Conceptual Design Report

A Search for the Charge Symmetry Breaking $dd \rightarrow \alpha\pi^0$ Reaction

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I. Physics Context

Introduction

Charge symmetry breaking in nuclear physics is driven in the strong interaction by the difference in down and up quark masses, and electromagnetically by the difference in down and up quark charges. In addition to the small mass difference between the proton and neutron, the quark mass difference leads to mixing in the meson-exchange picture of the nuclear force. For the isovector mesons, the overlap of the meson masses (broadened by the decay lifetime) makes the mixing of ρ^0 and ω apparent as resonant interference in e^+e^- scattering [Qu78]. Mixing between ρ^0 and ω is also an important contribution to the analyzing power difference observed between protons and neutrons in np elastic scattering [Vi92].

In the pseudoscalar channel, the π^0 and η do not overlap, so this mixing must be inferred from nuclear reactions. For example, it can generate an amplitude that interferes with S-wave π^0 production in np $\rightarrow$ dπ^0 near threshold, creating a small (less than 1%) fore-aft asymmetry in the cross section [Ni99]. Another way to measure such an effect is to look directly for the isospin-violating cross section for dd $\rightarrow \alpha\pi^0$ [Ch82], a daunting task given the small size expected.

The IUCF Cooler offers considerable advantages in conducting a search for the dd $\rightarrow \alpha\pi^0$ reaction near threshold. This Conceptual Design Report explores this possibility as a project for the remaining years (through FY2001) of Cooler operation. In brief, CE-78 proposes to use a tensor polarized deuteron beam at 231.4 MeV incident on a deuterium gas jet target in the T-region of the Cooler just upstream of a 6° bending magnet. This magnet (through which the beam passes) will bend away the forward cone of ^{4}He nuclei that will be refocussed and detected at the end of a magnetic channel. Near the target, two large arrays of Pb-glass detectors will capture the γ-rays from the decay of the π^0.

Past attempts to measure dd $\rightarrow \alpha\pi^0$

Several attempts have been made to observe π^0 production from the dd $\rightarrow \alpha\pi^0$ reaction. Poirier and Pripstein [Po61, Po63] reported an upper limit of 2 nb/sr at $\theta_{c.m.} = 90°$ using 460-MeV deuterons from the Berkeley 184-inch cyclotron. Later, this was reduced to 11 pb/sr by Akimov [Ak69], at which point he encountered the background dd $\rightarrow \alpha\gamma$. Most recently, a series of experiments at Saturne [Ba87, Go91] examined incident deuteron energies of 0.8 GeV and 1.10 GeV and looked for π^0 production at angles between 100° and 107°. After reporting an upper limit of 0.8 pb/sr at 0.8 GeV [Ba87], a positive result of $0.97 \pm 0.20 \pm 0.15$ pb/sr was claimed at the upper energy. (Comparable cross sections were observed for dd$\rightarrow \alpha\gamma$.) This result was considerably above a prediction made at 1.95 GeV by Coon and Preedom [Co86] and rescaled to the Saturne energy. Separation of the signal in the Saturne experiment was difficult, and it has been pointed out that the observed cross section is consistent with the production of uncorrelated γ's through radiative capture in the dd$\rightarrow \alpha\gamma\gamma$ process [Do99]. Thus there has been no definitive measurement to date of the dd $\rightarrow \alpha\pi^0$ reaction.

Existing experimental efforts using other techniques

TRIUMF experiment E704 [Op99a] has measured full angular distributions of the np$\rightarrow$dπ^0 reaction at 283.0 MeV just above the threshold at 275.0 MeV. Interference between the dominant S-wave production mechanism and the isospin breaking amplitude is expected to generate a fore-aft asymmetry in the production cross section at the level of –0.35% [Ni99]. The statistical precision in the data is $< 0.12\%$, but final results depend critically on the ability to model systematic effects in the response of the spectrometer and detector system. Such a model is being tested against a symmetric set of pp$\rightarrow$dπ^+ data measured at 300.6 MeV (to match the deuteron locus in the spectrometer). The level of systematic error control is not yet known [Op99b]. Here the dominant charge symmetry breaking effects are expected to be the production of an η-meson with its subsequent transformation by mixing into a π^0 and the isospin-breaking $\eta\pi$ transition potential [Ni99]. The main theoretical uncertainty is the strength of the ηNN coupling extracted from NN scattering analyses [El87], which varies up to a factor of 3.

Data have also been obtained at the Brookhaven AGS in Experiment E890 for the cross section ratio of the η production reactions π^+d $\rightarrow$ ppη and π^-d $\rightarrow$ nnη near the η production threshold [Ti99]. The ratio is less than one by $6.1 \pm 0.7\%$. Corrections for the different reaction thresholds and the different Coulomb entrance-channel distortions are sufficiently stable that this result is unchanged as the pion momentum is varied from 40 to 140 MeV/c above threshold. Interpretation of this result in terms of a $\pi^0 - \eta$ mixing angle gives answers close to 2°. At present, this interpretation is subject to change since the theoretical model does not include contributions from the initial- and final-state interactions in all partial waves.

It thus appears likely that within the operation time of this experiment, other significant results relating to the degree of $\pi^0 - \eta$ mixing will become available. In this context, any measurement of dd $\rightarrow \alpha\pi^0$ needs to produce a statistically significant measurement of the cross section, not an upper limit, in order to make a useful contribution toward a further understanding of isospin mixing.

Estimates of charge symmetry breaking in dd$\rightarrow \alpha\pi^0$

Careful estimates of the charge symmetry breaking to be expected in the dd$\rightarrow \alpha\pi^0$ reaction that consider multiple contributions to the reaction amplitude have only been made in the vicinity of the Δ resonance (deuteron energies from 500 to 700 MeV) where some mechanisms are expected to be at their largest [Ch82]. The value of 0.05 pb/sr is given at 0° where the momentum transfer is the smallest. Other angles are likely to have lower cross sections because of the poorer overlap between initial and final states that exists when the momentum transfer increases. However, these calculations are not a reliable guide near threshold, in part because of the need to understand the basic amplitudes away from the Δ resonance. Thus we must use estimates in which the dd $\rightarrow \alpha\pi^0$ cross section is scaled from other π^0-producing reactions (assuming that it conserves isospin by postulating a fictitious isoscalar π^0) and then apply a factor that represents the likely degree of charge symmetry violation present.

Greider [Gr61] has presented such a scheme based on rescaling the pd $\rightarrow$ ^{3}Heπ^0 reaction. Miller [Mi98] has calculated the isospin-conserving scaling factor for dd $\rightarrow$ $\alpha\pi^0$ at 231.4 MeV and found 0.16. The calculation was repeated at IUCF [St99] with a result of 0.31, a value that uses a more modern single-particle wavefunction for the nucleons inside ^{4}He. (This is similar to the factor, 0.14, by which the pd $\rightarrow$ ^{3}Heπ^0 cross section [Pi92] falls below the np $\rightarrow$ dπ^0 cross section [Hu91].) The cross section for pd $\rightarrow$ ^{3}Heπ^0 near $\eta = k_\pi/m_\pi = 0.2$ where the dd $\rightarrow$ $\alpha\pi^0$ experiment will run has been measured by Pickar to be 12.6 η μb [Pi92]. Using the more modern ^{4}He wavefunction, the "isospin-conserving" cross section for dd $\rightarrow$ $\alpha\pi^0$ becomes 3.9 η μb. (Other estimates made by Miller [Mi98] and reported in the Letter of Intent [Ba98] are based on the np $\rightarrow$ dπ^0 cross section coupled with a calculation of the overlap between initial and final states. This latter scheme is too sensitive to changes in the starting assumptions about kinematics to provide reliable estimates.)

Since the underlying mechanism for isospin violation is likely to reside in the π^0 production reaction np $\rightarrow$ dπ^0, perhaps the best estimate of the ratio of isospin-violating to isospin-conserving amplitudes is the fore-aft asymmetry calculated by Niskanen [Ni99]. At $\eta = 0.2$ ($E_d = 231.4$ MeV) this is –0.16%, giving a total dd $\rightarrow$ $\alpha\pi^0$ cross section of 2 pb.

