
12.19	0.916	.116	.011	-.323	.036
12.83	0.965	.083	.009	-.358	.047
13.46	1.010	.066	.008	-.340	.056
13.86	1.042	.073	.009	-.368	.055
14.50	1.090	.063	.008	-.226	.059
15.13	1.138	.042	.007	-.329	.083
15.53	1.166	.029	.007	-.261	.096
16.17	1.215	.037	.005	-.136	.068
16.80	1.261	.026	.005	-.266	.096
17.20	1.290	.032	.004	-.093	.066
17.84	1.339	.018	.004	-.357	.131
18.47	1.387	.021	.004	.096	.085

18.97	1.415	.016	.003	-.023	.095
19.50	1.464	.027	.003	.327	.052
20.14	1.520	.023	.003	.299	.060
20.53	1.538	.020	.003	.258	.081
21.17	1.587	.020	.003	.549	.074
21.80	1.633	.018	.003	.500	.078
22.75	1.704	.019	.003	.539	.067
23.38	1.751	.018	.004	.818	.072
24.02	1.798	.014	.003	.638	.080
24.97	1.867	.018	.002	.519	.057
25.60	1.914	.014	.002	.600	.067
26.23	1.960	.013	.002	.519	.068
27.34	2.037	.014	.002	.495	.074
28.28	2.102	.010	.002	.299	.082

$1_1^+; 1 - 15.11 \text{ MeV}$

3.35	0.252	1.95	.153	.001	.021
3.83	0.290	1.82	.141	.045	.020
3.99	0.299	1.29	.105	.026	.025
4.46	0.337	1.42	.108	.007	.018
5.10	0.380	1.07	.083	.023	.021
5.50	0.413	1.13	.086	.028	.019
6.14	0.463	.893	.070	.050	.022
6.78	0.510	.681	.055	.069	.026
7.17	0.538	.557	.056	.031	.043
7.81	0.588	.496	.047	.026	.040
8.45	0.638	.361	.038	.091	.047
8.85	0.665	.320	.029	.042	.065
9.49	0.714	.358	.032	.102	.033
10.12	0.763	.285	.027	.154	.037
10.52	0.791	.255	.023	.065	.033
11.16	0.840	.188	.018	-.054	.039
11.79	0.888	.131	.015	.003	.052
12.19	0.916	.135	.013	-.001	.037
12.83	0.965	.097	.010	.004	.048
13.46	1.010	.055	.008	-.150	.081
13.86	1.042	.076	.009	.028	.060
14.50	1.090	.047	.008	-.055	.094
15.13	1.138	.032	.007	.150	.115
15.53	1.166	.024	.005	.223	.117
16.17	1.215	.024	.005	.040	.117
16.80	1.261	.019	.005	.127	.138
17.20	1.290	.013	.004	.034	.175
17.84	1.339	.017	.004	.114	.124
18.47	1.387	.013	.004	.048	.156
18.87	1.415	.011	.003	.237	.134
19.50	1.464	.013	.003	-.046	.130
20.14	1.520	.014	.003	-.165	.117
20.53	1.538	.017	.003	.210	.098

21.17	1.587	.012	.003	-.044	.144
21.80	1.633	.014	.003	-.138	.113
22.75	1.704	.011	.003	-.369	.134
23.38	1.751	.010	.002	-.155	.122
24.02	1.798	.009	.002	-.115	.124
24.97	1.867	.010	.002	-.253	.108
25.60	1.914	.008	.002	-.253	.126
26.23	1.960	.007	.002	-.480	.136
27.34	2.037	.007	.002	-.173	.138
28.28	2.102	.004	.002	-.451	.231

