Radiative Capture Reactions near Zero Energy: $^{7}Be(p,\gamma)^{8}B$ and $^{3}He(\alpha,\gamma)^{7}Be$

Barry Davids, TRIUMF

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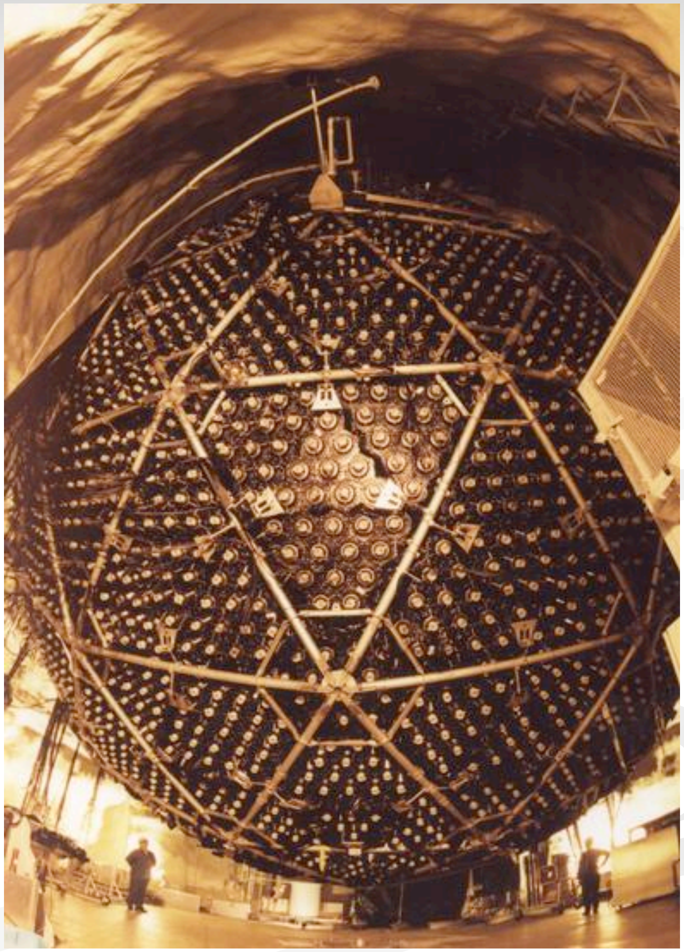
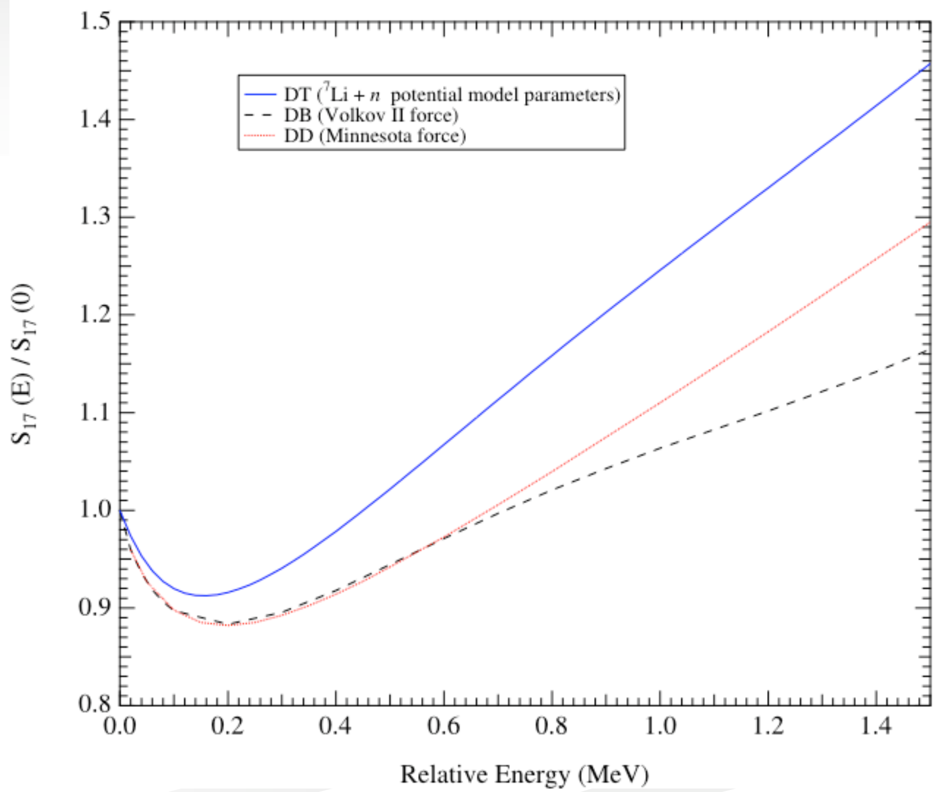
Radiative Capture Reactions in the Sun



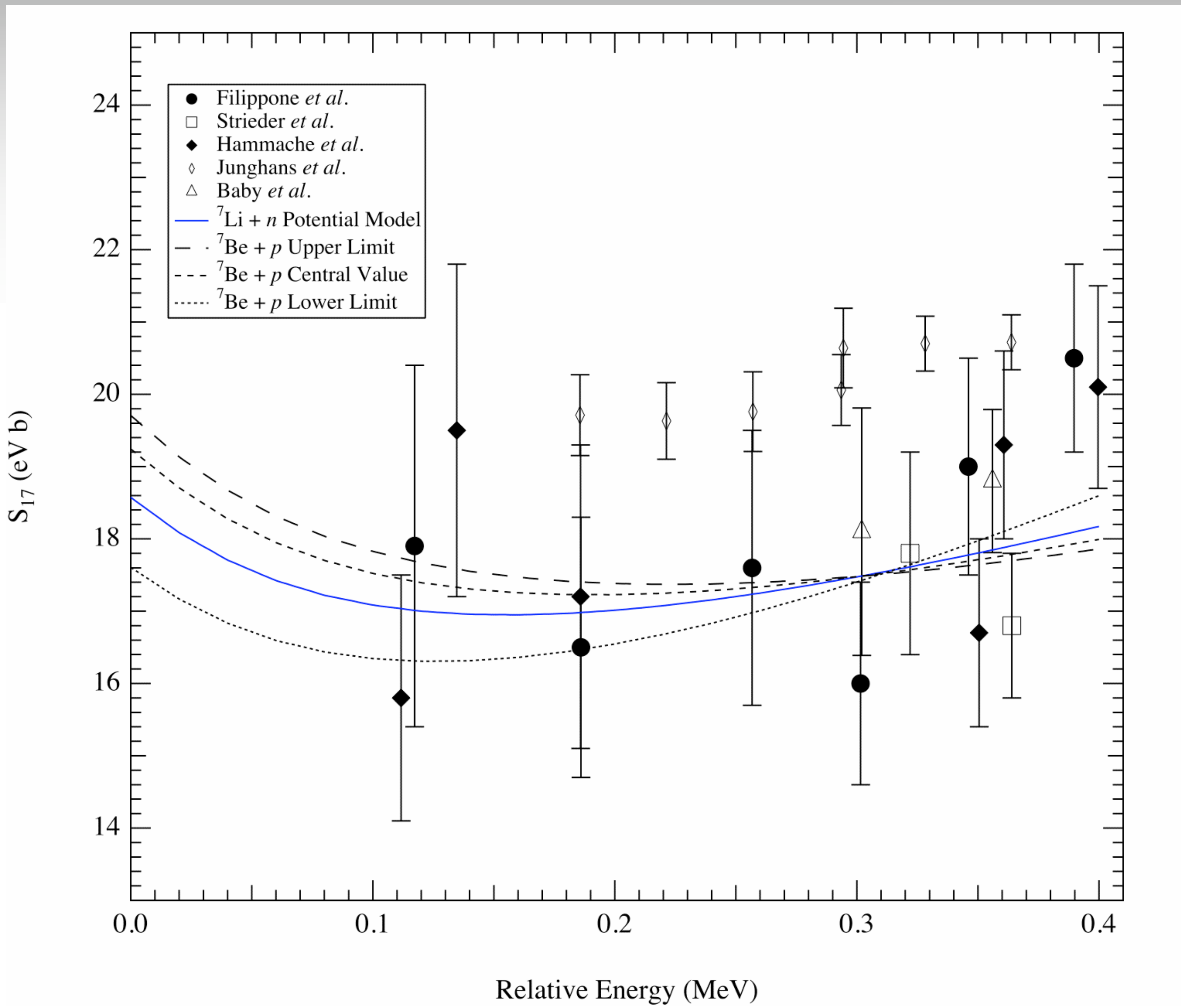
- Rates of radiative capture reactions needed for predictions of solar neutrino flux
- ^{8}B solar ν flux now measured to ± 8.6% by SNO, ^{7}Be flux measured to ± 10% by Borexino
- $S_{mn}(0)$ is the astrophysical S factor for the radiative capture $m + n \rightarrow (m+n) + \gamma$ at zero energy: S_{17} is for $^{7}Be(p,\gamma)^{8}B$ and S_{34} for $^{3}He(\alpha,\gamma)^{7}Be$
- ^{8}B flux $\propto S_{17}(0), S_{34}(0)^{0.81}$
- ^{7}Be flux $\propto S_{34}(0)^{0.86}$

