Charge Symmetry Breaking in $dd\to {}^4He\ \pi^0$

- Introduction
- The Indiana $dd\to {}^4He\ \pi^0$ experiment.
- Plane wave calculation including heavy meson exchange and π-η meson mixing.
- TRIUMF CSB experiment $np\to d\ \pi^0$

- Anders Gardestig and C. J. Horowitz

Isospin Violation Probes Strongly Interacting Systems

- Determine m_u, m_d: fundamental and poorly known parameters of Standard Model.
- Determine strong interaction phases and amplitudes for CP violation studies.
  - Need two interfering amplitudes for $\not{CP}$. $B \rightarrow \rho\rho$ can interfere with $B \rightarrow \rho\omega \rightarrow \rho\rho$ because of $\rho\omega$ mixing.
  - Extracted $\not{CP}$ parameters such as $\sin 2\alpha$ from other decays can be impacted by isospin violation [S. Gardner].

Determine Weak Interaction Matrix Elements for Standard Model Tests

- Super-allowed β decays give quark mixing V_{ud} after correcting for isospin violation.
  $|V_{ud}|^2 + |V_{us}|^2+|V_{ub}|^2= 1$?
  Brookhaven E865 result for $K^+\to \pi^0 e^+\nu$ branching ratio changes V_{us} and (if true) makes matrix unitary.
- NUTEV Anomaly Sensitive to CSB
  $(<\sigma_{NC}{}^{\nu}>-<\sigma_{NC}{}^{\bar{\nu}}>)/(<\sigma_{CC}{}^{\nu}>-<\sigma_{CC}{}^{\bar{\nu}}>)=1/2-2\sin^2\theta_W$.
- Assumes charge symmetry: $p\to n$ and $u\to d$
- Londergan and Thomas find that CSB in $u_v(x)$ in p compared to $d_v(x)$ in n related to np and ud mass differences can explain $\approx$ 1/3 of anomaly.

Separate E+M and Quark Mass Contributions to Isospin Violation

- Two apparently independent sources:
  - E+M makes proton heavier then neutron.
  - $\Delta m \equiv m_d - m_u$ makes n heavier then p.
- $\Delta M \equiv M_n - M_p$ = 1.29 MeV one of most basic and important parameters in nuclear astrophysics.
  - If $M_p \approx M_n$ Big Bang makes mostly ^{4}He.
  - If $M_p > M_n$ Big Bang makes ^{4}He and n (stable). H unstable.
  - In either case Universe drastically different.
- How to separate E+M and Δm effects?
  - Use different density dependence.
  - Study isospin violation in π^0-N scattering.

In a high density system

- Kinematics suppresses quark mass effects by large Fermi momentum. $(k_F^2+m^2)^{1/2} \sim k_F + m^2/2k_F$
- E+M effects grow as quarks move closer together. For example Coulomb exchange energy $\sim \alpha\, k_F$.
- In high density limit, isospin violation is dominated by E+M with quark mass terms unimportant. In this limit the proton is heavier then neutron.
  [CJH+J. Piekarewicz, PRC**63**, (2001) 011303]

Isospin Violating π^0-N Scattering (U. van Kolck)

- Chiral sym relates nucleon mass term to π-N scattering.
- Isospin breaking in nucleon mass term (n-p mass difference) related to isospin violating π-N scattering.
- Isospin viol. with symmetries of quark masses: $L_{qm}=\delta m/2[N^\dagger\tau_3 N-2N^\dagger\pi_3\tau\cdot\pi\ N/F_\pi^2]$
- With symmetries of hard photon exchange: $L_{em}=\bar{\delta}m/2[N^\dagger\tau_3 N+2N^\dagger(\pi_3\tau\cdot\pi\ -\pi^2\tau_3)/F_\pi^2]$
- $\Delta M=\delta m+\bar{\delta}m$ and measuring π^0-N scattering can decompose ΔM into quark mass and E+M parts.
- π^0 decay makes π^0 scattering hard. Look at isospin violation in π^0 production instead.

