

Deuteron-deuteron Elastic Scattering at 231.8 MeV

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In 2002, the CSB Collaboration completed data taking on the Cooler in their search for the $d+d \rightarrow {}^4\text{He}+\pi^0$ reaction. This search was successful, producing a significant although small cross section at two deuteron energies just above threshold. The theoretical understanding of this reaction requires a detailed treatment of the entrance channel wavefunction involving the interaction of the two deuterons. This effort, led by Antonio Fonseca from the University of Lisboa, involves the use of a 3-body t-matrix formalism based on the work of the Glöckle group [1]. In order to evaluate the quality of this calculation, the CSB Collaboration spent the last week of their beam time on a measurement of the cross section and three analyzing powers (t_{11} , t_{20} , and t_{22}) for d+d elastic scattering at the higher of the two CSB energies, 231.8 MeV. Analysis time was initially devoted to the main CSB data on pion production, and only this year has there been a significant effort on the analysis of the elastic scattering measurements.

The data was taken using the PINTEX detector system located in the A-region of the Cooler. Although a polarized deuterium target is available at that location, the limitations of time and the complexity of the setup precluded an effort to look at spin correlation coefficients. Instead, deuterium gas was fed into the storage tube usually used for the polarized target work. The polarized deuteron source was used to produce a beam that was cycled through five polarization states: unpolarized, vector (+) and (-) with tensor polarization, and pure tensor polarization (+) and (-). The silicon detector barrel was installed so that elastic scattering events could be triggered and identified using both the forward and recoil particles. The forward counter array consisted of the F-detector, wire chambers arrayed in X-Y and U-V orientations, and two thick scintillators for a total energy measurement. The main problem was to find a way to normalize the d+d cross section. Following the use of a comparison to d+p elastic scattering that was the reference for the CSB experiment, we also made measurements with H₂ and HD target gasses. The d+p scattering has a known sensitivity to deuteron polarization [1], so it also served as the polarimeter for the circulating beam. As the supply of HD gas was limited, we ran this only with unpolarized deuterons in order to obtain the cross normalization between d+d and d+p cross sections. Data acquisition ran for four days. During this time we switched periodically between D₂ and H₂ target gasses to track any polarization changes, and made the HD cross calibration at the beginning and end of the run.

The first part of the analysis was to extract beam polarizations from the d+p measurements. The relevant events were recorded using a trigger based on two forward particle tracks in the scintillator and wire chamber array. The selection of d+p elastic events was made on the basis of several cuts. Geometry required that there be two tracks in a plane that goes through the beam and that the tracks converge to a point within the target cell. If the angle of one of the tracks was greater than 37°, it was considered to be the proton. Inside this angle, the proton was assigned to the track with the largest energy. With this in place, we could verify that the kinematics tracked the expectation for d+p elastic scattering, as shown in Fig. 1. A cut was then placed on good kinematics. With these events selected, the full energy of the d+p event was calculated, and another cut made that required this to equal the beam energy. For the calculation of polarization, we need to be able to obtain the Fourier components of the distribution of the events in ϕ . Even with the preceding cuts, there were still breakup events in the data. So the analysis used the difference between the actual “deuteron” angle and the expected deuteron angle, based on the proton angle, to define a background distribution. This is shown in Fig. 2. Events belonging to two

regions on either side of zero difference were used to produce typical ϕ distributions for the background. The background curve allows us to estimate what fraction of these events should be subtracted from the d+p event sample.

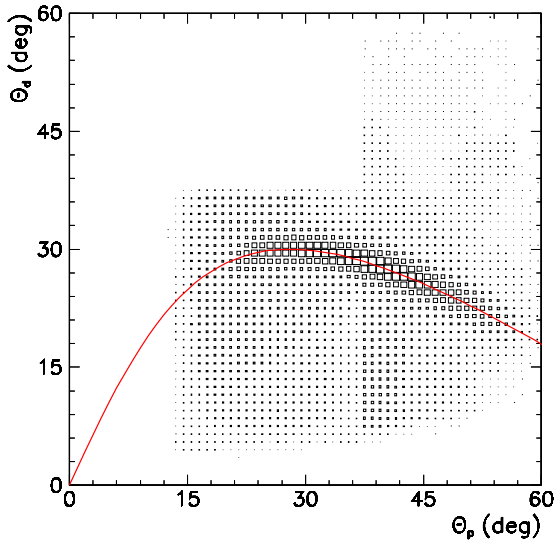


Figure 1: Distribution of events by deuteron (vertical) and proton (horizontal) scattering angle. The curve shows the kinematic locus for d+p elastic scattering.