This cross section is comparable to the upper limits obtained at higher energies. While the expansion of the available phase space makes the production cross section increase above threshold, the higher energies will be dominated by an ever-falling formfactor that arises from the overlap of the deuteron and ^{4}He wavefunctions. For the np $\rightarrow$ dπ^0 calculations of fore-aft asymmetry by Niskanen, the maximal isospin-violating effect was for $\eta = k_\pi/m_\pi = 0.5$ [Ni99] or a neutron energy of 313 MeV.

This degree of isospin mixing falls at the lower end of the range commonly used in theoretical estimates. It is roughly equal to the fractional neutron-proton mass difference, 0.14%. Other estimates are based on the difference in the current quark masses, $m_d - m_u =$ 3.8 MeV [Mi95], but the problem is to choose the scale of the violation. Dividing by the constituent quark mass of about 1/3 of the proton mass gives a mixing of 1.2%, a much larger value. Weinberg [Mi98] has suggested that the scale should be the pion mass, giving a mixing of 2.8%, but it is not clear where such an enhanced mixing would be observed ($\sigma_{\text{tot}} = 610$ pb for dd $\rightarrow$ $\alpha\pi^0$).

It should be noted that Dobrokhotov [Do99] has also estimated the dd $\rightarrow$ $\alpha\gamma\gamma$ cross section at 10 MeV above the dd $\rightarrow$ $\alpha\pi^0$ threshold (the IUCF experiment is proposed to run at 6 MeV above threshold) to be $d\sigma/dm_{\gamma\gamma} = 3.4$ pb/(MeV/c^2), a value comparable to the charge symmetry breaking cross section estimated above. The two γ's arise from double radiative capture between neutrons and protons from different deuterons. It is not clear how this estimate is affected by the acceptance of the magnetic channel in this experiment. These γ's are preferentially emitted at 90° in the np $\rightarrow$ dγ reaction, and so should be strongly sideways peaked in the Cooler experiment. This places a premium on a reconstruction of the π^0 kinematics as a part of this experiment.

Polarization effects

Because of restrictions on the spin structure of the reaction, $1^+ + 1^+ \rightarrow 0^+ + 0^-$, it is possible to know the tensor analyzing power of the reaction in advance [Vi96]. Let L_i and S_i be the angular momentum and total spin for the two deuterons in the entrance channel. In the exit channel, the angular momentum is the only contribution to the total angular momentum, $L_f = J$. Quantization along the beam axis requires $\langle L_i \; 0 \; S_i \; 0 | L_f \; 0 \rangle \neq 0$ which means that $L_i + S_i + L_f =$ even. The boson symmetry of the initial state in addition requires that $L_i + S_i =$ even, from which $L_f =$ even and only every other partial wave can contribute. Parity conservation requires $L_i = L_f \pm 1$, thus $L_i =$ odd and $S_i = 1$. The non-vanishing of the deuteron spin coupling with quantization along the beam direction requires that $\langle 1 \; m_{beam} \; 1 \; m_{tgt} | 1 \; 0 \rangle \neq 0$. Thus only $m_{beam} = \pm 1$ states can contribute and the tensor analyzing power is $A_{zz} = 1$ or $T_{20} = 1/\sqrt{2}$.

Because of the small anomalous magnetic moment of the deuteron, it is likely that the quantization axis of any polarized beam in the Cooler will be vertical. Thus p_{yy} polarization should be available. Given the performance for protons, it is reasonable to expect that we would have the two states, $p_{yy} = 0.85$ and $p_{yy} = -1.70$. The polarized cross section varies as $\sigma = \sigma_0 \; (1 + p_{yy} A_{yy}/2)$. Constraints on the Cartesian analyzing powers requires that $A_{yy} = -0.5$; thus an asymmetry constructed from these two count rates would be $\epsilon = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) = -0.288$. The number of events needed to produce a two-standard-deviation difference from zero is $C = (1 - \epsilon^2)/\delta^2$ where $\delta = 0.288/2 = 0.144$, or 44 events. This number must increase if there is a background subtraction to be made.

The analyzing power for uncorrelated γ production is expected to be close to zero [Do99], thus an analyzing power measurement would be an important confirmation that dd $\rightarrow \alpha\pi^0$ events had been observed unambiguously. However, measurement of a change in count rate for the total cross section also requires good spin-independent luminosity monitoring and an independent way to measure the polarization of the beam stored in the Cooler. Because of the development effort required and the short time span available for the experiment, we should plan to have this capability from the start. If the event rate were to prove marginal, it would be better to have taken the events with polarized beam than to be faced with the decision to repeat the experiment.

Experimental event rates

Beam in the Cooler goes through a cycle that includes storing a number of shots from CIS, cooling, ramping to the desired energy (the Cooler would be injected at $E_d = 90$ MeV), starting the target jet and data acquisition, acquiring data during a "flattop," and finally resetting the Cooler magnets. The CIS cycle time is now 1.25 s, and several shots are usually needed for maximum beam. Thus a reasonable estimate for the overhead time (not data acquisition) is about 20 s, and flattop data acquisition times much less than about 30 s become inefficient. Again, efficiency would suggest that the data acquisition time is also roughly the beam lifetime. Experience with the pd$\rightarrow$ pdπ^0 experiment [Ro93] using a deuterium target suggests that a 30 s lifetime corresponds to a jet target density of 2.5×10^{15} /cm^2, even though higher densities could be produced. Although beams as large as 10 mA of circulating current have been observed with unpolarized protons, experience suggests that stable operation for polarized beam with an average of about 2 mA can be sustained over a long time. Most experiments operate with less due in part to data acquisition rate limitations. This produces a luminosity of $\mathcal{L} = 3 \times 10^{31}$ cm^{-2}s^{-1} during the data acquisition flattop.

If we assume that the duty factor for Cooler operation is 3/5, that a typical livetime for data acquisition is 70%, and that about 33% of the π^0's will produce a 2–γ trigger, then a 2-pb production cross section will generate 0.7 events/day. The two-standard-deviation polarization measurement would require about 60 days of useful Cooler operation (after setup and breakdowns are removed), which is about as much time as the experimenters and IUCF will be able to support during the last year of Cooler operation.

Operation of the Cooler for 60 days at $\mathcal{L} = 3 \times 10^{31}$ cm^{-2}s^{-1} with tensor polarized beam would appear to be a meaningful goal of this experiment. While the analyzing power would only be useful at or above the rates discussed here, detection of the dd $\rightarrow$ $\alpha\pi^0$ reaction would be sensitive at a level somewhat below 1 pb. The required level of background suppression is comparable to that obtained in a search for pionium ($\pi^+\pi^-$ atoms) using a similar magnetic channel arrangement on the IUCF Cooler [Be96].

Primary background rate

Because of its impact on experimental design, it is important to estimate the total rate that will be experienced by the detectors in the forward charged-particle channel. This has been investigated in some detail by Mark Pickar [Pi00]. Despite the fact that cross sections for either d+d elastic scattering or deuteron breakup on the deuteron are lacking, it is possible to scale estimates from other targets using a model originally developed by Serber [Se47].

The largest charged particle flux in the direction of the magnetic channel will be the protons from the breakup of the beam deuteron. Because they are travelling at half the momentum of the beam, they will tend to be bent through the same angle as the ^{4}He nuclei formed by the dd $\rightarrow$ $\alpha\pi^0$ reaction. Thus much of this cross section will appear on the detectors at the front of the channel.

Pickar used a number of experiments that measured breakup protons as a function of target mass and energy. In particular, there are experiments from RIKEN at 270 MeV [Ok92] on nuclei as light as carbon. With some allowances for a failure to scale for the lightest masses, the total breakup cross section is likely to be near 120 mb. If the forward acceptance of the magnetic channel is assumed to be circular with a radius of 2°, then the fraction of this cross section that will enter the channel is 0.06. With a luminosity of $\mathcal{L} = 3 \times 10^{31}$ cm^{-2}s^{-1}, the rate into the channel is roughly 2×10^5 s^{-1}.