Cooler
CSB

the search
for $d+d \to \alpha\pi^0$

www.iucf.indiana.edu/~coolcsb

The Cooler-CSB Experiment at the Indiana University Cooler Synchrotron: A Test of Charge Symmetry Breaking and Isospin Conservation via the Reaction $d+d \rightarrow \alpha+\pi^0$

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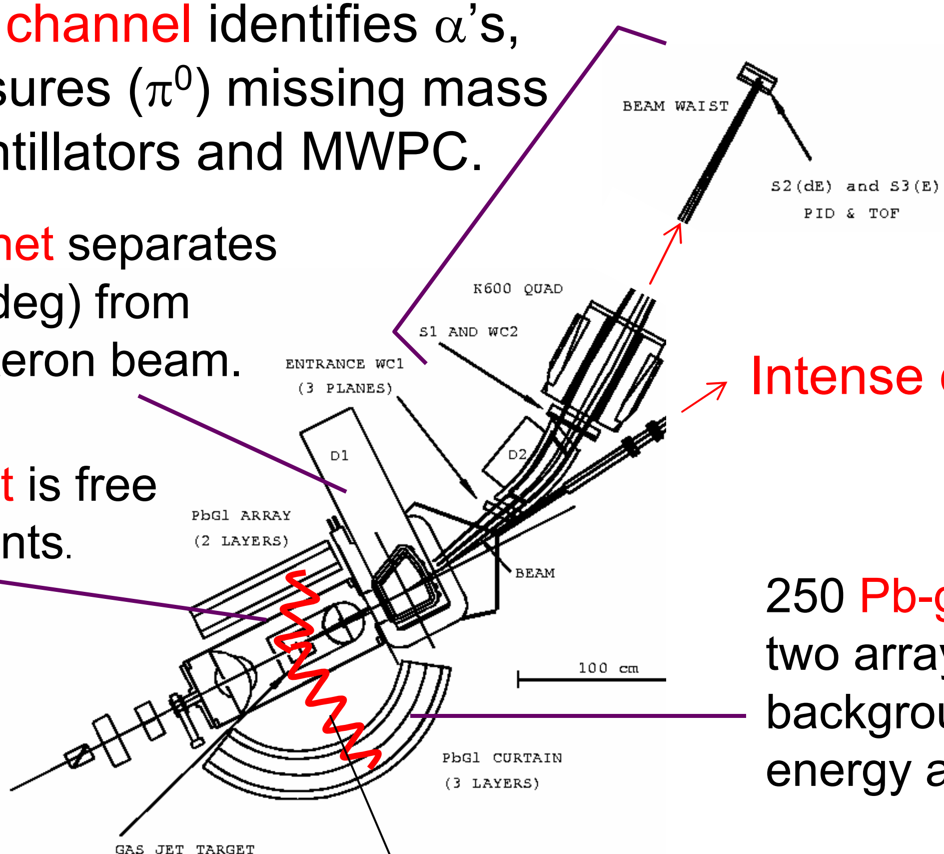
$d+d \rightarrow {}^4He+\pi^0$ at the IUCF Cooler

Magnetic channel identifies α's, and measures (π^0) missing mass using scintillators and MWPC.

6 degree magnet separates α's (bent 12.5 deg) from circulating deuteron beam.

Gas jet target is free of contaminants.



