

Measurement of Deuteron-induced Reaction Angular Distributions for and Deuteron EDM Polarimeter

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The presence of an electric dipole moment (EDM) aligned with the spin of a fundamental particle would violate the symmetries of time reversal and parity. Within the assumption that *CPT* is conserved, any process that violates time reversal also violates *CP*. Such *CP*-violating processes have been observed only in the decay of *K* and *B* mesons. Despite years of searching, an intrinsic EDM has never been observed. Searches continue because additional *CP*-violation is required if we are to understand the surplus of matter left after the Big Bang. Theories that go beyond the Standard Model by incorporating a super-symmetry between fermions and bosons can explain the matter surplus and also predict that an EDM will appear with 2-3 orders of magnitude below current experimental limits.

The Storage Ring EDM Collaboration [1] is pursuing the concept of using a storage ring to search for an EDM on a charged particle. Any charged particle traveling around the ring experiences an electric field in its frame of reference that arises from its motion through the magnetic field of the bending magnets. This electric field is stronger than any static field that can be sustained in the laboratory. If an EDM were present, this field would cause the spin of the particle to precess. For a polarized beam with its initial spin axis pointing along its momentum, the presence of an intrinsic EDM would be signaled by a growing vertical polarization component as the precession due to the EDM starts. In order for such a scheme to be sensitive, the precession caused by the forces on the magnetic moment as the particle travels in the ring's magnetic field must be suppressed. A scheme for doing this by using a static radial electric field has been described by Farley [2]. This method works well for particles such as the muon or deuteron that have a small anomalous magnetic moment. In addition, it may be possible to accumulate the EDM precession by forcing synchrotron oscillations that are in resonance with the magnetic precession of the spin [3]. This method works for a wider range of beams, including the proton and ^3He . In either case, it is essential to provide a continuous monitor of the beam polarization during the time that the beam is present in the storage ring.

In order to maximize the polarimeter efficiency, the EDM Collaboration is considering a scheme that would use a thin gas jet target in the path of the circulating, stored beam to slowly extract particles using Coulomb scattering onto a thick, annular target. The opening in the center of the target is smaller than the ring acceptance would be otherwise, so it becomes the limiting aperture and essentially the entire beam is lost onto the target. This target can be thick, thus increasing polarimeter efficiency. A full azimuthal array of (plastic scintillator) detectors could be positioned downstream of this target to intercept scattered particles in any angular range of interest. For both protons and deuterons, carbon appears to be a satisfactory choice for a target material. Large analyzing powers have been noted for both protons [4] and deuterons [5,6] at intermediate energies.

In the first proposal for a deuteron storage ring [7], the deuteron momentum was chosen to be $p=0.7$ GeV/c (or an energy of 126 MeV). A thick polarimeter target would span energies from 126 MeV down to about 60 MeV. This is a region in which there is very little data for elastic scattering from carbon and no data on inelastic or particle transfer reactions. So we joined forces with the EDM group at the KVI in Groningen to use the polarized deuteron beam there to fill in the gaps. The first run in October 2004 made use of ΔE -E telescopes (scintillator and NaI) to measure cross sections and analyzing powers across a broad energy and angle range. Once those data were analyzed, it became clear that at forward angles there was a peak in the analyzing powers that showed promise for polarimetry. Because this feature was becoming more prominent as the energy rose, we made a second run in July 2005 to measure the elastic scattering angular distributions at somewhat higher energies with the Big Bite Spectrometer (BBS) at the KVI.

In the first run, temporary wooden tables were placed to give support to two plastic scintillator ΔE – NaI E detector packages that were brought from IUCF. These detectors replaced the left and right Phoswich assemblies that were normally used for the In-Beam Polarimeter (IBP) in the main beamline. The detector assemblies were moved by hand to scattering angles between 18° and 60° . They were operated symmetrically so that the left-right asymmetry would be a measure of the vector analyzing power. The target was pressed powder carbon about 10 mg/cm^2 thick. The beam polarization was obtained using a CH_2 target in independent runs. In this case, detector arms on planes rotated 45° from the horizontal were used to determine the beam's vector polarization.

Figure 1. 2D histogram of the ΔE (scintillator) pulse height against the E (NaI) pulse height. The bands correspond to protons, deuterons, and tritons. The most intense feature is deuteron elastic scattering. These data were taken at 110 MeV and 27° lab angle.