Typical electronic coincident resolving times are of the order of 50 ns. Rates at the level above would result in pileup events roughly 1% of the time. For the forward MWPC detector, the relevant time is the width of the gate necessary to allow for drift times in the wire chamber gas. With a 1 mm spacing, these should be less than 100 ns, so pileup should be no more than 2% from breakup events. These rates, while high, appear to be manageable. They will need to be considered when planning for the biasing of the channel detectors since current drains are likely to be large.

Figure 2.A.1: Layout of the CE-78 experiment, including the "curtain" Pb-glass arrangement, gas jet target, 6° *bending magnet, and magnetic channel with its wire chambers and scintillation detectors.*

The next largest channel is deuteron elastic scattering (not at 0° in this case since the deuterons are close to beam momentum). Pickar estimates a cross section into a 2° cone of 0.4 mb, about 1/20 of the breakup cross section. Thus the elastic rate will be considerably less than the breakup. Products from other reaction channels should be even smaller.

II. Description of the Experiment

A. BRIEF OVERVIEW OF THE SYSTEM

The design of the magnetic channel and detector arrangement for CE-78 is based on other similar arrangements that have been employed in the IUCF Cooler T-region. The most recent was the use of a magnetic channel following the 6° magnet to search for pionic

Figure 2.A.2: Expanded overview of the region of the septum magnet.

atoms [Be96]. Figure 2.A.1 shows an overview of the proposed layout for CE-78 (but with a schematic arrangement for the Pb-glass).

The gas jet target sits upstream of a 6° magnet that is a permanent feature of the Cooler ring. Just above threshold, the ^{4}He nuclei from dd $\rightarrow \alpha\pi^0$ reaction emerge in a tight cone in the forward direction. The size of that cone can be regulated (realizing that this also changes the cross section) by small adjustments to the beam energy. The choice of $E_d = 231.4$ MeV results in a 1.7° half-angle cone. The circulating deuteron beam bends 6° in the magnet, exiting through a small beam pipe. The ^{4}He nuclei, being less rigid than the beam and having Z=2, bend through an angle of 12.5°. From there the ^{4}He nuclei are refocussed onto a set of detectors at the end of a magnetic channel. In previous magnetic channel experiments [Be96], the centerline was closer to the ring quadrupoles. For this application, the plan is to get a larger acceptance and better separation by placing a septum dipole magnet at the front of the channel. This magnet is of a new design while the channel quadrupoles are magnets already in house. The three quadrupoles refocus the ^{4}He nuclei to a double waist about 8.1 m from the target.

The first position detector in the magnetic channel is a multi-wire proportional chamber (MWPC-1) located just ahead of the septum magnet. An expended detail of this region is shown in Fig. 2.A.2. This detector measures the angle of the emerging ^{4}He nucleus, and contains three wire planes to help eliminate ambiguities from multiple hits. This chamber has a frame that is cut away to accommodate the beam exit pipe from the 6°-magnet box. Confirming information is obtained from a second wire chamber (MWPC-2) located after the septum magnet. With MWPC-1, angles calculated for each particle allow a projection back to the target.

Important information on the momentum of the ^{4}He nuclei is obtained from a time-of-flight measurement in the magnetic channel. The first scintillator, ΔE_1 (2 mm thick,

Figure 2.B.1: Correlation between ^{4}He scattering angle and ^{4}He momentum.

shown as SC1 in Fig. 2.A.2), is located ahead of the first MWPC. The detectors at the end of the channel, also plastic scintillators, provide the second timing measurement. Also at the end of the channel will be a third MWPC. Horizontal position on this detector will be used to confirm the momentum deduced from the time-of-flight measurement and correct for time slewing for different paths through the channel. Position measurements on this detector will also be necessary to confirm the setting of the magnetic elements of the channel.

The detectors at the end of the channel will be a stack of three scintillators. The first two, ΔE_2 and E (each 3 mm thick), provide a ΔE and E measurement for the identification of particle type. This identification is supplemented by the ΔE measurement from the first scintillator and the time-of-flight measurement. Redundancy in the ΔE measurements helps to reduce misidentification from reactions or high energy loss events in one of the ΔE measurements. Behind these scintillators will be one additional detector to veto particles that completely penetrate the detectors in front of it.

As an additional constraint on the measurement, it is important to record both of the γ-rays from the decay of the π^0. This is done with two walls of Pb-glass arranged on the beam left and right sides of the target. Some of the bars have been used previously in IUCF experiments to measure the capture γ-rays from np $\rightarrow$ dγ. Others are on loan from Argonne National Laboratory.

The box containing the target is rebuilt so that gas jet utilities and pumping enter only on the top and bottom of the box. The sides are made of smooth aluminum to allow for cleaner detection of the π^0 decay γ-rays. The location of the target is a compromise between moving it forward to permit a larger angular acceptance into the magnetic channel (which increases the production cross section) and moving it backward away from the 6° magnet to improve the solid angle for γ-ray detection.

B. ^{4}He MAGNETIC CHANNEL

The magnetic channel has been designed to accept ^{4}He nuclei from the dd $\rightarrow \alpha\pi^0$ reaction in order to provide a measure of the total reaction cross section. At 231.4 MeV, the ^{4}He nuclei spread into a cone in the laboratory with a half-angle of 1.7°. At 0°, reactions that give rise to forward or backward-going ^{4}He nuclei produce momenta in the lab that differ by 3.1%, a spread that is small enough that it makes sense to capture them all in a magnetic channel as if they formed a monoenergetic beam. The angle-momentum correlation is plotted in Fig. 2.B.1. The ^{4}He energy range spans from 106.4 to 120.1 MeV.

Figure 2.B.2: Beam envelope in Y (above center) and X (below center) in cm. Distances along the line are marked in m. The dashed line gives the dispersion. The lower of the two lines in X marks the envelope for a momentum spread of ±1.55%.

In the 6° bending magnet, the ^{4}He nuclei are bent an average of 12.5°. This does not produce quite enough separation to clear the edge of the existing flange for those nuclei travelling closest to the beam. We expect that a suitable combination of steering magnets will be turned on when the beam ramp is complete to move the beam centerline closer to the magnetic channel entrance. After cooling, the transverse spread of the beam is reduced, allowing space for such a change. Combinations of steering magnets that produce simple closed-orbit distortions have been identified and are used routinely in Cooler experiments to adjust the position and angle of the beam at target positions around the ring. This may imply that the best position for the gas jet target is displaced from the center of the Cooler beam line.

The ion optics of the channel was checked with the program TRANSPORT. The result is shown in Fig. 2.B.2. After the septum magnet, the ^{4}He nuclei are dispersed. Given an initial spot size at the target of ±0.3 cm horizontally, the spread in momenta yields a final spot size of ±2.7 cm horizontally. For a ±0.3 cm vertical beam spot size the vertical image at the end of the channel has a size of 0.75 cm.

Focussing is provided by three quadrupoles and the sloped edges of the septum magnet. The edge angles are set for 22° at entrance and exit, a number that is large due to the desire to simplify the magnet design by keeping the pole faces flat and parallel. 3D calculations are underway to determine whether the effective angle is close to this value. The dipole field of the septum magnet is 1.43 T. A magnetic shield is also needed in order to ensure that the field from the septum is made small before it reaches the position of the beam in the Cooler ring.

The channel used previously in the Cooler T-region is still available. It will need to be examined in light of the requirements for CE-78 to see whether time and effort can be saved by modifying it for this application.