Intense deuteron beam

250 Pb-glass detectors in two arrays remove trigger background and check π^0 energy and γ coplanarity.

See both γs from π^0 decay

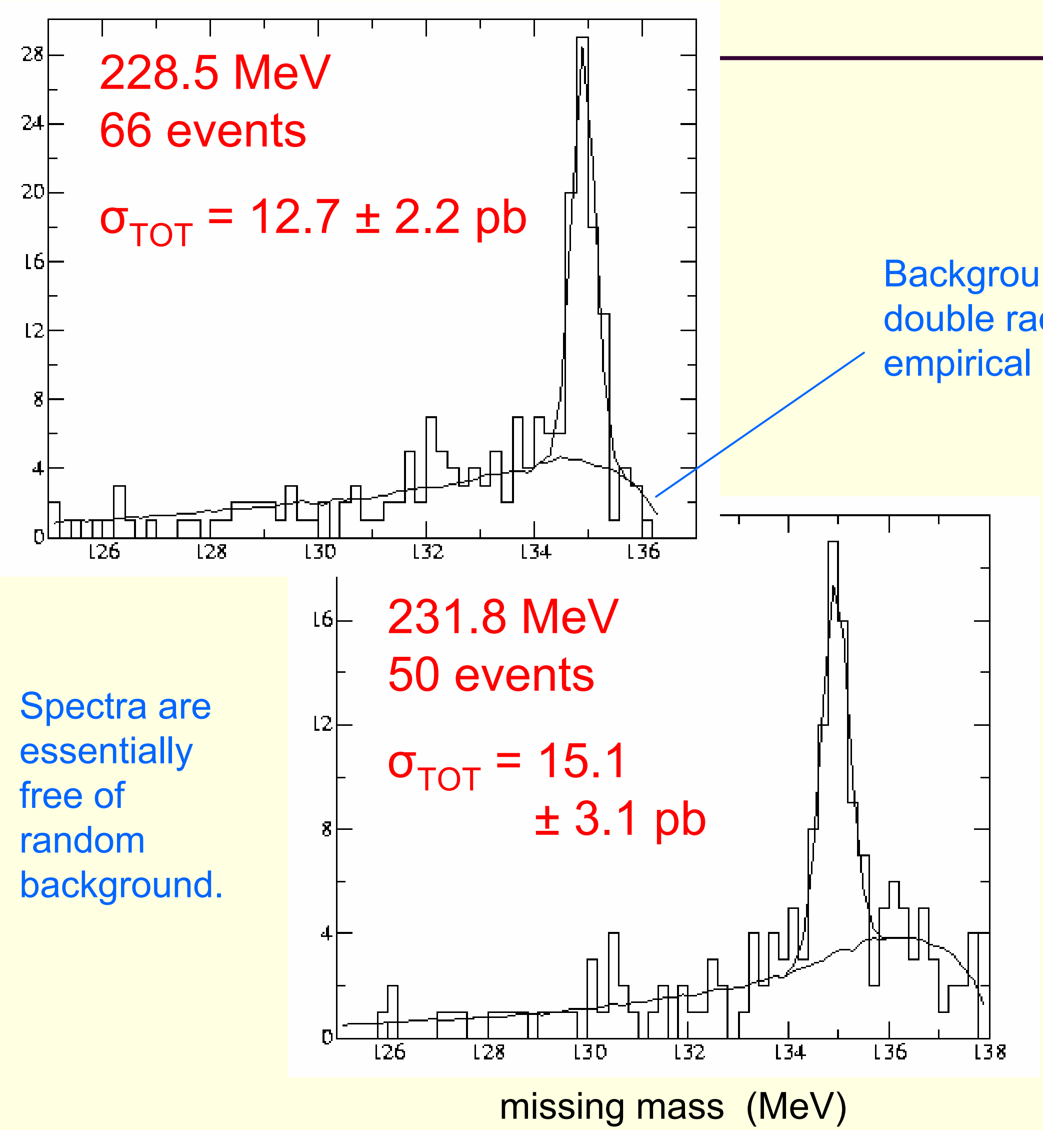
Experimental Results

- Data was taken at two near threshold energies: 228.5 MeV (η_π=0.1434) and 231.8 MeV (η_π=0.209). Also some d+d elastic scattering data taken to help check initial state distortions.
- See a clear pion signal reconstructing to pion mass at both energies while background moves with phase space. Low background for two gamma plus He events.
- Luminosity calibration from dd and pd elastic scattering.

PRELIMINARY RESULTS

Events in these spectra must satisfy:

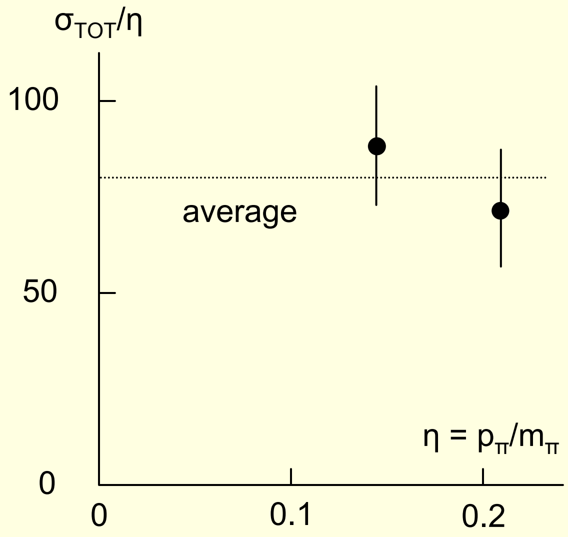
- correct pulse height in channel scintillators
- usable wire chamber signals
- good Pb-glass pulse height and timing



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

Spectra are essentially free of random background.