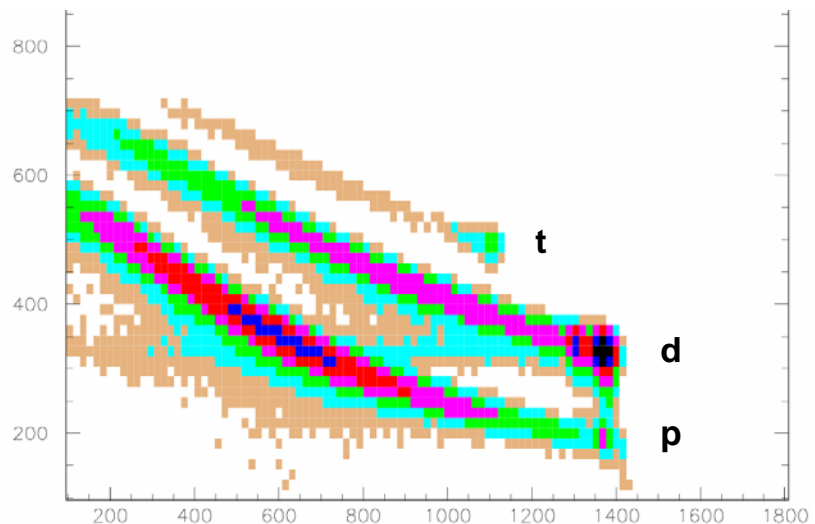
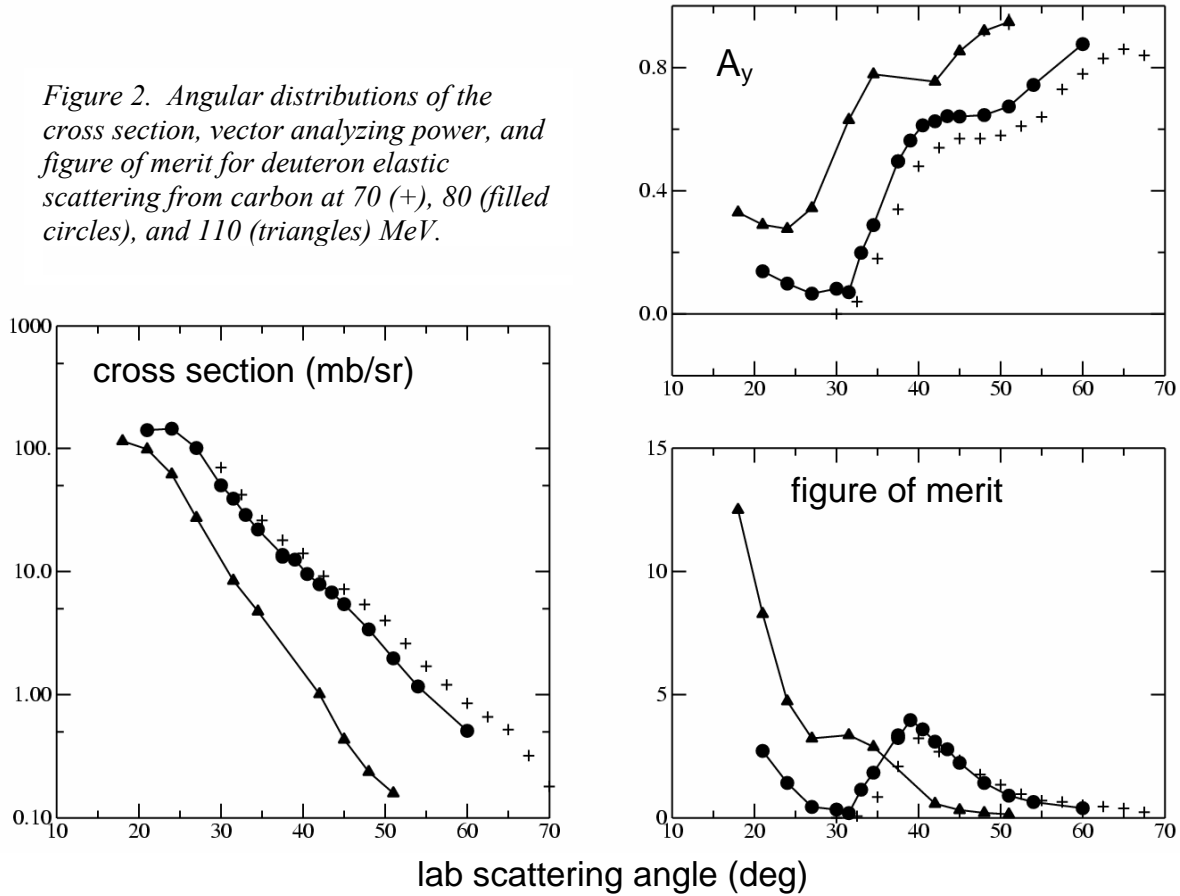


