Transfer and breakup reactions involving ^{7}Be at ISOLDE

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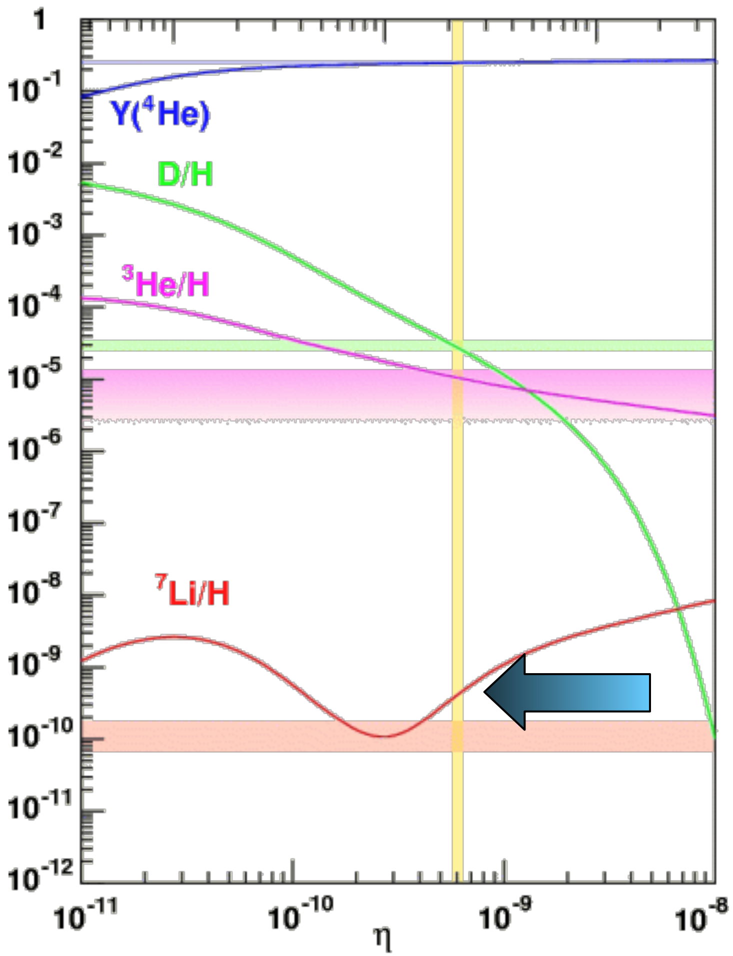
ISOLDE Workshop and Users meeting, December 5-6, 2019

The Cosmological ^{7}Li problem



Observed values represented by bands, predicted values represented by lines.

$\eta_b^{WMAP} = n_B/n_\gamma = 6.079(9) \times 10^{-10}$ ratio of the baryon and photon number densities

The primordial abundance of ^{7}Li inferred from observational data ~ factor 3 below the abundance predicted by BBN theory using **baryon-to-photon** ratio η from measurements of **cosmic microwave background**.

BBN theory using η_b^{WMAP}: $^7\mathrm{Li/H} = 5.12\,^{+0.71}_{-0.62} \times 10^{-10}$

Observationally extracted: $^7\mathrm{Li/H} = 1.58\,^{+0.35}_{-0.20} \times 10^{-10}$

Serious discrepancy

Good agreement of BBN predicted abundances with observations for ^{2}H, ^{3,4}He.

For decades, one of the **important unresolved problems**

Nuclear physics aspect of the primordial lithium problem

Possible solutions - **Nuclear**/**Astrophysical**/**Physics beyond standard BBN**

Improved understanding of stellar depletion mechanism of ^{7}Li? It is very difficult to justify enough destruction of ^{7}Li *Ryan (1999)*

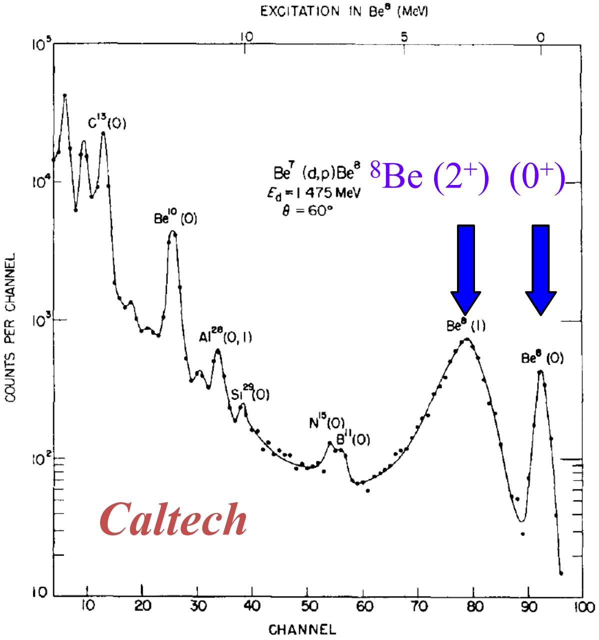
Destruction of mass-7 nuclides through interaction with WIMP particles, unstable particles in the early universe that could have affected BBN.
Cyburt (2006), Goudelis (2016) Fields (2011)

In the condition of BBN, ^{7}Li is effectively destroyed through ^{7}Li(p,α)^{4}He, to a level that the majority of the surviving ^{7}Li is produced indirectly through the decay of ^{7}Be ($T_{1/2}$ = 53.12 d) after the cessation of nucleosynthesis.

Nuclear aspect of the ^{7}Li problem are therefore the reaction rates of ^{7}Be production, mainly **^{4}He(^{3}He,γ)^{7}Be** and its destruction through **^{7}Be(n,p)^{7}Li**, **^{7}Be(n,α)^{4}He** and **^{7}Be(d,p)2α**.

Incomplete nuclear physics input for BBN calculations: Can resonant enhancement alleviate this discrepancy?