Cross sections are consistent with S-wave pion production.

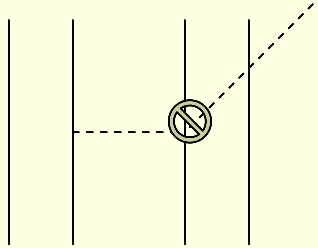


CSB Theory Collaboration

- Antonio Fonseca (dd scattering wave function), Anders Gardestig (plane wave calc.), Chris Hanhart (chiral counting and loops), Chuck Horowitz (CSB operators) , Gerry Miller, Andreas Nogga (^{4}He wave function), Bira van Kolck, … have formed collaboration. Four workshops at Seattle, Albuquerque, Bloomington, and Philly.
- There will be a CSB Workshop in Seattle Oct 20, 2003 and all are welcome.
- I will present plane wave results.
- Full distorted wave calculations with realistic ^{4}He wave function underway.

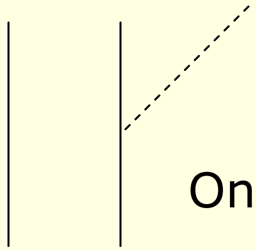
Leading Order Contribution Near Threshold is Pion Rescattering Term.

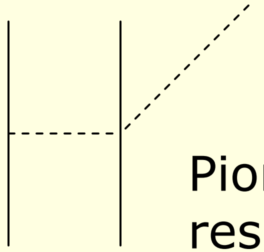
- Chiral symm relates isospin breaking mass and π^0-nucleon scattering terms
- $L_{qm}=\delta m/2\{N^+\tau_3 N-2N^+\pi_3\pi.\tau N/F_\pi^2\}$,
- $L_{em}=\bar{\delta}m/2\{N^+\tau_3 N+2N^+(\pi_3\pi.\tau-\pi^2\tau_3)N/F_\pi^2\}$,
- $\Delta M=\delta m+\bar{\delta}m$
- Strong isospin dependence of these terms reduces their contribution to $dd\rightarrow{}^4He\ \pi^0$
- Not true for CSB in $np\rightarrow d\pi^0$ TRIUMF experiment

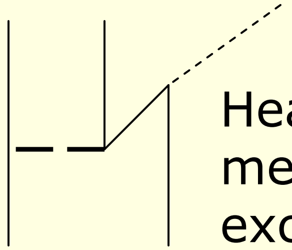


pp→ pp π^0 results for s-wave π

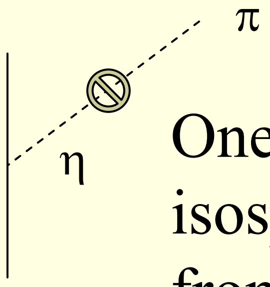
- Same $^3P_0 \to {}^1S_0s$ quantum numbers!
- Threshold s-wave cross section 5 times larger than one-body contribution.
- Neutral pion rescattering small on-shell.
- Large contributions from sigma and omega heavy meson exchange currents can explain data.
- Convergence of chiral pert theory poor because of large nucleon momenta even at threshold.



