

$0^+ \rightarrow 0^-$  EXCITATIONS IN  $^{16}\text{O}$   
WITH 200 MeV PROTON INELASTIC SCATTERING

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Proton inelastic scattering studies provide a potentially rich source of new nuclear structure information. Within the framework of the distorted wave impulse approximation (DWIA), the nucleon-nucleus transition matrix contains three types of nuclear structure factors: the spin-independent longitudinal transition density  $\rho$ , the spin-dependent transverse transition density  $\Sigma_T$  (which varies as  $\sigma \times \mathbf{q}$ ), and the spin-dependent longitudinal transition density  $\Sigma_L$  (which varies as  $\sigma \cdot \mathbf{q}$ ). The inelastic excitation of natural-parity transitions involves both  $\rho$  and  $\Sigma_T$ , while the inelastic excitation of unnatural-parity transitions normally involves both  $\Sigma_T$  and  $\Sigma_L$ .<sup>1</sup>

The transverse magnetic form factor measured in back-angle electron scattering experiments provides detailed information about the transverse spin density  $\Sigma_T$ . Since the longitudinal spin density  $\Sigma_L$  does not contribute in leading order to either  $(e, e')$  or  $(\pi, \pi')$ , this represents a new aspect of nuclear structure which can be investigated with proton inelastic scattering. Additional interest in determining  $\Sigma_L$  comes from the expectation that the pion field in the nucleus is sensitive to the longitudinal spin response. A determination of  $\Sigma_L$  could provide information about the effects of meson-exchange and isobar currents, and possibly to unexpected enhancements of the pionic field. It is of interest to search for these effects in proton inelastic scattering<sup>2</sup>.

The most favorable case for the investigation of  $\Sigma_L$  in proton inelastic scattering involves  $0^+ \rightarrow 0^-$  transitions, for which  $\Sigma_T$  vanishes and one is therefore sensitive to  $\Sigma_L$ . For these transitions, the initial and final nuclear states have angular momentum zero, and the most general form of the transition amplitude for  $0^+ \rightarrow 0^-$  excitations in a spin-0 target using a spin- $\frac{1}{2}$  proton which respects rotation and parity invariance is given by

$$A = A_q(\sigma \cdot \mathbf{q}) + A_K(\sigma \cdot \mathbf{K})$$

where  $A_q$  and  $A_K$  are scalar functions of energy and momentum transfer, while  $\mathbf{q}$  and  $\mathbf{K}$  are unit vectors in the direction of momentum transfer  $\mathbf{k}' - \mathbf{k}$  and average momentum

$(\mathbf{k}' + \mathbf{k})/2$ , respectively, and  $\sigma$  is the Pauli spin matrix. For this particular case of interest, as in elastic scattering, one can only measure three independent observables. These are the cross section ( $\sigma$ ), the analyzing power ( $A_y$ ) and the spin rotation parameter ( $Q$ ). Experimental data for these observables completely specify the transition amplitude within a phase and provide severe constraints on the choice of acceptable theoretical models. One needs also the complete measurement to extract information on the longitudinal spin density  $\Sigma_L$ .

There are several  $0^+ \rightarrow 0^-$  transitions of interest in light nuclei, such as those leading to the 10.957 MeV,  $T=0$  state and the 12.797 MeV,  $T=1$  state in  $^{16}\text{O}$ , the 6.902 MeV state in  $^{14}\text{C}$ , and the 5.880 MeV state in  $^{18}\text{O}$ .