R. W. Kavanagh
Nuclear Physics 18 (1960) 492



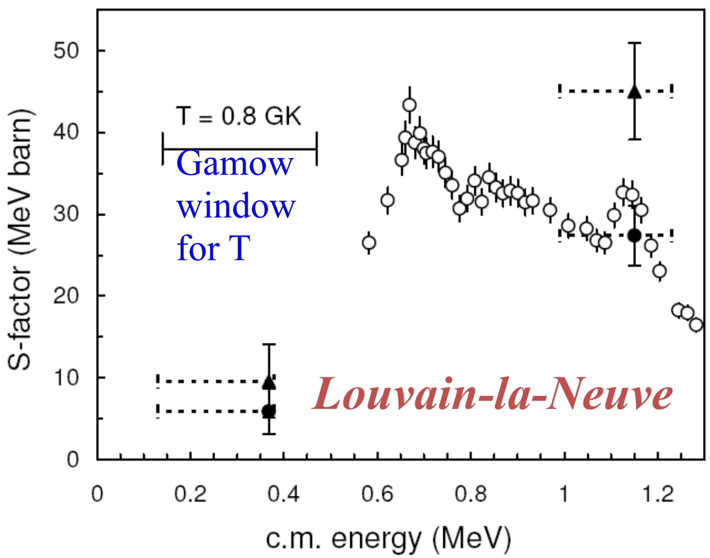
^{7}Be(d,p)^{8}Be*$\rightarrow 2\alpha$ (Q = 16.490 MeV)

upto E_x= 11 MeV

E_{cm} = 0.6 – 1.3 MeV, reaction rate relied on an extrapolation to lower energies. Differential cross section multiplied by 4π (assuming isotropic angular distribution) and arbitrarily by 3 (to estimate contribution of **higher energy ^{8}Be states**) *Parker (1972)*

An experiment performed at lower energy found a significantly reduced cross-section in the BBN Gamow window compared to Parker's estimate.

Angulo et al
Astrophys. Jour. 630 (2005) L105



$^{7}Be(d,p)^{8}Be^{*} \rightarrow 2\alpha$ (Q = 16.490 MeV)

(E_{7Be}= 5.55, 1.71 MeV) **upto E_x= 13.8 MeV**

○ Kavanagh (1960)

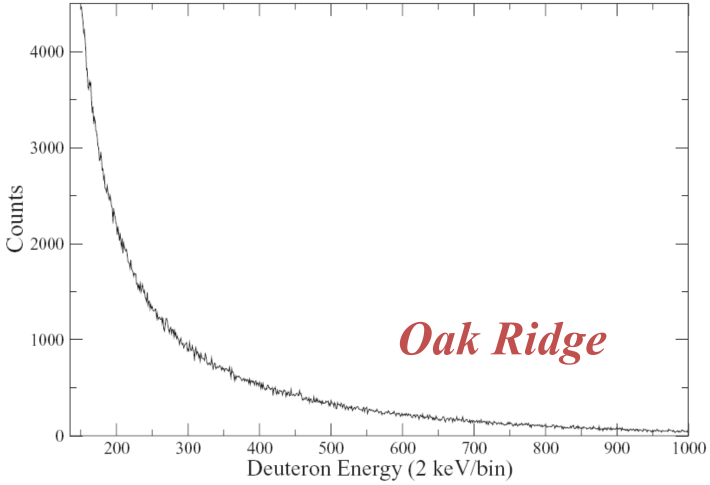
● Angulo (2005), $^{8}Be^{*}$ (g.s + 1st ex.s)

Cross section overestimated previously

Small angular range covered (~ 7-17 deg) and full isotropy for proton angular distribution **assumed** in calculating average cross section

Other works suggested resonant enhancement through a 16.7 MeV (5/2+) resonance state in ^{9}B *Cyburt (2005), Chakravorty (2011)*

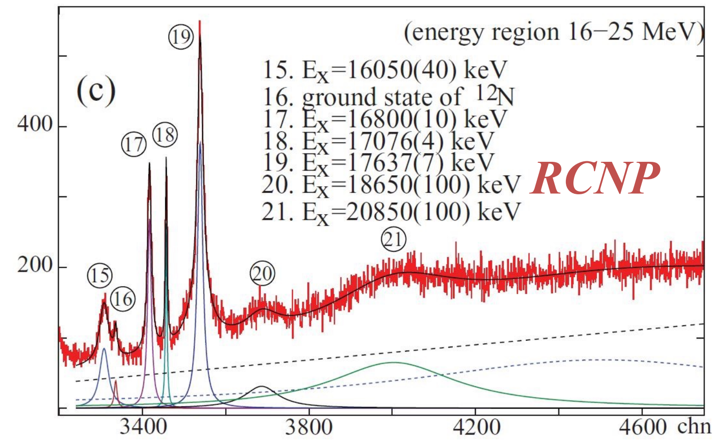
O'Malley et al
Phys. Rev. C 84, 042801(R) (2011)



^{2}H(^{7}Be,d)^{7}Be (E$_{7Be}$= 10 MeV)

No evidence for a resonance observed

Scholl et al Phys. Rev. C 84, 014308 (2011)

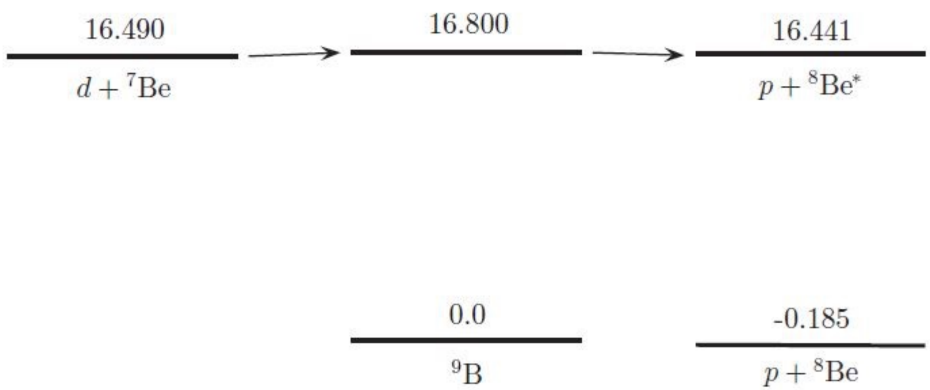


High resolution study of ^{9}Be(^{3}He,t)^{9}B, E= 140 MeV/A, the state is strongly excited.

Energy: **16.800(10) MeV**, width: 81(5) keV

Without experimental knowledge on its decay properties, conclusion about resonant enhancement to the d + ^{7}Be reaction remain uncertain.

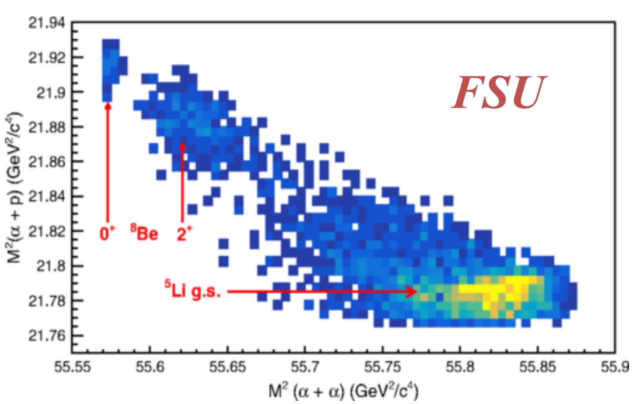
Proposed ^{7}Be destruction mechanism, d + ^{7}Be → ^{9}B* → p + ^{8}Be*



O.S.Kirsebom et al., PRC 84, 058801 (2011)

The 16.8 MeV state in ^{9}B formed by fusion of ^{7}Be + d and decays by proton emission to a **highly excited state in ^{8}Be**, 16.626 MeV above the ground state, which subsequently breaks up into two α particles.

