Deuteron-deuteron Elastic Scattering at 231.8 MeV

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In 2003, IUCF reported the first definitive measurement of the d+d → ^{4}He+π^0 reaction [1]. This process is suppressed because it does not conserve isospin and, since the pion wavefunction is odd under charge symmetry, it does not obey charge symmetry. The measurements, made just above threshold at 228.5 and 231.8 MeV, depended on the suppression of background made possible by the observation of both pion decay photons and on the reconstruction of the pion mass from kinematics based on the observation of the recoil ^{4}He angle and energy (needed to discriminate against double radiative capture).

Theoretical calculations for this reaction [2] are based on a combination of production processes, including charge symmetry breaking pion rescattering (at leading order but suppressed) and a series of one-body and heavy meson exchange amplitudes that rely on meson isospin mixing (either π^0-η or ρ^0-ω). In the initial estimates [2], simple Gaussian wavefunctions were used for the nuclear bound states and the entrance and exit channels were treated as plane waves. For the entrance channel in particular, one would expect considerable modification of the internal structure of the deuteron bound states because of their weak binding. Antonio Fonseca at the University of Lisbon has undertaken to make this calculation using a *t*-matrix to describe the three-body interaction within the Alt, Grassberger, and Sandhas [3] equation for four strongly interacting particles. Such an approach works best at higher energies where multiple scattering, handled by multiple applications of the *t*-matrix, contributes less to the final amplitude.

In preparation for checking the entrance channel interaction, we undertook a measurement of the d+d cross section and analyzing powers iT_{11}, T_{20}, and T_{22} following the charge symmetry breaking experiment in the Cooler. These data were measured with the PINTEX broad range detector system. A nearly complete description of the analysis process was given in the last Annual Report. Since then, the analysis has been finished and a publication of the results is in preparation. There were two significant issues to resolve. The first was the removal of what appeared to be significant systematic errors in the calculation of T_{20} and the second was the calculation of the final values of the d+d cross section. These issues will be reviewed here and the final results shown.

The analyzing powers were obtained from a Fourier series analysis of the distribution of elastic scattering events in azimuthal angle φ. For a given bin in the center-of-mass scattering angle θ, the φ distribution is described by $F + G\cos\varphi + H\cos^2\varphi$. If the azimuthal distribution is normalized by dividing by the unpolarized distribution so as to set the cross section to unity, then the analyzing powers can be written as:

$$iT_{11}(\theta) = \frac{2}{\sqrt{3}}\frac{G(\theta)}{p_y} \qquad T_{20}(\theta) = \sqrt{8}\,\frac{1-F(\theta)}{p_{yy}} \qquad T_{22}(\theta) = \frac{4}{\sqrt{3}}\frac{H(\theta)}{p_{yy}}$$

Because G and H are relatively small, errors in the normalization are not so apparent. Because T_{20} involves the difference $1-F$, it is much more sensitive to anything that alters the value of F. The relative luminosities for the different polarization states were checked carefully for systematic errors. Finally, we used the total trigger rate for two forward prongs as a measure of the relative luminosity. This was checked for spin independence by comparing against the readout of the Cooler ring current transformer, after careful subtraction of the background from the transformer signal. (The trigger for one forward prong and a recoil in the silicon detectors turned out to depend on the tensor polarization of the beam.)

The issue was traced to the statistics of taking the ratio of polarized to unpolarized count rates. The data as a function of φ was divided into a number of bins. For the larger scattering angles where the cross section was smaller, this often resulted in relatively few events in each bin, particularly after subtraction of the background. In this case, the statistical error that results when you divide by a number of events is asymmetric with more tolerance for large values of the ratio than small ones. In the fitting process the error was made symmetric about the value of the ratio, with the result that the chi square minimization yielded values of F that were too small. This systematic problem was reduced using two analysis changes. First, fewer bins were used to sample the φ distribution. Second, the analysis was performed for the combination of signal and background together and again for the background alone. Once there were values of T_{20} for both of these cases, the cross section weighted difference was taken to obtain the value of T_{20} for the signal. This meant that the ratio of polarized to unpolarized events was calculated with larger event samples. The main signature of the systematic problem was a difference in the values of T_{20} when calculated with positive and negative tensor beam polarizations. After these changes, those differences disappeared. The final values of T_{20} are shown in Fig. 1.

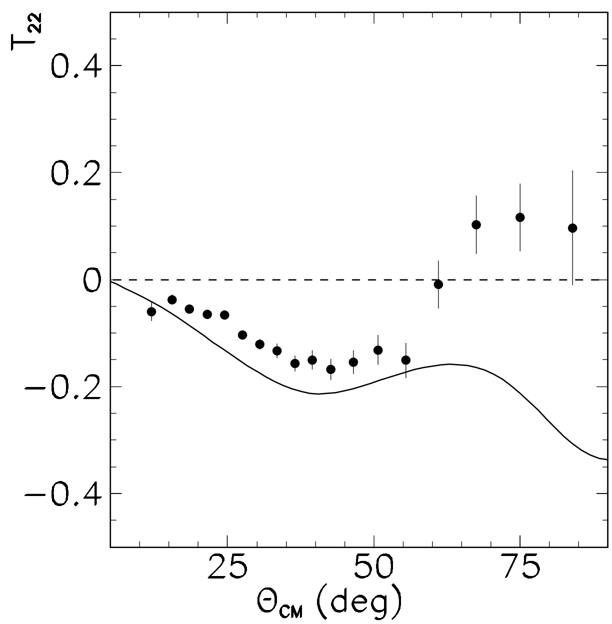

Figure 1: Measurements of the tensor analyzing power $T_{20}(\theta)$ as a function of the center-of-mass scattering angle. The calculation is from Antonio Fonseca.