To date, only limited experimental work has been possible because these transitions are weak and usually occur in regions of high level density. The existing measurements include ( $\sigma$ ) and ( $A_y$ ) measurements for one or both of the transitions in  $^{16}\text{O}$  at 65 and 135 MeV for (p,p') and 35 and 80 MeV for (p,n) experiments.<sup>3,4,5,6</sup> At higher energies, there are unpublished (p,p') data, including ( $\sigma$ ) and ( $A_y$ ) measurements at 180 and 200 MeV for only the  $0^-$ ,  $T=0$  transition in  $^{16}\text{O}$ .<sup>6,7</sup> Most of these measurements were not taken with sufficient resolution to separate the  $0^-$ ,  $T=0$  state at 10.957 MeV from its strong neighboring doublet ( $3^+$  and  $4^+$ ) which is only about 140 keV away. For the  $T=1$  state at 12.797 MeV, there are (p,p') cross section and analyzing power data at 65 MeV only.<sup>2</sup>

These measurements require excellent energy resolution and so are especially well suited for the newly commissioned K600 magnetic spectrometer. During 1988, this experiment (E318) was approved and twenty four shifts of beam time were allocated for it. Some of this time was devoted to a study of dispersion matching and focus conditions; an overall resolution of about 25–30 keV was achieved. We have measured  $\sigma$  and  $A_y$  angular distributions for the two lowest  $0^-$  ( $T=0$ , 10.957 MeV;  $T=1$ , 12.797 MeV) excitations in  $^{16}\text{O}$  at  $E_p=200$  MeV for c.m. angles between  $7.0^\circ$  and  $45.0^\circ$  in  $4^\circ$  steps. Each step was analyzed in four separate angle bins. In order to achieve maximum efficiency in taking data for the inelastic transitions, we stopped the elastic group in a copper block immediately in front of the focal plane detector. We also used a third short scintillator in coincidence with the existing pair to restrict the measurement to a small portion of the focal plane near the region of interest. The polarization of the incident beam (typically 0.76) was periodically monitored using an in-beam polarimeter upstream of the target in beam line two (BL2).

Boric acid ( $\text{H}_3^{10}\text{BO}_3$ ) and boron oxide ( $^{10}\text{B}_2\text{O}_3$ ) targets, isotopically enriched in  $^{10}\text{B}$ , with different thicknesses between 3 and 5  $\text{mg}/\text{cm}^2$  and with 250  $\mu\text{g}/\text{cm}^2$  gold backing have been used in this experiment. They appear to be stable as long as provision is made for heat conduction out of the target. This has been achieved with thin layers of gold on the front and back surfaces of the target. For our purposes, a heavy odd-mass material such as  $^{197}\text{Au}$  is good, since the continuum spectrum of gold is weak and virtually free of narrow excited states.

In Fig. 1, Momentum spectra for the  $^{16}\text{O}(\bar{p},p')^{16}\text{O}$  reaction with 200 MeV protons at  $\theta_{lab}=16.0^\circ$  (top) and at  $\theta_{lab}=6.5^\circ$  (bottom) are shown, where a 3.55  $\text{mg}/\text{cm}^2$   $^{10}\text{B}_2\text{O}_3$  target was used and an overall resolution of 25 keV was achieved. It is clear that the ( $0^-$ ,  $T=1$ ) state at 12.797 MeV is well separated from its strong  $2^-$  neighboring state.

