INELASTIC SCATTERING

MEASUREMENTS OF THE SPIN OBSERVABLES $D_{NN'}$ AND P IN INELASTIC PROTON SCATTERING FROM ^{12}C AND ^{16}O AT 200 MeV

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We have recently measured the normal–component spin observables $D_{NN'}$, P, and A_y at 200 MeV for the 1^+, T=0 (12.71 MeV) and T=1 (15.11 MeV) states in ^{12}C and for the 4^-, T=0 (17.79 and 19.80 MeV) and T=1 (18.98 MeV) states in ^{16}O. The data represent the first physics measurements performed using the newly commissioned K600 Focal Plane Polarimeter, which is described elsewhere in this report.[1,2] These spin observables were determined at five angles for the ^{12}C 1^+ transitions, corresponding to center–of–mass momentum transfers between 80 and 250 MeV/c, and at three angles for the 4^- transitions in ^{16}O, at momentum transfers of 225 to 400 MeV/c. The angles were chosen to match those at which the in-plane spin transfer observables had been measured previously for these same transitions in experiment E245.[3] During the 39 shifts allocated for this run, we completed all of the measurements originally proposed (E306) and in fact added two additional points to the ^{12}C angular distributions, despite a loss of approximately six shifts to various machine instabilities or failures in the cyclotron RF, polarized ion source, or other systems.

The primary motivation for this work is to exploit the increased sensitivity predicted for the polarization transfer observables to some of the spin–dependent (and generally weaker) terms of the effective interaction used to describe nucleon–nucleus scattering at intermediate energies. Within the context of the impulse approximation, this process can be related to the free N–N scattering amplitudes, albeit in a model–dependent way. Comparison of measured observables to their calculated values thus tests not only our understanding of the nuclear response for these transitions, but our ability to efficiently parameterize the N–N interaction and then modify it appropriately to compensate for the many effects that arise when the scattering occurs within the nuclear medium. If discrepancies are found between measured and calculated values, one must search for some clue as to where the calculation erred. Cross–sections and analyzing powers represent sums over many terms in this process, making it difficult to isolate specific shortcomings in either the interaction or the nuclear structure. A very promising approach involves measurement of a complete set of inelastic proton scattering spin observables for a variety of nuclear transitions.

This is most easily demonstrated in a static, plane–wave impulse approximation in which only direct terms are included. In this approximation, each of the five spin transfer coefficients, denoted by $D_{ij'}$, can be expressed in terms of sums of interaction and structure products. By adding and subtracting these spin observables from one another in particular combinations, certain components of the interaction and structure can be effectively isolated. One finds that for unnatural parity transitions:[4]

$$C^2X_T^2 = D_0\sigma_0 \equiv \sigma_0[1 + (D_{SS'} + D_{LL'})\cos\theta + D_{NN'} - (D_{LS'} - D_{SL'})\sin\theta]/4$$

$$E^2X_L^2 = D_1\sigma_0 \equiv \sigma_0[1 + D_{SS'} - D_{LL'} - D_{NN'}]/4$$

$$B^2X_T^2 = D_2\sigma_0 \equiv \sigma_0[1 - (D_{SS'} + D_{LL'})\cos\theta + D_{NN'} + (D_{LS'} - D_{SL'})\sin\theta]/4$$

$$F^2X_T^2 = D_3\sigma_0 \equiv \sigma_0[1 - D_{SS'} + D_{LL'} - D_{NN'}]/4$$

where $(\hat{S}, \hat{L}, \hat{N}) = (\hat{n} \times \hat{k}, \hat{k}, \hat{n})$. C is the spin–orbit and B, E, and F are tensor amplitudes of the free N–N force, and X_T and X_L are respectively the transverse and longitudional nuclear form factors as developed by Kerman, McManus and Thaler.[5] Note that complete sets of spin observables are required to isolate individual terms in the interaction. There is a similar factorization of interaction and structure terms in a relativistic plane–wave impulse approximation framework.[6] Though the above relationships are rigorously true only in a static PWIA without exchange, previous investigations suggest[6] that these should serve as useful guides to our intuition at typical IUCF energies, at least near the peak of the transition form factors.