C. WIRE CHAMBERS

The wire chambers at the front of the magnetic channel measure the angles of the outgoing ^{4}He nuclei. In this part of the channel, the rate of breakup protons is expected to be at least 2×10^5 s^{-1}. Thus the use of drift chambers is precluded and the best approach appears to be multi-wire proportional chambers with readout gates less than 100 ns wide. It is desirable to obtain spatial resolution close to 1 mm. This can be achieved with MWPCs using 1-mm spacing, but quality control on the materials and construction become significant issues in chamber performance. In the clusterized readout scheme provided by LeCroy PCOS-III, it is possible to obtain the same resolution using 2-mm spacing and tilting the chamber (about 18°) so that half of the particle tracks cross charge collection cell boundaries. Rotating the wire planes about the diagonal can produce this effect for both X and Y. The non-orthogonality introduced by this rotation is compensated by counter-rotating the X and Y wire directions on their respective planes.

Because of the high rates, multiple hit ambiguities may be an issue for X and Y reconstruction at the first MWPC. So an additional U plane (rotated at 45°) will be added to this chamber.

The second chamber located after the septum magnet will be used to confirm hits recorded in the first chamber and make sure that they are consistent with the correct trajectory through the septum magnet. This chamber should also have X–Y planes only with a 1-mm resolution so that tracking to the gas target position retains a level of precision comparable to the Cooler beam spot size.

At the end of the magnetic channel, it is important to have a third X and Y position measurement. This gives information on the correctness of the channel magnet settings, and can supplement a measurement of ^{4}He time-of-flight (next subsection) as a measurement of the ^{4}He momentum. The bend angle and dispersion in the channel are not large, so this measurement is sensitive to multiple angle scattering in the vacuum windows and detectors in the front of the channel. For the same reason, 2-3 mm MWPC wire spacing is adequate.

D. ^{4}He ENERGY MEASUREMENT AND PARTICLE IDENTIFICATION

In the characterization of dd $\rightarrow \alpha\pi^0$ events it is important to be able to reconstruct all three components of the ^{4}He momentum. The best way of doing that in the magnetic channel appears to be a measurement of time-of-flight. There is a 6.6-m separation between ΔE_1 and ΔE_2, giving a time spread (including energy loss corrections) between 96.5 and 106.3 ns (or 9.8 ns) for the range of ^{4}He momenta generated in this experiment. Off-axis ^{4}He nuclei will travel somewhat different distances, but this can be corrected using the MWPC hit position information.

These scintillators also give information on the particle type through their pulse height. In this experiment, it will be important to have redundant measurements of dE/dx, thus the E detector is preceeded by two ΔE detectors. Particle type can be identified from the correlations among the measurements as well as with time-of-flight. This will be illustrated in more detail in Section IV.

E. Pb-GLASS

Because of the low cross section expected for dd $\rightarrow \alpha\pi^0$, it is important to observe the decay of the π^0 along with a careful determination of the momentum of the ^{4}He nucleus. IUCF has available 162 Pb-glass modules that were last used to observe the γ-rays from np $\rightarrow$ dγ [Xu95] and an additional set of 121 modules on loan from Argonne National Laboratory. These must compete for space around the target region with the set of pumps needed to maintain the Cooler ring vacuum when the gas target is running.

Pb-glass offers the advantage that it is sensitive primarily to Čerenkov light from secondary electrons and positrons produced by γ-rays and thus suppresses any sensitivity to nuclear fragments produced by neutrons or charged particles. The segmentation of the detectors as well as a measurement of the signal timing offers crude information on the direction of the emitted γ-ray. Tests on individual modules with cosmic rays show that they have an energy resolution of about 50% for an energy deposition of 30-MeV-ee and a time resolution of roughly 1.5 ns, which can provide a position determination along the length of each module of about 15 cm. The modules are 50 cm (IUCF) and 36 cm (Argonne) in length with a 6.4-cm square cross sections (except that the IUCF modules taper in one dimension to 4.2 cm).

The panels in Fig. 2.E.1 illustrate the properties of the distribution of γ-rays in the laboratory assuming that the π^0's are produced isotropically in the center-of-mass. No detector acceptance is included. The deuteron beam energy is taken to be 231.4 MeV, which leads to a maximum opening angle of 1.7° for the ^{4}He nuclei and 54° for the π^0. The γ-ray energies range between 42 and 105 MeV (panel a) and have an intensity that is enhanced at forward angles (panel b). Despite the rather low energies for the pions (less than 13.7 MeV), γ-ray opening angles range down to 130° (panel c). The plane of the γ's from pion decay need not be the scattering plane, thus a "coplanarity" check based only on laboratory ϕ angles has a width of about 50° (panel d).

The most practical arrangement is to place the Pb-glass in two sets of stands that are supported from the floor on beam left and right. This leaves the top and bottom of the target box to accommodate the ports for pumping and luminosity monitoring. One possible arrangement is shown in Fig. 2.E.2. The IUCF bars are arranged in three partial cylinders at radii of 50, 58, and 66 cm from the target. Each cylinder consists of two Pb-glass bars positioned vertically and touching at their ends. The Argonne bars are arranged in a wall with square corners, which allows a stack four bars high near the target to improve ϕ coverage with these shorter bars. Both arrangements are constrained at forward angles by the presence of the windings and return yoke for the 6° bending magnet. (Fig. 2.E.2 also contains a circular pipe to represent the vacuum box.) Leakage of the magnetic field outside of the 6° magnet is significant, and this installation must include a field clamp between the magnet and the Pb-glass photomultiplier tubes. Each tube also has an individual mu-metal shield.

The response of the Pb-glass to γ-rays from π^0 decay has been simulated by Mark Pickar using GEANT. The total energy recorded by the Pb-glass simulation is shown in the left panel of Fig. 2.E.3. This has a resolution comparable to the spread seen from response tests of the IUCF bars using cosmic rays (right panel). While this distribution is clean enough to give a trigger with high efficiency, the energy information is not sufficient

Figure 2.E.1: GEANT simulations of the distribution of (a) the γ-ray energy (GeV), (b) the laboratory polar angle (°), (c) the laboratory opening angle between the two γ's (°), and (d) the laboratory "coplanarity" (°). Spikes in the distributions are an artifact of thresholds in the GEANT simulation.

to really aid in characterizing the kinematics of the π^0. Most of the energy is deposited in the counter where the initial γ converts (usually making an electron-positron pair). A threshold of 10 MeV will capture most of this signal with little loss in efficiency. With this threshold, the GEANT simulation predicts that 45.5% of the dd $\rightarrow \alpha\pi^0$ reactions will produce a γ in the beam-right cylindrical wall. The beam-left wall will see a γ 47.0% of the time. The overlap of these two is 59.0%, the chance that one or more γ-rays will appear in any part of the Pb-glass array.

The efficiency for coincident pairs of γ's from the same π^0 was calculated assuming a

Figure 2.E.2: Panels showing top and front views of the arrangement of Pb-glass detectors on either side of the target box.

Figure 2.E.3: The left panel shows a summed energy distribution (MeV) for the array on beam right as calculated from GEANT. The right panel shows a pulse height spectrum (arbitrary units) for one Pb-glass module generated by relativistic cosmic ray muons passing through the variable thickness of a tapered IUCF bar. The peak corresponds to an energy deposition of approximately 30 MeV-ee from an electromagnetic shower.

10-MeV threshold for both γ's. This efficiency is predicted to be 33.0%.

A number of other arrangements of the Pb-glass modules were investigated. Among these was the idea that better ϕ information could be obtained if alternate layers were stacked with the bars running both vertically and horizontally. In these arrangements, much efficiency is lost since many events deposit essentially all of their energy in a single bar of Pb-glass. While several lower-energy γ's exit this bar, their subsequent interactions tend to be Compton scattering that does not generate a recoil electron with enough energy to produce a Čerenkov signal. Likewise, layers of plastic scintillator between the Pb-glass bars are not helpful since many events also do not have any charged particles that exit the conversion bar.

F. TARGET BOX

In order to maintain a high ring vacuum inside the Cooler ring, the volume near the gas jet target is divided into a series of concentric baffles that direct gas toward a pump. The baffles have openings for the passage of the beam and any interesting reaction products. In the present configuration, most of the pumping equipment extends to the sides, under which are mounted rough pumps that exhaust at atmospheric pressure. It is most desirable to have the Pb-glass counters also mounted to the side so that the support frames are straightforward to build and the counters can be moved aside with relative ease. This means that the vacuum hardware must be rearranged.

