High-lying resonances in the ^{7}Be + d reaction

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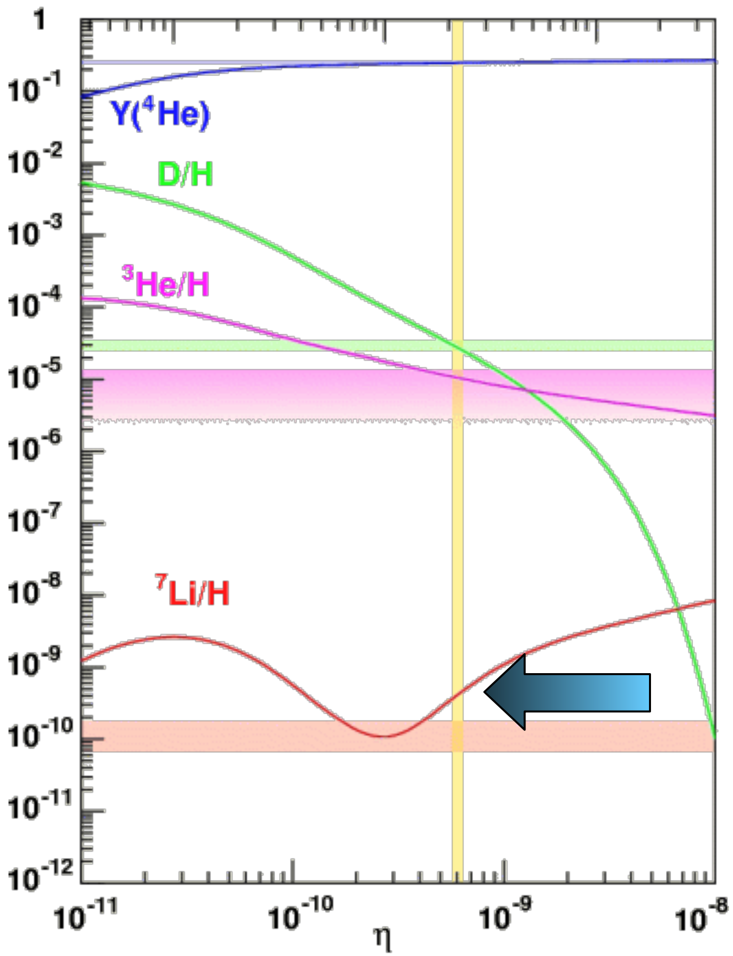
The standard **Big Bang** model of the Primordial Universe is very successful in accounting for the observed relative abundance of the light elements.

The only astrophysical input to the Big Bang Nucleosynthesis (BBN) calculation is the **baryon density** of the Universe, which is now known precisely.

However, BBN theory fails to predict correctly the **observed abundance of ^{7}Li.**

The Cosmological ^{7}Li problem



BBN theory over predicts the abundance of ^{7}Li by about a factor ~ 3 and up to five sigma deviation from observation. The theory uses the **baryon-to-photon** ratio η from measurements of **cosmic microwave background**.

BBN theory using η: $\frac{^7\text{Li}}{\text{H}} = 5.12^{+0.71}_{-0.62} \times 10^{-10}$

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

Serious discrepancy

Observed values represented by bands, predicted values represented by lines

$\eta = n_B/n_\gamma = 6.079(9) \times 10^{-10}$

baryon-to-photon ratio

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

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

Nuclear physics aspects of the primordial lithium problem

Astrophysical solutions

Improvements in the observationally inferred primordial lithium abundance. Lithium may be destroyed in metal-poor stars through diffusion and turbulent mixing. *Korn, Nature (2006); Ryan (1999)*

Physics beyond standard BBN

Destruction of mass-7 nuclides through interaction with WIMP particles, unstable particles in the early universe that could have affected BBN. Existence of ^{8}Be as a bound nuclide during BBN. Interpretations assumed nuclear reaction rates known accurately *Goudelis (2016), Coc (2012), Fields (2011), Cyburt (2006)*

Nuclear physics

In the condition of BBN, ^{7}Li is effectively destroyed through **^{7}Li(p,α)^{4}He**, so that 95% of the primordial ^{7}Li is the by-product of the electron capture β-decay of the primordial ^{7}Be after the cessation of nucleosynthesis.