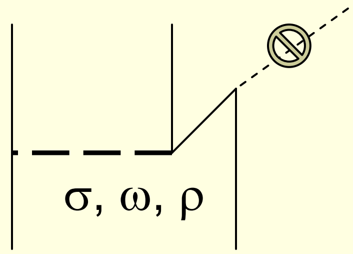




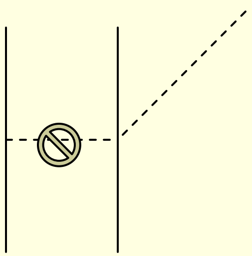
N^2LO Contributions

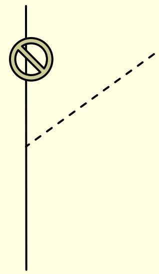


One body with isospin violation from π-η mixing



σ, ω, ρ heavy meson exchange with π-η mixing

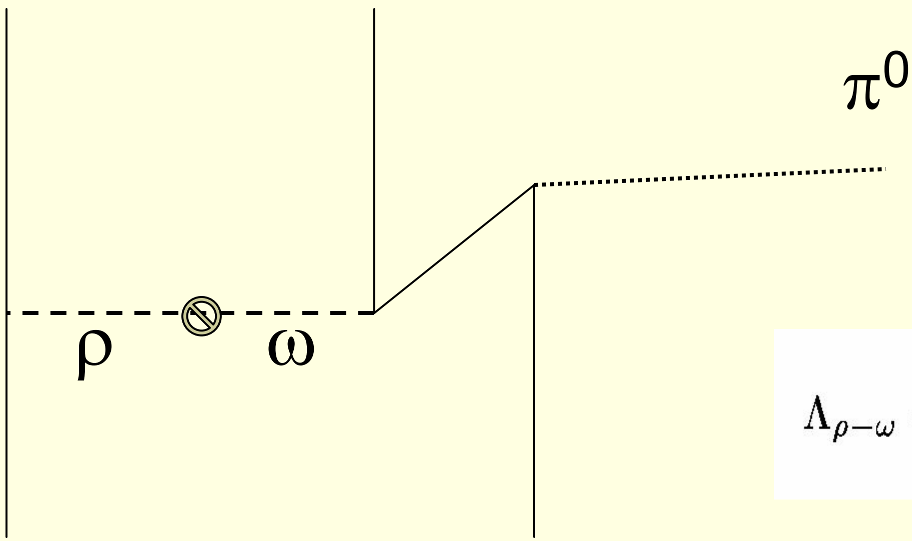




Isospin violation in ^{4}He wave function, very sensitive to difference r_n-r_p

Pion rescattering after π-η mixing

Also Rho-Omega Mixing



$$\Lambda_{\rho-\omega} = \frac{1}{(2m_\pi)^{1/2}} f\left(\frac{< \rho|H\omega >}{m_\omega^2}\right)\frac{1}{M}$$

$$H_{\rho-\omega} = -\Lambda_{\rho-\omega}\left(\frac{g_\rho g_\omega}{4\pi M}\right)\frac{1}{2}\sum_{i\neq j}\left\{(1+\tau_i^3\tau_j^3)\sigma_j\cdot(f_{ij}^\rho p_i + p_i f_{ij}^\rho) + i[1+\tau_i^3\tau_j^3(1+C_\rho)]\sigma_i\wedge\sigma_j\cdot q_j f_{ij}^\rho\right\}$$

Plane wave calculation to characterize operators

Anti-symmetrized spin-isospin wave functions

The spin-isospin parts of the wave functions are

$$|\alpha\rangle = \frac{1}{\sqrt{2}}\left([(12)_1(34)_1]_0[(12)_0(34)_0]_0 - [(12)_0(34)_0]_0[(12)_1(34)_1]_0\right)$$

$$|d_1\rangle = (12)_1(12)_0$$

$$|d_2\rangle = (34)_1(34)_0$$

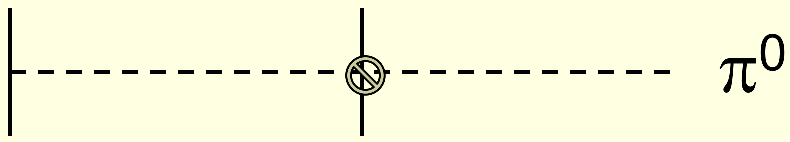
where the first brackets is spin and the second isospin.