Part of this rearrangement entails moving the location of the gas jet target upstream. The optimum location for the neutron tagger setup, the present experiment occupying this area, is several inches closer to the 6° magnet. Moving the tagger target location upstream would represent a loss in tagged neutron rate of a factor of about 4 due to a combination of smaller solid angle and changed production angle. At this writing, these needs remain incompatible.

The present concept for this box is a rectangular structure. Pumps and other vacuum utilities would emerge from the top and bottom. The left and right sides would be aluminum plates made as thin as reasonable and still maintain their integrity under vacuum. As compared to stainless steel (used elsewhere in the Cooler for high vacuum) the absorption of γ-rays is somewhat less ($\lambda_{\rm abs} = 59$ g/cm^2 as opposed to 42 g/cm^2) and the lighter density ($\rho = 2.7$ g/cm^3 as opposed to 7.9 g/cm^3) allows a greater thickness to resist buckling.

This box would also contain ports on the top and bottom to hold the scintillation counters associated with the measurement of the luminosity and beam polarization. This is discussed in detail in Section III.

Because of the large amount of work, disassembly of the present tagger setup and reassembly of a box for CE-78 is expected to require access to the Cooler ring for 2–3 months. This is best done during a beam-off period so that the ring vacuum may remain open as required. The present program to measure the n+p cross section at 186 MeV will extend through the end of 2000. Making the change at that time to CE-78 would preclude further use of the tagger unless this experiment were to end (prematurely) with enough time remaining to allow the tagger to be reconstructed. Details of the proposed time line are given in Section V.

There will be several trigger modes for the electronics, including:

- ○ the primary event stream. This requires at least one Pb-glass detector above threshold, signals in the ΔE_1, ΔE_2, and E scintillators, and no signal in the VETO scintillator. Readout includes all Pb-glass and channel detectors.
- ○ the luminosity monitor.
- ○ cosmic ray calibration.
- ○ periodic readout of the scalers.

Some other event streams may be added that require fewer scintillators than the primary event stream. These would be for diagnostic or monitoring purposes, and could be downscaled to prevent loading the system.

Crucial in designing the electronic system is the decision to locate most of it near the experiment in the Cooler vault. This has the advantage that cable runs are short and can be made less noisy, but removes a lot of the electronics from direct inspection when the beam is on. Since event rates are likely to be high, the choice to put the electronics near the experiment also reduces dead time by shortening the time required to process information and transfer it to the VME-crate in digital form. To compensate for lack of access, a number of crucial discriminator and logic modules will be CAMAC compatible so that their functions can be altered remotely through the data acquisition computer. Some cables will then run to the data acquisition area for remote inspection.

Figure 2.G shows a block diagram of the elements to be read out as part of the primary event trigger. In some cases, the number of modules of a particular type are noted in Fig. 2.G by a number above the box describing the module. All of the 238 channels of Pb-glass signal will be split and sent to FERA modules to digitize the pulse height. A grand OR will be created by two layers of 16-fold discriminators to be fed to the event trigger. At the same time these logic signals will be collapsed at a ratio of 8-to-1 to multiplex them into time digitizers. It is likely that a number of adjacent Pb-glass detectors will see some energy from a shower, and this time and energy information will be preserved. Signals from the scintillation detectors in the channel will also go to FERA readout. In this case, all signals are preserved for the 8-fold logic unit that will decide whether the trigger condition is met. If it is, gate signals will be issued to all readout modules and to the event trigger module. This readout gate will also select the time window for sampling the MWPCs. As part of this event, tag bits will register the state of the Cooler ring timing and the polarization state of the ion source.

Scalers that look at the rates in various parts of the electronics will be read out periodically. In addition, another event stream consisting of the luminosity detectors will be triggered and read out independently.

III. Luminosity Monitoring

In the IUCF Cooler, a measurement of the cross section cannot rely on the usual measures of beam current from a dump and target thicknesses measured independently.

Figure 2.G: Block diagram of the major electronic data acquisition systems. Signals flow from left to right. Numbers following an x *at the top of a module indicate the number of modules of that type that are required. Gate inputs are indicated by the letter* g*; summed logic outputs by the symbol* Σ*.*

Instead, the overlap of gas jet target and beam must be monitored during the experiment by detecting some other reaction channel whose cross section is known. For d+d elastic scattering at 231.4 MeV, there are no nearby experiments from which to obtain a reference cross section. Some channel must be chosen, and then calibrated against another known cross section. In the same way, operation with polarized beam requires simultaneous measurement of some polarization effect using a reaction whose spin dependence is already known. Again, no reference data is available.

Thus we must choose some process with little guidance, and propose a scheme to calibrate it. The risk is that what we choose may not have an analyzing power suitable as a continuous monitor. In this case, there must also be a contingency plan that, while perhaps not as satisfactory, is at least known to work. Since the position of the gas jet has been moved upstream from the 6° magnet, there is room inside the vacuum box holding the gas jet target and vacuum pumping baffles to insert a number of scintillation detectors at various scattering angles. For purposes of illustration, we have chosen to monitor the luminosity and beam polarization by observing d+d elastic scattering at $90^\circ_{\mathrm{c.m.}}$ or 44°_{lab}. A reliable rate requires that each detector consist of a telescope of two counters, and that the recoil be observed on the opposite side of the beam. Thus a pair of such telescopes will deliver a single coincidence rate. The beam will be tensor polarized with a vertical quantization axis. It is possible to monitor such a polarization by looking at d+d scattering in both the horizontal and vertical planes, and comparing the coincident count rates.

For two similar detectors mounted on opposite sides of the beam, one problem is maintaining acceptance when there are small motions of the beam. A solution to this involves choosing one side as the "reference" side, and either placing a collimator ahead of the detector or reducing its size relative to the detector on the opposite side. Thus the coincident flux does not fill the opposite-side detector, and small beam motions have a safety margin for acceptance. Beam motions do involve changes to the scattering angle. Because the entrance channel contains identical particles, the cross section is symmetric about $90^\circ_{\mathrm{c.m.}}$ and its derivative vanished at that point. The slope of the cross section with angle in the laboratory comes only from the Jacobian of the transform from center-of-mass to lab, and is not particularly large. So the d+d elastic scattering is not very sensitive to the motion of the beam. It may prove helpful to make these detectors moveable inside the vacuum, which in turn would require flexible optical coupling through fibers.

Since the dd $\to \alpha\pi^0$ reaction is sensitive only to the tensor component of the beam polarization, in principle this is all we need to monitor. Since the angular distribution of the vector analyzing power for d+d elastic scattering is anti-symmetric about 90°, this detector arrangement will be insensitive to any vector component in the beam polarization. The count rate does depend on the tensor polarizations t_{20} and t_{22} according to

$$\sigma = \sigma_0 \ (1 + t_{20}T_{20} + 2t_{22}T_{22})$$

where T_{20} and T_{22} are the corresponding analyzing powers. The polarization of the beam from the atomic beam source can be described using the fractions of the beam that are in the three projections of the deuteron spin, f_{-1}, f_0, and f_1, where $\sum f_i = 1$. The vector and tensor components of the polarization are $p_\xi = f_1 - f_{-1}$ and $p_{\xi\xi} = 1 - 3f_0$. For a vertical orientation of the beam's quantization axis, the values of the two spherical tensor polarizations for a horizontal scattering plane are $t_{20} = -p_{\xi\xi}/\sqrt{2}$ and $t_{22} = -p_{\xi\xi}/(2\sqrt{3})$. For the vertical scattering plane, t_{22} changes sign. Thus the *asymmetry* in the coincident count rates between horizontal and vertical scattering planes directly measures the product $t_{22}T_{22}$, and the t_{22} (and hence $p_{\xi\xi}$) polarization is known given information on T_{22}.