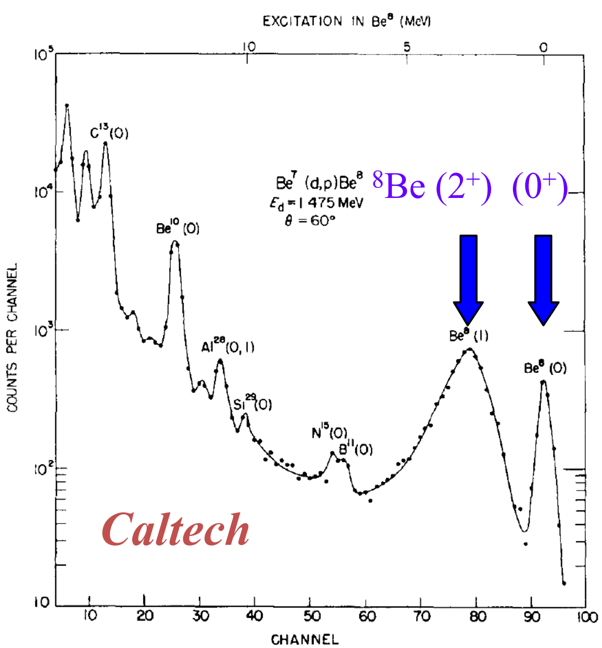
Nuclear aspects of the ^{7}Li problem would involve the reaction rates of ^{7}Be production, mainly **^{3}He(α,γ)^{7}Be** and its destruction through **^{7}Be(n,p)^{7}Li**, **^{7}Be(n,α)^{4}He** and **^{7}Be(d,p)2α**.

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

It has been argued that the ^{7}Li discrepancy could be resolved, if the ^{7}Be(d,p) reaction rate is substantially larger than previously considered.

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

^{7}Be(d,p)^{8}Be*→2α (Q = 16.674 MeV)



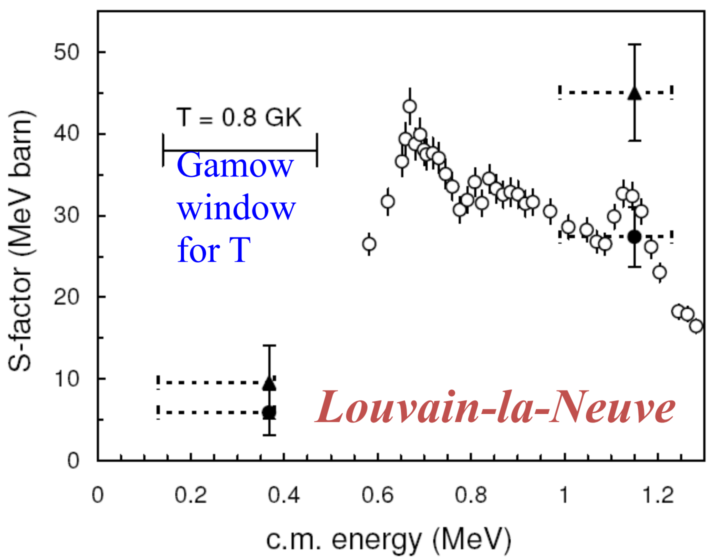
Experimental data at cm energies of 0.6 – 1.3 MeV. The reaction rate relied on an extrapolation to lower energies. Protons corresponding to the **^{8}Be 0^{+} g.s and 1st excited state (3.03 MeV, 2^{+})** were detected, up to excitation energies of 11 MeV.

Lacking complete angular distributions, these data were converted to total cross section by multiplying by (1) 4π and (2) a factor of ~ 3 to take in to account contributions from **higher excited states in ^{8}Be.** A constant S-factor ~ 100 MeV-barn was adopted. *Parker (1972)*

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

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

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



- ○ Kavanagh (1960)
- ● Angulo (2005), data includes contribution from the g.s + 1st excited state of ^{8}Be only
- ▲ Angulo (2005) Total S-factor