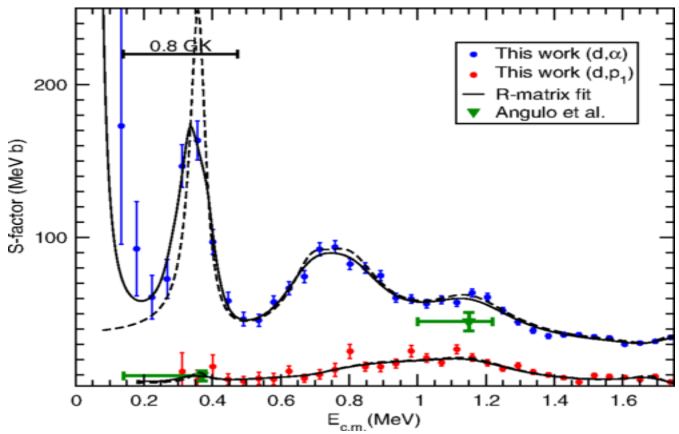
However, recent work (2019) shows, d + ^{7}Be → 2α + p may proceed through intermediate state in **^{8}Be** by ^{7}Be(d,p)^{8}Be(α)^{4}He or **^{5}Li** by ^{7}Be(d, α)^{5}Li(p)^{4}He sequence, or in a "democratic" three-particle decay of the ^{9}B compound system.

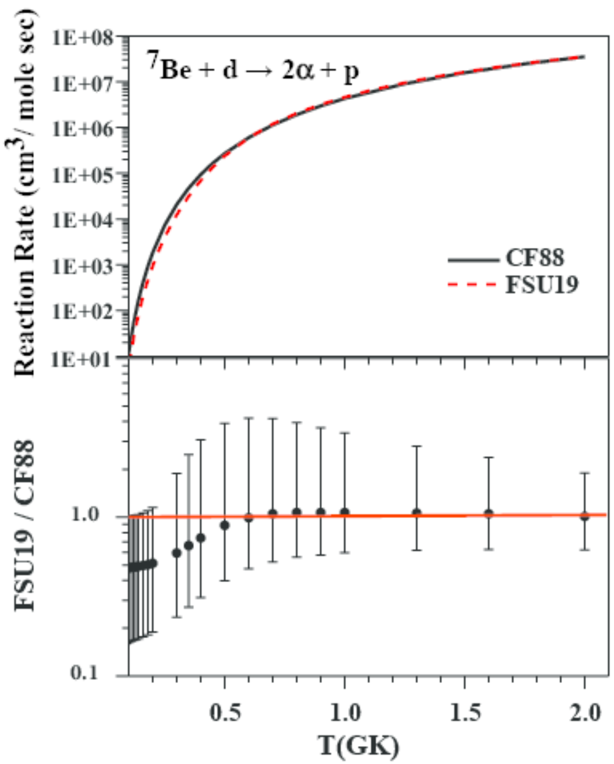


Rijal et al Phys. Rev. Lett. 122 (2019) 182701

^{7}Be + d measured at E_{cm} ≈ 0.2 – 1.5 MeV, measured cross sections dominated by the (d,α) channel towards which prior experiments mostly insensitive.

Rijal et al
Phys. Rev. Lett. 122 (2019) 182701





A new resonance at 0.36(5) MeV observed which reduces the predicted abundance of primordial ^{7}Li but not sufficiently to solve it. Additional experiments with improved statistics needed to reduce the **uncertainty in the resonance energy**. R-matrix analysis : 16.849 (5) MeV, 5/2+ state in ^{9}B?

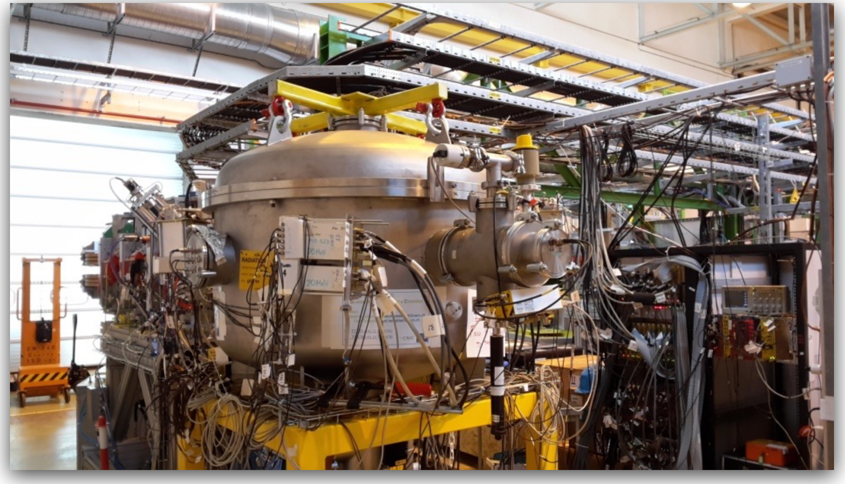
Moshe Gai
arXiv:1908.06451v1 [nucl-ex] (2019)

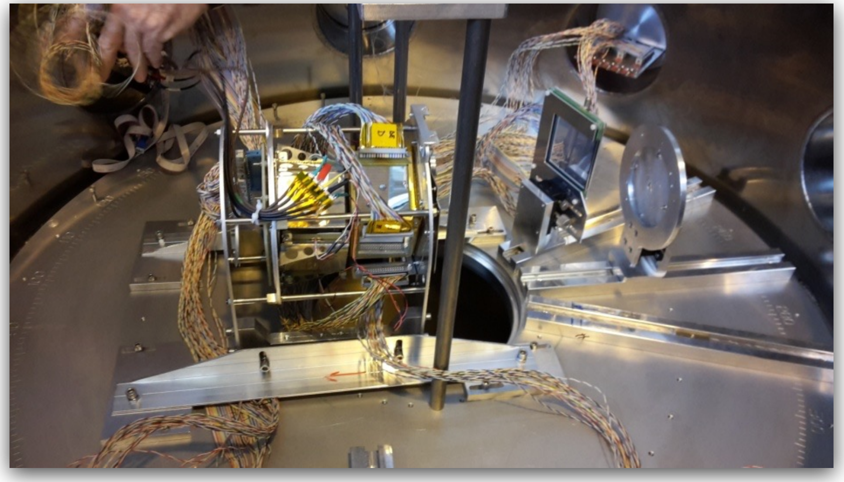
BBN d + ^{7}Be rate (CF88) and Rijal (FSU19) rates are hardly different

Speculation: Is it the same as the ^{9}B state at E_{cm} = 0.31(1) MeV by *Scholl (2011)*?