Extrapolation of S_{17}

- Cyburt, Davids, and Jennings examined structure models and experiments in Phys. Rev. C 70, 045801 (2004)
- Extrapolation is model-dependent
- Even below 400 keV, the GCM cluster model of Descouvemont and Baye and the Davids and Typel potential model based on ^{7}Li + n scattering lengths differ by 7%



Radiative Capture Data



Results of Analysis

- Model-dependent analysis of high precision Seattle data finds slight preference for ^{7}Li + n potential model over cluster model, but difference not significant
- Using a minimally structure-dependent pole model taking account of rise at low energy, fit radiative capture data below 425 keV, allowing data to determine shape, consistent with cluster and potential models; 2 parameter fit, with a fixed at 45 keV

$$S_{17}(E) = S_{17}(0)\left[1 - a\frac{E}{Q(E+Q)}\right] + \beta E$$

- Junghans *et al*. result: 21.4 ± 0.7 eV b
- All other radiative capture: 16.3 ± 2.4 eV b

Mirror ANC's

- Timofeyuk, Johnson, and Mukhamedzhanov have shown that charge symmetry implies a relation between the ANC's of 1-nucleon overlap integrals in light mirror nuclei
- Charge symmetry implies relation between widths of narrow proton resonances and ANC's of analog neutron bound states
- Tested by Texas A & M group for ^{8}B-^{8}Li system
- Ground state agreement excellent: inference of $S_{17}(0)$ from DWBA analysis of proton transfer to ^{7}Be (17.3 ± 1.8 eV b) and isospin mirror, neutron transfer to ^{7}Li (17.6 ± 1.7 eV b) [PRC 63, 055803 (2001) & PRC 67, 062801 (2003)]
- Excellent agreement with radiative capture data other than that of Junghans *et al*.
- 1^{+} 1st excited state shows 2.5σ discrepancy between theory and experiments (Texas A & M and Seattle)

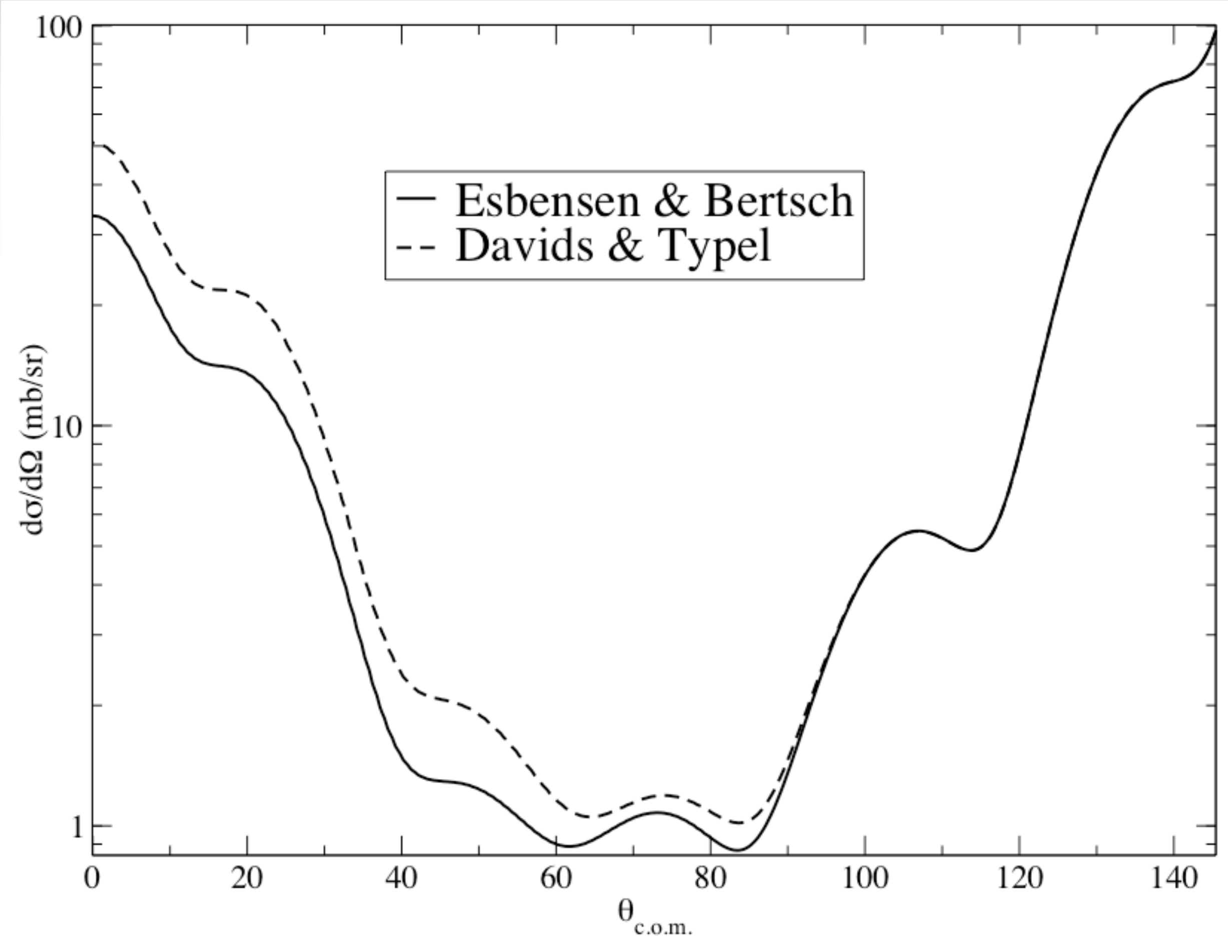
TRIUMF Experiment

- Measure ANC's of the valence neutron in ^{8}Li via the elastic scattering/transfer reaction $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ at 11 and 13 MeV
- Interference between elastic scattering and neutron transfer produces characteristic oscillations in differential cross section
- Amplitudes of maxima and minima yield ANC

Calculations

- DWBA calculations performed with FRESCO by Natasha Timofeyuk, Sam Wright, & Ian Thompson
- Optical potentials from Becchetti (14 MeV ^{8}Li on ^{9}Be, modified to be appropriate for ^{7}Li), two from Potthast (energy-dependent global fit to combined ^{6}Li+^{6}Li and ^{7}Li+^{7}Li data from 5-40 MeV)