$2_1^+; 1 - 16.11 \text{ MeV}$

5.50	0.413	.024	.009	.069	.220
6.14	0.463	.021	.010	-.097	.284
6.78	0.510	.048	.011	.190	.139
7.17	0.538	.030	.024	.359	.452
7.81	0.588	.038	.014	.290	.207
8.45	0.638	.061	.016	.195	.150
8.85	0.665	.040	.023	.534	.271
9.49	0.714	.082	.014	.058	.093
10.12	0.763	.096	.0.5	.179	.079
10.52	0.791	.088	.012	.068	.074
11.16	0.840	.089	.012	-.119	.070
11.79	0.888	.093	.012	-.043	.068
12.19	0.916	.098	.010	-.033	.049
12.83	0.955	.098	.010	.008	.046
13.46	1.010	.095	.011	-.086	.048
13.86	1.042	.100	.010	-.068	.048
14.50	1.090	.090	.009	.030	.049
15.13	1.138	.077	.007	-.091	.057
15.53	1.166	.067	.007	-.084	.059
16.17	1.215	.067	.007	-.084	.048
16.80	1.261	.060	.006	-.129	.051
17.20	1.290	.061	.006	-.085	.044
17.84	1.339	.053	.005	-.058	.046
18.47	1.387	.039	.004	-.190	.060
18.87	1.415	.042	.004	-.120	.043
19.50	1.464	.038	.004	-.135	.045
20.14	1.510	.032	.003	-.151	.051
20.53	1.538	.028	.003	-.102	.063
21.17	1.587	.024	.003	-.166	.072
21.80	1.633	.014	.002	-.167	.108
22.75	1.704	.013	.002	-.246	.103
23.38	1.751	.011	.003	-.126	.110
24.02	1.798	.006	.002	-.634	.225
24.97	1.867	.007	.002	-.107	.129
25.60	1.914	.005	.001	.056	.165
26.23	1.960	.004	.001	-.138	.186
27.34	2.037	.005	.001	-.019	.156
28.28	2.102	.004	.001	-.034	.197

$2_1^-; 1 - 16.58 \text{ MeV}$

12.83	0.965	.012	.005	.554	.179
14.50	1.090	.023	.005	.372	.102
16.17	1.215	.023	.004	.404	.078
17.84	1.339	.031	.004	.634	.049
19.50	1.464	.025	.003	.534	.039
21.17	1.587	.027	.003	.420	.040
23.38	1.751	.019	.002	.370	.037
25.60	1.914	.012	.001	.252	.045
27.81	2.073	.004	.001	.137	.162

 $2_2^-; 0 - 13.35 \text{ MeV}$

19.50	1.464	.009	.003	-.249	.156
21.17	1.587	.014	.003	-.445	.090
23.38	1.751	.011	.002	.392	.084
25.60	1.914	.010	.002	.167	.074
27.82	2.075	.009	.002	.242	.111

 $(2_3^-; 0) - 18.30 \text{ MeV}$

4.46	0.337	.354	.040	-.251	.053
6.14	0.463	.371	.031	-.287	.027
7.81	0.588	.378	.039	-.164	.047
9.49	0.714	.464	.040	-.165	.031
11.16	0.840	.463	.035	-.159	.017
12.83	0.965	.380	.028	-.036	.013
14.50	1.090	.288	.022	-.106	.016
16.17	1.215	.166	.013	.040	.018
17.84	1.339	.106	.008	.155	.020
19.50	1.464	.055	.005	.337	.023
21.17	1.587	.034	.003	.170	.037
23.38	1.751	.024	.002	.204	.034
25.60	1.914	.024	.002	.145	.029
27.82	2.075	.026	.002	.062	.037

 $(4_1^-; 0) - 19.28 \text{ MeV}$

16.17	1.215	.017	.026	-.430	.797
17.84	1.339	.047	.020	-.412	.221
19.50	1.464	.056	.006	-.177	.038
21.17	1.587	.048	.005	-.401	.012
23.38	1.715	.038	.003	.029	.037
25.60	1.914	.037	.003	.068	.031
27.82	2.075	.032	.003	-.002	.047

$(2_2^-;1) - 19.40 \text{ MeV}$

4.46	0.337	.807	.069	.104	.029
6.14	0.463	.721	.055	.229	.019
7.81	0.488	.713	.061	.257	.030
9.49	0.714	.475	.049	.093	.045
11.16	0.840	.422	.034	.180	.025
12.83	0.965	.262	.021	.241	.025
14.50	1.090	.159	.015	.090	.038
16.17	1.215	.066	.024	-.015	.209
17.84	1.339	.027	.018	-.014	.395

$(4_1^-;1) - 19.65 \text{ MeV}$

9.49	0.714	.081	.030	.125	.221
11.16	0.840	.074	.015	.111	.115
12.83	0.965	.082	.011	.147	.067
14.50	1.090	.175	.015	.198	.030
16.17	1.215	.181	.016	.317	.028
17.84	1.339	.224	.017	.258	.019
19.50	1.464	.209	.015	.301	.010
21.17	1.587	.202	.015	.292	.012
23.38	1.715	.148	.011	.293	.011
25.60	1.914	.104	.008	.309	.012
27.82	2.075	.072	.006	.279	.021