Experiment IS 554 @

5 MeV/u ^{7}Be on CH_2 (15 μm), CD_2 (15 μm) and ^{208}Pb (1 mg/cm^2) targets, beam intensity I ~ 5 x 10^5 pps



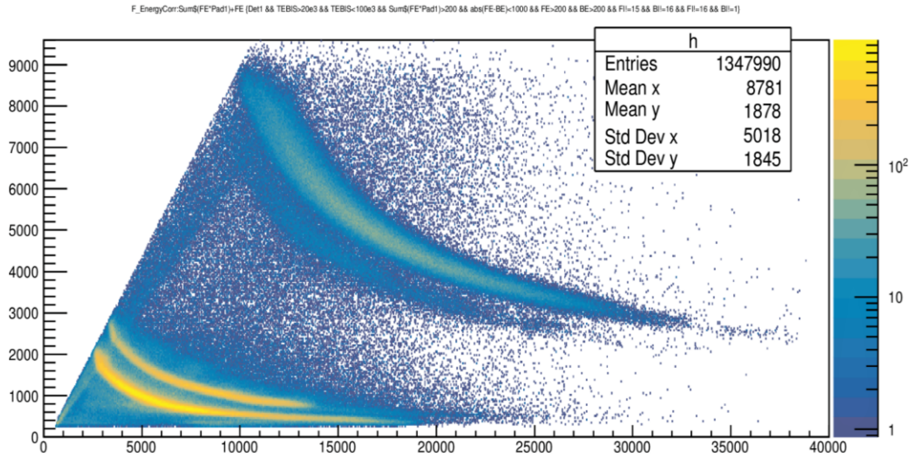


Charge particle detector setup

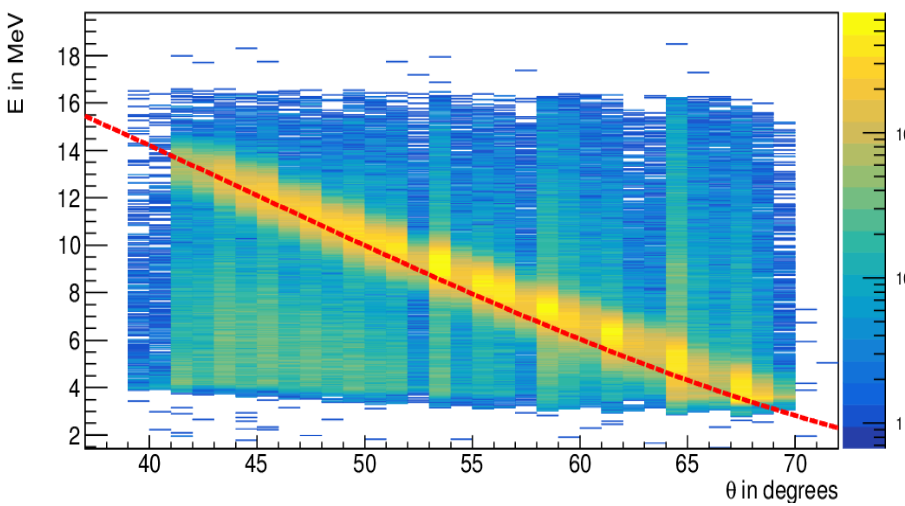
1 x S3 annular DSSD (24 x 32 strips, 1000 μm) covering front angles 8° – 25°
5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40° – 80°
2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 110° – 140°
The W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads

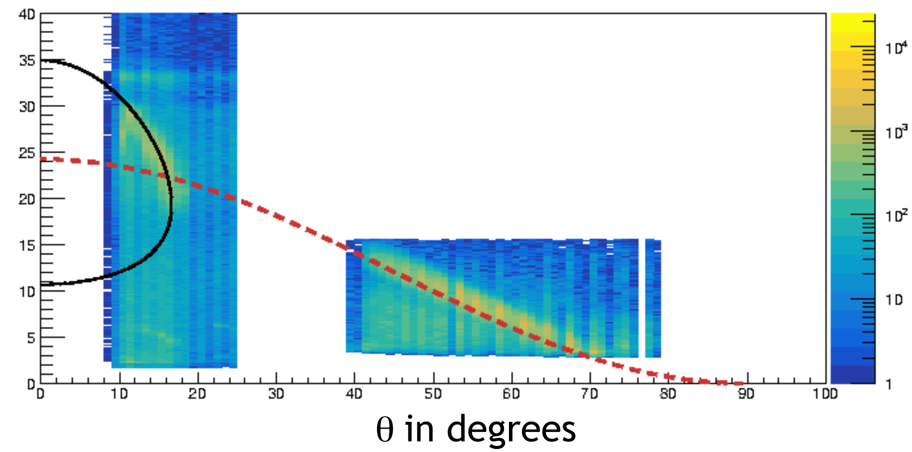
^{7}Be on CD_2

Preliminary



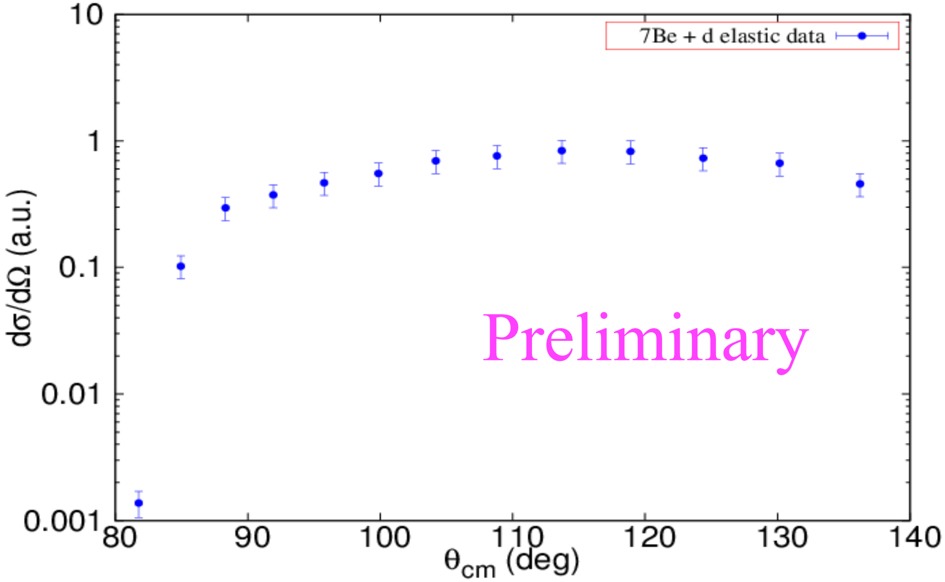
ΔE vs E_{tot} curve from ^{7}Be on CD_2 target in DSSD1. Angular correction applied on ΔE. Gates for energy matching applied.