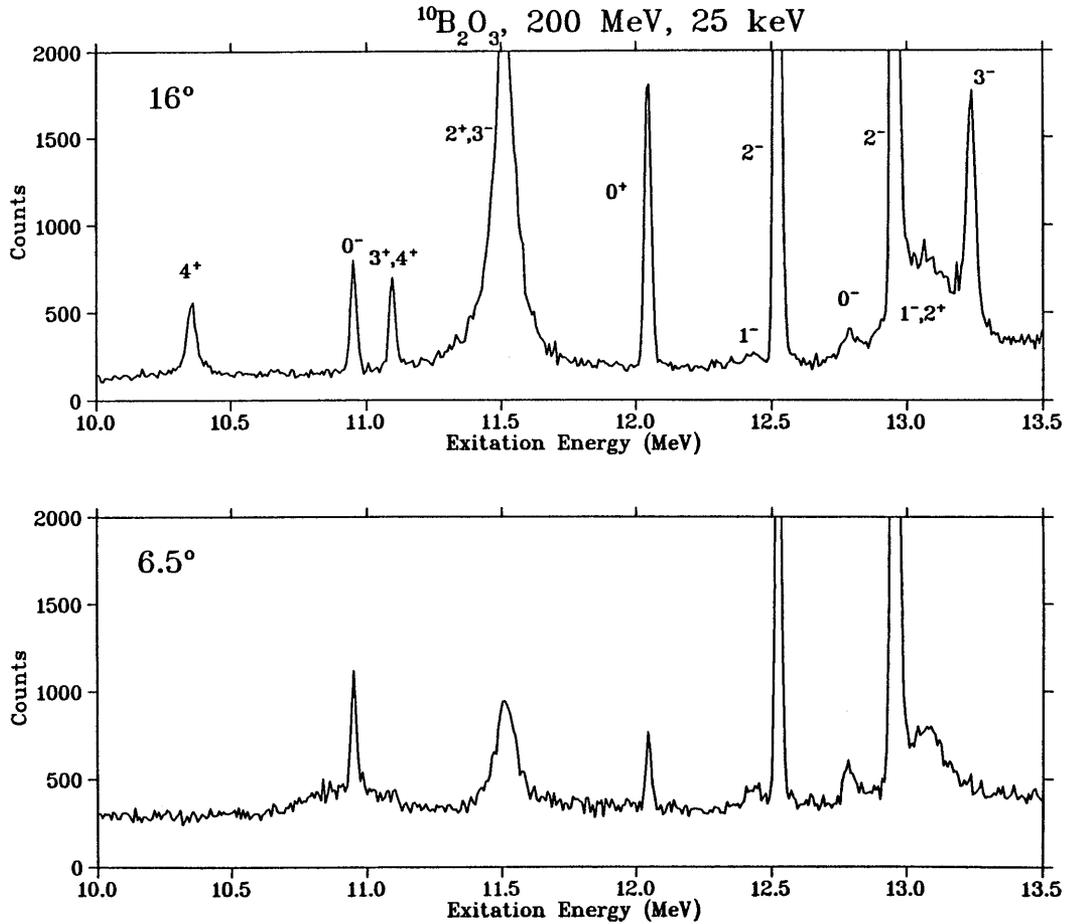


Figure 1. Momentum spectra for the  $^{16}\text{O}(\bar{p}, p')^{16}\text{O}$  reaction with 200 MeV protons from a  $3.55 \text{ mg/cm}^2$   $^{10}\text{B}_2\text{O}_3$  target with 25 keV resolution at  $\theta_{lab}=16.0^\circ$  (top) and at  $\theta_{lab}=6.5^\circ$  (bottom).

These unique transitions are interesting for several reasons. Since the spin-orbit component of the effective N-N interaction cannot contribute and the central component is weak, the excitation must occur primarily through the tensor component. In nonrelativistic plane wave impulse approximation (NRPWIA), if one uses only the direct term of the transition matrix element, the following relations are predicted:

$$P = A_y = 0$$

where  $P$  is the polarization function. If exchange is included, the calculation predicts that

$$P = -A_y \neq 0$$

In fact, this relation is general and model independent. In contrast to the NRPWIA calculations, relativistic plane wave impulse approximation (RPWIA) calculations predict

non-zero values for the analyzing power and other spin observables without the explicit inclusion of exchange. This result has its origin in the lower components of relativistic wave functions. By having opposite parity than their upper counterparts, lower components are able to restore the correct parity in certain operators that were otherwise forbidden to contribute in a nonrelativistic approach. These operators generated precisely those terms in the amplitude necessary for nonzero values for some of the spin observables.<sup>8</sup>

Therefore, high quality data should provide useful information about the least understood component (tensor) of the effective interaction, and the exchange nature of the non-relativistic nucleon-nucleus effective interaction at intermediate energies.