The t_{20} tensor polarization is the same in both the vertical and horizontal planes, thus the cross section and the estimate of the luminosity are changed by the factor $1 + t_{20}T_{20}$. The t_{20} polarization is known once t_{22} has been measured, thus we also need to know the T_{20} analyzing power in order to correct the *sum* of vertical and horizontal plane count rates to obtain the luminosity.

The scheme described above yields the tensor beam polarization and luminosity for any single polarized beam state. In this way we have the information needed to derive both the cross section and the T_{20} tensor analyzing power of the dd $\to \alpha\pi^0$ reaction by comparing the total cross sections for two polarization states in which the tensor polarization has been changed. The calibration of this system must provide the unpolarized cross section, T_{20}, and T_{22} for d+d scattering at $90^\circ_{\mathrm{c.m.}}$. Both T_{20} and T_{22} are symmetric about $90^\circ_{\mathrm{c.m.}}$; the identical particles in the entrance channel are not in principle a problem. Measurements at much lower energy [11.5 MeV, Kö72] in fact show a maximum in T_{22} for d+d scattering at

Figure 3: Layout of the vertical plane detector system inside the targer vacuum box for monitoring the polarization and luminosity and for calibrating the system.

$90^\circ_{\mathrm{c.m.}}$. Because the survival of vector and tensor polarization in the Cooler stored beam is not guaranteed, it is not sufficient to measure the polarization in the injection beam line. We must have a reference reaction that can operate at the gas jet target.

The only reference in this energy range for tensor (and vector) polarized deuterons (and also the cross section) is d+p elastic scattering. Measurements have been reported from RIKEN at 270 MeV [Sa96]. Additional data to expand the angular distributions has recently been completed by K. Sekiguchi [Se98]. Observation of d+p elastic scattering requires that there be hydrogen in the gas jet target. One way to obtain this is to use HD gas or a known mixture of H_2 and D_2. The T_{22} angular distribution shows large values over most of its range. One way to exploit this is to observe the forward-going d–p pairs from scattering at large center-of-mass angles. Figure 3 positions the coincident detectors at $\theta_{\mathrm{lab}} = 10^\circ$ for protons and 19° for deuterons ($\theta_{\mathrm{c.m.}} = 159^\circ$). In this case, there are four detector telescopes in the plane and thus a count rate for deuteron (or proton) scattering to either side of the beam. In order to monitor the tensor polarization through T_{22}, there must be both horizontal and vertical scattering detectors. A separation of left and right scattering also makes possible a measurement of the vector polarization during the calibration run. This is important as a monitor of the performance of the polarized ion source and the transmission of the polarization to the stored beam in the Cooler. The extraction of the data goes as it did for the description of the d+d system. A known (and large) value of T_{22} allows the tensor polarization to be known, and the cross section, corrected for the effect of T_{20}, gives the luminosity. For the observation of tensor effects, sums of left and right, or down and up, count rates are made. Unpolarized runs can be included in order to check the luminosity calibration in the absence of any beam polarization. (During production running, the use of an unpolarized state would take statistics away from the measurement of the tensor analyzing power.)

The RIKEN experiment ran at 270 MeV and we need the calibration at 231.4 MeV. Polarization calibrations have been transfered before from one energy to another on the Cooler by ramping the beam in the middle of the measurement [Po97]. In this case, the Cooler would first take the beam to 270 MeV where the beam polarization would be determined. Then it would ramp to 231.4 MeV to transfer this calibration. At the end of each cycle, it would return to 270 MeV and verify that the polarization had not changed. This would then be repeated for each filling of the Cooler.

The luminosity calibration, however, requires that we know the d+p cross section at 231.4 MeV. For this, it will be necessary to interpolate measurements made at other energies. The next lower energy measurement of the d+p cross section is found at 190 MeV [Ch54]. Fortunately, d+p elastic scattering varies slowly with energy [Gl96] and measurements even farther away may be used to establish a smooth interpolation. The final errors on the reference cross section may be several percent, and this will likely be the limit on the quality of the luminosity calibration. Likewise, it is expected that the deuteron analyzing powers at 231.4 MeV will be close to those at 270 MeV. This calibration can confirm that. As was the case for d+d, the choice of either the deuteron or proton detector to have the smaller solid angle will help to prevent a loss of coincident count rate when there are small motions of the beam. Separate systems for both sides of the beam will respond oppositely to such a motion, so their average rates should correspond to the reported cross section (since the average is not sensitive to the shift in first order).

One concern with both the monitor and calibration reactions is that the scintillator telescopes are not well suited to discriminate in pulse height against p+p coincidences from deuteron breakup. Experience with using p+d scattering in the cyclotron beam lines at 200 MeV [We93] has shown that a measurement of the relative time of flight between the coincident detectors can allow a characterization of the breakup background so that, if large enough, it can be subtracted from the elastic scattering count rates.

As stated earlier, there needs to be an alternative in case d+d elastic scattering proves to be a poor monitor of the beam polarization. One possibility is to leave the d+p detector system in place, and introduce hydrogen into the gas jet target from time to time to make sampling checks of the beam polarization. A continuous monitor that does not disturb the deuteron gas jet would have to be set up in another part of the Cooler ring. One candidate is the A-region where the Pintex detectors are well equipped to measure the forward angular distributions from d+p elastic scattering with full azimuthal sensitivity. While perhaps overly complex, this detector system is more than adequate for a determination of the beam polarization. As in the scheme described for the T-region, the calibration of the tensor analyzing powers would have to be transferred from 270 to 231.4 MeV.

The overlap between the gas jet and the beam tends to be extended along the beam axis. One way to obtain sensitivity to this effect is to split one of the scintillation detectors along a diagonal so that its thickness is a triangular taper that changes moving radially away from the beam. Two opposite tapers can yield position information through relative pulse height. (The scintillator thickness is a small fraction of the deuteron range in plastic.) As the scattering vertex moves along the beam axis, the separation of the deuterons from

Figure 4.A.1. The distribution of ^{4}He nuclei in (a) X and Y on the first MWPC and (b) X on the first MWPC.

$90^\circ_{\mathrm{c.m.}}$ scattering expands or contracts. Computer analysis of this information can yield the beam axis profile of the gas jet target. Changes in the scattering angle will also yield coincident events, but the position changes are anti-correlated rather than correlated.

IV. Event and Background Characterization

A. EVENT PROPERTIES

The Pb-glass and magnetic channel detectors will provide information that can characterize each event. In this section, we explore what the signature of $dd \to \alpha\pi^0$ will be. Since the number of events is small, it will be crucial to overdetermine the properties of this signature as a way to eliminate background from the sample. Even so, a subtraction may finally be necessary, based on the characteristics of the background events. This background falls into a number of classes that will be summarized in the next section. There are four important aspects to the $dd \to \alpha\pi^0$ signature.

(1) *The detectors in the magnetic channel will be used to determine whether the ^{4}He nuclei lie on a sphere of constant momentum in the center-of-mass.* The transverse momentum spreads the ^{4}He nuclei into a circle with a radius of 1.7° on the first MWPC, as shown in Fig. 4.A.1 (panel a). The projection enhances the rate along the circumference of the circle, but events can appear anywhere within it. When projected onto one of these two axes, the distribution of events is uniform (panel b). The third axis of the sphere is represented by the spread in momenta for the ^{4}He nuclei. This momentum will be measured using the time-of-flight between the ΔE_1 and ΔE_2 scintillators. There the signal is spread between 96.5 and 106.3 ns. We expect the precision of the MWPC position measurement to be close to 1 mm, and the time measurement less than 1.0 ns (10%). For some events

near the center of the sphere in Fig. 4.A.1 (panel a), it may prove more accurate to calculate the momentum from the X and Y position once the two-fold ambiguity between large and small momentum has been resolved. These three axes can be used to define a sphere. All dd $\rightarrow \alpha\pi^0$ events should lie on the surface of the sphere with no events either inside or outside. Such a cut can be made having calculated the center-of-mass momentum and requiring a narrow tolerance on its range. This is satisfactory provided all measurements have roughly equal relative precision. Otherwise it may prove better to make the selection based on correlations in 2-dimensional slices that compare one well and one poorly known coordinate.