Experimental sensitivity to the spin–orbit and tensor terms of the effective interaction is enhanced between 200 and 300 MeV, where the relative strength of the central interaction is minimized. In selecting the excited states for this work, we have chosen strong, unnatural–parity, spin–flip transitions, which should serve to emphasize the spin-dependent terms of the interaction, yet are states for which the nuclear structure has been carefully studied. In particular, different aspects of the 1^+ states in ^{12}C have been studied by a wide variety of probes, though possible ambiguities in the nuclear wave functions have still not been satisfactorily resolved. The 4^- transitions in ^{16}O, being "stretched" states, can only be excited (via a 1p–1h mechanism) when a single value of angular momentum is transferred to the target nucleus. This results in a simple proportionality between the transverse and longitudinal form factors, which greatly simplifies the nuclear structure. By chosing transitions with fairly well–determined nuclear structure, we hope to gain insight into the effective interaction amplitudes. The combination of low and high spin data will allow us to examine the isoscaler and isovector q dependences over a large range of momentum transfer, though the large exchange contributions predicted for excitation of some of these states will significantly complicate the relationship between the momentum transfer of the (p, p′) reaction and the effective momentum transfer at which the N–N scattering occurs within the nucleus.

Before taking data, we thoroughly tested all of the changes and improvements we had made to the focal plane polarimeter system since our last run.[1] These changes included the addition of new and more sophisticated algorithms and sorting conditions in the online analysis. We also developed diagnostic software to calculate various ratios and sums based on either cumulative or incremental scaler values to aid in rapidly noting and identifying possible hardware problems. We also had made a number of hardware changes, such as isolating the scintillator high voltage power supply to reduce noise in the scintillator signals, and changing the ADC delay–lines to coaxial cables to eliminate cross–talk found in the twisted–pair cables we had been using. As a final check on the whole system, we began our production run by repeating a calibration point from our November calibration run.[2] This was done by elastically scattering the 200 MeV proton beam from ^{12}C at 24.26°, which is where we had found the p + ^{12}C analyzing power to be nearly equal to zero. The calibration point was found to be in agreement with our earlier determinations of the FPP's effective analyzing power and efficiency.

Three shifts were then required to optimize the beamline for dispersion matching, and approximately half a shift was used to alter the focal plane of the K600 to improve our data rate. Since the medium dispersion mode of the K600 Spectrometer has a 9% momentum bite, which corresponds to approximately a 36 MeV energy bite at 200 MeV, approximately 60% of our momentum acceptance (and ~ 75% of our event rate) was in energy regimes that were not the primary focus of this investigation. We were able to eliminate these events from our data stream by stopping the ground state on a copper block mounted on a movable track inside the K600 vacuum box, and disabling particular pre–amp cards on the VDC's of the K600 focal plane. By doing this, elastic scattering events did not produce any first–level triggers, while regions of either very low or very high excitation were vetoed at a second–level in hardware, leaving us with a 14 MeV energy bite. Throughout the run, resolution of the carbon and oxygen states was about 30 keV and 70 keV, respectively, as shown in Figs. 1 and 2. Fig. 1 is a 200 MeV ^{12}C(p,p′)^{12}C*