Figure 1 shows the quality of the particle identification in a plot of the ΔE (scintillator) signal against the E (NaI) signal. Clear bands appear for protons, deuteron, and tritons. No $Z=2$ bands were observed. The most intense feature is deuteron elastic scattering at the upper end of the deuteron band. The protons in the middle of their band come from deuteron breakup. With the ability to separate particle types, we could follow the analyzing powers for various groups. Figure 2 shows the results for deuteron elastic scattering cross section and vector analyzing power (A_y) at 110 MeV (triangles) and 80 MeV (solid circles). For comparison, the 70-MeV results from Kato [5] are also shown. The cross section shows a sloping pattern typical of rainbow scattering [8] where the amplitude is dominated by scattering from the far side of the

nucleus (away from the detector) causing the normal interference pattern to disappear. This far side dominance is also accompanied by a dominance of the $m=1$ state (along an axis perpendicular to the scattering plane), which leads the analyzing power to approach one as the scattering angle increases. This is clearly evident in the analyzing powers, where the measurements rise close to one at progressively smaller angles as the bombarding energy increases. In both cases, there is a smooth trend with energy. (Subsequently it was learned that the energies were not right, and that the “80 MeV” data was in fact closer to 75 MeV and the “110 MeV” data was closer to 114 MeV.)

Figure 2. Angular distributions of the cross section, vector analyzing power, and figure of merit for deuteron elastic scattering from carbon at 70 (+), 80 (filled circles), and 110 (triangles) MeV.



The statistical importance of a set of data for the measurement of a polarization can be gauged using the figure of merit σA_y^2 . This quantity, plotted in the lower right panel, goes as $1/\text{error}^2$. Where it is large, the statistical precision of the measurement is improved. The figure of merit alone is not a sufficient condition for polarimeter design. One should also consider the size of the analyzing power. In particular, small analyzing powers often allow systematic errors in the measurement process to be a larger fraction of the observed polarization and should be avoided. Originally, it was expected that the peak in the figure of merit between 30° and 50° would be the optimal operating region for a polarimeter. The start of a peak at smaller angles is accompanied by an analyzing power that was expected to be small. However, as the energy rises, these two features merge into one: a larger analyzing power peak at forward angles which has a much improved figure of merit. Note that the analyzing power there is consistently as large as 0.3. So

this energy region covers a transition from rainbow scattering as the polarimeter feature at the lower energies to the forward angle maximum as the polarimeter feature at the higher energies. Unfortunately, the scattering angle range was limited by the geometry of the IBP to angles greater than about 18° and we were not able to map this forward-angle feature. This was the motivation to return to the KVI for additional BBS data on elastic scattering at forward angles.