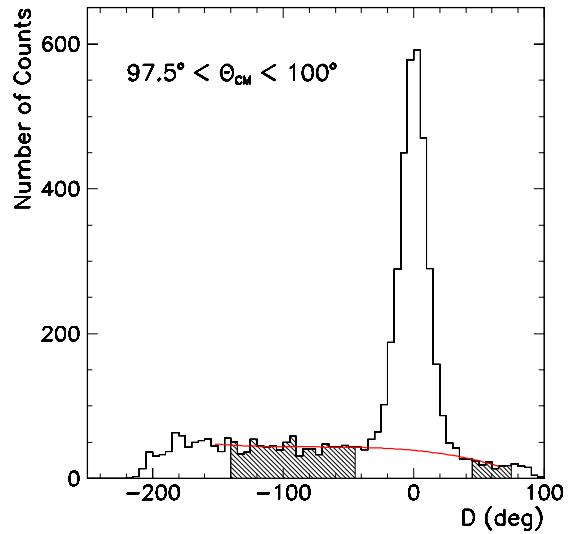


Figure 2: Example of the distribution of event in deuteron angle difference for center of mass angles between 97.5° and 100° . A fitted background is shown, along with two regions used to obtain background ϕ distributions.

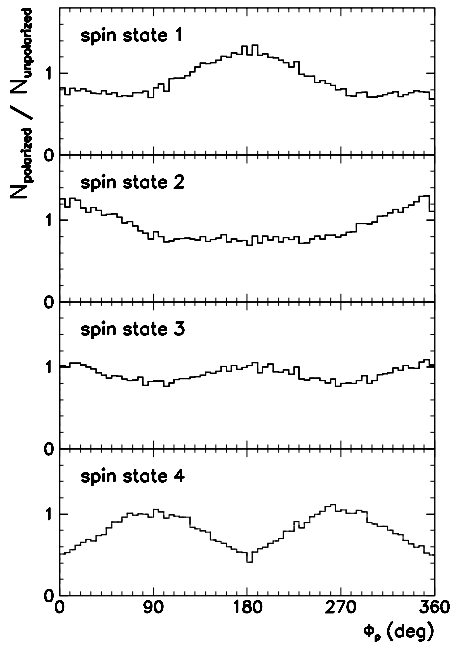


Figure 3: Distributions of polarized d+p events (divided by the unpolarized) for the four polarized states in the deuteron beam. These are:

- 1 = vector + (with tensor +)
- 2 = vector - (with tensor +)
- 3 = tensor +
- 4 = tensor -

Vector polarization produces a $\cos \phi$ component; tensor polarization produces a $\sin \phi$ component.

The distribution of events in azimuthal angle (ϕ) had notches for the gaps in the plastic scintillators. In order not to have these influence the extraction of the beam polarization, each distribution

had its background removed and was then divided by the distribution for the unpolarized beam. The resulting distributions are shown in Fig. 3. They are smooth and Fourier components can be extracted easily. With the analyzing powers known from experiments at RIKEN [2,3], the only unknowns for each distribution are the vector and tensor polarizations (with the assumption that the quantization axis is vertical). These can be extracted from the distribution for each spin state with no additional assumptions.

The polarizations were constant throughout the run, and constant with the d+p scattering angle used to select the reference analyzing power data. Small corrections for the energy dependence [1] were included. The polarizations found for these measurements are:

state 1	vector +	$p_y = 0.68 \pm 0.02$	$p_{yy} = 0.79 \pm 0.05$
state 2	vector -	-0.62 ± 0.02	0.58 ± 0.05
state 3	tensor +	0.00 ± 0.02	0.74 ± 0.05
state 4	tensor -	0.00 ± 0.01	-1.85 ± 0.05

These results are consistent with polarization measurements made at the output of the RFQ just ahead of the injector synchrotron.