FRESCO DWBA Calculations by Sam Wright



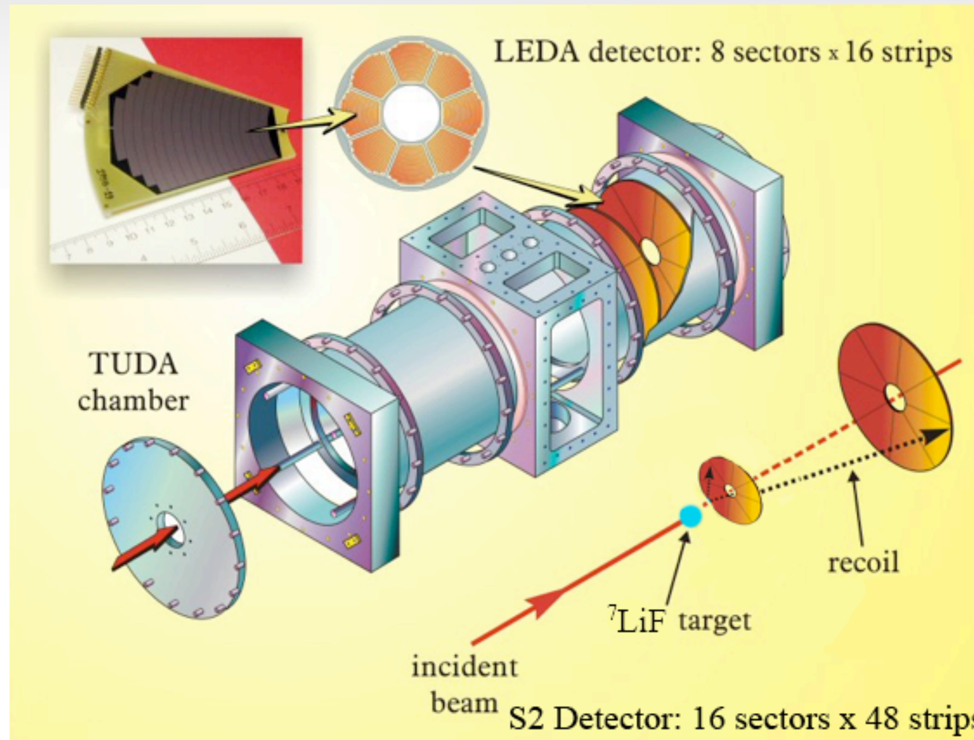
Advantages of the Method

- Identical initial and final states => single vertex is involved
- Statistical precision greater (compared with distinct initial and final states)
- Single optical model potential needed
- Elastic scattering measured simultaneously
- More than one beam energy allows evaluation of remnant term in DWBA amplitude (in principle)
- Absolute normalization of cross section enters only as a higher-order effect in ANC determination

$$T_{fi} = \int\int \chi^{(-)}(\mathbf{k_b}, \mathbf{r_b})^* \langle \Psi_{^8Li}\Psi_{^7Li}|(V_{n^7Li}+V_{^7Li^7Li}-U_{^7Li^8Li})|\Psi_{^7Li}\Psi_{^8Li}\rangle \chi^{(+)}(\mathbf{k_a}, \mathbf{r_a}) d\mathbf{r_a} d\mathbf{r_b}$$

Experimental Setup

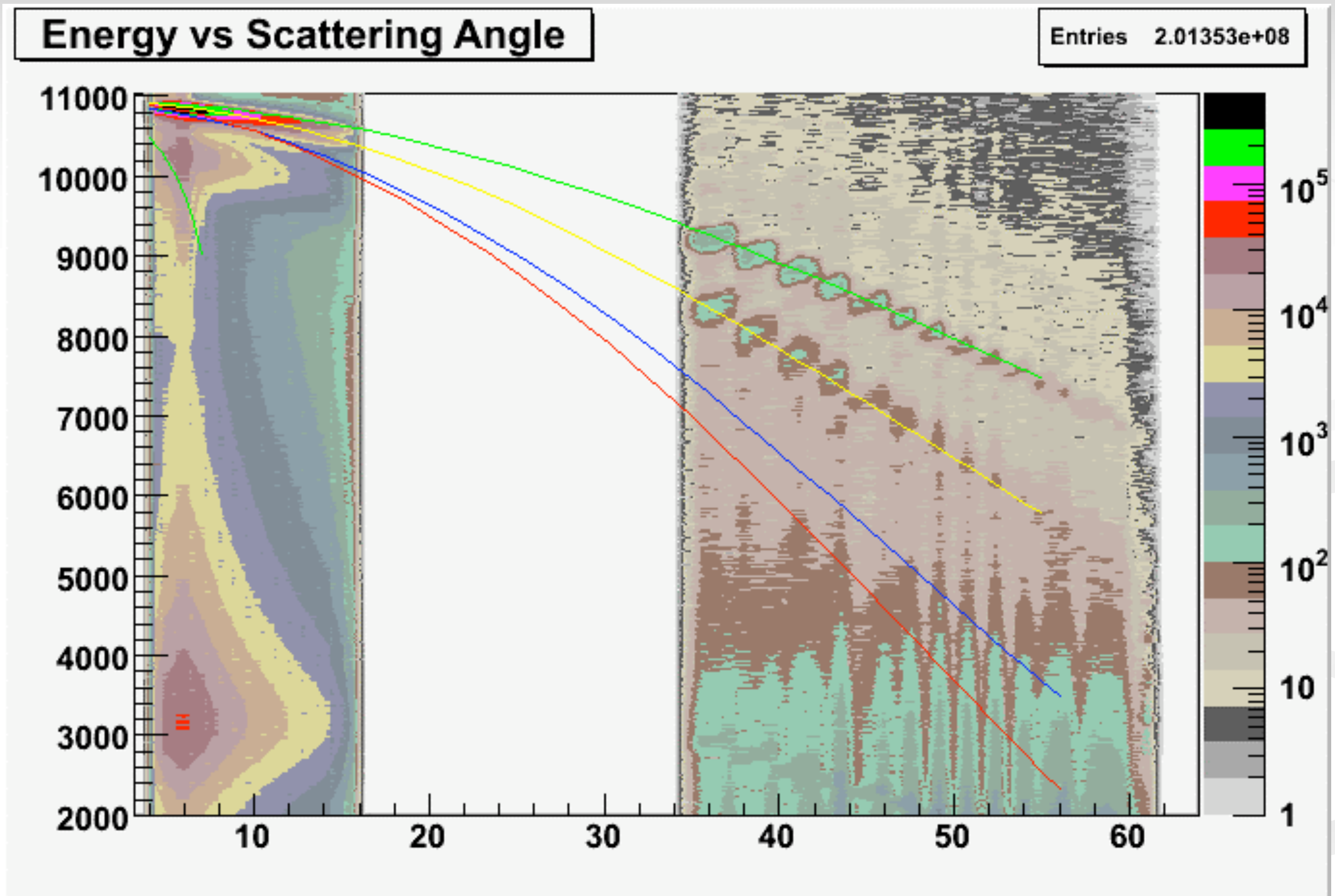
- Two annular, segmented Si detectors
- 25 μg cm^{-2} ^{7}LiF target on 10 μg cm^{-2} C backing
- LEDA detector covers lab angles from 35-61°
- S2 detector covers 5-15° in the lab
- ^{7}Li cm angular coverage from 10-30° and 70-122°
- ^{8}Li beam intensities of 2-4 × 10^7 s^{-1}