$^{7}Be + d$ elastic scattering

^{7}Be + d elastic scattering



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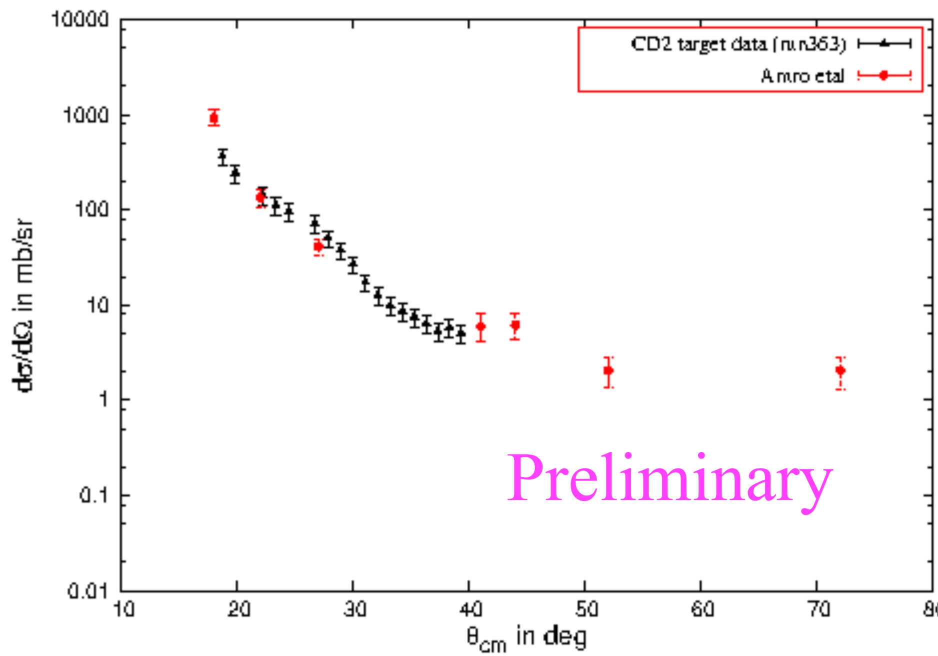
Data only from the pentagon detectors

^{7}Be + ^{12}C elastic scattering

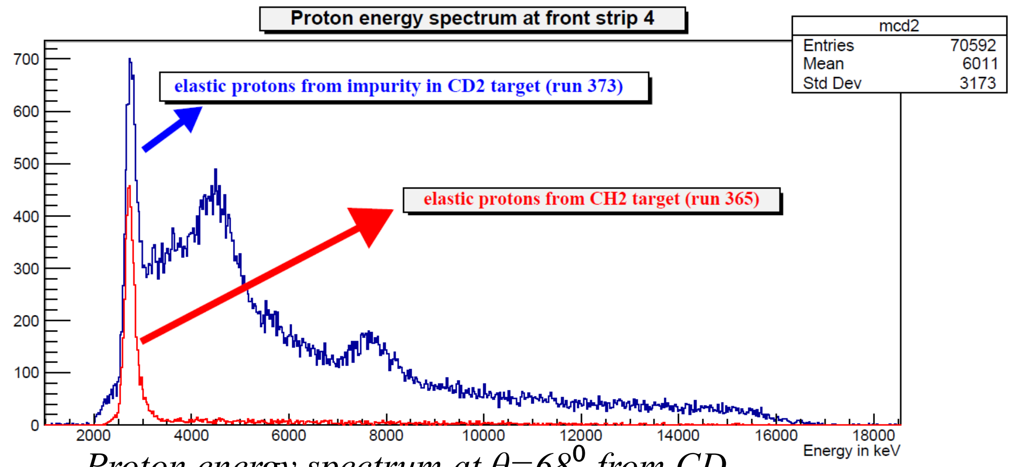
Data only from S3 detector



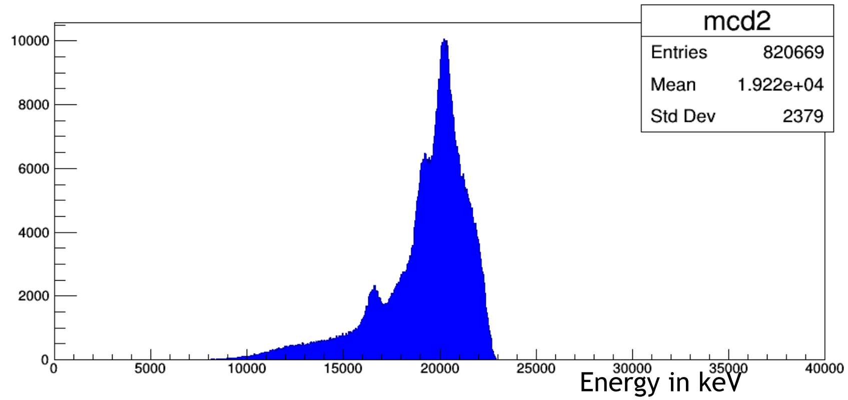
$^7Be(d,p)^8Be^*$ Preliminary

CD_2 target proton impurity (~ 2%). Elastic protons from the proton impurity overlaps with transfer protons.

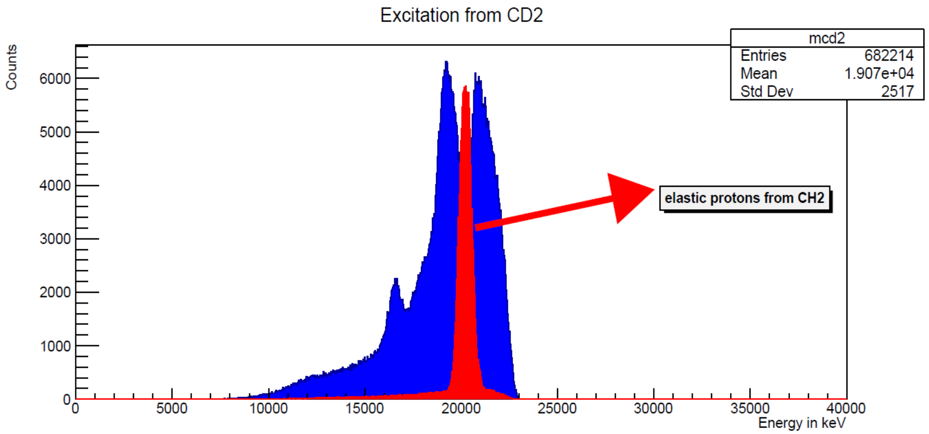
Elastic protons subtracted using 7Be runs on CH_2 target