(2) *The scintillators and time-of-flight measurements in the magnetic channel will be used to identify each particle.* Many experiments have relied on differences in dE/dx as reflected in scintillator pulse heights to identify particle type. In this application, redundancy is crucial. Errors in pulse height measurements often arise from randomly high energy loss events from delta-ray production, nuclear reactions, or pileup. In our case, intense Z=1 groups (especially protons) can tail into and contaminate Z=2 groups. Some of these events will be suppressed in the event trigger because they enter the veto detector.

To investigate a range of possibilities, energy loss calculations were made for the five types of particles, p, d, t, ^{3}He, and ^{4}He. The geometrical acceptance into the septum magnet is tight, and will restrict the momentum range in each case something close to the momentum spread of the ^{4}He events of interest after they have been dispersed by the 6° magnet. These events are momentum dispersed a second time by the septum magnet. Due to different energy losses between the two magnets, protons and tritons will be bent away from the channel centerline by a few degrees. These angles are shown in panel (a) of Fig. 4.A.2. The five particle types are arrayed along the horizontal axis. The three cases for each particle represent the extreme and central momenta. Thus protons and tritons that survive the original momentum selection may not appear in the detectors at the end of the channel. To avoid some secondary reaction products, we plan to insert anti-scattering baffles into the vacuum pipe so that the pipe walls are invisible from the detectors at the end of the channel.

Panels (b) and (c) in Fig. 4.A.2 show that the distribution of particle groups is well separated in each scintillator pulse height correlation plot. The tritons, being lower energy, stop in the ΔE_2 detector. Panel (d) shows that momentum-selected protons and ^{3}He nuclei penetrate through to the VETO detector and will (except for reaction losses) be removed from the trigger. (Protons and tritons arrive at the end only by virtue of having multiple scattered upstream or originated from some direction other than the target.) Most, but not all, deuterons likewise make it to the VETO. In panel (e) we find that with time-of-flight included, we do not gain a good leverage against deuterons. So the separation of deuterons from ^{4}He is finally the most difficult. It will rely on scintillator pulse heights with only the redundancy to remove high pulse height errors.

(3) *The angles of the two γ's from π^0 decay must be used to confirm the* dd $\rightarrow \alpha\pi^0$ *kinematics.* This angle information cannot be obtained with great precision from the Pb-glass detector array. The widths of the counter bars in scattering angle is roughly $5° - 7°$. Time measurements between ΔE_1 and the Pb-glass trigger time depend on the laboratory azimuthal angle, but the resolution is not expected to be any better than about 15 cm

Figure 4.A.2. (a) Angle deviations from the channel centerline after the septum magnet for particles with the same momentum spread as the ^{4}He nuclei. Correlations between pulse heights in ΔE_2 by ΔE_1 (b), E by ΔE_2 (c), and VETO by E (d) for various particle groups. Correlations between ΔE_1 and TOF (e).

($> 14°$). Since the kinematics for the dd $\rightarrow \alpha\pi^0$ reaction are two-body, the direction of the π^0 is known from the ^{4}He direction and momentum. It is then possible to check whether the γ's and π^0 lie in the same plane and whether the γ opening angle is consistent with the π^0 laboratory momentum. The energy resolution shown in Fig. 2.E.3 is not sufficient to be used in the reconstruction.

The choice of Pb-glass to detect the decay γ's was based on the availability of a large set of such detectors. These detectors have the advantage of being selectively sensitive to γ rays above some threshold energy. Another possible detector with better angle resolution would involve a few layers each composed of lead converter plates followed by X-Y MWPC's. Such a detector would have to be designed and built for this purpose.

(4) *The point of origin of rays in the magnetic channel will be used to eliminate backgrounds.* The apparent position transverse to the beam of this origin can be calculated from the hit positions on the first and second MWPC's. Differences arise if a particle comes from some other point, such as the walls of the vacuum baffle, or has the wrong momentum going through the 6° and septum magnets. Most of the angles of the ^{4}He nuclei are too small to be of use in locating the event origin point along the beam axis, although some information may be obtained for the events close to the 1.7° edge.

B. BACKGROUND PROPERTIES

There are many ways for signals that mimic dd $\rightarrow \alpha\pi^0$ to appear in the detectors. It is useful to divide such backgrounds into classes and then discuss the discrimination provided by the experimental design against each class.

(1) *Backgrounds that contain a ^{4}He nucleus and one or two γ rays that do not arise from the decay of a π^0.* The best example of this background is the dd $\rightarrow \alpha\gamma\gamma$ reaction in which the γ's are produced in the double radiative capture of n-p pairs [Do99]. The forward-going ^{4}He nuclei will overlap with, but not be confined to, the $\alpha\pi^0$ momentum sphere discussed in the previous subsection. Likewise the reconstruction of the π^0 decay properties (coplanarity and opening angle) will produce diverse results. Because these events can coincidentally overlap with the kinematics for the $\alpha\pi^0$ reaction, a final subtraction will be necessary based on properties of the $\alpha\gamma\gamma$ final state measured away from the $\alpha\pi^0$ kinematics. The window on this background is not large since the magnetic channel is tuned to ^{4}He nuclei that leave behind enough energy to make a π^0 and the arrangement of Pb-glass detectors favors two γ rays that emerge back-to-back.

It is also possible to produce a ^{4}He and a single γ from the dd $\rightarrow \alpha\gamma$ radiative capture process. The ^{4}He nuclei so produced have too much momentum to fall within the acceptance of the magnetic channel.

(2) *Two-step reactions in which some reaction products excite the Pb-glass detectors and a forward-going particle has a reaction in a vacuum window or detector that converts it into a ^{4}He of about the right momentum.* A reaction that can produce neutral particles headed into the Pb-glass would be dd $\rightarrow$ ^{3}Heγn. Some neutrons can be observed if they produce decay γ's following the absorption of the neutron onto a nucleus in the detector. The forward-going ^{3}He would undergo a neutron pickup reaction in a vacuum window or detector. The minimum ^{3}He energy of 110 MeV to produce a ^{4}He nucleus of the right

Figure 5: Projected timeline

momentum on, for example, ^{12}C is easily satisfied. As in class (1), these events could appear with conditions identical to a real dd → $\alpha\pi^0$ event, but would be spread across the system acceptance. In addition, the second reaction in material in the early part of the magnetic channel would likely deflect the particle direction enough to be differentiated in the vertex reconstruction described in part (4) of the preceeding section. Because of time slewing in the Pb-glass light collection, there may not be a clean separation by time-of-flight between neutrons and γ's there, although such information could be helpful. As was the case for class(1), this background would need to be characterized and subtracted from a sample of candidates to obtain the real event rate.

(3) *Accidental coincidences.* More than one reaction that occurs within the trigger coincidence time window can lead to enough signals in the magnetic channel and Pb-glass that the appearance of a dd → $\alpha\pi^0$ event is generated. In addition to the checks discussed for the preceeding two classes, such events are apt to be distributed in the time difference measured between the ΔE_1 and Pb-glass detectors. Even with RF operating in the Cooler, beam in the ring is spread over a sufficiently large portion of the ring circumference that reference to the RF is not selective. Again, subtraction of such events will be necessary.

The discussion of these various background event classes makes it clear that the trigger and the subsequent analysis need to be as selective as possible. The plan at present is to require only one Pb-glass signal in forming the trigger if event rates permit. If it were reasonable to expect that this would provide sufficient information to cleanly separate dd → $\alpha\pi^0$ events, the data from this experiment could be almost doubled. The risk is that, even with a requirement to observe two γ hits, the number of background events will be so large that the subtraction will render any signal statistically meaningless.

V. Timetable and Milestones

The time available to develop, commission, and run CE-78 ends with the end of Cooler operations. This is now expected to be at the end of FY2002 (October 1, 2002). Figure 5 shows one scheme for how this project might fit within this time frame.