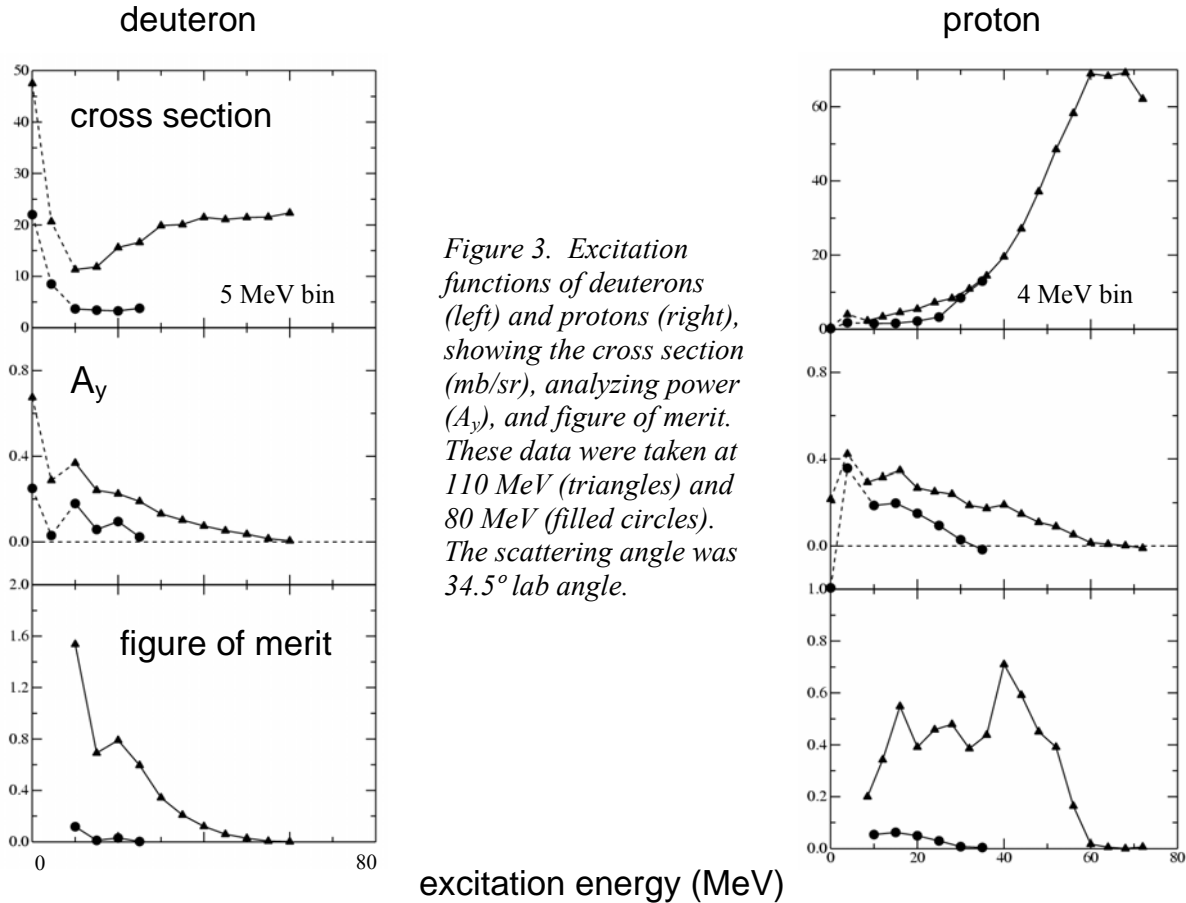


Figure 3. Excitation functions of deuterons (left) and protons (right), showing the cross section (mb/sr), analyzing power (A_y), and figure of merit. These data were taken at 110 MeV (triangles) and 80 MeV (filled circles). The scattering angle was 34.5° lab angle.

The NaI detector also allowed us to extend the cross section and analyzing power measurements for some ways into the continuum. Some results from these measurements are shown in Fig. 3 for deuterons and protons. Again triangles represent 110 (~ 114) MeV measurements and filled circles 80 (~ 75) MeV measurements. Discrete state information is connected to the higher excitations with a dotted line. Otherwise, the cross sections are summed over the bin width noted in the figure. In both cases, the analyzing power remains positive for many MeV of excitation. This arises from the same effects of the spin-orbit distortions that give rise to rainbow scattering, and thus these features grow larger with increasing scattering angle. It is thus possible that using a looser trigger condition that admits many of these events into the acceptance of the polarimeter would result in a larger figure of merit. For the protons, the large cross section peak comes from deuteron breakup, a process that tends to suppress spin dependence. It is important to keep these protons out of the polarimeter acceptance. Striking the right balance between these two contributions requires a careful modeling of the polarimeter based on the data shown here. It is likely that these protons, which are more penetrating than the

deuterons, can only be removed with the use of range absorbers between the target and the detector.