$(3_1^-;1) - 20.60 \text{ MeV}$

12.83	0.965	.101	.009	.025	.036
14.50	1.090	.103	.009	.205	.034
16.17	1.215	.091	.008	.209	.029
17.84	1.339	.078	.007	.111	.026
19.50	1.464	.053	.004	.183	.026
21.17	1.587	.039	.004	.066	.036
23.38	1.751	.021	.002	.052	.045
25.60	1.914	.013	.001	-.132	.057
27.82	2.075	.006	.002	.207	.152

Experimental Angular Distributions
 $^{12}\text{C}(\vec{p}, p') ^{12}\text{C}^* - 597 \text{ MeV}$

θ_{cm}	$q(\text{fm}^{-1})$	$\frac{d\sigma}{d\Omega}(\frac{\text{mb}}{\text{sr}})$	$\pm$	Δ	A_Y	$\pm$	Δ
$0_1^+; 0 - 0.00 \text{ MeV}$							
3.36	0.317	2259.	25.		.166	.011	
3.62	0.344	2172.	24.		.155	.011	
3.88	0.370	1965.	23.		.181	.011	
4.14	0.392	1847.	22.		.212	.012	
4.40	0.419	1730.	22.		.198	.012	
4.66	0.442	1556.	21.		.227	.013	
4.80	0.456	1487.	20.		.269	.016	
5.06	0.480	1460.	18.		.293	.016	
5.32	0.505	1350.	16.		.296	.016	
5.58	0.530	1244.	15.		.297	.017	
5.98	0.569	1091.	13.		.298	.011	
6.24	0.591	1060.	13.		.297	.011	
6.50	0.618	996.	13.		.322	.012	
6.76	0.634	905.	12.		.331	.012	
7.02	0.666	846.	12.		.319	.013	
7.28	0.693	759.	12.		.331	.013	
7.54	0.714	708.	11.		.325	.014	
7.80	0.741	662.	10.		.365	.014	
8.06	0.766	596.	10.		.353	.015	
8.24	0.781	545.	6.4		.394	.012	
8.50	0.805	503.	6.0		.384	.013	
8.76	0.831	447.	5.6		.403	.014	
9.02	0.858	405.	5.5		.415	.014	
9.28	0.880	364.	5.2		.415	.015	
9.54	0.906	321.	4.9		.408	.016	
9.80	0.928	286.	4.6		.380	.017	
10.06	0.954	245.	4.2		.401	.018	
10.32	0.979	214.	4.0		.390	.020	
10.51	0.997	199.	2.5		.369	.013	
10.76	1.019	173.	2.3		.360	.014	
11.02	1.045	153.	2.2		.370	.015	
11.28	1.071	126.	2.0		.333	.016	
11.54	1.094	110.	1.8		.347	.017	
11.80	1.117	95.4	1.7		.334	.019	
12.06	1.142	77.3	1.5		.326	.021	
12.32	1.168	66.6	1.4		.348	.022	
12.58	1.190	55.1	1.3		.301	.025	
12.76	1.210	47.6	.51		.271	.012	
13.02	1.233	38.6	.48		.251	.014	
13.28	1.258	31.2	.38		.219	.015	

13.54	1.285	25.0	.38	.207	.017
13.80	1.307	19.4	.33	.182	.020
14.06	1.330	15.5	.30	.125	.022
14.32	1.355	11.4	.26	.120	.026
14.58	1.381	8.48	.22	.019	.030
14.83	1.402	5.69	.18	-.054	.031
15.02	1.423	4.45	.15	-.192	.041
15.28	1.445	3.21	.13	-.244	.048
15.54	1.471	2.28	.11	-.384	.056
15.80	1.495	1.38	.08	-.529	.069
16.06	1.519	.951	.069	-.515	.084
16.31	1.544	.720	.060	-.285	.101
16.57	1.567	.686	.064	.125	.101
16.83	1.593	.660	.064	.454	.090
17.09	1.615	.934	.081	.775	.057
17.28	1.635	1.06	.026	.827	.020
17.54	1.659	1.34	.030	.893	.016
17.79	1.683	1.59	.034	.908	.014
18.05	1.705	1.94	.039	.881	.014
18.31	1.731	2.18	.039	.866	.013
18.57	1.756	2.53	.043	.829	.013
18.83	1.779	2.63	.043	.813	.013
19.08	1.800	2.88	.043	.754	.013
19.34	1.826	2.70	.043	.778	.013

