Cooler CSB

Observation of $dd \rightarrow \alpha \pi^0$

Ed Stephenson
Indiana University Cyclotron Facility

CSB–V
Seattle, WA
October 20-22, 2003

Summary of the analysis
Review of the experiment
CSB summer analysis:
- match GEANT to experiment (adjust PMT response functions)
- rework Pb-glass fit (new routines)
- build luminosity simulation (scintillator non-linearity under study)

No surprises!

Mark Pickar

PRL is out: 91, 142302

d+d elastic scattering:
(use hydrogen target for reference cross section and analyzing power)

DONE: geometry + efficiency
IN PROCESS:
- identify d+d and d+p events
- extract deuteron polarization
- find good acceptance limits
- get σ, iT₁₁, T₂₀, T₂₂ data

Paul Pancella
Observation of the Isospin-forbidden \( d+d \rightarrow ^4\text{He}+\pi^0 \) Reaction near Threshold

\[
d + d \Rightarrow ^4\text{He} + \pi^0
\]
isospin: 0 0 0 1 —— pion had 3 charge states

**CHARGE SYMMETRY** says that the physics is unchanged when protons and neutrons are swapped, or when up and down quarks are swapped.

The pion wavefunction is not symmetric under up-down exchange. Deuterons and helium reverse exactly. Thus, an observation of this process is also an observation of charge symmetry breaking.

\[
\psi = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})
\]
History of the search for $d+d \rightarrow ^4\text{He}+\pi^0$

according to J. Banaigs et al. PRL 58, 1922 ('87)

Trends in:

- **theory**
- **experiment**

solid: upper limits on $^4\text{He}+\pi^0$
open: measurements of $^4\text{He}+\gamma$

Observation of $d+d \rightarrow ^4\text{He}+X$
where $X = \omega$ or $\eta$

Saturne experiment:
also L. Goldzahl et al. NP A533, 675 ('91)

Energies near 1 GeV
(energy) Pb-glass for photons
Spectrometer for $^4\text{He}$ (angle)

look for excess events here

At 1.1 GeV, Goldzahl reports
$0.97 \pm 0.25 \text{ pb/sr}$
for $\theta_\pi = 107^\circ$

But Dobrokhotov et al. PRL 83, 5246 ('99)
say this could be $^4\text{He}+\gamma+\gamma$ (isospin-allowed double radiative capture)

We must separate this background!
Search just above threshold (225.5 MeV)  
(No other $\pi$ channel open for d+d.)  
Capture forward-going $^4$He.  
Pb-glass arrays for $\pi^0 \rightarrow \gamma\gamma$.  
Efficiency on two sides $\sim 1/3$.  
Insensitive to other products ($\gamma_{\text{beam}} = 0.51$)

Target density $= 3.1 \times 10^{15}$  
Stored current $= 1.4$ mA  
Luminosity $= 2.7 \times 10^{31}$ /cm$^2$/s  
Expected rate $\sim 5$ /day

6° bend in Cooler straight section  
Target upstream, surrounded by Pb-glass  
Magnetic channel to catch $^4$He ($\sim 100$ MeV)  
Reconstruct kinematics from channel time of flight and position.  
(Pb-glass energy and angle too uncertain for $\pi^0$ reconstruction. $\alpha\gamma\gamma$ looks the same.)
COOLER-CSB MAGNETIC CHANNEL and Pb-GLASS ARRAYS

- separate all $^4$He for total cross section measurement
- determine $^4$He 4-momentum (using TOF and position)
- detect one or both decay $\gamma$'s from $\pi^0$ in Pb-glass array

In addition:
Luminosity monitored by $d+d$ elastic at 2 angles.
Cross section calibrated against $d+p$ database.
SEPARATION OF $\alpha\pi^0$ AND $\alpha\gamma\gamma$ EVENTS

Calculate missing mass from the four-momentum measured in the magnetic channel alone, using TOF for z-axis momentum and MWPC X and Y for transverse momentum.

MWPC spacing = 2 mm

needed TOF resolution $\sigma_{GAUSS} = 100$ ps

MWPC1 X-position (cm)

Y-position (cm)

Time of Flight ($\Delta E_1 - \Delta E_2$) (ns)

[Monte Carlo simulation for illustration. Experimental errors included.]

$\alpha\pi^0$ peak $\sigma_{TOT} = 10$ pb

$\alpha\gamma\gamma$ prediction from Gårdestig

$\alpha\gamma\gamma$ background (16 pb)

Difference is due to acceptance of channel. Acceptance widths are:
- angle = 70 mr (H and V)
- momentum = 10%

Major physics background is from double radiative capture.

Cutoff controlled by available energy above threshold.
COMMISSIONING THE SYSTEM using p+d → $^3$He+π⁰ at 199.4 MeV

$^3$He events readily identified by channel scintillators.