The other analyzing powers, iT_{11} and T_{22}, are shown in Figs. 2 and 3. In a general way, the trends of all of the angular distributions are also present in the calculation, even though detailed agreement is missing. The forward angle peak in the vector analyzing power is a manifestation of the *NN* spin-orbit interaction. In these calculations, which should work best at forward angles, that contribution appears to be too large. For the tensor analyzing powers, the small values seen at forward angles are relatively well reproduced. Differences appear only for the larger angles where one would expect that the single application of the three-body *t*-matrix would be insufficient to capture the mechanism of the larger momentum transfers.

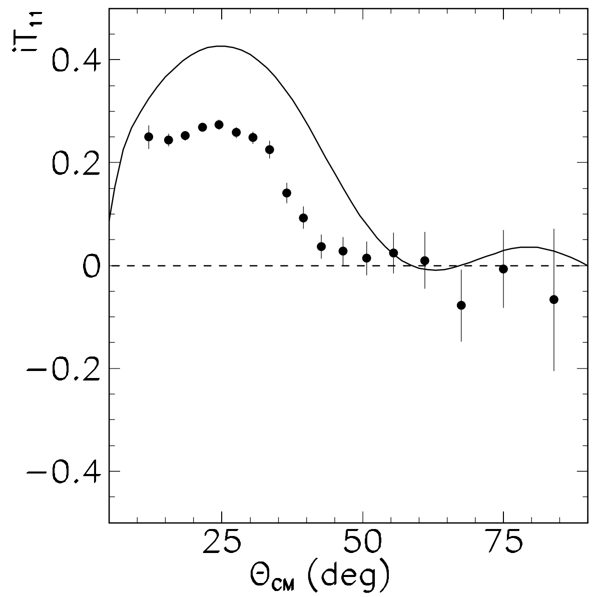

Figure 2: Measurements of the vector analyzing power $iT_{11}(\theta)$ as a function of the center-of-mass scattering angle. The calculation is from Antonio Fonseca.

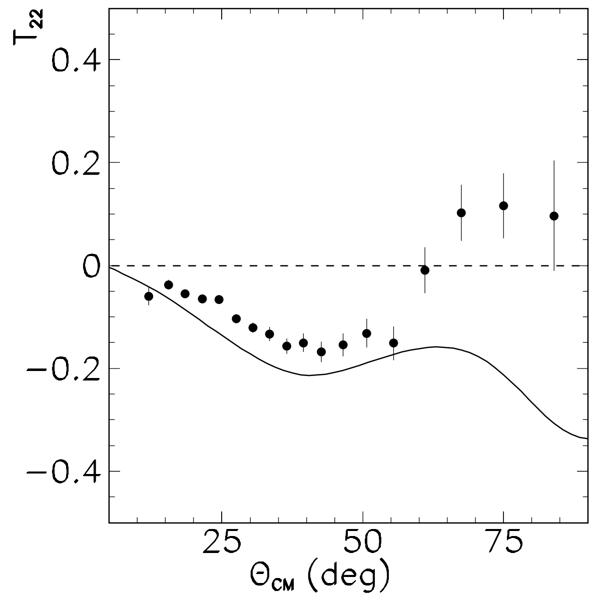

Figure 3: Measureents of the tensor analyzing power $T_{22}(\theta)$ as a function of the center-of-mass scattering angle. The calculation is from Antonio Fonseca.

Cross section measurements with the Cooler are more difficult because there is no simple way to obtain an absolute value of the luminosity. The circulating beam passes through a tube that is used to capture and increase the density of the target gas before it is pumped away. The density of this gas along the beam path is not known. So instead we were forced to do a relative normalization to another scattering. For that purpose we chose d+p elastic scattering. Cross section values in the relevant range of energies have been recently reported from the KVI [4]. In order to make a cross calibration, we used HD molecular gas as the target. In this case the luminosity for d+d and d+p scattering is the same, and one needs only to compare the count rates. In actual fact, the presence of both reactions at the same time in the data led to very large backgrounds that were not typical of the scattering from either hydrogen or deuterium alone. So the straightforward method of making such a background subtraction did not appear to be reliable.