$2_1^+; 0 - 4.44 \text{ MeV}$

4.14	0.392	9.16	.96	.255	.067
4.40	0.419	8.68	.92	.297	.068
4.66	0.442	9.28	1.0	.292	.065
4.80	0.456	10.5	1.1	.368	.060
5.06	0.480	10.7	1.0	.235	.062
5.32	0.505	11.7	1.1	.333	.054
5.58	0.530	11.9	1.2	.329	.034
5.98	0.569	12.2	1.2	.387	.035
6.24	0.591	12.4	1.0	.381	.038
6.50	0.618	12.5	1.4	.345	.042
6.76	0.634	12.9	1.5	.422	.050
7.02	0.666	13.1	1.4	.437	.052
7.28	0.693	14.4	1.4	.450	.053
7.54	0.714	15.7	1.6	.442	.042
7.80	0.741	17.1	1.7	.452	.038
8.06	0.766	19.2	1.8	.450	.076
8.24	0.781	20.6	1.2	.492	.061
8.50	0.805	20.7	1.2	.487	.061
8.76	0.831	20.8	1.2	.505	.060
9.02	0.858	23.4	1.3	.512	.052
9.28	0.880	22.1	1.3	.477	.059
9.54	0.906	23.3	1.3	.414	.059
9.80	0.928	24.5	1.4	.519	.052
10.06	0.954	26.0	1.4	.510	.054

10.32	0.979	26.3	1.4	.532	.053
10.51	0.997	28.6	.94	.484	.032
10.76	1.019	28.5	.94	.486	.032
11.02	1.045	27.4	.94	.533	.032
11.28	1.071	27.9	.94	.517	.032
11.54	1.094	27.5	.94	.538	.031
11.80	1.117	27.0	.94	.491	.033
12.06	1.142	28.0	.94	.498	.032
12.32	1.168	27.8	.94	.493	.032
12.58	1.190	26.0	.90	.497	.033
12.76	1.210	25.2	.39	.506	.016
13.02	1.233	24.8	.39	.496	.016
13.28	1.258	25.4	.40	.503	.015
13.54	1.285	23.2	.37	.461	.017
13.80	1.307	22.5	.36	.477	.017
14.06	1.330	21.7	.36	.469	.017
14.32	1.355	20.5	.35	.473	.017
14.58	1.381	20.1	.35	.428	.018
14.83	1.402	18.5	.33	.438	.018
15.02	1.423	17.6	.33	.447	.018
15.28	1.445	16.7	.32	.434	.018
15.54	1.471	15.8	.31	.427	.019
15.80	1.495	14.3	.27	.393	.020
16.06	1.519	13.8	.29	.418	.020
16.31	1.544	12.8	.28	.375	.021
16.57	1.567	11.6	.27	.415	.022
16.83	1.593	10.5	.25	.392	.023
17.09	1.615	9.80	.24	.352	.025
17.28	1.635	9.05	.08	.349	.009
17.54	1.659	8.19	.07	.331	.010
17.79	1.683	7.50	.07	.317	.010
18.05	1.705	6.57	.07	.289	.011
18.31	1.731	5.96	.06	.283	.012
18.57	1.756	5.37	.06	.256	.012
18.83	1.779	4.70	.06	.242	.013
19.08	1.800	4.19	.05	.203	.014
19.34	1.826	3.69	.05	.184	.015

$0_2^+; 0 - 7.65 \text{ MeV}$

2.91	0.279	.155	.063	-.238	.210
3.88	0.371	.301	.056	-.172	.072
4.61	0.443	.458	.065	-.152	.035
5.58	0.530	1.26	.168	.066	.018
6.31	0.598	1.70	.26	.067	.049
7.28	0.689	2.55	.37	.230	.035
8.57	0.814	3.38	.46	.235	.025
9.54	0.906	3.56	.48	.330	.023
10.83	1.028	3.55	.46	.337	.006
11.80	1.116	2.97	.38	.333	.006
13.09	1.241	2.42	.32	.334	.013

