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Polarization in Three-Nucleon Breakup: Experiment and Theory

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Abstract

A variety of analyzing powers for d+p breakup reactions initiated by polarized deuterons incident on protons have been measured at deuteron bombarding energies of 16 and 79 MeV. The results are compared with Faddeev calculations using both separable (at 16 and 79 MeV) and local (at 79 MeV) interactions. These calculations include nucleon-nucleon forces in the S, P, and D states and the $^3S_1$-$^3D_1$ tensor force.

1. Introduction

The study of reactions involving three nucleons has been stimulated over the years by the quest for answers to several fascinating questions for nuclear physics. These include the off-energy-shell properties of the nucleon-nucleon (NN) force and the nature of three-body forces. The mathematical accuracy with which the three-body problem can be solved by using the Faddeev method [1,2] and employing the *ansatz* of pairwise two-body forces between the particles has greatly improved as techniques and computing facilities have been developed. However, some features of the calculations still remain in question, and these must be settled before the calculations can be used to extract from the data truly fundamental properties of the NN interaction. Basically, these difficulties arise because, for many situations of interest, the complexity of the solution process would require an inordinate amount of computer time were one to employ a realistic NN force, such as the Reid soft-core potential [3]. Therefore, procedures have been developed in attempts to expedite the solution process while still maintaining accuracy and sound physics. One such procedure [4,5] is to use separable, nonlocal NN interactions. These interactions are chosen, of course, to fit the two-body data over an appropriate energy range; however, one needs to be wary that the additional freedom in such interactions does not yield unphysical results. Another procedure [6-8] is to use one of the accepted local interactions, but to economize on computer time by adopting an appropriate perturbational scheme. Here we will present the results of calculations using both procedures. No Coulomb corrections are included in these calculations.

The experimental measurements are of d+p breakup observables using polarized deuterons of 16 MeV at the Los Alamos Ion Beam Facility and 79 MeV at the Indiana University Cyclotron Facility. For most of this work, it is the first time polarization observables, rather than just breakup cross sections, were measured for the kinematic configurations described. At 16 MeV we have determined analyzing powers in a kinematically incomplete experiment and have also determined analyzing powers and cross sections for several final-state geometries in kinematically complete experiments.

At 79 MeV we have measured analyzing powers in kinematically complete experiments.

In presenting all our results, we employ the symmetric choice for the y axis [9] and display the absolute data errors, which are dominated by counting statistics.

2. Data at E_d = 16 MeV

Data at a deuteron bombarding energy of 16 MeV were obtained using the tandem Van de Graaff accelerator and Lamb-shift polarized ion source at the Los Alamos Ion Beam Facility. The target and detectors were located in a large cubical scattering chamber, the "supercube", which has four independently rotatable turntables for mounting detectors in each azimuthal quadrant and which also has the capability of being rotated about the beam direction. The Si detectors were arranged in ΔE-E configurations to perform particle identification and were mounted such that both coplanar and noncoplanar data could be obtained. The data-taking procedure was that of the "three spin state method" described in ref. [10].

2.1. Kinematically incomplete experiment

This experiment employed a hydrogen gas target and has been completed and published [11]. Briefly, the proton continuum from the ^{1}H(d,p)pn reaction was detected at lab angles from 15° to 42.5°, and at each angle the analyzing powers A_y, A_{xx}, A_{yy}, and A_{xz} were measured as a function of the proton continuum energy. This was the first such experiment performed in such detail and with sufficient energy resolution in the final state to observe effects from pn pairs emerging in a singlet state. Because of this, several earlier misconceptions were cleared up by this work. Faddeev calculations using a separable NN interaction were found to be in reasonable agreement with the data.

2.2. Symmetric, constant-relative-energy (SCRE) geometry

The SCRE geometry is expected to be sensitive to certain aspects of the NN interaction