Proton energy spectrum at $\theta=68^0$ from CD_2 and CH_2 target runs in DSSD1

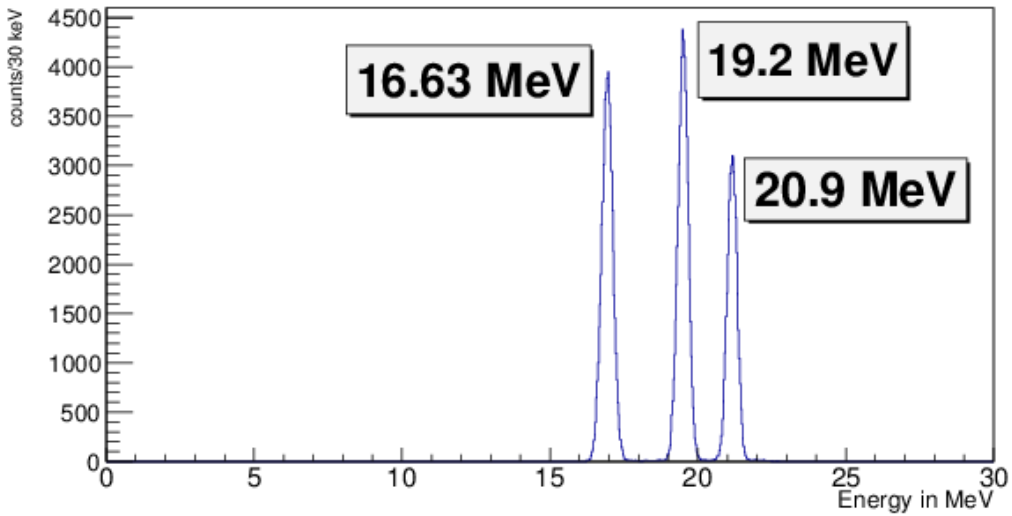


Excitation energy spectrum of $^8Be^*$ from CD_2 runs with proton impurity

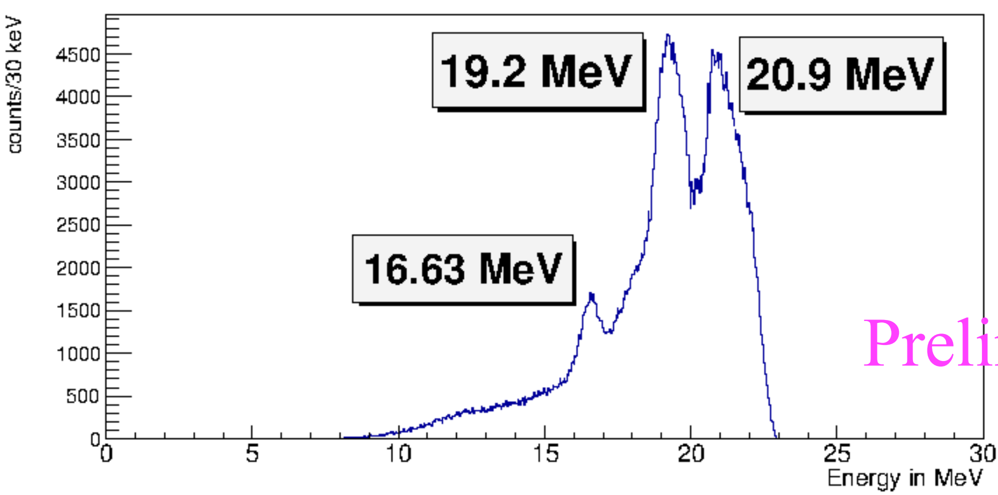


Excitation energy spectrum of $^8Be^*$ from CD_2 runs (in blue, after removing elastic protons) and CH_2 runs (in red)

^{8}Be excitation energy from pentagon detectors

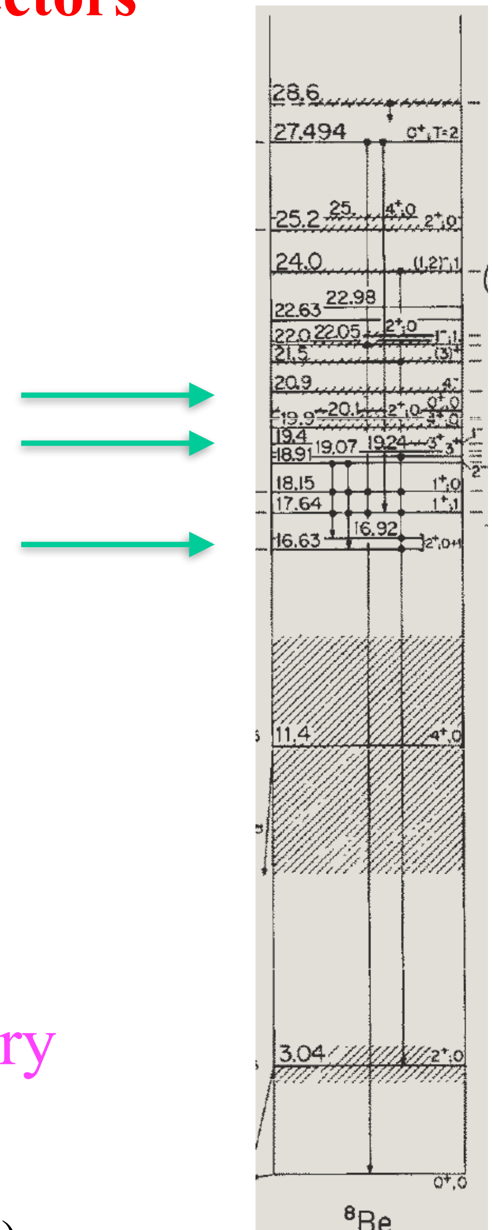


Excitation energy of 8Be* (simulations)

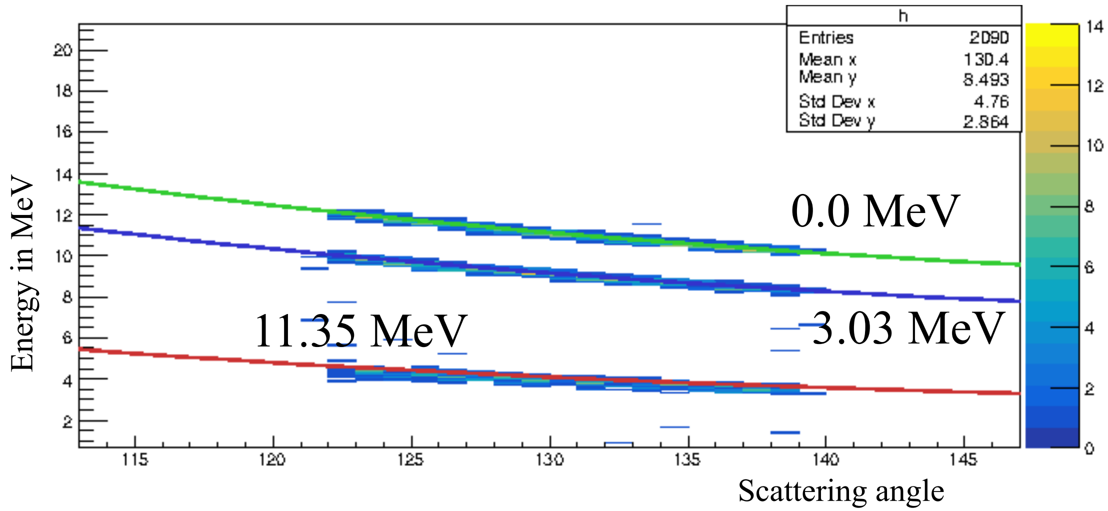


Preliminary

Excitation energy of ^{8}Be* (after removing elastic protons)