At this stage, our data are still preliminary; comparison with both relativistic and nonrelativistic calculations have been carried out for these transitions at 200 MeV. The relativistic calculation is based on the relativistic impulse approximation. The computer code DREX<sup>9</sup> was used to generate this calculation. The nonrelativistic calculations are based on the Franey-Love t-matrix<sup>10</sup> and the computer code DW81<sup>11</sup> was used. Both models use a microscopic t-matrix fit to N-N phase shifts and knock-on exchange is included explicitly. For the nuclear structure, it was assumed in both models that the  $0^+ \rightarrow 0^-$  transition is described by a pure  $|1p_{1/2}^{-1}, 2s_{1/2}\rangle$  single particle transition. For the distortion, Woods-Saxon phenomenological Schrödinger optical potentials fitted to elastic cross section, analyzing power and spin rotation data were employed in the DW81 calculations, while the DREX calculations use the prescription of Ref. 12; both give an excellent description of all the elastic scattering data.

As shown in Fig. 2, there is no quantitative agreement between the DW81 calculation and the IUCF data for the  $T=0$  cross section and analyzing power. After multiplying the calculated DW81 cross section by a factor of 0.6, the general shape of the data is poorly produced. The agreement with the DREX calculation is not good either. For the cross section, the DREX calculation required a normalization factor of 1.2. There are significant differences in magnitude and angular dependence between both calculations and the data, especially for angles  $\geq 20^\circ$  in the c.m. frame.

The most general form of the wave function for these states is given, in a  $1\hbar\omega$  basis space, by

$$\sqrt{1-\alpha^2} |1p_{1/2}^{-1}, 2s_{1/2}\rangle + \alpha |1p_{3/2}^{-1}, 1d_{3/2}\rangle .$$

The beta decay rate of the  $0^-$  state in  $^{16}\text{N}$  at 0.1201 MeV is known experimentally,<sup>13</sup> and in order to reproduce the experimental  $ft$ -values of this forbidden beta decay, van der Werf *et al.*<sup>14</sup> found that a value of  $\alpha = 0.125$  for the  $|1p_{3/2}^{-1}, 1d_{3/2}\rangle$  component is needed. We adopted the same value for  $\alpha$  and found that such an admixture in the wave function helps to achieve qualitative agreement between theory and our data. This is shown in Fig. 3, for the  $0^-$ ,  $T=0$  cross section, after multiplying the calculated DW81 cross section by a factor of 0.60, the general shape of the data is well produced. We find that the calculated cross section is very sensitive to the amplitude of the  $|1p_{3/2}^{-1}, 1d_{3/2}\rangle$  component, while the analysing power calculation is insensitive for this admixture.

For the  $0^-$ ,  $T=1$  transition, our data are the only available data in this energy region. At this stage, our data are still preliminary, and we are developing a multi-peak model to fit the  $0^-$ ,  $T=1$  region to disentangle this state from its neighbors and hence allow