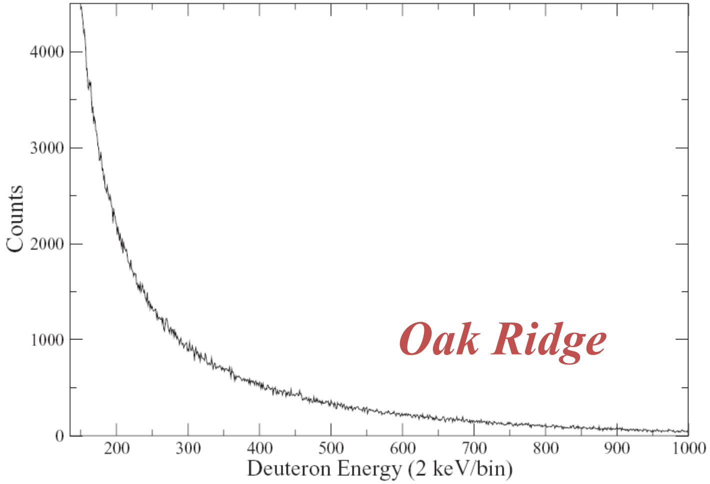
Cross section was measured at E = 5.55, 1.71 MeV, up to excitation energies in ^{8}Be of 13.8 MeV. In addition to feeding of the g.s and 1st ex states of ^{8}Be, able to observe **higher energy levels** mainly through the broad 11.4 MeV (4^{+}) state.

Higher energy states not observed by *Kavanagh* contribute about 35% of the total S-factor. Reaction rate is smaller by a factor of ~2 at 1.0-1.23 MeV and by ~ 10 at energies relevant to BBN.

The **$^{7}Be(d,p)2\alpha$ S-factor** at BBN energies was not underestimated by Parker, but on the contrary, **overestimated.**

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

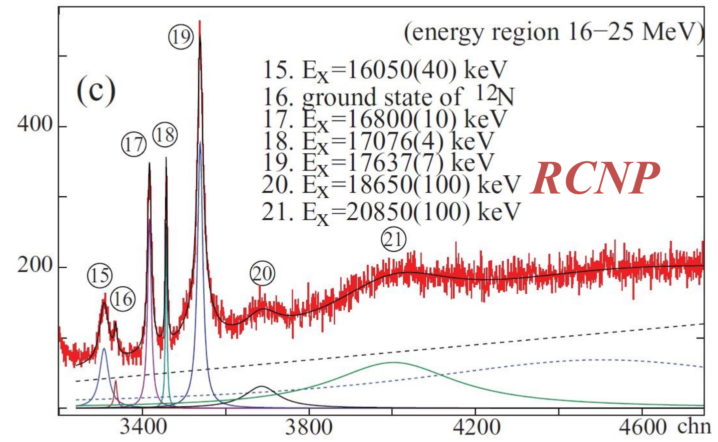
O'Malley et al
Phys. Rev. C 84, 042801(R) (2011)



^{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)

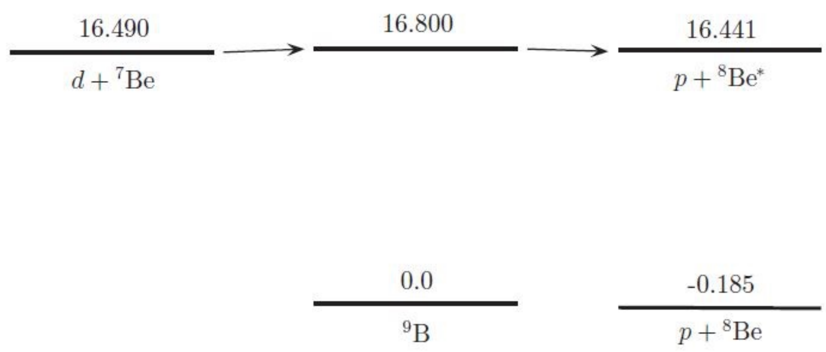


High resolution study of ^{9}Be(^{3}He,t)^{9}B, E= 140 MeV/A, the state is strongly excited.

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.