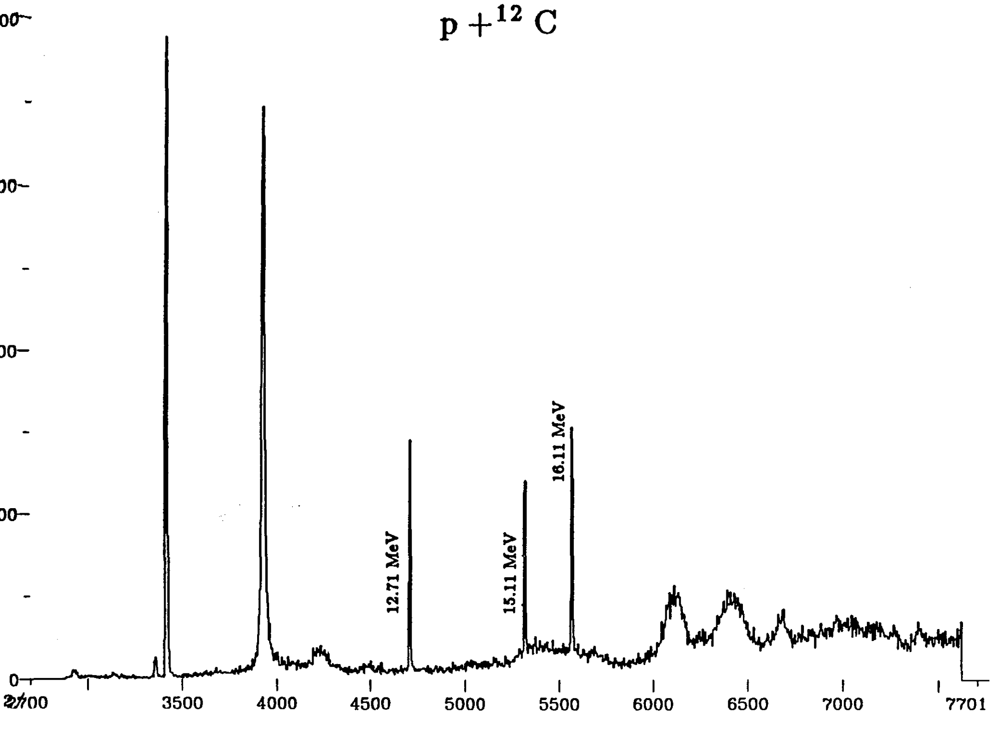

Figure 1. Typical spectrum for the reaction ^{12}C(p,p′)^{12}C* at 200 MeV for $\theta_{lab} = 16°$. The 1$^+$, T=0 state (12.71 MeV), the 1$^+$, T=1 state (15.11 MeV), and the 2$^+$, T=1 state (16.11 MeV) are readily apparent. The experimental resolution for these states is less than 30 keV.

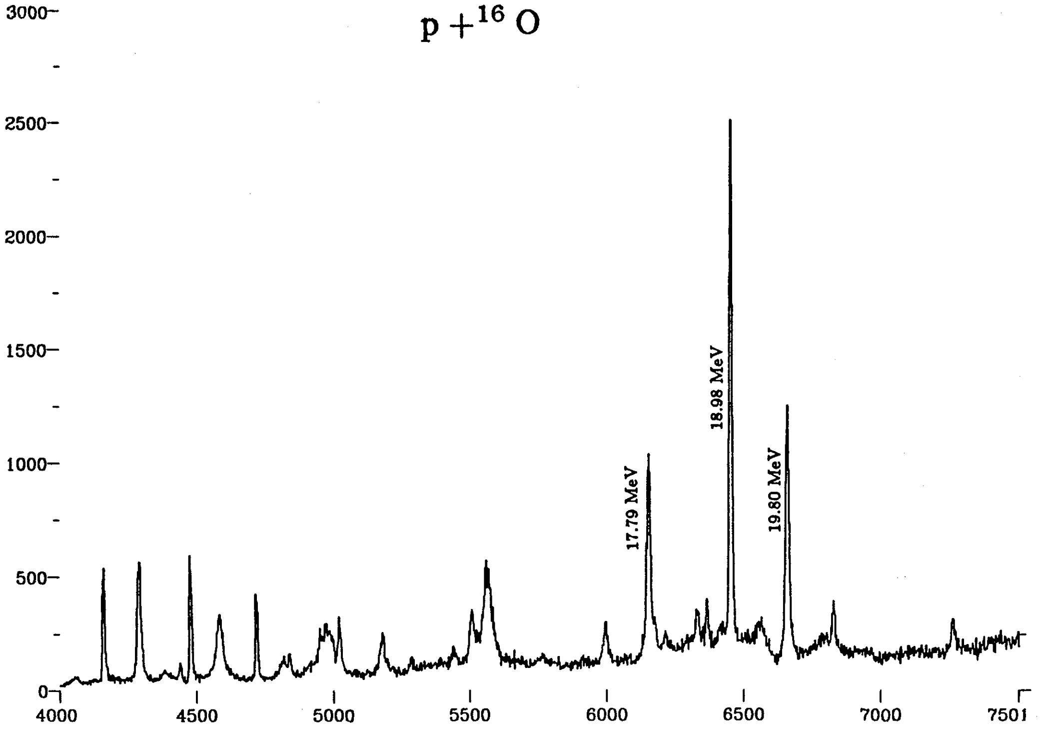

Figure 2. Typical spectrum for the reaction $^{16}O(p,p')^{16}O^*$ at 200 MeV for $\theta_{lab} = 28°$. A $H_3\,^{10}BO_3$ target was used. The 4^- states at 17.79 MeV (T=0), 18.98 MeV (T=1), and 19.80 MeV (T=0) have experimental resolutions of about 60–70 keV.