Instead we chose to model the spectra with the HD gas as a sum of the spectra from hydrogen and deuterium alone, using the relationship

$$[HD] = A[H_2] + B[D_2]$$

Here the brackets may refer to either a spectrum or the sum of a designated part of a spectrum. By looking at this relationship using the cuts for either d+d or d+p events, two independent equations of this form are obtained, from which it was possible to solve for A and B. The cross sections for d+d elastic scattering were them obtained from the relationship

$$\sigma_{d+d}(\theta) = \left\langle \frac{\sigma_{d+p}\Omega_{d+p}}{N_{d+p}} \right\rangle \frac{B}{A} N_{d+d}(\theta) \frac{\varepsilon_{d+p}}{\varepsilon_{d+d}(\theta)\Omega_{d+d}(\theta)}$$

In this equation N represents the number of recorded events. For the reference d+p scattering inside the brackets, the ratio of this event count to the d+p cross section and solid angle was averaged over a range of angles where we felt that the efficiency for recording d+p events was uniform. That efficiency was $\varepsilon_{d+p} = 0.58$, a value that was less than one mainly from the effects of the software window on the total energy recorded for the two forward prongs (0.79) and the presence of notches between segments of the downstream plastic scintillators (0.865). (A check revealed that the energy losses were not associated with these detector gaps, so these two efficiencies were independent.) An additional efficiency (0.941) was found for the reconstruction of the two prongs from the wire chamber information. Other losses included incomplete wire chamber information and the software selection of coplanar events.

In a similar manner, the number of events, solid angle, and efficiency were considered for d+d events, but in this case the efficiencies were angle dependent. Minor losses were noted for the selection on particle identification in either the forward scintillators or the recoil silicon detectors. A smaller efficiency was noted (0.73) when the notches in the forward detectors were considered. These notches also included gaps in azimuthal angle that occurred in the construction of the silicon recoil detectors. The most difficult correction required that we make a Monte Carlo simulation of the acceptance of recoil events so that we could consider the acceptance of these detectors in scattering angle θ. In this case, the efficiency depended on changes in the detector thickness and electronic threshold and changes in the luminosity along the beam track through the gas tube as well as the geometry of the silicon detectors themselves. The distribution of events along the gas tube was checked against the forward reconstruction of gas tube position with d+p events, during which it became apparent that there were significant losses for d+p due to the electronic thresholds in the forward scintillators and the recording of particle energy for tracks that passed near the point where the scintillator coupled to the photomultiplier light guide. These issues were included in the Monte Carlo simulation. This resulted in an efficiency that depended on the d+d scattering angle. The final cross section values are shown in Fig. 4.

The calculation of d+d elastic scattering considers relative angular momenta up through $L = 18$. But for computational reasons, the angular momenta in the three-body t-matrix are limited to angular momentum values below $J = 2$ except for the inclusion of all P-wave phase shifts. This second set of limitations means that in the three-body scattering, there is insufficient angular momentum coverage to ensure convergence. The total three-body cross section is underestimated in this approximation by about 30% and the forward angle d+p scattering cross section would be low by almost a factor of 3. In combination, these shortfalls contribute to the underestimate of the d+d cross section angular distribution. In addition, the treatment of the scattering sends the system through the t-matrix only once. So at larger angles where multiple two- and three-body encounters are probably needed to achieve the larger momentum transfers, the calculation fails to include enough strength. This may also account for the difficulty in reproducing the larger angle analyzing powers. These issues tend to mask the central question, which is the quality of the calculation of the $^{3}P_{0}$ phase shift involved in the CSB reaction.

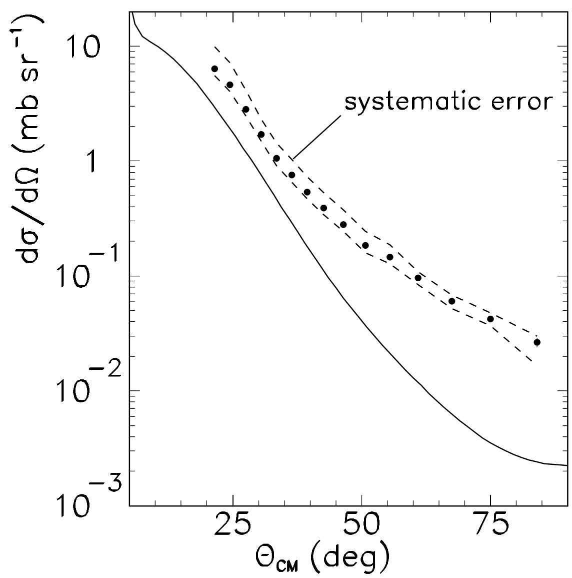

Figure 4: Measurements of the d+d elastic scattering cross section as a function of the center-of-mass scattering angle. The upper and lower bands for systematic errors are noted by the two dashed curves. The solid curve is a calculation by Antonio Fonseca.

1. E.J. Stephenson *et al.*, Phys. Rev. Lett. **91**, 142302 (2003).
2. A. Gårdestig *et al.*, Phys. Rev. C **69**, 044606 (2004).
3. E.O. Alt *et al.*, Phys. Rev. C **1**, 85 (1970).
4. K. Ermisch *et al.*, Phys. Rev. C **71**, 064004 (2005).