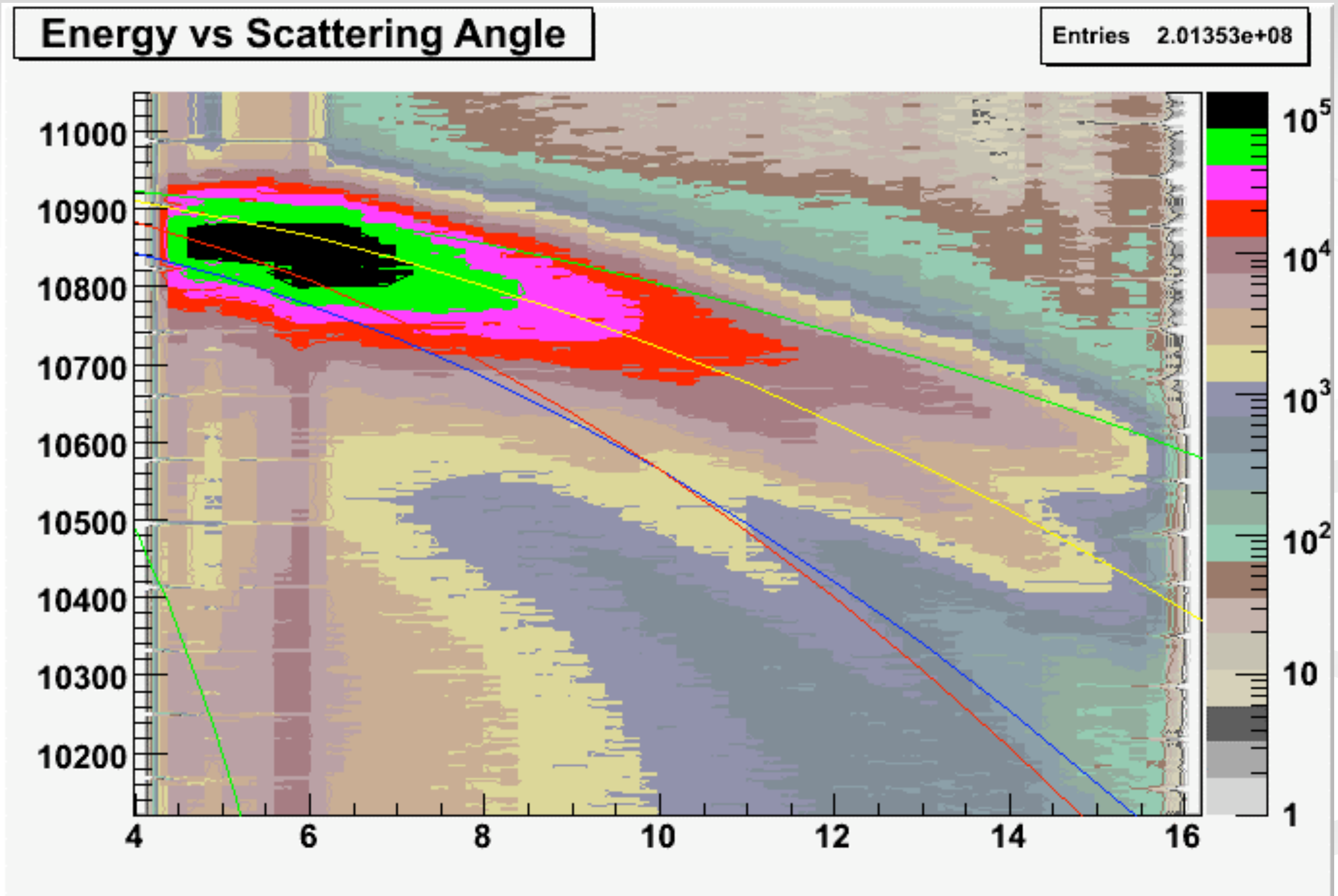
Particle ID and Background Rejection

- For lab angles < 45°, total energy measurements alone cannot separate ^{7}Li from ^{8}Li
- Below 45° we require kinematic coincidences
- ^{7}Li detection in LEDA at lab angles from 35-52° accompanied by ^{8}Li detection in same detector
- ^{7}Li detection in S2 should be accompanied by very low energy ^{8}Li detection in LEDA detector
- F, C elastic scattering backgrounds distinguishable everywhere in singles or with kinematic coincidences

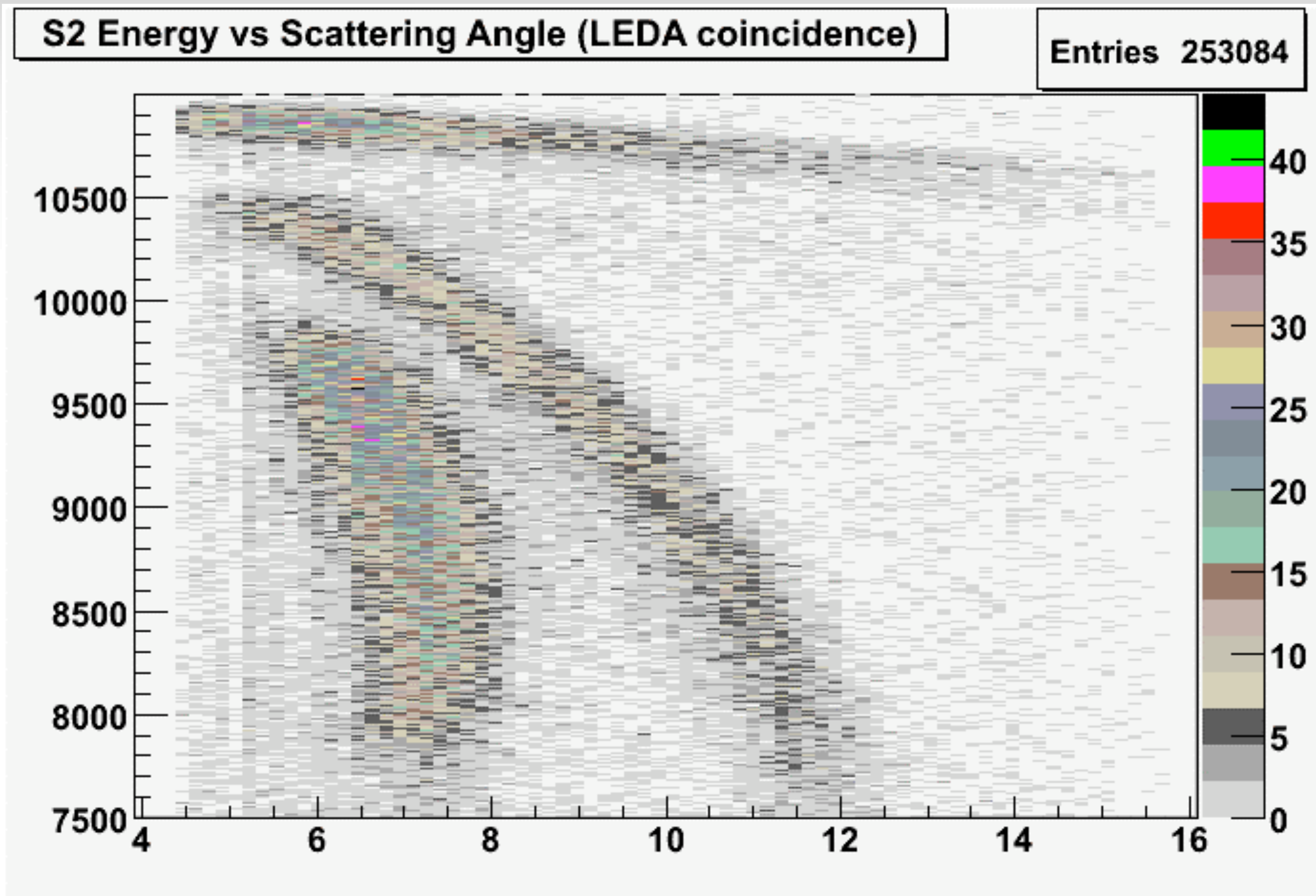
11 MeV Data


Energy vs Scattering Angle
Entries 2.01353e+08
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
10
20
30
40
50
60
10^5
10^4
10^3
10^2
10
1