Beginning the week of January 17, 2000, IUCF started on the change from proton to deuteron beam operation with CIS and the Cooler. This change includes the installation for the first time of RFQ vanes suitable to the deuteron charge-to-mass ratio and a debuncher for the line between the end of the linac and CIS. In March, we expect to commission the first deuteron beams in CIS and inject them into the Cooler. If time permits, there will also be a development of deuteron polarization and some time for experimenters to take a first look at deuteron beams in the Cooler.

If development time becomes available in March, there are several tests that would be of benefit to the development and design of CE-78. These include:

- measuring the deuteron breakup rate and spectrum
- testing a MWPC and scintillator for high rate capability
- testing particle identification with a three scintillator stack
- checking the background in the area where the Pb-glass scintillators will be placed and recording the Pb-glass scintillator response

These checks will provide important information for the design of the CE-78 equipment.

Running of the tagger in the Cooler T-region will continue at least through the end of 2000. The commissioning run at the end of 1999 demonstrated for the first time the operation of the entire system, and some preliminary data was obtained using a plastic scintillator as a target. Additional runs will use a liquid hydrogen target and explore techniques for obtaining a full angular distribution. There is also a tentative plan for n+d elastic scattering as well. As the schedule in Fig. 5 makes clear, once the changeover to CE-78 begins, there is not sufficient time to return to tagger operation before the end of Cooler funding. This represents some lost physics opportunities. If the results of the n+p elastic scattering experiment prove to be different from the prevailing Nijmegen phase shift solution, then it would be important to have benchmark data at other neutron energies.

The year 2000 represents design and construction time for all of the CE-78 equipment. Some staging is possible since the calibration of the luminosity system can begin before the magnetic channel and Pb-glass assemblies are in place. If the target box assembly can be completed by the end of 2000, then it can be installed during a 2.5-month winter access period (no other Cooler running). Following this would be two calibration runs for luminosity and polarization. The risk that the T_{22} analyzing power for d+d elastic scattering is too small could be checked in advance during the fall of 2000 using the Pintex detector system. Such a run would need to be explored with the Pintex collaboration.

Completion of the construction of the Pb-glass assemblies and the magnetic channel with its detectors would need to be done by the spring of 2001. An installation period would follow where Cooler experiments would continue to operate. So far, about 40% of the time during a Cooler running cycle has been open access time. This time would allow bringing in major pieces of equipment, hooking up detectors and electronics, and making preliminary tests of the system.

It is important to have a reaction that simulates many of the features of dd $\to \alpha\pi^0$ in order to verify that the hardware and software handling of the data is adequate. For this, we have chosen to look at the pd $\to {}^3\mathrm{He}\pi^0$ reaction. At 200.7 MeV, the half-angle of the forward cone of ^{3}He particles is also 1.7°. The fractional momentum spread in the

^{3}He nuclei is nearly identical to that for dd $\rightarrow \alpha\pi^0$. At least one run should be devoted to observing and recording data from this reaction. This is shown in Fig. 5 at the end of 2001. Following this commissioning test, some time is allowed for replay and reconfiguring the equipment. These are periods when operation of the Cooler could return to protons. Changes between proton and deuteron operation are expected to take only a few days following the initial installation and testing of the deuteron vanes.

The year 2002 contains two extended periods of deuteron operation, aimed in part at CE-78. To meet the integrated luminosity requirement for this experiment requires about two months of running. This is divided in Fig. 5 into four two-week periods preceeded by a one-week test of any system changes.

This schedule is very tight in all aspects, including design and construction, installation and calibration, as well as initial testing and production running. These requirements need to be considered in light of other obligations of the laboratory, including the production of a large endcap calorimeter for the STAR detector, other major detector initiatives for Cooler experiments, and the possible start of conversion of the cyclotrons to proton therapy.

VI. Manpower

The manpower requirements for CE-78 will be considered in two categories: scientific and technical. In both cases it is important to consider the amount of effort required, when it will be needed, and what are the critical skills for accomplishing the task.

The scientific effort behind CE-78 appears as part of the author list on this report. In addition, it is also useful to understand what other obligations each collaborator has and when they will be available to assist. From the Indiana University faculty, Andy Bacher and Hermann Nann both have faculty appointments and spend part of their time teaching. Hermann also helps Mike Snow with his experiments at NIST and LANSCE on ultra-cold neutrons. Andy is hoping to arrange a one-semester sabbatical leave for the fall of 2001 to devote more time to CE-78. Chris Allgower began a post-doctoral appointment in the fall of 1999, and intends to split his time between CE-78 and the construction of the STAR endcap calorimeter. Dennis Friesel, Chuck Foster, and Ed Stephenson are all on the IUCF staff. Dennis will contribute to the development and run by run preparation of the polarized deuteron beam. Chuck carries primary responsibility for the Radiation Effects Research Program at IUCF. Ed Stephenson will be contributing to CE-78 as part of his management responsibilities for coordinating the Cooler research program. Georg Berg will be leaving IUCF in March, 2000 to work at RCNP in Osaka, Japan. (The contributions from Jack Doskow, Walt Fox, Tom Rinckel, and Keith Solberg will be counted with the support staff discussed below.)

To augment the local effort, an agreement was made with Protvino to have one scientist visit IUCF for three years (Dimitri Patalahka). He would then have additional help from two other scientists who would rotate through their positions every 4 months. One of these is presently helping the Pintex (Cooler A-region) collaboration, and the other (Alexei Prudkoglyad) is working on CE-78. This adds two full-time people to the collaboration.

This effort is augmented with outside users. Mark Pickar is available during summers, but otherwise teaches full time at Minnesota State University. Paul Pancella, who is in a similar teaching position at Western Michigan University, is planning a sabbatical year so that he can be at IUCF from June, 2000 through August, 2001. He will divide his efforts between the Pintex collaboration and CE-78. Help from other potential participants is still being arranged.

The support staff requirements have been estimated by making a list of the tasks (items to construct and install) and assigning an amount of effort to each. The totals for the next two years are given here.

Effort (person-weeks)

category	2000	2001
engineering	18	2
drafting	28	6
machine shop	61	8
professional	6	16
technical	13	33

Most of the design, drafting, and shop work takes place in 2000, with installation coming in 2001 (as described earlier). To meet these and all other demands of the laboratory, IUCF presently has two design engineers (Jack Doskow and Walt Fox). Designs for wire chambers are handled by Keith Solberg. There is one draftsman and three machinists. One additional machinist is being sought. Some drafting is handled by the engineers. Installation will be coordinated by Tom Rinckel with help from a few technicians (and scientists) as needed. Some machine shop work will be contracted out of IUCF since modern CAM equipment is better able to handle the production of certain parts efficiently.

Engineering and drafting for the STAR endcap calorimeter is being handled by separately funded staff members. Following approval for IUCF to begin a program in proton therapy, additional staff members would be added to these categories to begin the work of designing and building the required beam lines.

It is clear that CE-78 represents a commitment from some of the IUCF staff for the majority of their time over the next two years. These same people will be involved in any other scientific program improvement (for Pintex detectors in particular) and in supporting the ongoing experimental and operations efforts on the Cooler. The declining NSF operations budget will not allow an expansion of the present staff.

VII. Budget

Like support staff effort, budget items for CE-78 can be distributed over 2000 and 2001. A summary is given below.

Budget Summary (k$)

item	2000	2001
target box	15	
cryopump		30
gases		3
channel stand	3	
septum magnet	14	
vacuum pipe	8	
MWPC	10	
scintillators	2	
Pb-glass stands	5	
cables	9	
timing system	15	
electronics	65	40
TOTAL	146	73

The largest single item on this list is new electronics. A large amount of what will be needed is available from the IUCF pool or from experiments that will be dismantled (tagger). In addition, new electronics will be needed for the Pb-glass detectors in the form of 16-channel discriminators, FERA QCD's, and CAMAC programmable logic. Some of these purchases can be shifted to 2001 as necessary. These amounts are available from the NSF grant.

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