Recoil cone on first MWPC

It is important to identify loss mechanisms.

Pb-glass energy sums nearest neighbors.

NOTE: Main losses in channel from random veto, multiple scattering, and MWPC multiple hits.
Calibrating the luminosity of the IUCF Cooler

PLAN: Monitor with d+d elastic. Measure ratio of d+d cross section to d+p (known) with molecular HD target.

Reference d+p cross sections: thesis of Karsten Ermisch, KVI, Groningen ('03).

dot = 108 MeV
circle = 120 MeV
X = 135 MeV
line = adopted cross section

**NOTE:**
Target distribution monitored using position sensitive silicon detector looking at recoil deuterons from small-angle scattering.
Detector acceptance determined using Monte-Carlo simulations.
INDENTIFICATION OF $^4\text{He}$ IN THE CHANNEL

We absolutely need coincidence with the Pb-glass (decay $\gamma$) to extract any signal at all.

Proton rate from breakup $\sim 10^5$ /s.
Handle this with:
- veto longer range protons
- set timing to miss most protons
- reduce MWPC voltage to keep $Z=1$ tracks below threshold
- divide $\Delta E-1$ into four quadrants

Set windows around $^4\text{He}$ group.
Rate still $10^3$ too high.

The $^4\text{He}$ flux, most likely from $(d,\alpha)$ reactions, is smooth in momentum and angle. It represents the part of phase space sampled by the channel.
\[ \pi^0 \rightarrow \gamma \gamma \text{ from } p+d \rightarrow ^3\text{He}+\pi^0 \]

**Pb-glass Hit Patterns**

**LEFT**

**RIGHT**

beam goes into X

cosmic ray muon

color scale: red > pink > blue
SINGLE AND DOUBLE GAMMA SIGNALS

data for all of July run

Beam left-side array

A single $\gamma$ may be difficult to extract.

But select on the similar locus on the other side of the beam, and the signal becomes clean.

Many $\gamma$'s come from beam halo hitting downstream septum.

List of requirements:
> correct PID position in channel scintillator energy
> correct range of TOF values
> correct Pb-glass cluster energies and corrected times
Energy of Cooler beam known from ring circumference and RF frequency (~ 16 keV)

Calculation of He momentum depends on good model of energy loss in channel. This is also needed to set channel magnets.

Calculation of time of flight required knowing the time offsets for each scintillator PMT and tracking changes through the experiment. Final adjustments were made in replay.

Run plan:
- started in June at 228.5 MeV to keep cone in channel
- during 1-week break decided to raise energy to 231.8 MeV
demonstrate that peak stayed at pion mass
- provide two cross sections to check energy dependence

(Limits were luminosity, rate handling, available time.)
For good resolution, we need FWHM $\sim 0.2$ ns.

PMT signal transit time drifts and occasionally jumps as the tube ages, responding to heat.

Timing is affected when people change PMT voltage or swap other equipment.

This is also connected to missing mass reconstruction errors arising from 6° magnet dispersion, pulse height, and position effects.

**Time Stability Problem**

A narrow peak helps $\pi^0$ separation statistically.

There are 6 PMTs used for TOF.

Mean-timing the ones for $\Delta E_2$ leaves 4 free time parameters.
To make run-by-run corrections to TOF, we need a marker. We use deuterons that stop and the back of the E scintillator.

Choose Energy

Choose Trajectory

Resulting TOF peaks

$\Delta E$ scintillator:
Results for June run:

CHANNEL

SOLID = A
OPEN = B
UP = C
DOWN = D

1 ns
RESULTS

Events in these spectra must satisfy:
- correct pulse height in channel scintillators
- usable wire chamber signals
- good Pb-glass pulse height and timing

Background shape based on calculated double radiative capture, corrected by empirical channel acceptance using $^4$He.

Cross sections are consistent with S-wave pion production.

Systematic errors are 6.6% in normalization.

Peaks give the correct $\pi^0$ mass with 60 keV error.

Spectra are essentially free of random background.

228.5 MeV
66 events
$\sigma_{TOT} = 12.7 \pm 2.2$ pb

231.8 MeV
50 events
$\sigma_{TOT} = 15.1 \pm 3.1$ pb
EXISTENCE?
For the candidate events, check to see whether there is any cone.

**XY-1 position**

\[ T = 228.5 \text{ MeV}, \quad \theta_{\text{max}} = 1.20^\circ \]

\[ T = 231.8 \text{ MeV}, \quad \theta_{\text{max}} = 1.75^\circ \]

Circles with these centers also minimize the missing mass width.
The missing mass should be independent of the TOF. In fact, the time adjustments are made separately for each segment of $\Delta E1$. 