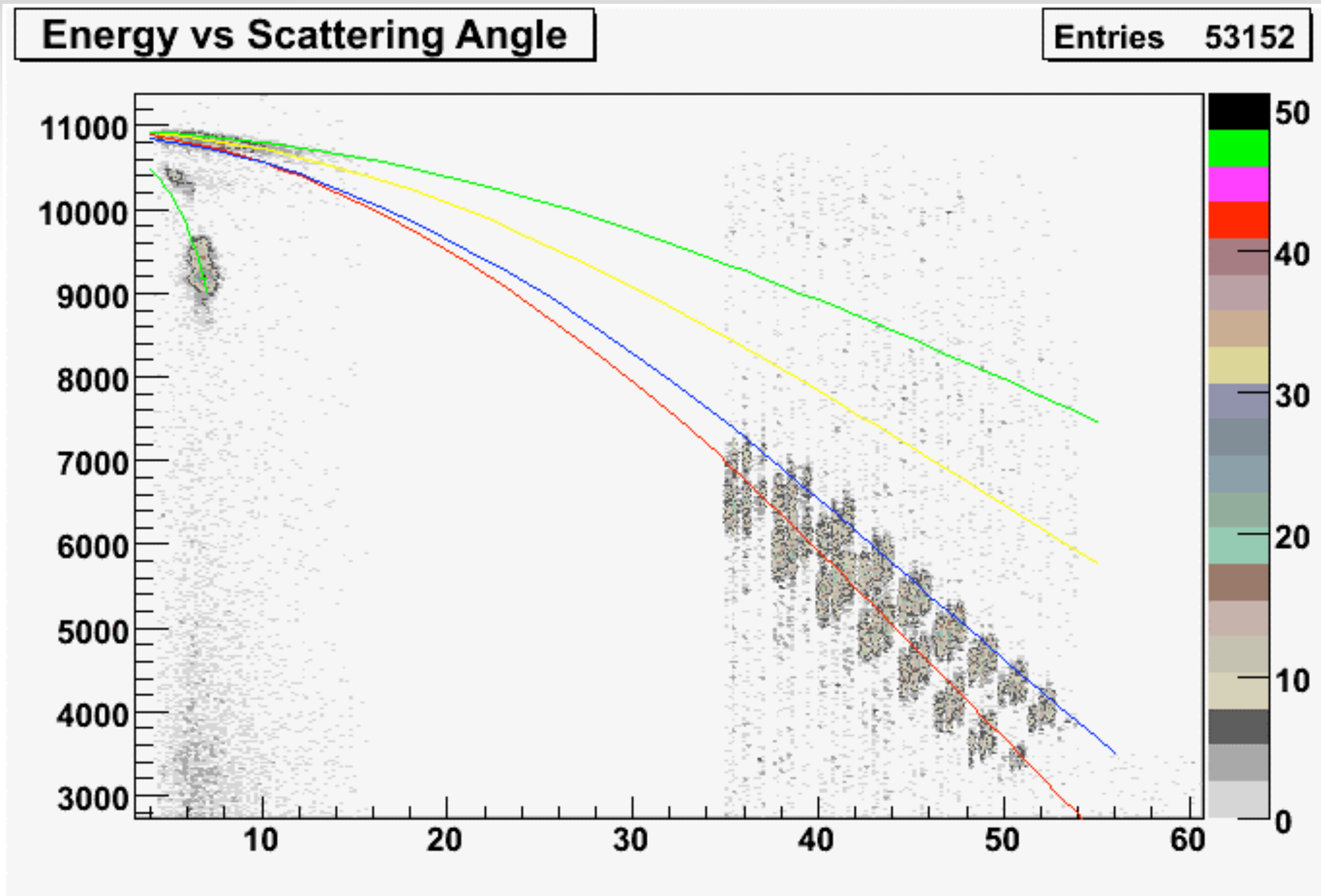
Small Angles



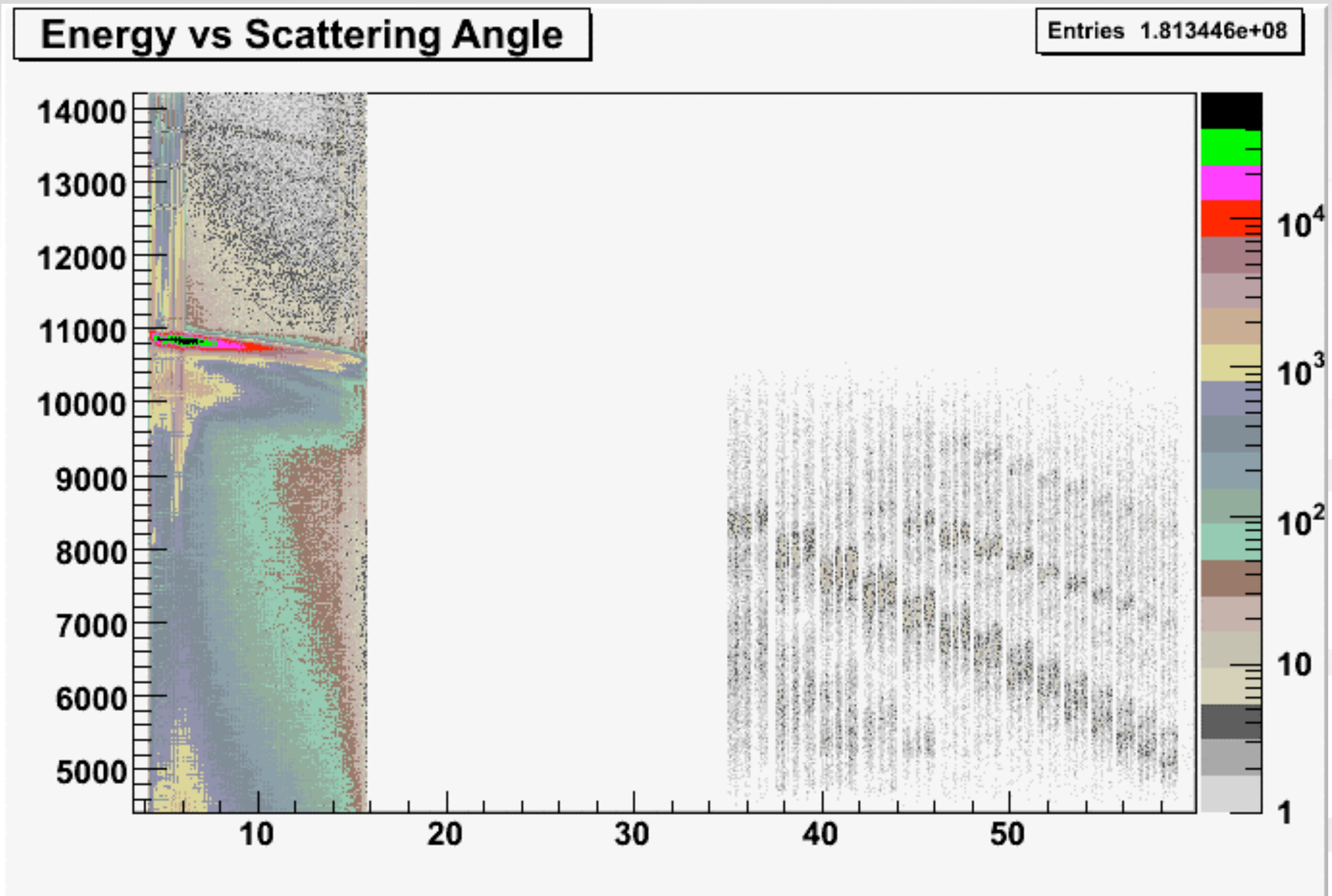
Small Angle Coincidence Data



Coincidences: Energy-Angle Correlation



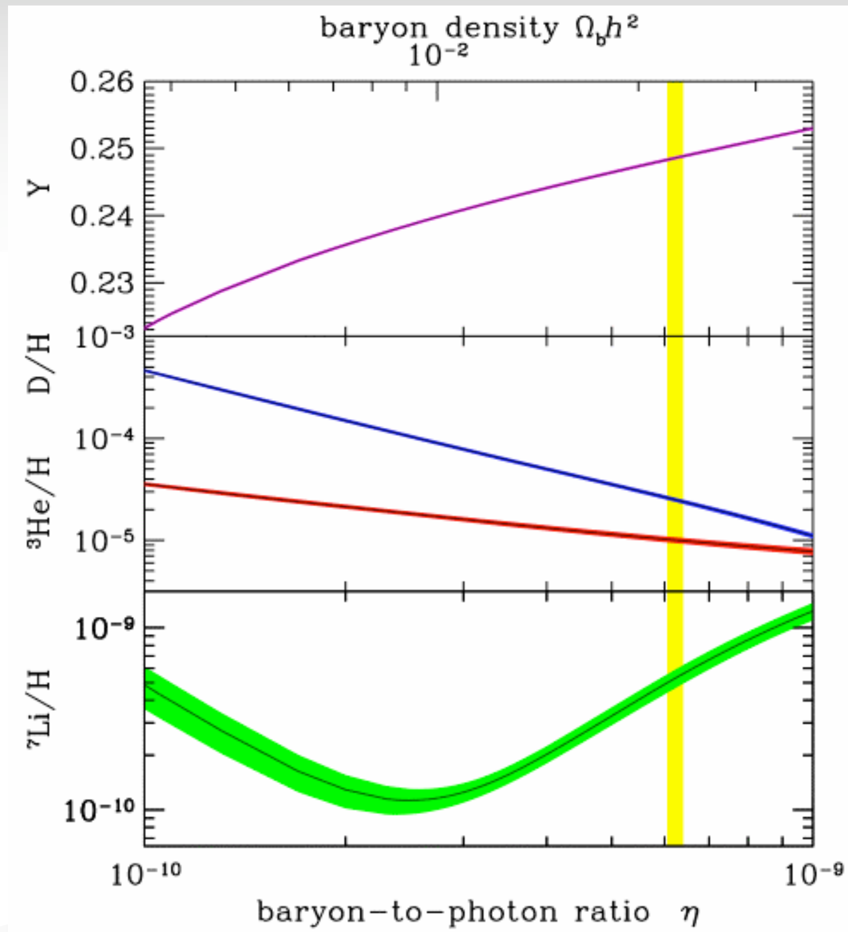
11 MeV Data Revisited



All S2 data, Elastics in LEDA

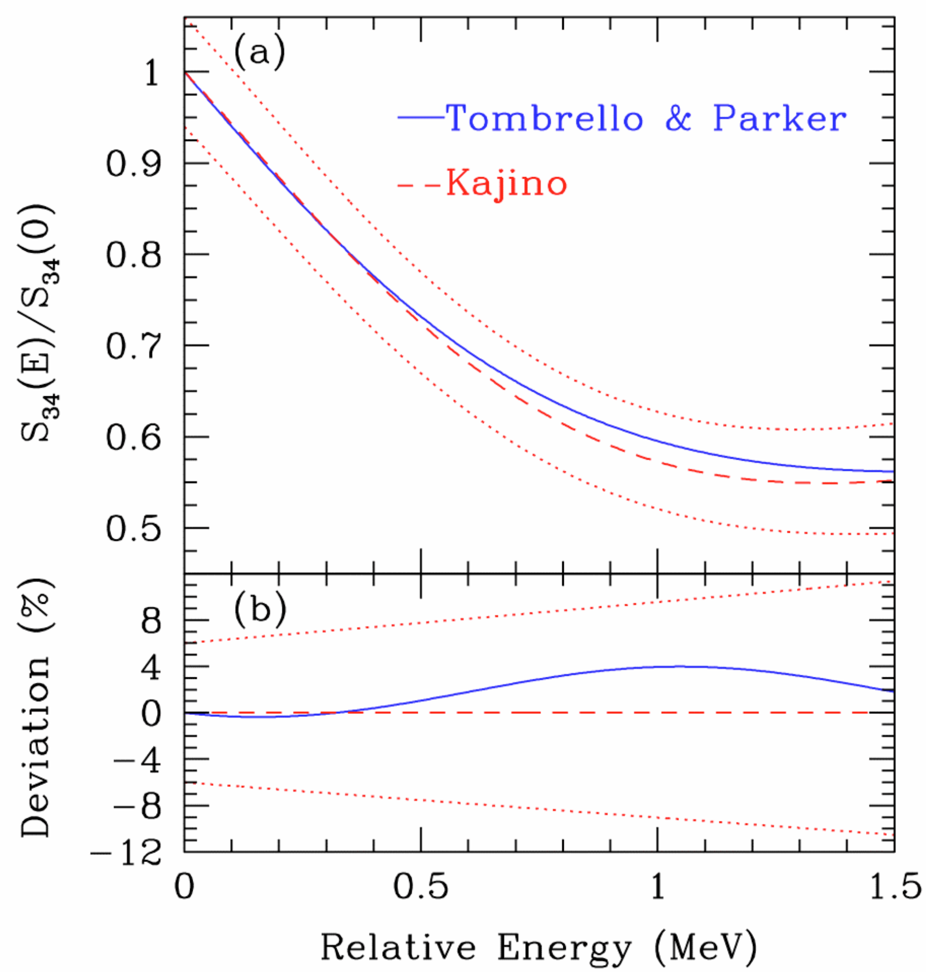
Radiative Captures in Big Bang Nucleosynthesis

- BBN a robust prediction of hot big bang cosmology for > 40 yr
- Explains origin of large universal He abundance, trace quantities of D, ^{3}He, & ^{7}Li
- Given GR, cosmological principle, abundance predictions depend only on mean lifetime of neutron, number of active, light neutrino flavours, universal baryon density, and nuclear reaction rates
- ^{7}Li produced via ^{3}He$(\alpha,\gamma)^7$Be