14.06	1.330	1.51	.20	.278	.016
15.35	1.448	.891	.117	.231	.015
16.31	1.540	.380	.051	.124	.023
17.60	1.666	.157	.022	-.066	.029
18.57	1.752	.042	.007	-.156	.057

$3_1^-;0 - 9.64 \text{ MeV}$

4.61	0.443	.238	.043	.208	.057
5.58	0.530	.570	.080	.297	.031
6.31	0.598	.678	.097	.347	.033
7.28	0.689	1.61	.21	.448	.015
8.57	0.814	2.49	.32	.486	.011
9.54	0.906	3.85	.50	.512	.009
10.83	1.028	5.17	.67	.529	.007
11.80	1.116	6.16	.80	.532	.007
13.09	1.241	7.14	.93	.541	.009
14.06	1.330	8.49	1.1	.516	.009
15.35	1.448	6.62	.86	.488	.009
16.31	1.540	5.61	.73	.463	.009
17.60	1.666	4.58	.59	.418	.007
18.57	1.752	3.38	.44	.374	.008

$1_1^-;0 - 10.84 \text{ MeV}$

6.79	0.644	.113	.028	.314	.113
9.05	0.858	.399	.055	.434	.026
11.31	1.071	.714	.093	.407	.010
13.57	1.285	.729	.095	.372	.008

$4_1^+;0 - 14.08 \text{ MeV}$

4.61	0.443	.087	.032	.016	.149
5.58	0.530	.096	.033	.340	.126
6.79	0.644	.107	.022	.425	.091
10.83	1.028	.091	.022	.322	.100
11.80	1.116	.109	.021	.352	.098
13.09	1.241	.180	.026	.701	.106
14.06	1.330	.195	.028	.557	.087
15.35	1.448	.221	.031	.419	.079
16.31	1.540	.216	.028	.465	.078
17.60	1.666	.259	.021	.324	.059
18.57	1.752	.134	.016	.320	.060

$1_1^+; 0 - 12.71 \text{ MeV}$

3.88	0.370	.384	.068	-.391	.058
4.68	0.448	.308	.049	-.464	.045
5.58	0.530	.281	.044	-.398	.046
6.27	0.597	.225	.046	-.366	.808
7.28	0.693	.204	.033	-.311	.049
8.56	0.812	.142	.028	-.315	.076
9.54	0.906	.094	.018	-.163	.075
10.81	1.026	.079	.012	-.008	.058
11.80	1.117	.048	.009	.009	.077
13.09	1.239	.032	.006	.253	.083
14.06	1.330	.024	.006	.297	.102
15.34	1.452	.018	.004	.284	.094
16.31	1.544	.016	.004	.284	.098
17.61	1.665	.015	.003	.430	.087
18.57	1.756	.014	.003	.549	.082

 $1_1^+; 1 - 15.11 \text{ MeV}$

3.88	0.370	1.39	.189	.104	.028
4.68	0.448	1.00	.134	.046	.021
5.58	0.530	.676	.093	.033	.027
6.27	0.597	.487	.071	-.006	.039
7.28	0.693	.347	.051	.046	.039
8.56	0.812	.192	.032	.015	.061
9.54	0.906	.140	.026	-.106	.073
10.81	1.026	.081	.015	-.014	.112
11.80	1.117	.045	.011	-.009	.151
13.09	1.239	.027	.008	-.242	.149
14.06	1.330	.023	.006	-.081	.149
15.34	1.452	.014	.004	-.134	.126
16.31	1.544	.014	.003	.045	.120
17.61	1.665	.012	.003	-.220	.126
18.57	1.756	.008	.003	-.226	.156

 $2_1^+; 1 - 16.11 \text{ MeV}$

4.68	0.448	.044	.015	-.292	.179
5.58	0.530	.056	.016	.055	.150
6.27	0.597	.053	.030	-.272	.299
7.28	0.693	.061	.021	-.312	.166
8.56	0.812	.087	.021	.215	.111
9.54	0.906	.091	.019	.095	.094
10.81	1.026	.096	.016	-.059	.060
11.80	1.117	.082	.014	.133	.058
13.09	1.239	.076	.012	-.014	.047

14.06	1.330	.048	.008	.015	.065
15.34	1.452	.041	.006	-.121	.048
16.31	1.544	.029	.005	.022	.056
17.61	1.665	.019	.003	-.189	.067
18.57	1.756	.013	.003	-.199	.088