A similar treatment was made for the deuterium target data. The trigger required that there be one event in the silicon barrel (with possibly two strips hit) and a forward track. Because of the lack of polar angle information from the silicon, the only geometry constraint is coplanarity. Kinematics could not be checked. Scintillator particle identification was used to separate forward deuterons, as shown in Figs. 4 and 5 for the forward and recoil particles. Silicon detector deuterons were distinguished from

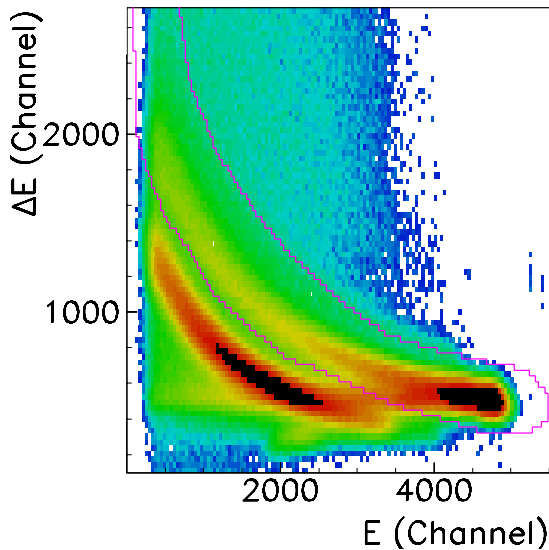


Figure 4: Distribution of the F-scintillator signal pulse height against the sum of the K- and E-scintillator pulse heights. The gate contour selects the forward deuteron events.

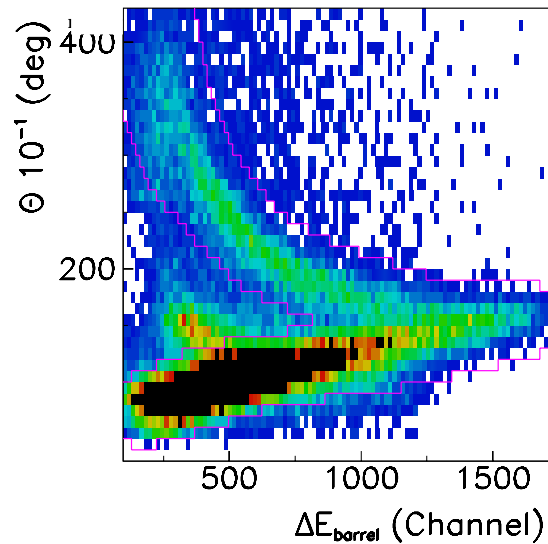
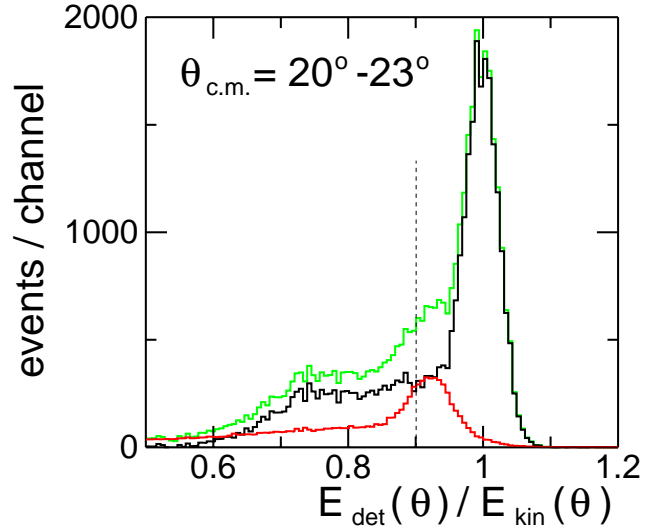


Figure 5: Distribution of the forward lab angle against pulse height in the middle row of silicon barrel detectors. The gate contour selects the recoil deuteron events.

protons only in the region where they punched through the detector. For small angles where the recoil deuterons stopped, deuterons and protons could not be distinguished. The last check was on the energy of the forward track as a function of the laboratory scattering angle. As was the case for the d+p events, we wished to extract the analyzing power information from the azimuthal distributions. Again, there was background. In this case we made a model to correspond to the breakup and quasi-elastic contributions to the background (red curve in Fig. 6). The quasi-elastic shape was scaled from the d+p elastic scattering measurements, and an empirical curve was used for the breakup contribution. Once subtracted

from the energy distribution (green), this left us with the black curve. For the purpose of calculating the analyzing power, we used the sum in the peak that was above the dashed line cut. The tail that extends down to 60% of the peak height appears to be a feature of the energy collection of the system, and needs to be included with the peak sum for cross section purposes.