- Primordial ^{7}Li abundance $\propto$ $S_{34}(300\text{ keV})^{0.96}$

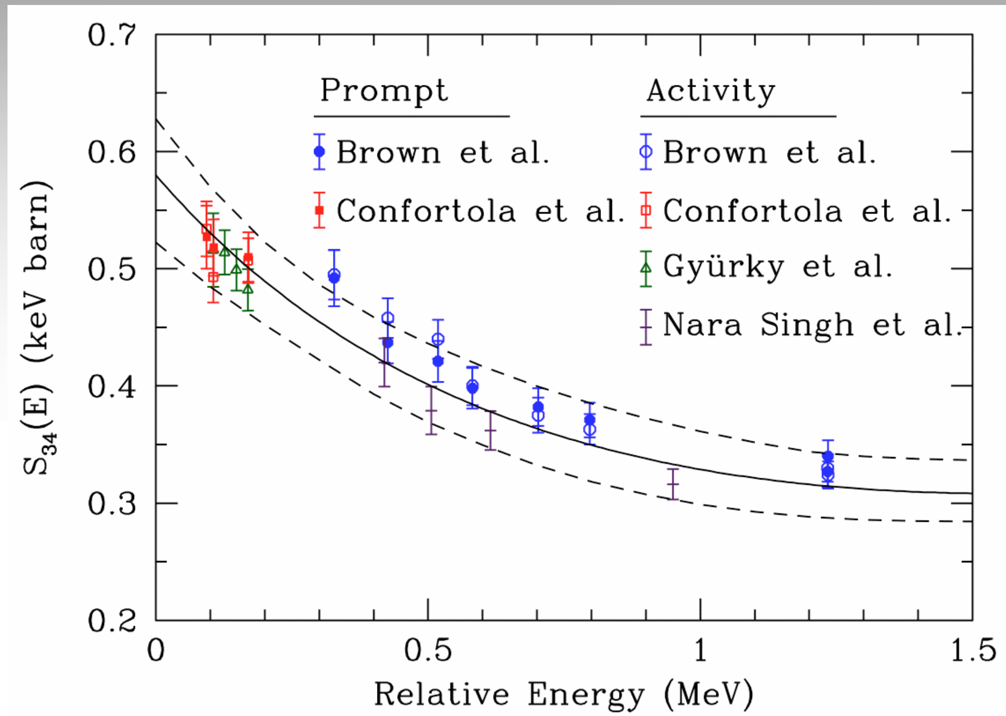


Theoretical S_{34} Models

- Potential model and cluster model of Kajino [NPA 460, 559 (1986)] shapes agree below 500 keV, but is it fortuitous? Absolute values of calculations significantly underestimate data
- Uncertainty in cluster model $S_{34}(E)$ derived from theoretical estimates of uncertainty in $S_{34}(0)$ and its logarithmic derivative, shown by dotted lines
- Can we use data and well-known physics to determine $S_{34}(E)$ independent of structure model?
- We (Cyburt, BD) use a formalism capable of handling discrepant modern measurements dominated by systematic uncertainties