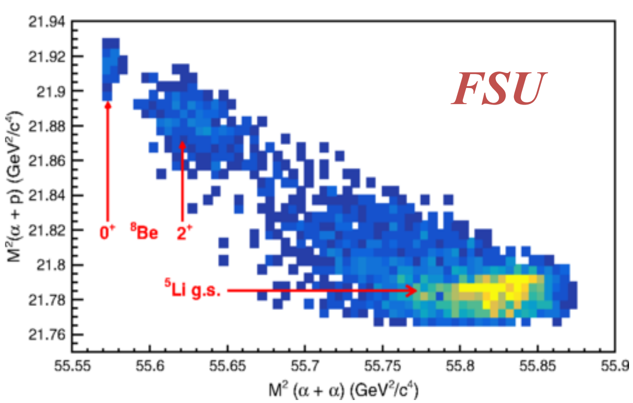
Proposed ^{7}Be destruction mechanism, d + ^{7}Be → ^{9}B* → p + ^{8}Be*



O.S.Kirsebom et al., Phys. Rev. C 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.

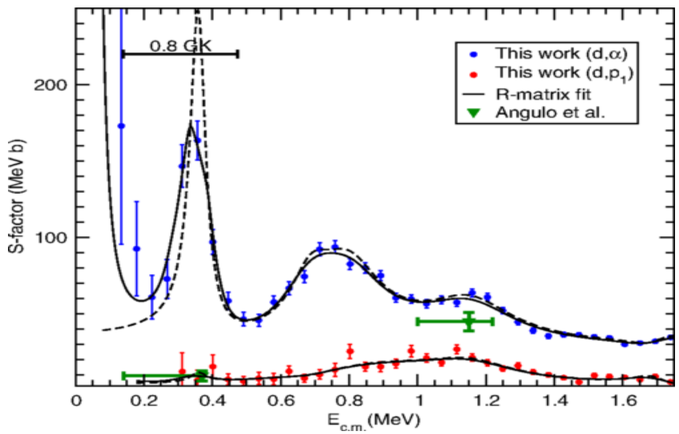
However, recent work (2019) shows, d + ^{7}Be → 2α + p may proceed through intermediate state in **^{8}Be** by ^{7}Be(d,p)^{8}Be(α)^{4}He or **^{5}Li** by ^{7}Be(d,α)^{5}Li(p)^{4}He sequence, or in a “democratic” three-particle decay of the ^{9}B compound system.



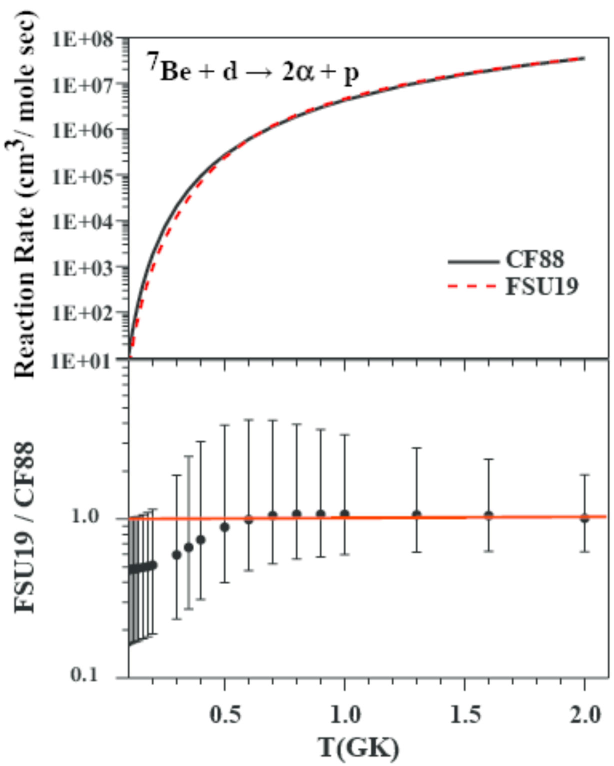
Rijal et al Phys. Rev. Lett. 122 (2019) 182701