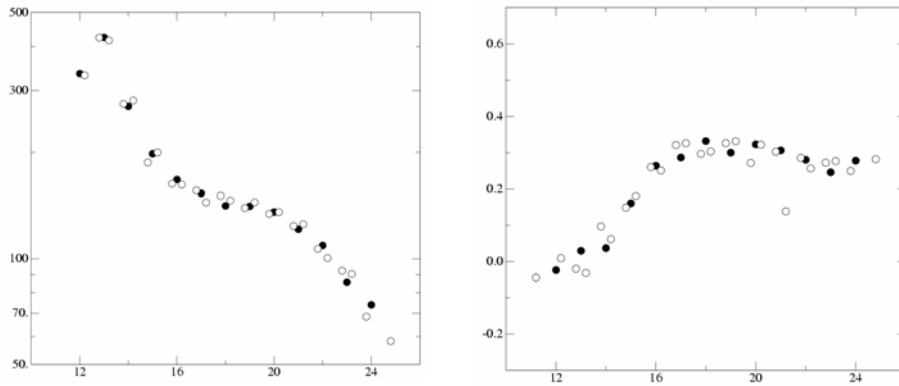


Figure 4. Measurements of the cross section (left, mb/sr) and analyzing power (right) for deuteron elastic scattering from carbon at 110 MeV as a function of lab scattering angle.

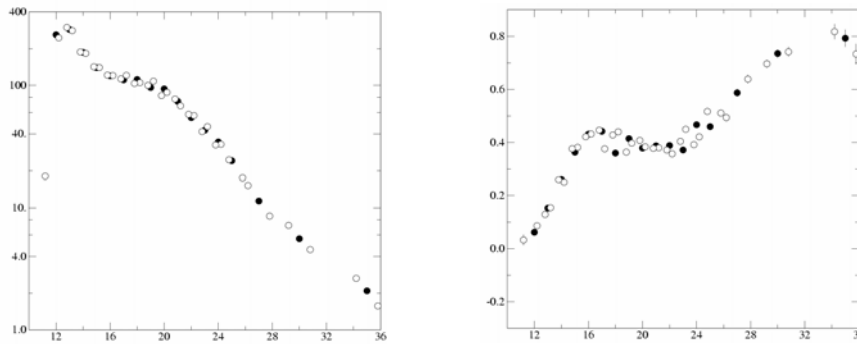


Figure 5. Measurements of the cross section (left, mb/sr) and analyzing power (right) for deuteron elastic scattering from carbon at 133 MeV as a function of lab scattering angle.

The spectrometer measurements ran in July 2005. Data acquisition went quickly. In addition to the cross section and vector analyzing power angular distributions shown in Fig. 4, we were able to obtain data on the ground state (d,p) transition and to duplicate this data at 133 MeV (see Fig. 5). In each of these figures, the angle cuts in the spectrometer data were imposed in software. The solid circles represent the central bin with a width of 1° . On either side we obtained another bin of similar width which overlaps with the first set of data. These overlap points are plotted as open circles and slightly displaced for clarity in the direction toward their companion central angle. In each case, the rapid fall at small angles in the cross section is due to shadowing of the spectrometer acceptance by the internal Faraday cup. In the preliminary analysis, there is more scatter than one would expect purely on the basis of counting statistics and there are occasional angles where erroneous data has been included. In the measurements, we used two polarized beam states with opposite signs of the vector polarization. Unfortunately, both of these states were contaminated at a level of 20% with tensor polarization which flipped sign with changing

spin state and thus were not separable from the vector polarization in their effects on the data. However, it is clear that the analyzing power has a strong, large analyzing power feature that is growing as the energy rises. This set of data allows us to set limits on the acceptance of the polarimeter.

The next phase of this analysis involves making a model of these measurements so that they may be included in a Monte Carlo simulation of the polarimeter performance. Such a model must include the effects of energy loss, multiple scattering, detector acceptance, target geometry, and any possible absorbers. The parameters describing these features can be changed to optimize the performance. We will also be considering for the resonant ring design polarimeters that operate at higher energies. For this we may need additional measurements between 133 and 200 MeV from the KVI. Above these energies, there is some additional data from other polarimeter projects that may be considered [6,9].

1. For a collaboration list, see http://www.bnl.gov/edm/icons/EDMcollaboration_010210.htm
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