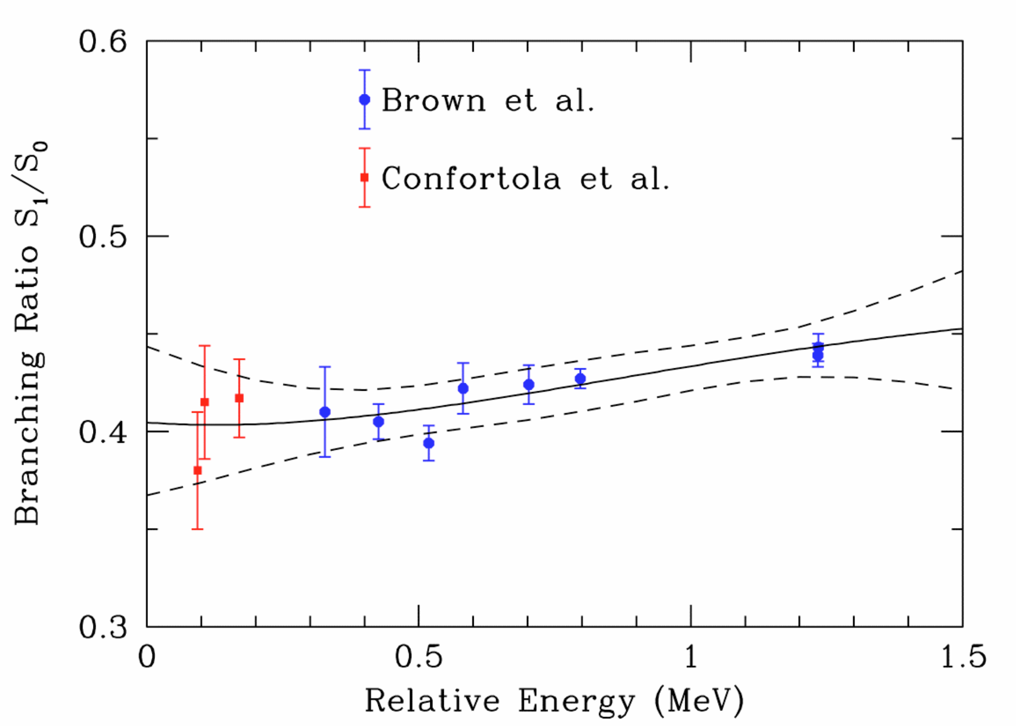
Modern S_{34} Data



- Total errors of modern data, MCMC results for mode and central 68.3% CL interval
- Shape of cross section near threshold described by Mukhamedzhanov and Nunes, NPA 708, 437 (2002)
- We take account of fact that only $l = 0$ and $l = 2$ incoming partial waves can contribute to the $E1$ capture, finding

$$S(E) = \frac{Q}{E+Q}\left[s_0 (1 + aE + \ldots)^2 + s_2 \left(1 + \frac{4\pi^2 E}{E_G}\right)\left(1 + \frac{16\pi^2 E}{E_G}\right)(1 + cE + \ldots)^2 \right]$$

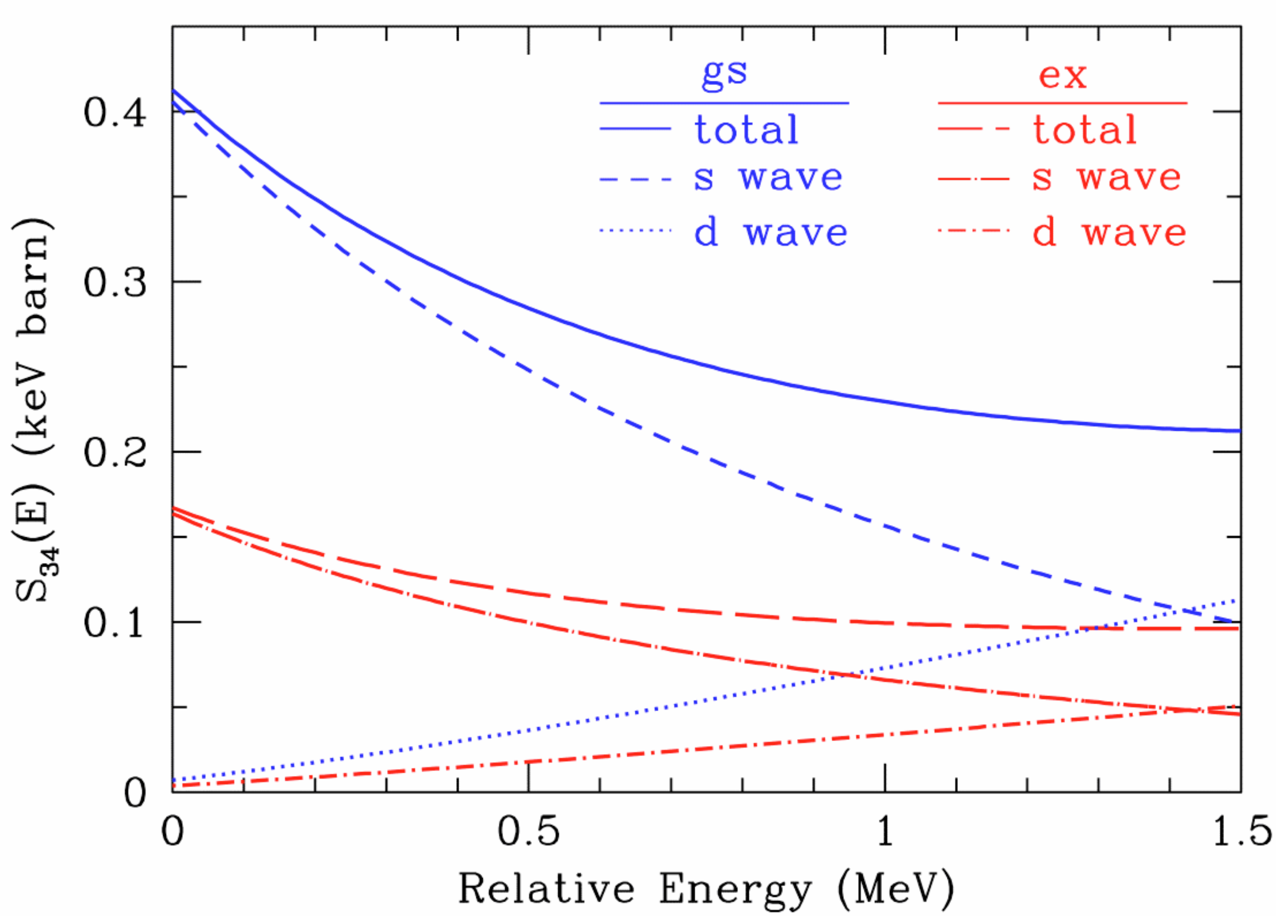
Modern Branching Ratio Data



- Precise data for the branching ratio between the ground and first excited state transitions permit simultaneous fit of both transitions using same form but different parameters
- Modern data allow simultaneous determination of 3 parameters, s_0, s_2, & a for each transition; 4 parameter fit was not higher quality, hence $c \equiv 0$