Figure 6: Measurements of the forward track energy for $d+d$ events (green) for one center-of-mass angle bin, along with the background (breakup and quasi-elastic) and the subtracted signal (black). For analyzing power calculations, $d+d$ events were those above the dashed line cut. The horizontal axis is the ratio of the measured energy to the kinematic value.



At this time, preliminary results are available for the analyzing powers $iT_{11}(\theta)$ and $T_{22}(\theta)$, as shown in Figs. 7 and 8. These analyzing powers are extracted from the $\cos \phi$ and $\sin \phi$ terms that fit

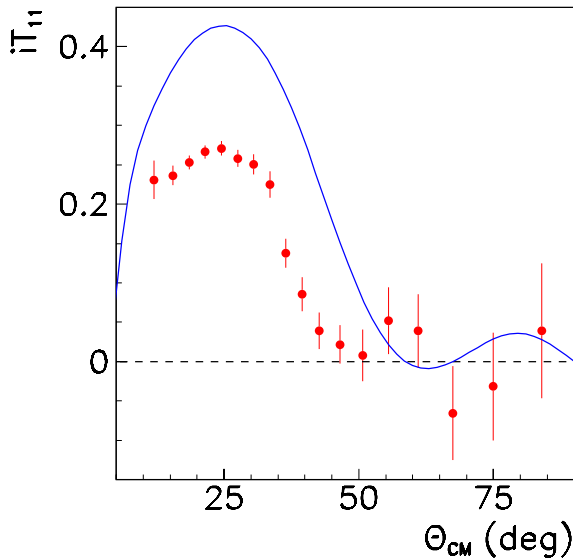


Figure 7: Measurements of the vector analyzing power iT_{11} for $d+d$ elastic scattering at 231.8 MeV. These data are preliminary. The curve is a calculation by A. Fonseca.

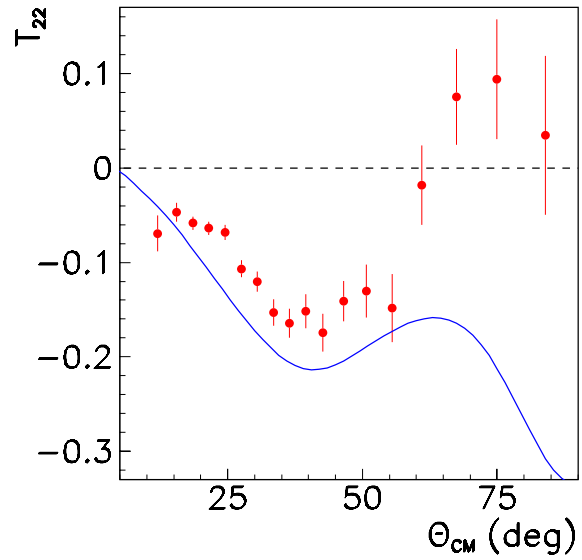


Figure 8: Measurements of the tensor analyzing power T_{22} for $d+d$ elastic scattering at 231.8 MeV. These data are preliminary. The curve is a calculation by A. Fonseca.

the azimuthal distributions. The cross section and T_{20} angular distributions are still under analysis. T_{20} is particularly sensitive to the relative normalization of the polarized and unpolarized luminosities, and

attempts to reproduce the d+p analyzing powers have shown that there are significant systematic errors. The cross section relative normalization still needs an evaluation of the detector efficiencies for d+p and d+d events. Agreement with Antonio Fonseca's calculations is encouraging and would suggest that we have a reasonable model of the main spin dependence in the d+d interaction.

1. W. Glöckle, H. Witała, D. Hüber, H. Kamada, and J. Golak, Phys. Rep. **274**, 107 (1996).
2. H. Sakai *et al.*, Phys. Rev. Lett. **84**, 24 (2000).
3. K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002).