$2_1^-; 1 - 16.58 \text{ MeV}$

11.31	1.071	.031	.010	.453	.148
13.57	1.285	.035	.009	.660	.086
15.83	1.495	.030	.004	.465	.070
18.08	1.705	.020	.003	.406	.046

$2_2^-; 0 - 13.35 \text{ MeV}$

15.80	1.495	.009	.003	.186	.141
18.05	1.705	.010	.002	.178	.110

$(2_3^-; 0) - 18.30 \text{ MeV}$

3.36	0.317	.279	.059	-.166	.090
5.06	0.480	.309	.047	-.410	.039
6.79	0.644	.384	.057	-.291	.040
9.02	0.858	.368	.052	-.190	.032
11.28	1.071	.301	.040	.042	.021
13.54	1.285	.179	.024	.203	.021
15.80	1.495	.047	.007	.137	.035
18.05	1.705	.027	.004	.095	.044

$(4_1^-; 0) - 19.28 \text{ MeV}$

13.57	1.285	.109	.018	-.221	.053
15.80	1.495	.078	.011	-.249	.037
18.05	1.705	.031	.006	-.366	.070

$(2_2^-; 1) - 19.40 \text{ MeV}$

3.36	0.317	.646	.106	.281	.054
5.06	0.480	.729	.099	.105	.023
6.79	0.644	.461	.066	.133	.034
9.05	0.858	.293	.047	.155	.052
11.31	1.071	.146	.025	.037	.062

$(4_1^-; 1) - 19.65 \text{ MeV}$

9.05	0.858	.052	.025	-.081	.262
11.31	1.071	.152	.034	.235	.049
13.57	1.285	.287	.038	.212	.017
15.80	1.495	.225	.030	.224	.012
18.05	1.705	.153	.020	.216	.012

$(3_1^-; 1) - 20.60 \text{ MeV}$

9.02	0.858	.084	.017	.070	.094
11.28	1.071	.086	.014	-.004	.056
13.54	1.285	.099	.014	.138	.035
15.80	1.495	.028	.042	.072	.042
18.05	1.705	.036	.052	.131	.035

Experimental Angular Distributions
 $^{12}\text{C}(\vec{p}, \vec{p}')^{12}\text{C}^* - 698 \text{ MeV}$

θ_{cm}	$q(\text{fm}^{-1})$	$\frac{d\sigma}{d\Omega}(\frac{\text{mb}}{\text{sr}})$	$\pm$	Δ	A_y	$\pm$	Δ
$0_1^+; 0 - 0.00 \text{ MeV}$							
3.68	0.390	2623.		23.	.189		.011
3.94	0.419	2452.		22.	.225		.011
4.20	0.445	2317.		21.	.223		.012
4.47	0.467	2166.		21.	.243		.012
4.73	0.496	2015.		20.	.240		.012
4.99	0.521	1869.		17.	.239		.015
6.44	0.671	1117.		13.	.262		.015
6.70	0.696	1027.		12.	.295		.015
6.96	0.725	936.		12.	.291		.016
7.22	0.749	864.		11.	.308		.016
7.49	0.778	763.		10.	.311		.017
7.75	0.800	704.		10.	.336		.018
8.01	0.831	634.		9.5	.335		.019
9.47	0.978	294.		4.0	.328		.019
9.73	1.005	259.		4.0	.321		.018
9.99	1.032	219.		3.5	.341		.019
10.26	1.061	186.		3.3	.321		.017
10.52	1.091	153.		3.0	.332		.016
10.78	1.118	131.		2.7	.309		.015
11.04	1.140	109.		2.5	.290		.016
11.30	1.168	89.1		2.3	.284		.016
11.56	1.195	74.4		2.1	.281		.014
12.89	1.330	18.2		.23	.180		.016
13.15	1.357	13.6		.20	.130		.019
13.41	1.382	9.79		.17	.076		.022
13.67	1.412	7.00		.14	-.041		.027
13.93	1.441	4.22		.11	-.033		.034
14.19	1.464	2.83		.09	-.234		.042
14.45	1.488	1.77		.07	-.214		.053
14.71	1.518	1.19		.06	-.046		.064
14.97	1.543	1.07		.06	.224		.066
16.30	1.680	2.53		.05	.822		.020
16.56	1.702	2.99		.06	.757		.019
16.82	1.733	3.37		.06	.759		.018
17.08	1.760	3.72		.07	.718		.018
17.34	1.790	4.13		.07	.718		.017
17.60	1.814	4.43		.07	.680		.017
17.86	1.839	4.50		.07	.643		.017
18.12	1.865	4.75		.08	.629		.017
18.38	1.890	4.69		.08	.624		.017