[12-14] and has a final state characterized by equal polar angles of the two emerging protons and equal relative energies between all pairs of particles. Here we used a rotating polyethylene target and detected the protons in coincidence in a kinematically complete experiment. For this experiment, and the other kinematically complete experiments described below, the events from each detector are displayed by an on-line computer in a two-dimensional, energy-sharing spectrum. In such a spectrum, the breakup events occur along a locus allowed by conservation of energy and momentum and were clearly evident in all the experiments. Such kinematic loci are illustrated in fig. 8 of ref. [9]. In the SCRE geometry, there is only one kinematic variable, the angle α that the c.m. reaction plane makes with the beam direction. For $\alpha = 0°$ (c. m. proton momenta forward) and $\alpha = 180°$ the lab geometries are coplanar, but for other values of α, noncoplanar lab geometries result. For the SCRE geometry with the symmetric choice of y axis, the analyzing powers not prohibited by parity conservation are A_x, A_{xx}, A_{yy}, A_{yz}, and $A_{zz} = -A_{xx} - A_{yy}$ [9]. Here we measured A_{xx} and A_{yz}. In fig. 1 we show the results of our SCRE measurements along with the results of Faddeev calculations using separable NN interactions. The solid curves are from calculations using the NN force of ref. [11], and the dashed curves are results using a more recent version of the NN force, the force labelled 2^1S_0R, 4T4R, P, D in ref. [15]. This latter force is an improvement over that of ref. [11] in the following sense. First, it fits the NN phase shifts for some states better and over a larger energy range. Second, it simulates a short-range repulsive component in the $^1S_0$ and $^3S_1$-$^3D_1$ NN states by incorporating appropriate nodes in the form factors. It was somewhat disappointing, though not entirely unexpected, to find that the calculated analyzing powers are so similar for the two NN interactions (fig. 1). We note that both calculations seem to underestimate A_{xx} in the middle of the angular range. In making such comparisons, however, it should be realized

that at 16 MeV the relative energy of each emerging nucleon pair is only about 1.5 MeV, and therefore one expects the Coulomb force to make its influence felt, at least to some extent. Some estimates of Coulomb effects in elastic scattering are shown in ref. [15].

2.3. Collinear geometry

In this final-state geometry, one of the nucleons (here the neutron) is left at rest in the c.m. system, thereby constraining the c.m. momenta of the other two (here the protons) to be equal in magnitude and oppositely directed. Breakup differential cross sections in such a geometry have been measured previously [16-18]. Two of these studies [16,17] indicated enhanced sensitivity to the NN interaction at collinearity. A third study [18], however, concluded that there is no such sensitivity and that a sensitivity was deduced in ref. [16] only because the data were compared with calculations that used only an S-wave NN force.

We studied this question further by measuring several tensor analyzing powers, as well as breakup cross sections, for d+p breakup at 16 MeV. The apparatus was the same as for the work described in sect. 2.2. Two collinear geometries were studied, with detected proton lab angles of 33.4°-33.4° and 24.4°-40.0°. In addition, two geometries just outside of the collinear region were also investigated, with proton lab angles 31.4°-31.4° and 24.4°-35.0°. In fig. 2 we show the analyzing power having the best statistical accuracy, the combination $-A_{xz}-A_{yy}/2$ at 24.4°-40.0°. These data are displayed as a function of arclength around the kinematic locus, with the collinearity point being at arclength = 0. The curves show the results of Faddeev calculations using the NN interactions mentioned in sect. 2.2. The agreement of the calculations with experiment is reasonable, considering that the Coulomb force is neglected. Also, there appears to be no striking anomaly at the collinearity point. These comments are true as well for the other measurements, which are not shown here.

3. Data at E_d = 79 MeV

In order to obtain data that would be less susceptible to uncertainties in interpretation because of the Coulomb force, we performed measurements of tensor analyzing powers in the SCRE geometry using a 79-MeV polarized deuteron beam at the Indiana University Cyclotron Facility. The two ΔE-E detector systems each consisted of a 0.5-mm-thick Si detector and a 10-mm-thick, hyper-pure Ge detector. The target was polyethylene, about 10 mg/cm^2 thick. Supporting the detector systems left and right of the incident beam were two platforms that can rotate independently about the beam direction, thus allowing independent adjustment of the detector-system polar and azimuthal angles. The data obtained so far are shown in figs. 3 and 4 along with the results of Faddeev calculations. The solid curves are from a calculation using a separable NN interaction that is a modified version of the improved force mentioned in sect. 2.2. The modification was to the $^1S_0$ and tensor components, and it was felt that the changes would improve the interaction for use in three-body calculations at higher energies, but would leave the results at lower energies essentially unchanged. The dashed curves are from a calculation [6,8] using the (local) Reid soft-core interaction [3], in which the pure s-wave parts of the force are included exactly, and the higher partial-wave components are treated in first order. The crossed curves are from a calculation using a separable simulation of the Paris potential [19]. It is seen that the local potential reproduces the analyzing power A_{yy} better than the seperable interactions. It appears, therefore, that at this higher energy the breakup is sensitive enough to the NN interaction to indicate some difficulty with these separable interactions. Further work is needed to discover just where the trouble lies.