spectrum taken with a natural carbon target at $\theta_{lab} = 16°$. The 1^+, T=0 state at 12.71 MeV is centered near channel 4700, while the 1^+, T=1 state (15.11 MeV) is seen near channel 5300. At this angle, the state at 16.11 MeV (2^+, T=1) is also strong and easily resolved near channel 5550. Fig. 2 shows inelastic proton scattering from a $H_3\,^{10}BO_3$ target at $\theta_{lab} = 28°$, which is near the peak of the cross section for the ^{16}O 4^- states. The states of interest, at 17.79 MeV (T=0), 18.98 MeV (T=1) and 19.80 MeV (T=0), are centered near channels 6150, 6450 and 6650, respectively.

Because the cyclotrons had been shut down for 11 days prior to our run, it took several days for the magnets to stabilize and for the beam tune to remain constant at the level needed for high resolution data acquisition on the K600. We had a number of failures of the polarized ion source and the RF system throughout the run, usually lasting between one and six hours. Once beam returned, we could generally start taking data almost immediately, since the dispersion matching conditions would remain stable over time scales of several days. The K600 focal plane and focal plane polarimeter worked smoothly and consistently throughout the run, though about a week and a half into the run the communication system of the wire chamber high voltage power supply failed, and we had to replace it with manually controlled supplies. The only component of the polarimeter system that failed was a single LeCroy 2731A Latch and Delay PCOS module.

The statistical quality and angular range of our measurements is demonstrated in

Figs. 3, 4, and 5, in which preliminary values for the spin observables $(P - A_y)$ and $D_{NN'}$ are shown for the strong isoscalar and isovector 1^+ states in ^{12}C and for the isovector 4^- state in ^{16}O. We want to emphasize that the data points shown in these figures are based upon on-line analyses with crude peak-summing, and the error bars reflect only statistical uncertainties. Though detailed comparisons with various theoretical predictions would therefore be very premature at this point, it is useful to point out that in many cases the discrepancies between the data and most of the calculations are greater than the variations among the different calculations. For the ^{12}C 1^+ states (Figs. 3 and 4), we show three distorted-wave impulse approximation (DWIA) calculations,[7] each of which uses Cohen-Kurath wave functions[8] and the same distorted waves, the latter based on optical model parameters adjusted to simultaneously fit elastic scattering cross section, analyzing power, and spin rotation coefficient data.[9] For the 4^- isovector state in ^{16}O (Fig. 4), the wave function is described by a $d_{5/2}p_{3/2}^{-1}$ configuration which is almost a pure T=1 state, as suggested by earlier pion scattering experiments.[10] Distortions for the ^{16}O states were obtained in a manner similar to that of the ^{12}C work.[9] In both cases, the three effective interactions shown are the Love-Franey[11] and Bonn[12] interactions, based on the free N-N