$2_1^+; 0 - 4.44 \text{ MeV}$

3.68	0.390	9.87	.82	.152	.102
3.94	0.419	8.94	.78	.320	.104
4.20	0.445	9.73	.78	.160	.104
4.47	0.467	9.82	.82	.253	.100
4.73	0.496	10.1	.82	.152	.101
4.99	0.521	13.2	.95	.257	.086
6.18	0.642	17.2	.87	.311	.058
6.44	0.671	19.3	.95	.373	.054
6.70	0.696	20.7	1.0	.401	.052
6.96	0.725	21.1	1.0	.349	.052
7.22	0.749	24.2	1.0	.342	.049
7.49	0.779	24.8	1.1	.367	.048
7.75	0.800	29.2	1.2	.407	.043
8.01	0.831	30.8	1.2	.402	.042
9.47	0.978	36.8	1.4	.435	.022
9.73	1.005	35.6	1.4	.389	.026
9.99	1.032	33.8	1.4	.459	.028
10.26	1.061	33.5	1.4	.442	.014
10.52	1.091	34.8	1.4	.424	.022
10.78	1.118	32.5	1.3	.405	.022
11.04	1.140	30.1	1.3	.508	.023
11.30	1.168	34.5	1.4	.462	.022
11.56	1.195	33.2	1.3	.498	.023
11.82	1.222	28.4	1.3	.462	.020
12.89	1.330	25.9	.28	.430	.013
13.15	1.357	25.9	.28	.431	.013
13.41	1.382	24.3	.27	.419	.013
13.67	1.412	22.8	.26	.421	.014
13.93	1.441	21.0	.25	.386	.014
14.19	1.464	19.4	.24	.415	.015
14.45	1.488	18.3	.23	.402	.015
14.71	1.518	17.2	.23	.418	.016
14.97	1.543	15.5	.22	.384	.017
16.30	1.680	8.63	.10	.335	.014
16.56	1.702	7.53	.09	.317	.015
16.82	1.733	6.67	.09	.322	.016
17.08	1.760	5.69	.08	.257	.017
17.34	1.790	5.02	.07	.281	.018
17.60	1.814	4.23	.07	.221	.020
17.86	1.839	3.63	.06	.214	.022
18.12	1.865	3.15	.06	.197	.024
18.38	1.890	2.56	.05	.199	.026

$0_2^+;0 - 7.65 \text{ MeV}$

3.42	0.355	.243	.045	-.106	.094
4.64	0.483	.702	.144	-.058	.024
5.62	0.586	1.82	.37	.107	.013
6.21	0.645	1.98	.40	.147	.020
7.19	0.747	3.56	.72	.223	.012
9.77	1.006	4.60	.93	.299	.014
10.74	1.117	3.67	.74	.310	.015
13.18	1.358	1.74	.34	.295	.015
14.15	1.463	.764	.16	.247	.022
16.59	1.704	.089	.02	-.010	.033
17.56	1.812	.061	.02	.426	.042

 $3_1^-;0 - 9.64 \text{ MeV}$

3.42	0.355	.221	.042	.210	.097
4.64	0.483	.411	.087	.317	.038
5.62	0.586	1.02	.21	.314	.020
6.21	0.645	1.15	.24	.398	.035
7.19	0.747	2.83	.57	.417	.015
9.77	1.006	7.02	1.42	.416	.014
10.74	1.117	8.26	1.67	.455	.014
13.18	1.358	9.28	1.87	.464	.012
14.15	1.463	7.89	1.59	.437	.011
16.59	1.704	4.99	1.00	.388	.008
17.56	1.812	3.18	.64	.333	.008

 $1_1^-;0 - 10.84 \text{ MeV}$

5.13	0.533	.049	.016	.116	.160
6.70	0.696	.197	.054	.108	.108

 $4_1^+;0 - 14.08 \text{ MeV}$

5.13	0.533	.091	.016	.145	.086
9.77	1.006	.093	.038	.467	.100
10.74	1.117	.135	.033	.688	.090
13.18	1.358	.270	.065	.600	.088
14.15	1.463	.308	.068	.447	.080
16.59	1.704	.296	.062	.364	.078
17.56	1.812	.201	.045	.301	.076