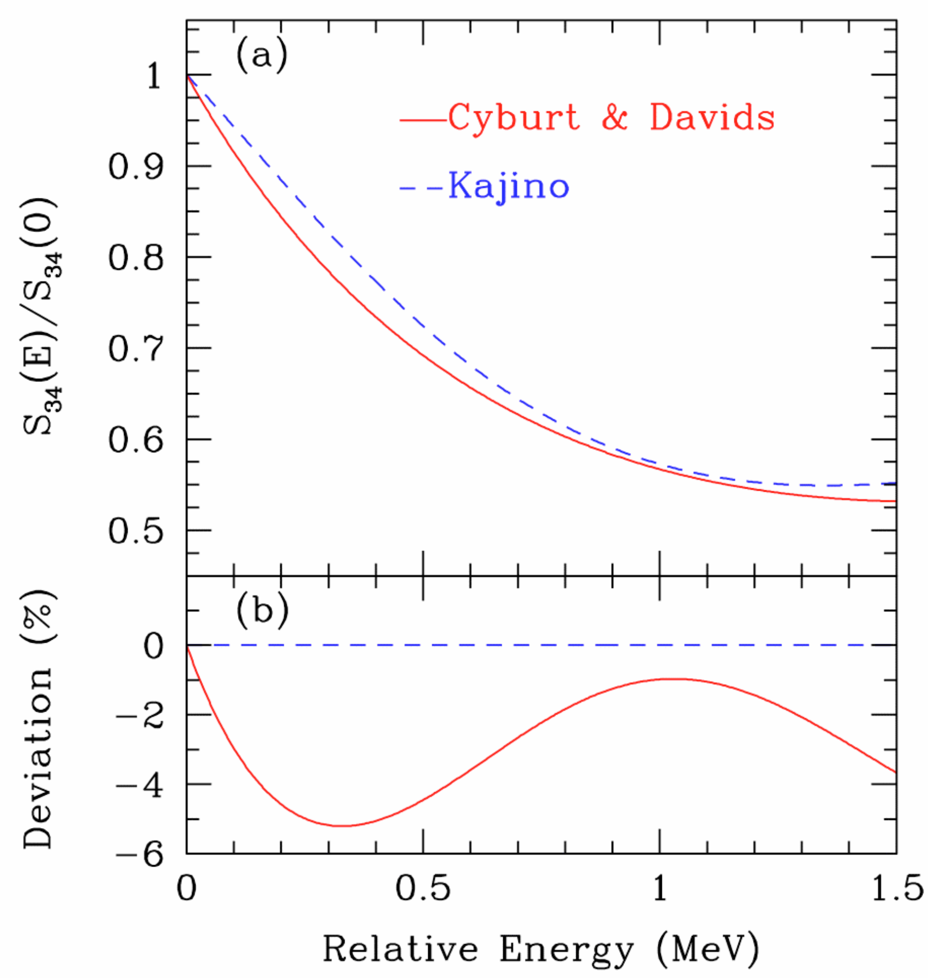
$$S(E) = \frac{Q}{E+Q}\left[s_0 (1 + aE + ...)^2 + s_2 \left(1 + \frac{4\pi^2 E}{E_G}\right)\left(1 + \frac{16\pi^2 E}{E_G}\right)(1 + cE + ...)^2 \right]$$

Partial Wave Contributions



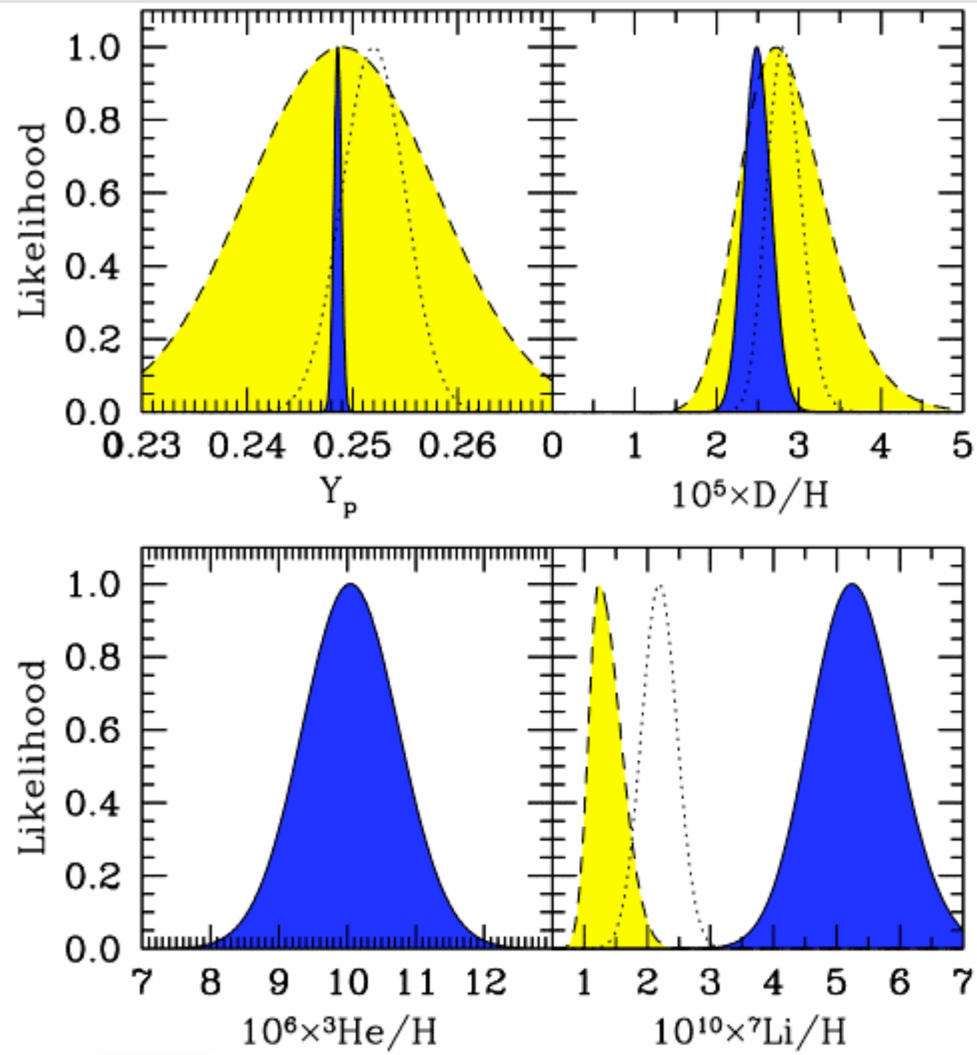
Comparison with Cluster Model

- Significant differences with most commonly used cluster model found
- Data are able to determine shape without dependence on structure model
- $S_{34}(0) = 0.580 \pm 0.043$ keV b at the 68.3% CL (± 7.4%)
- $S_{34}(0) = 0.580 \pm 0.054$ keV b at the 95.4% CL (± 9.3%)
- Size of latter smaller than 68.3% CL interval from 1998 RMP evaluation of solar nuclear fusion cross sections
- Cyburt and Davids, ArXiv: 0809.3240 [nucl-ex], to be published in Phys. Rev. C



Comparison of Observations with BBN Predictions

- Using this $S_{34}(E)$, the BBN prediction based on the WMAP5 universal mean baryon density (± 2.7%) differs from the primordial ^{7}Li abundances inferred from globular cluster stars and halo field stars by 4.2σ and 5.3σ respectively [Cyburt, Fields, & Olive, JCAP 11, 012 (2008)]
- Unresolved, this discrepancy shakes the foundations of "precision" cosmology (one of the pillars!)
- Assumptions of ΛCDM cosmology must be questioned (effects of inhomogeneities, Copernican principle, alternative gravitational theories?)



Summary

- Improvements in precision of solar neutrino flux measurements and observations of cosmic microwave background radiation require renewed attention to nuclear uncertainties, namely radiative capture rates, for which simplicity of transition operator implies particularly direct connection between structure and reactions
- $^{7}Be(p,\gamma)^{8}B$ has been measured very precisely once, and this measurement dominates other radiative capture measurements and ANC determinations which are 1-2σ lower; TRIUMF experiment aimed at confirming ANC determination of Texas A & M via $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ and $^{12}C(^{8}Li,^{7}Li)^{13}C$ still under analysis; neutrino flux agreement with standard solar model good
- $^{3}He(\alpha,\gamma)^{7}Be$ has been measured precisely several times since turn of century; quality of data permit determination of reliable, structure model-independent best value and confidence interval using MCMC method that takes account of discrepancies among systematic uncertainty-dominated data sets
- The 5σ disagreement of primordial Li abundances inferred from observations of field halo stars with precise BBN predictions made possible by the improvements in knowledge of $^{3}He(\alpha,\gamma)^{7}Be$ and CMB measurements raises serious doubts about the assumptions of the standard ΛCDM cosmological model

Derek Howell,
Simon Fraser University and TRIUMF

Richard Cyburt,
Joint Institute for Nuclear Astrophysics &
National Supercondicting Cyclotron Laboratory,
Michigan State University