**IS IT CORRECT?**

T = 228.5 MeV

T = 231.8 MeV

135 MeV

raw TOF
Framework from CHIRAL PERTURBATION THEORY

based on symmetries of QCD
uses nucleons (N) and pions (π) in low-momentum expansion

There are two contributions to charge symmetry breaking: (δm_N and δm_{N})

1. difference in the down and up quark masses

\[ \mathcal{L}^{(1)}_{qm} = \frac{\delta m_{N}}{2} \left( N^\dagger \tau_3 N - \frac{2}{D F^2_\pi} N^\dagger \pi \pi \cdot \tau N \right) \]

2. electromagnetic

\[ \mathcal{L}^{(-1)}_{hp} = \frac{\delta m_{N}}{2} \left( N^\dagger \tau_3 N + \frac{2}{D F^2_\pi} N^\dagger (\pi \pi \cdot \tau - \pi^2 \tau_3) N \right) \]

NOTE: δm_N and δm_{N} are not measures of either the quark mass difference or EM effects, but represent their contribution to the neutron-proton mass difference.

contributes to neutron-proton mass difference

contributes to pion production

THESE ARE CONNECTED

NOTE: There are also indirect contributions through neutron-proton mass difference, pion mixing, etc.
THEORETICAL CHALLENGE (estimates from Anders Gardestig)

Still to be included:
realistic wavefunctions (D-wave, etc.)
distorted waves (d+d)
$\Delta$-excitations
photon loops
heavy meson exchange

\[ d + d \rightarrow ^4\text{He} + \pi^0 \]

Coulomb isospin mixing
process (operators)

chiral perturbation theory
(pion nucleon scattering)

$\pi - \eta$ mixing
(one-body amplitude)

heavy meson exchange

\[ \frac{1}{2} f_\pi \left( \delta m_N - \frac{\delta m_N}{2} \right) \approx 0.0022 \]

\[ \frac{g_\eta}{m_\eta^2} \langle \pi^0 | H | \eta \rangle \approx 0.0035 \]

largest so far

applies to: $\sigma, \rho, \omega, \gamma$
SUMMARY - one possible result

The relationship $\delta m_N + \bar{\delta} m_N = 1.29$ MeV is assumed. Band widths reflect experimental errors.

A value of one means that $\eta$-$\pi$ mixing is unchanged from the calculation of van Kolck.

$\langle \eta | H | \pi \rangle = -0.0059 \frac{g_{\pi NN}}{\sqrt{4\pi \cdot 3.68}}$

$n+p \rightarrow d+\pi^0$ fore-aft asymmetry

$\eta$-$\pi$ mixing is unchanged from the calculation of van Kolck.

This band applies for $\eta$-$\pi$ mixing dominance.

Further calculations are needed to specify the slope appropriate for $d+d \rightarrow ^4\text{He}+\pi^0$.

TRIUMF experiment measures this gap

Cottingham sum rule EM estimate

$\delta m_N$ (MeV)

$d+d \rightarrow ^4\text{He}+\pi^0$ cross section
Experimental (active):

C. Allgower, A.D. Bacher, C. Lavelle, H. Nann, J. Olmsted, T. Rinckel, and E.J. Stephenson, Indiana University Cyclotron Facility, Bloomington, IN 47408

M.A. Pickar, Minnesota State University at Mankato, Mankato, MN 56002

P.V. Pancella, Western Michigan University, Kalamazoo, MI 49001

A. Smith, Hillsdale College, Hillsdale, MI 49242

H.M. Spinka, Argonne National Laboratory, Argonne, IL 60439

J. Rapaport, Ohio University, Athens, OH 45701

Technical support:

J. Doskow, G. East, W. Fox, D. Friesel, R.E. Pollock, T. Sloan, and K. Solberg, Indiana University Cyclotron Facility, Bloomington, IN 47408

Experiment (historical):

V. Anferov, G.P.A. Berg, and C.C. Foster, Indiana University Cyclotron Facility, Bloomington, IN 47408

B. Chujko, A. Kuznetsov, V. Medvedev, D. Patalahka, A. Prudkoglyad, and P.A. Semenov, Institute for High Energy Physics, Protvino, Moscow Region, Russia 142284

S. Shastry, State University of New York, Plattsburgh, NY 12901

Theoretical:

Antonio Fonseca, Lisbon
Anders Gardestig, Indiana
Christoph Hanhart, Juelich
Chuck Horowitz, Indiana
Jerry Miller, Washington
Fred Myhrer, South Carolina
Jouni Niskanen, Helsinki
Andreas Nogga, Arizona
Bira van Kolck, Arizona

spokesperson for CE-82 and letter of intent
post-doc
technical manager
student

Underline did June/July shift work