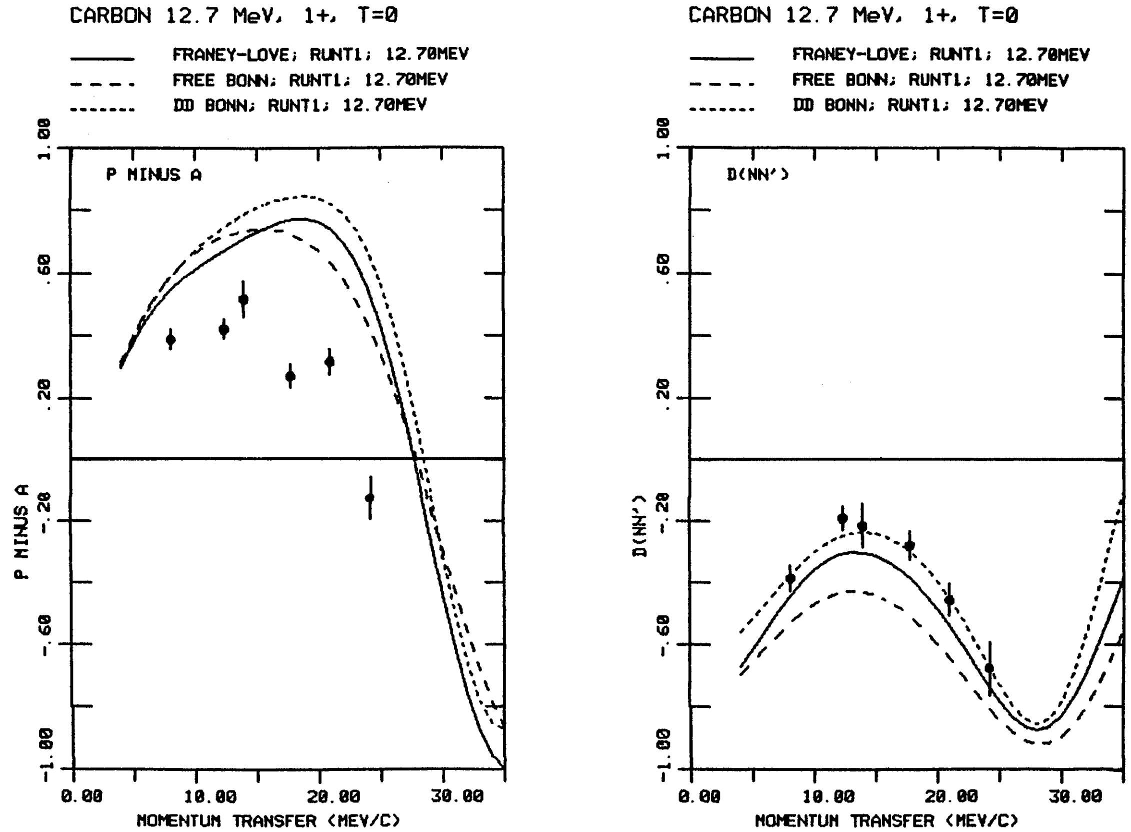

Figure 3. Preliminary results for the spin observables $(P - A_y)$ and $D_{NN'}$ for the isoscalar 1^+ state (12.71 MeV) in ^{12}C. The curves correspond to three DWIA calculations based on the effective interactions indicated at the top of the figures.

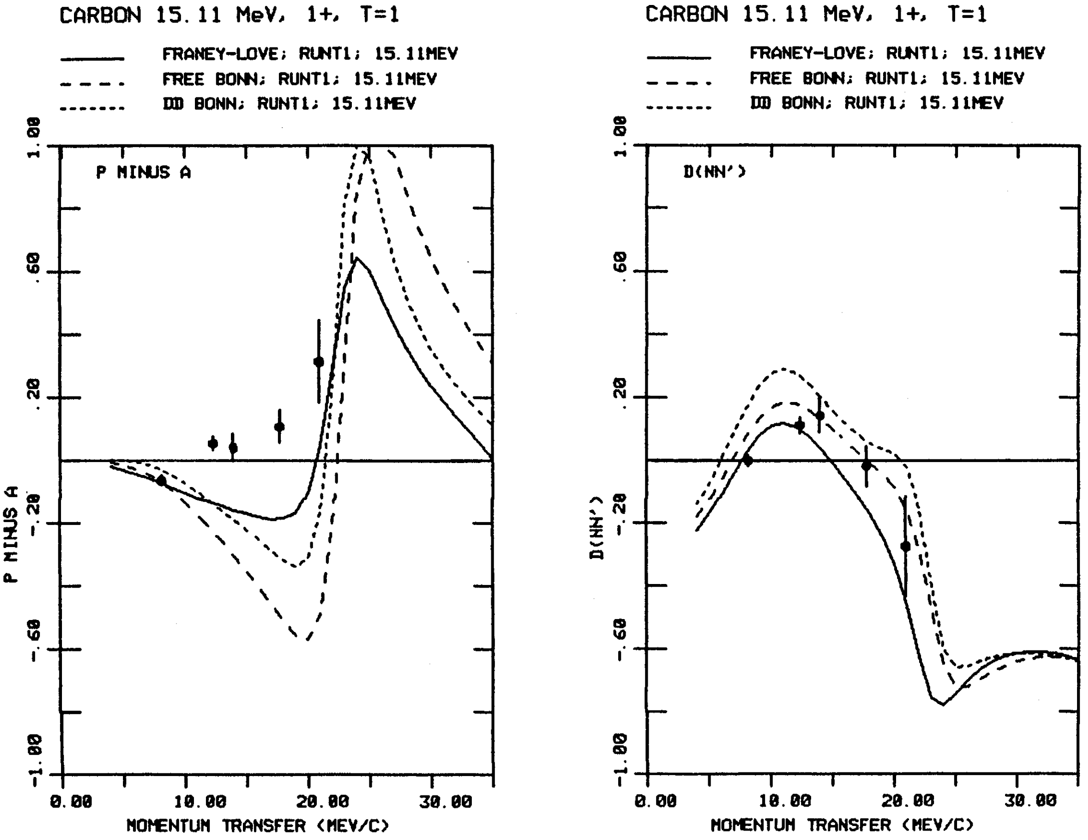

Figure 4. Preliminary results for the spin observables $(P - A_y)$ and $D_{NN'}$ for the isovector 1^+ state (15.11 MeV) in ^{12}C. The curves correspond to three DWIA calculations based on the effective interactions indicated at the top of the figures.