$1_1^+; 0 - 12.71 \text{ MeV}$

2.77	0.297	.273	.097	-.185	.173
3.42	0.362	.330	.086	-.294	.089
4.07	0.424	.339	.083	-.352	.073
4.48	0.467	.290	.066	-.351	.051
5.13	0.536	.241	.058	-.410	.055
5.78	0.612	.236	.055	-.457	.055
6.05	0.638	.242	.085	-.246	.168
6.70	0.696	.206	.051	-.203	.079
7.35	0.763	.235	.038	-.120	.112
9.60	0.992	.068	.018	-.055	.097
10.26	1.061	.044	.012	.259	.109
10.91	1.129	.040	.012	.181	.126
13.02	1.342	.018	.007	.260	.201
13.67	1.412	.015	.007	.266	.256
14.32	1.478	.015	.006	.242	.212
16.43	1.691	.017	.005	.550	.094
17.07	1.760	.012	.004	.521	.125
17.72	1.828	.011	.004	.591	.117

 $1_1^+; 1 - 15.11 \text{ MeV}$

2.77	0.297	.930	.214	-.049	.060
3.42	0.362	1.20	.261	-.016	.037
4.07	0.424	.935	.210	-.025	.041
4.48	0.467	.718	.143	-.054	.027
5.13	0.536	.550	.119	.019	.034
5.78	0.612	.409	.090	-.102	.043
6.05	0.638	.324	.101	.007	.143
6.70	0.696	.322	.076	-.237	.075
7.35	0.763	.202	.055	.122	.104
9.60	0.992	.100	.025	.046	.083
10.26	1.061	.075	.020	.152	.097
10.91	1.129	.051	.015	-.014	.136
13.02	1.342	.024	.009	.323	.167
13.67	1.412	.021	.008	.236	.177
14.32	1.478	.018	.007	-.292	.217
16.43	1.691	.013	.004	-.172	.116
17.07	1.760	.010	.003	-.245	.158
17.72	1.828	.009	.003	-.042	.152

 $2_1^+; 1 - 16.11 \text{ MeV}$

5.13	0.536	.038	.020	-.001	.288
9.60	0.992	.100	.025	.223	.075
10.26	1.061	.084	.021	.130	.080

10.91	1.129	.055	.017	.161	.120
13.02	1.342	.057	.014	-.016	.073
13.67	1.412	.039	.010	.066	.092
14.32	1.478	.034	.009	-.073	.098
16.43	1.691	.016	.004	-.294	.098
17.07	1.760	.013	.004	-.403	.111
17.72	1.828	.009	.003	-.406	.146

$2_1^-;1$ - 16.58 MeV

10.26	1.061	.033	.010	.424	.127
13.67	1.412	.037	.009	.442	.064
17.07	1.760	.020	.004	.483	.047

$2_2^-;0$ - 13.35 MeV

17.07	1.760	.014	.004	.389	.099
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$(2_3^-;0)$ - 18.30 MeV

3.42	0.355	.309	.089	-.481	.102
5.13	0.533	.404	.088	-.475	.031
6.70	0.696	.546	.127	.044	.063
10.26	1.061	.319	.067	.085	.017
13.67	1.412	.082	.018	-.075	.035
17.07	1.760	.030	.007	.186	.034

$(4_1^-;0)$ - 19.28 MeV

13.67	1.412	.061	.016	-.487	.086
17.07	1.760	.074	.016	-.035	.025

$(2_1^-;1)$ - 19.40 MeV

3.42	0.355	.607	.139	.042	.058
5.13	0.533	.869	.185	-.024	.023
6.70	0.696	.484	.125	.041	.091
10.26	1.061	.151	.035	-.197	.045

$(4_1^-; 1) - 19.65 \text{ MeV}$

6.70	0.696	.047	.027	.310	.310
10.26	1.061	.138	.032	.172	.060
13.67	1.412	.232	.049	.181	.018
17.07	1.760	.174	.036	.209	.011

$(3_1^-; 1) - 20.60 \text{ MeV}$

10.26	1.061	.071	.016	-.083	.062
13.67	1.412	.060	.013	.023	.045
17.07	1.760	.019	.004	.062	.057

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