4. Conclusions

We have discussed measurements and Faddeev calculations of analyzing powers for the d+p breakup reaction at polarized deuteron bombarding energies of 16 and 79 MeV. We found that calculations using separable NN interactions did reasonably well in reproducing the 16-MeV data, taking into consideration the fact that the presence of the Coulomb force injects some uncertainty into the comparison at that energy. At 79 MeV, we discovered that neither of the two separable NN interactions we used gave satisfactory agreement with the tensor analyzing power A_{yy}, but the local-potential calculation did quite well, even though the higher partial waves in the NN interaction were treated in perturbation. It seems, therefore, that this energy is a good one at which to study NN interaction properties important for three-body dynamics.

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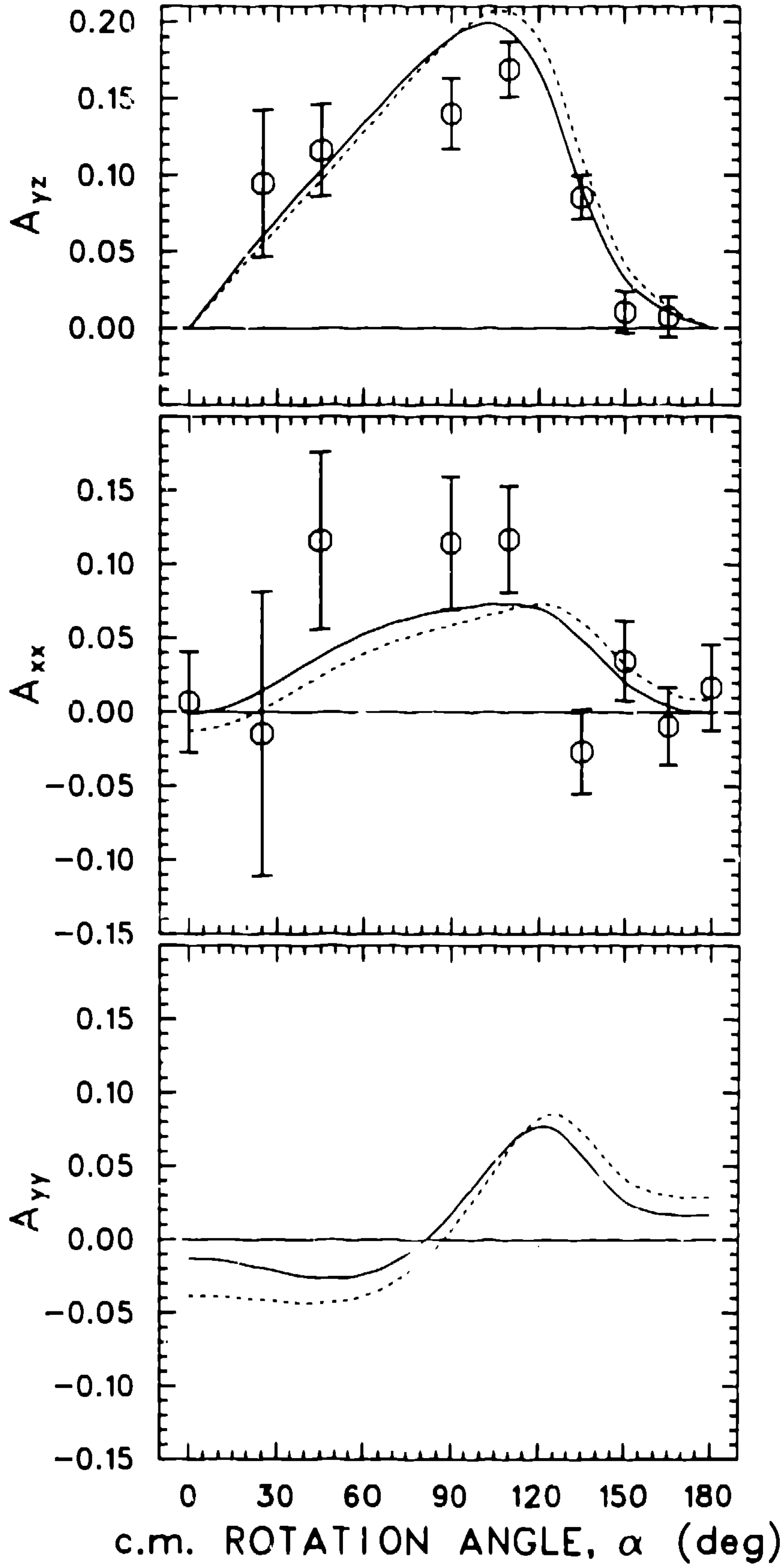
Figure Captions

Fig. 1. Measurements (points) and Faddeev calculations (curves) of tensor analyzing powers for the d+p breakup reaction in the SCRE geometry. The polarized deuteron bombarding energy is 16 MeV. The calculations are described in sect. 2.2.