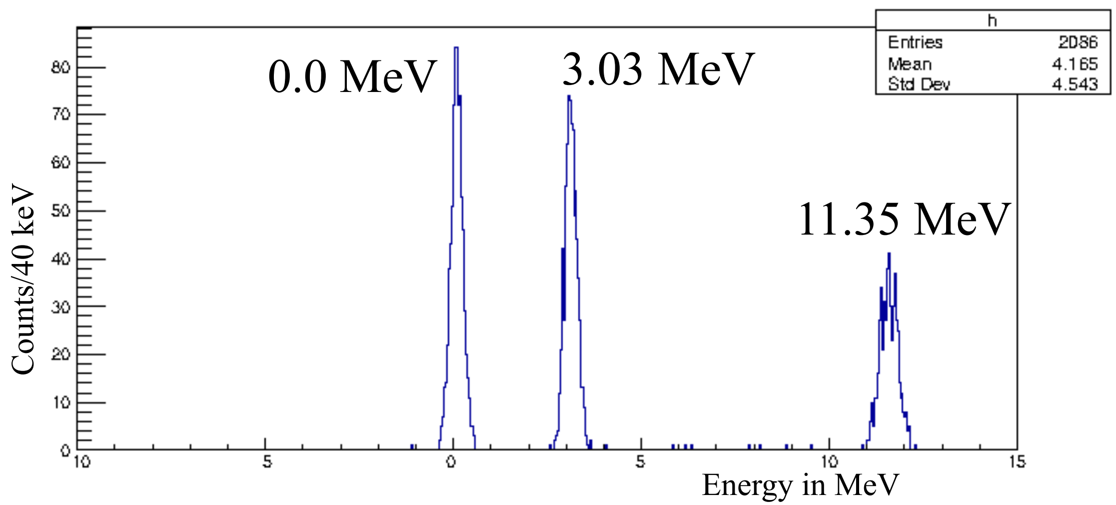
^{8}Be excitation energy from BB7 detectors



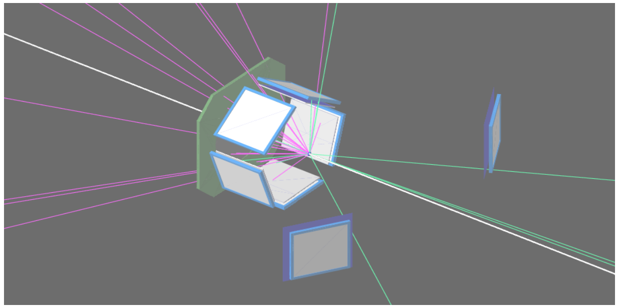
Energy vs theta of the protons of ^{7}Be(d,p)^{8}Be*

Simulations

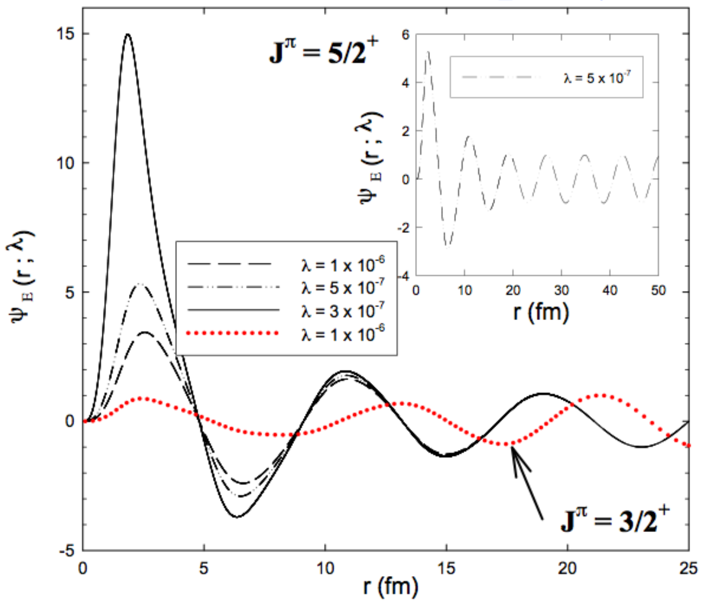
Analysis of back angle data going on

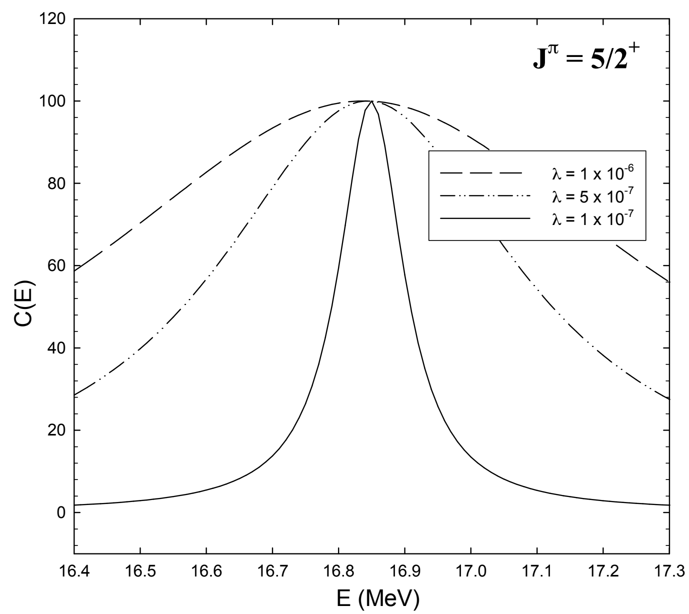


Excitation energy of ^{8}Be*



Detection of 16.84 MeV (5/2+) resonance state from $^7Be + d \rightarrow {}^9B$ using **supersymmetric quantum mechanics**