scattering amplitudes, and a modified Bonn interaction in which nuclear medium effects have been incorporated in a density–dependent way.[12]

Though more detailed off–line analysis and yield–extraction techniques will need to be developed, the statistical quality of the data is readily apparent, as are the general trends of the angular distributions. As stated above, we have completed all of the measurements that were proposed, as well as two additional angles for the carbon data. We expect the final statistical uncertainty in these measurements to be better than 0.05 for $D_{NN'}$ and 0.03 for P at most angles. A second-pass analysis is currently underway, with the goal of obtaining final results by late summer.

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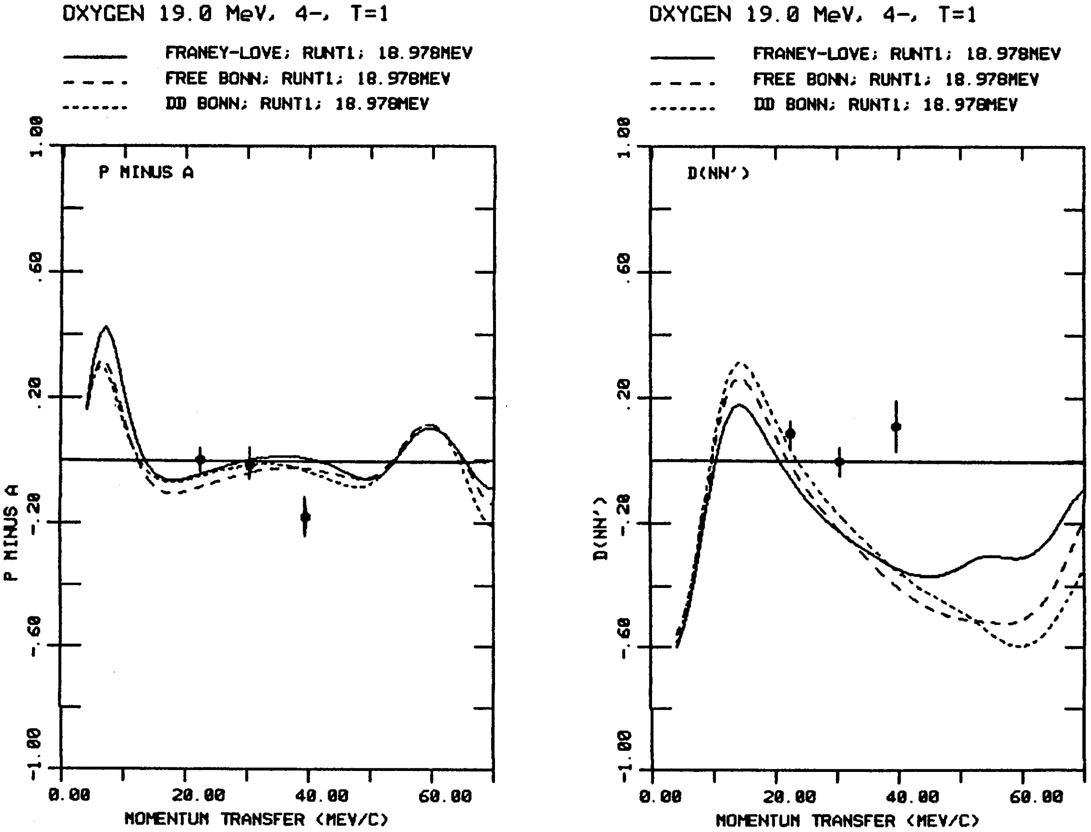

Figure 5. Preliminary results for the spin observables $(P - A_y)$ and $D_{NN'}$ for the isovector 4^- state (18.98 MeV) in ^{16}O. The curves correspond to three DWIA calculations based on the effective interactions indicated at the top of the figures.