π Rescattering is Isospin Disfavored

- Operator has two isospins (τ) but only one spin operator (σ).

$$\mathcal{O}_{i,j} = -\frac{f}{4\pi\mu F_\pi^2\sqrt{2\mu}}[\delta m_N(\boldsymbol{\tau}^{(i)}\cdot\boldsymbol{\tau}^{(j)} + \tau_3^{(i)}\tau_3^{(j)}) - \bar{\delta} m_N(\boldsymbol{\tau}^{(i)}\cdot\boldsymbol{\tau}^{(j)} - \tau_3^{(i)}\tau_3^{(j)})]$$
$$(\boldsymbol{\sigma}^{(i)} - \boldsymbol{\sigma}^{(j)})\cdot(-i\hat{\boldsymbol{r}})\frac{d}{dr}\left(\frac{e^{-\mu r}}{r}\right),$$

- The two τs convert both deuterons to isospin 1 but σ can only convert one of the two deuterons spins to spin 0.
- The s-wave alpha particle is a mixture of spin 0, isospin 1 pairs or spin one, isospin zero pairs.
- Operator gives zero for plane wave initial state. Distortions and or d-waves in ^{4}He or deuterons can change this.



Other Contributions add coherently

- 1-body and sigma are coherent
- Omega involves $-\sigma_3 \cdot p_1$ compared to $\sigma_1 \cdot p_1$ for sigma exchange. For $^3P_0 \rightarrow {}^1S_0$, $\sigma_3 \cdot p_1 = -\sigma_1 \cdot p_1$ so omega and sigma add coherently.
- One body + σ + ω HMEC are coherent.
- Should evaluate rho-omega mixing and other HME in $np \rightarrow d\pi^0$.

Results with gaussian He and d and plane wave dd initial state

- Pure s-wave π at lower E=228.5 MeV
- One body π-η mixing alone σ=4.8 pb.
- Heavy meson exc amplitudes compared to one-body:
  - Sigma $M_{\sigma}=0.62\ M_1$.
  - Omega $M_{\omega}=0.66\ M_1$.
  - Rho $M_{\rho}=-0.17\ M_1$.
  - Rho-omega mixing $M_{\rho\text{-}\omega}=-0.12\ M_1$.
- $\sigma_{1+\sigma+\omega+\rho+\rho\text{-}\omega}$=19.2 pb [2.6 pb] Experiment= 12.7 ± 2.2 pb
- Based on <$\pi H\eta$>=-4200 MeV^2, $g_{\eta}^2/4\pi=3.68$ [--0.6] and <$\rho H\omega$>=-4500MeV^2.

Coherent Pion Bremstrahlung

- Can arrange spin one deuterons so axial charges of all 4 nucleons contribute coherently.
- We find heavy meson exchange currents increase cross section because all pairs contribute with same sign and add coherently to one-body.
- Plane wave calculations with heavy meson exchange and isospin violation from reasonable π-η mixing parameters can explain large observed cross section.
- Important to include dd distortions and full ^{4}He wave function! Calculations underway.

CSB in $np \rightarrow d\pi^0$ (A. K. Opper)

- Forward, backward asymmetry violates CS $A_{fb}(\theta)=(\sigma(\theta)-\sigma(\pi-\theta))/(\sigma(\theta)+\sigma(\theta))$
- TRIUMF exp at 279.5 MeV detects both forward and backward d in same spectrometer setting. Result angle integrated:

  $$A_{fb}=+17.2 \pm 8(\text{stat}) \pm 5.5(\text{sys}) \times 10^{-4}$$

  based on careful simulation of spectrometer acceptance.

$np \to d\pi^0$ Theory (Niskanen)

- A_{fb} depends on interference of s+p waves and CSB and CS amplitudes. This increases uncertainty. No isospin cancellations for δm, $\bar{\delta} m$ terms:

$$A_{fb} = -28\{ g_{\eta NN}/(4\pi(3.68))^{1/2} \langle \pi H \eta \rangle /(-5900 \text{ MeV}^2) - 0.87/\text{MeV}(\delta m - \bar{\delta} m/2) \} \times 10^{-4}.$$

  This is – for $\pi\eta$ mixing, + for δm.
- Positive exp result may be evidence for δm terms.
- Different isospin dependence makes $np \to d\pi^0$ and $dd \to {}^4He\pi^0$ sensitive to different combinations of CSB operators.
- Important to improve calculation of A_{fb}, including HME for example, and assess theoretical uncert.