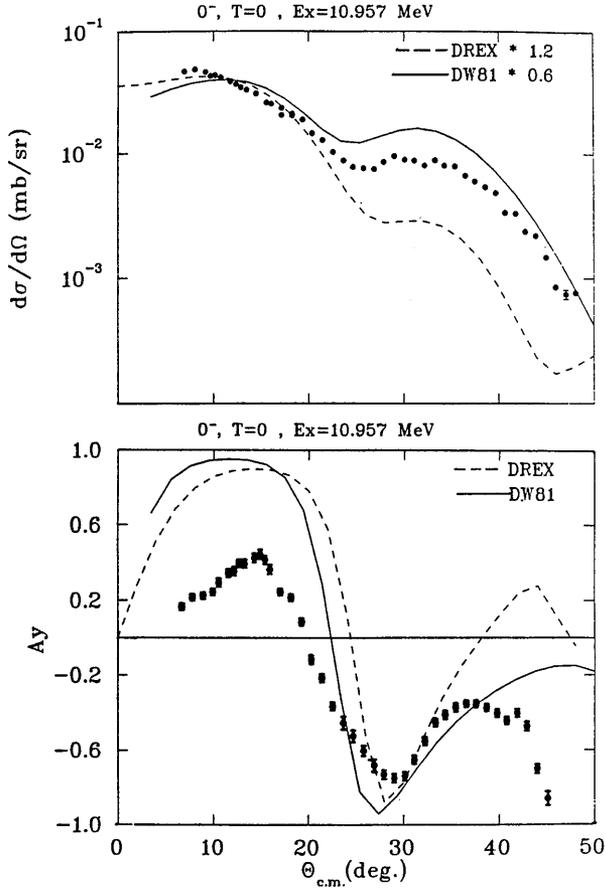
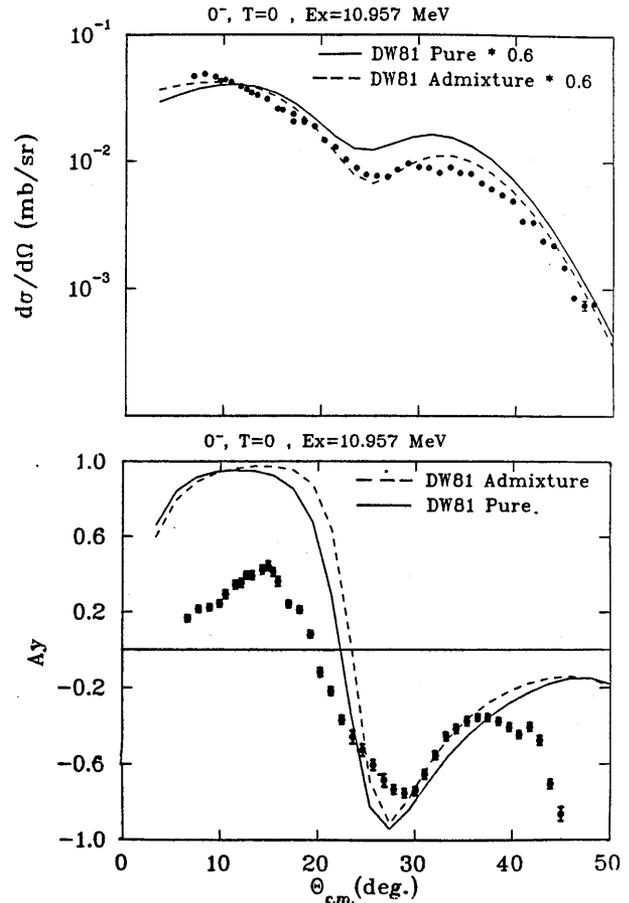


Figure 2. Cross section (top) and analyzing power (bottom) for the 200 MeV proton inelastic excitation of the  $0^-$ ,  $T=0$  state at 10.957 MeV, compared to the experimental data. The solid curves represent the DW81 calculations while the dashed curves represent that of the DREX. Both predictions employ the full effective NN interaction.

Figure 3. Cross section (top) and analyzing power (bottom) for the 200 MeV proton inelastic excitation of the  $0^-$ ,  $T=0$  state at 10.957 MeV, compared to experimental data. The solid curves represent the DW81 calculations with pure  $|p_{1/2}^{-1}, s_{1/2}\rangle$  single particle transition while the dashed curves represent DW81 calculations with an admixture of  $|p_{3/2}^{-1}, d_{3/2}\rangle$  in the wave function on the order 12.5%.



reliable extraction of the peak sums. We have also carried out the same calculations mentioned above for this transition and found that the  $|1p_{3/2}^{-1}, 1d_{3/2}\rangle$  component in the wave function is necessary to achieve good agreement with the data.

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### THE $^{20}\text{Ne}(p,p')$ REACTION AT 135 MeV

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This experiment searched for possible  $6^-$  particle-hole states of  $^{20}\text{Ne}$  using 135 MeV proton inelastic scattering with the K600 spectrometer. In previous work<sup>1</sup> no definite identification of either  $T=0$  or  $T=1$  states was possible, due mainly to the poor (160 keV) resolution obtained.

By using the angular dependences of the differential cross section and analyzing power found<sup>2</sup> for the  $6^-$  states of  $^{28}\text{Si}$  as a guide, it is possible to find likely candidates. The most promising of these are found at  $13.37 \pm 0.05$  MeV and  $13.80 \pm 0.05$  MeV. These are shown in Fig. 1. Here there are factors which must cast some uncertainty on the tentative