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

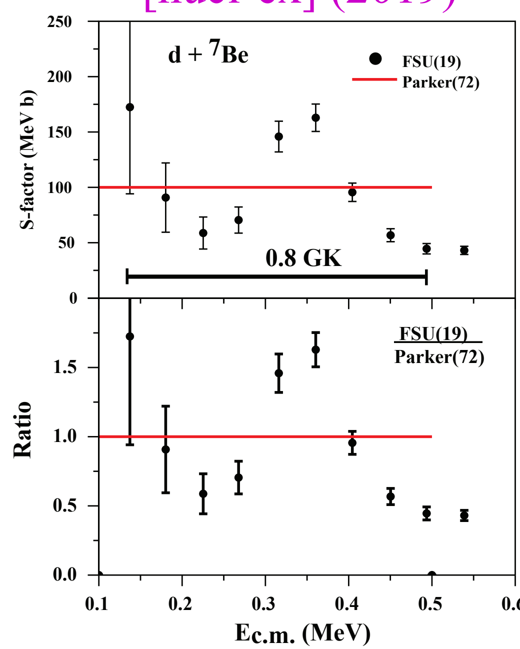
Rijal et al
Phys. Rev. Lett. 122 (2019) 182701



A new resonance at 0.36(5) MeV observed claims to **reduce 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)

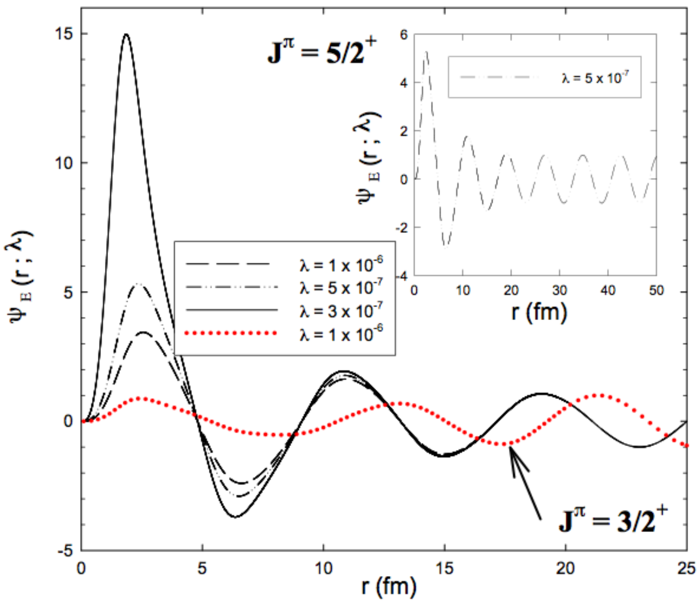


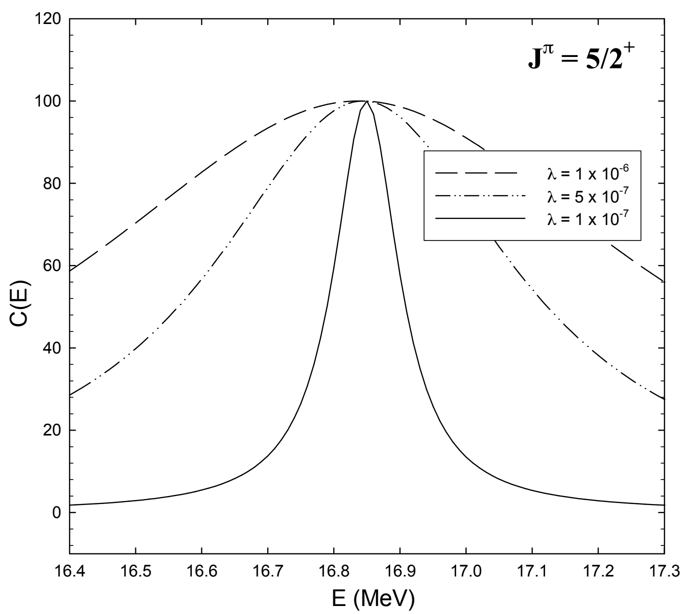
Speculation: Is it the same as the ^{9}B resonance at **16.80 MeV** from measurement of (^{3}He,t) reaction *Scholl (2011)*?

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

No reduction in ^{7}Li abundance.