Fig. 2. Measurements (points) and Faddeev calculations (curves) of the indicated combination of tensor analyzing powers around the kinematic locus for the d+p breakup reaction at a polarized deuteron bombarding energy of 16 MeV. The two protons in the final state are detected at lab angles of 24.4° and 40.0°. The collinearity point occurs at arclength = 0. The calculations are described in sect. 2.2.

Fig. 3. Measurements (points) and Faddeev calculations (curves) of the tensor analyzing power A_{yy} for the d+p breakup reaction in the SCRE geometry at a polarized deuteron bombarding energy of 79 MeV. The calculations are described in sect. 3.

Fig. 4. The tensor analyzing power A_{xx} at 79 MeV. See the caption to fig. 3.



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0.10
0.05
0.00
A_{yz}
0.15
0.10
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0.00
−0.05
−0.10
−0.15
A_{xx}
0.15
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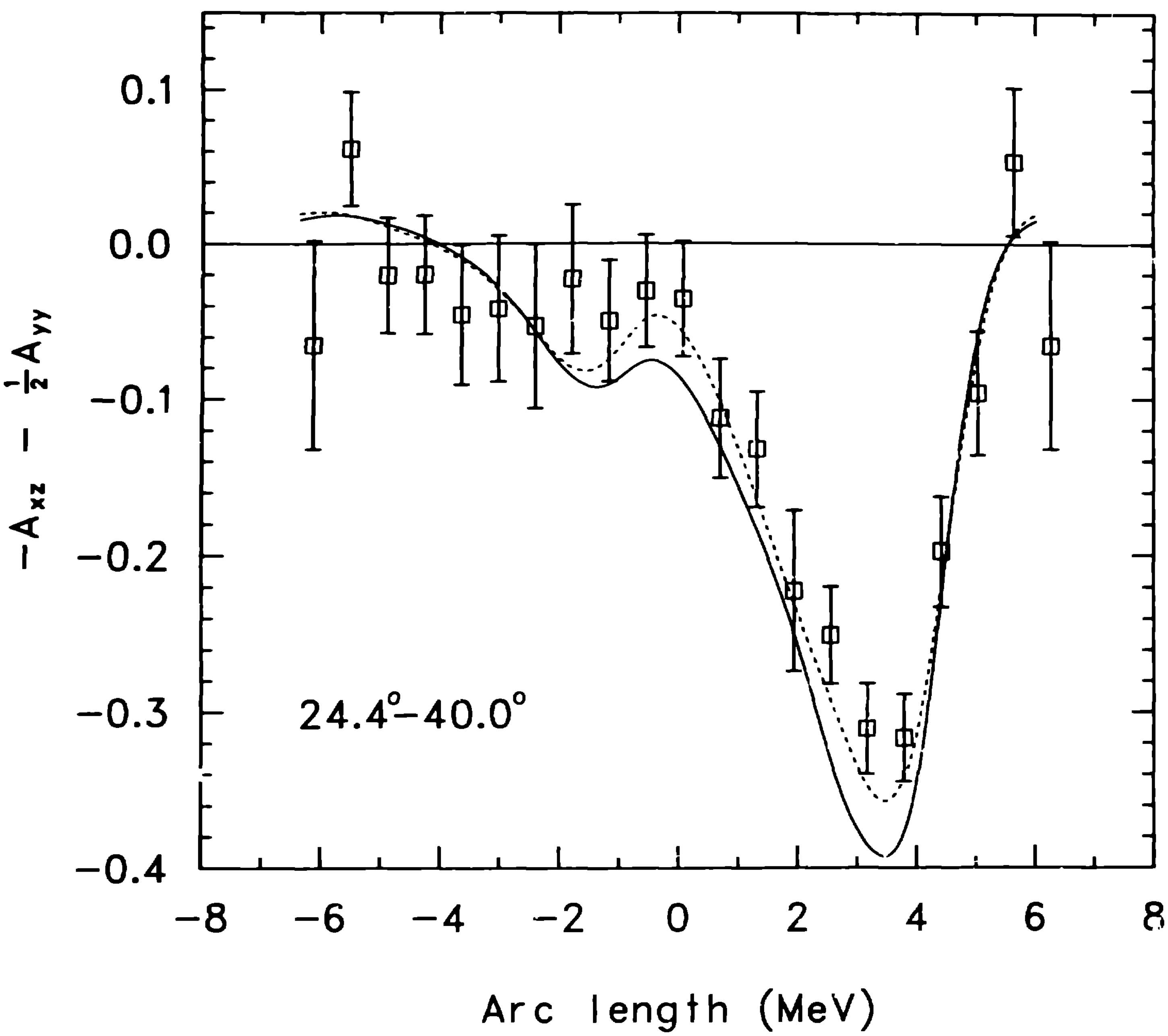
0.05
0.00
−0.05
−0.10
−0.15
A_{yy}
0
30
60
90
120
150
180
c.m. ROTATION ANGLE, α (deg)