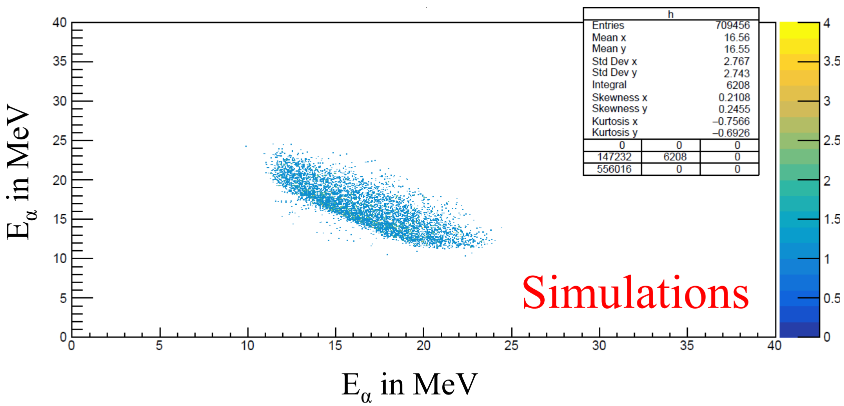
S. K. Dutta, D. Gupta, S.K. Saha

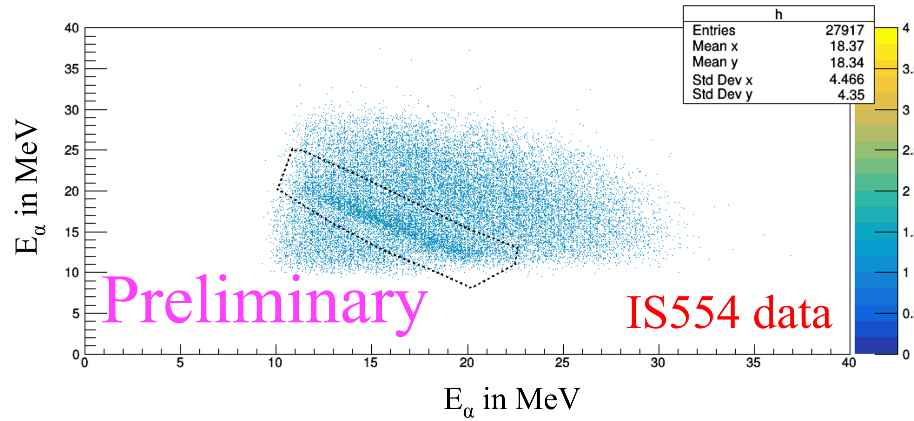
Phys. Lett. B 776, 464 (2018)
Jour. Phys. G: Nucl. Part. Phys. 41, 095104 (2014)

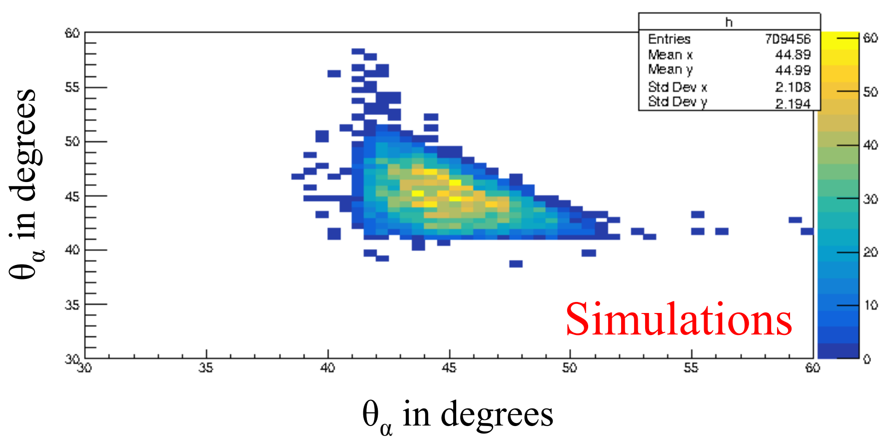
Unstable or unbound systems, with very shallow potentials, pose serious numerical challenges in detecting **resonance states**. We could successfully circumvent this problem by using supersymmetric quantum mechanics.

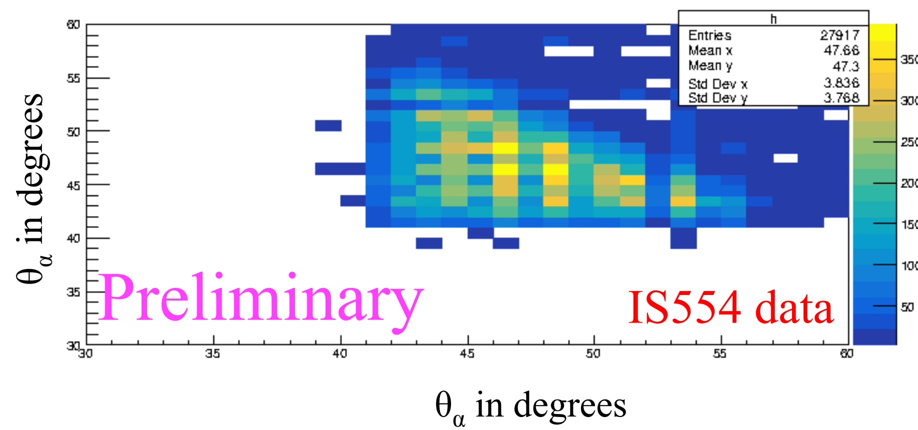
This transforms the shallow well to a deep well-barrier isospectral potential, generating **resonance state wave-function**. The resonance state energies obtained were found to be in excellent agreement with the experimental values.

α-α coincidence









Energy and angular correlations of coincident alphas detected by the pentagon DSSDs. Simulations show the energy correlation of the alphas emitted from the **16.63 MeV state of ^{8}Be**.

Outlook

Primordial ^{7}Li abundance essentially determined by the ^{7}Be production and destruction channel

The production channel ^{3}He(α,γ)^{7}Be leads to an overall uncertainty ~ 7%. *Broggini (2012)*

The destruction channel ^{7}Be(*d,p*)2α via the 16.8 MeV state in ^{9}B is unable to enhance the reaction rate by the amount needed to resolve the cosmological lithium problem. Speculation on the new resonance at **0.36 MeV** corresponding to the **16.8 MeV state of ^{9}B**. The decay properties of the state remains to be known.

^{7}Be destruction involving neutrons ^{7}Be(n,p)^{7}Li, ^{7}Be(n, α)^{4}He does not solve the anomaly. *Damone (2018), Barbagallo (2016)*

It is **not yet time for a firm conclusion** about the anomaly from our data. However, the indications are that it may not be possible to find a solution from nuclear physics alone.

It would be interesting in future to see if the lithium problem truly points to ***new fundamental physics.***

IS 554 collaboration

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