Supersymmetric quantum mechanics to study the ^9B resonance





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

arXiv:2004.09105 [nucl-th] (2020)
Phys. Lett. B 776, 464 (2018)
J. Phys. G: Nucl. Part. Phys. 41, 095104 (2014)

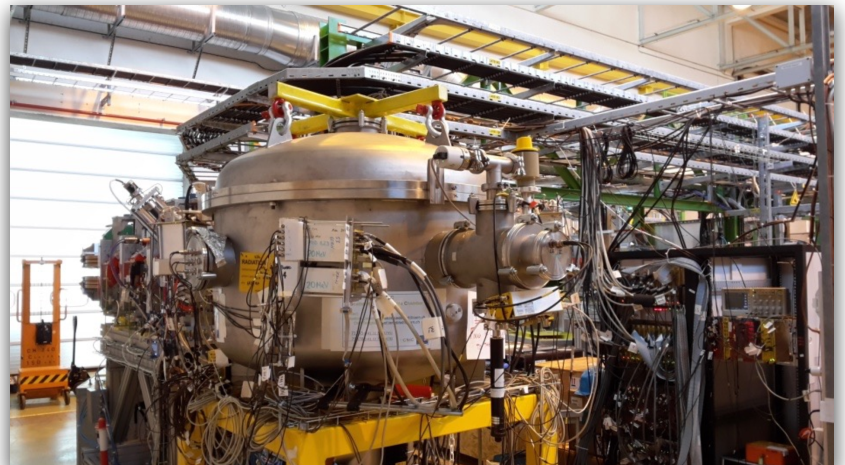
Unstable/unbound systems, with very shallow potentials, pose serious numerical challenges in detecting **resonance states**. We could successfully circumvent this problem by using supersymmetric quantum mechanics.

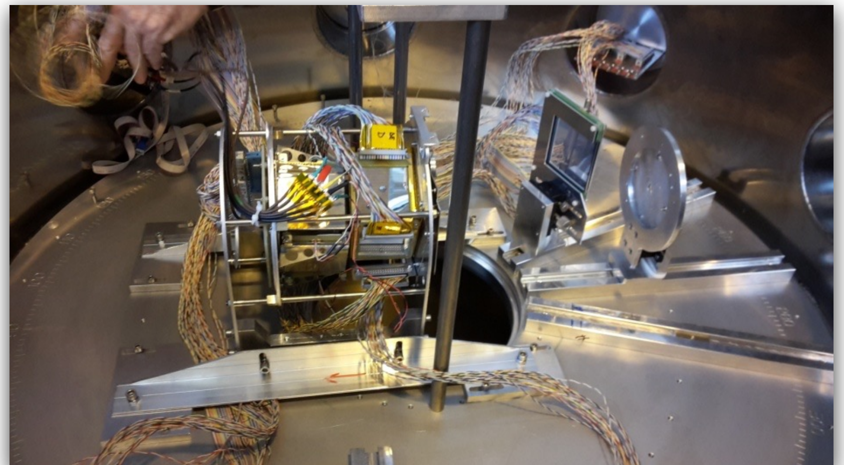
This transforms the shallow well to a deep well-barrier isospectral potential, generating **resonance state wave-function**. The resonance state energies obtained were found to be in excellent agreement with the experimental values.

Resonance energy E_R=**16.84 MeV ($5/2^+$)**
Width Γ = **69 keV**

Experiment IS 554 @ ISOLDE CERN

5 MeV/u ^{7}Be on CD_2 (15 μm), CH_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^o – 25^o

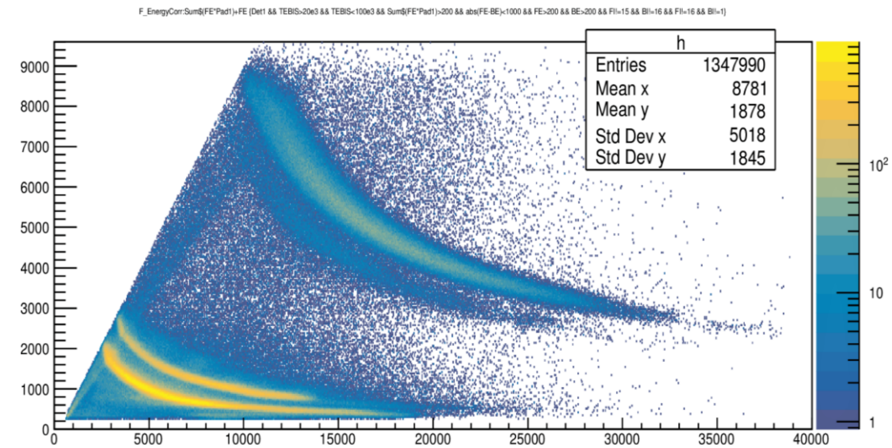
5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40^o – 80^o