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−0.1
−0.2
−0.3
−0.4
−8
−6
−4
−2
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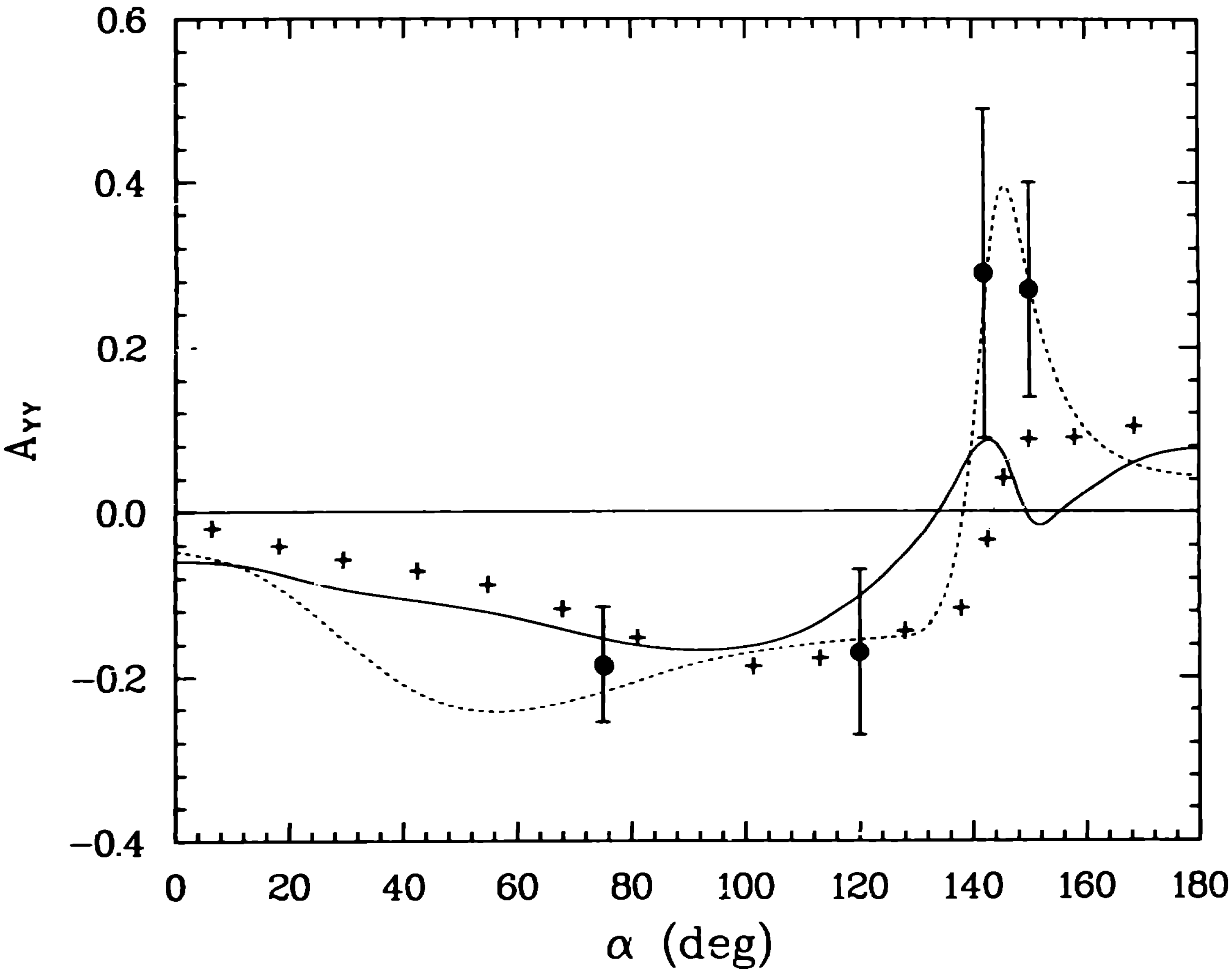
2
4
6
8
$-A_{xz} - \frac{1}{2}A_{yy}$
24.4°–40.0°
Arc length (MeV)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A_{YY}
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40
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80
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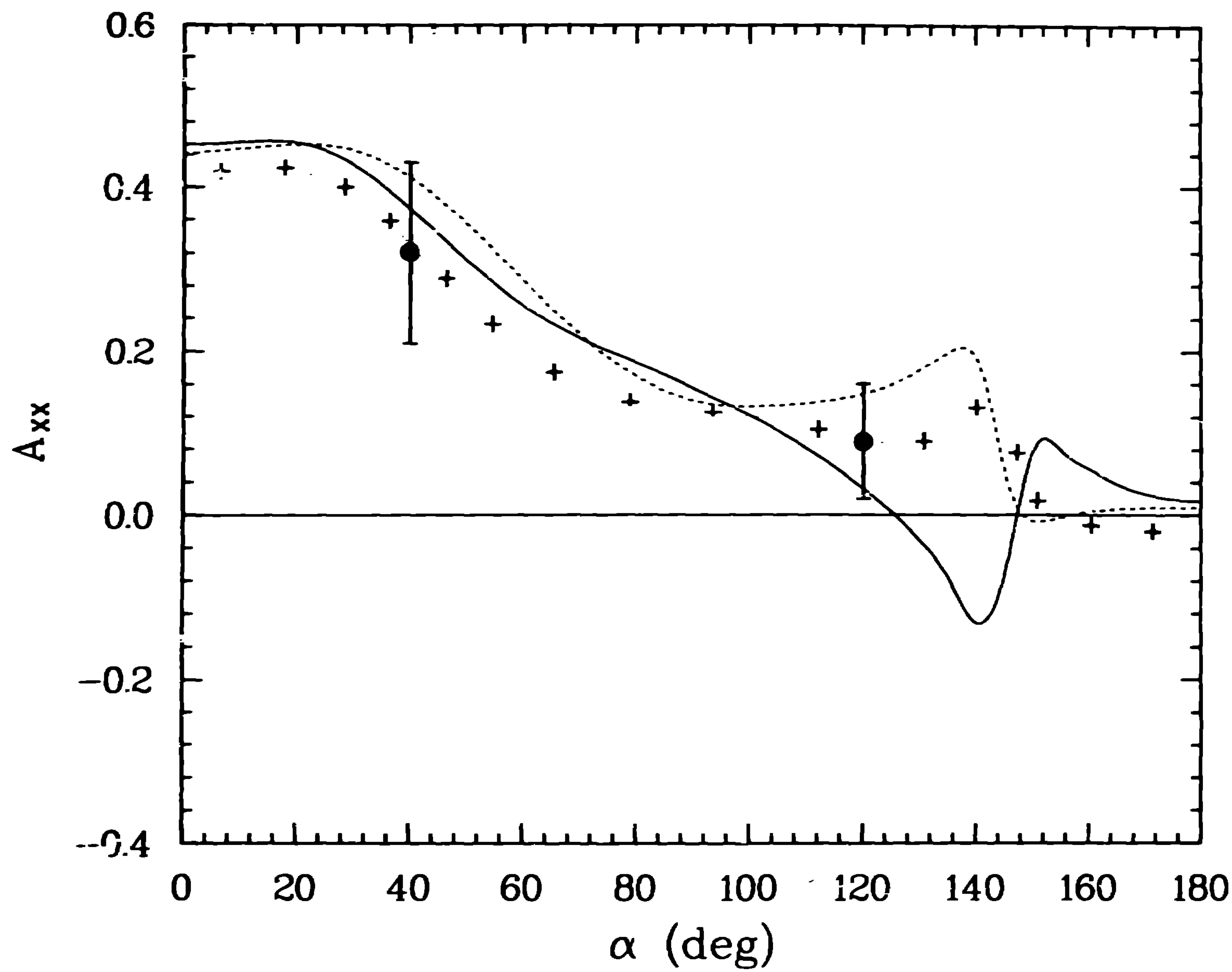
140
160
180
α (deg)



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α (deg)