2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 130^o – 170^o

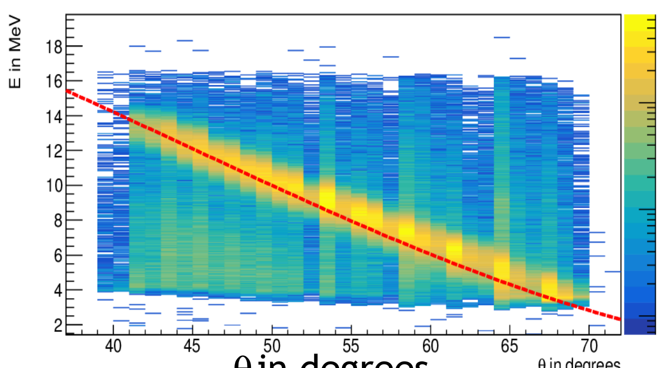
The W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads

^{7}Be on CD_2

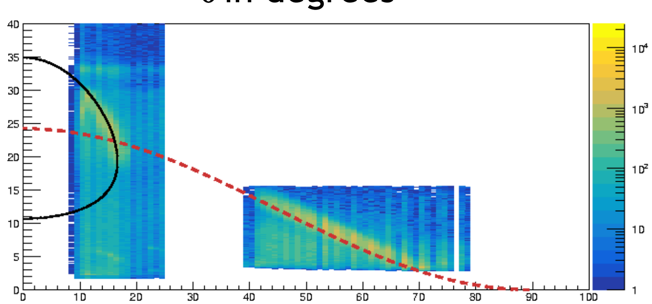
IS 554



ΔE vs E_{tot} spectrum from DSSD1

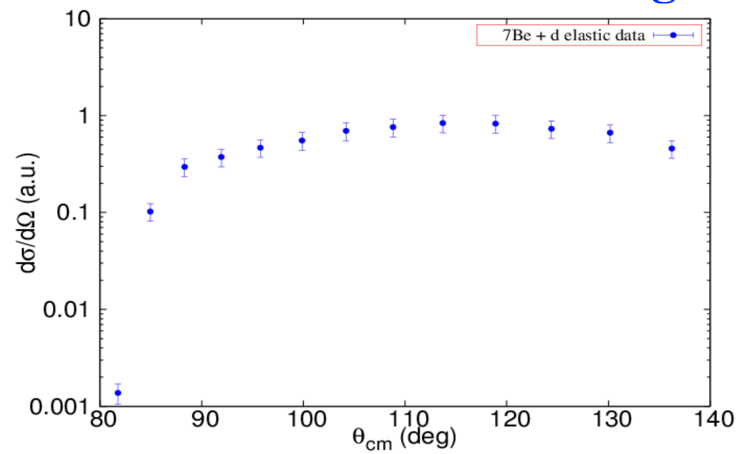


θ in degrees



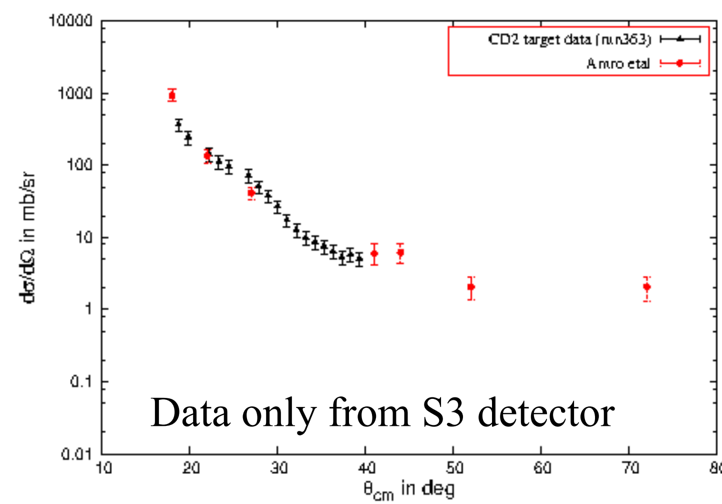
S3 DSSD1

^{7}Be + d elastic scattering



Data only from the pentagon detectors

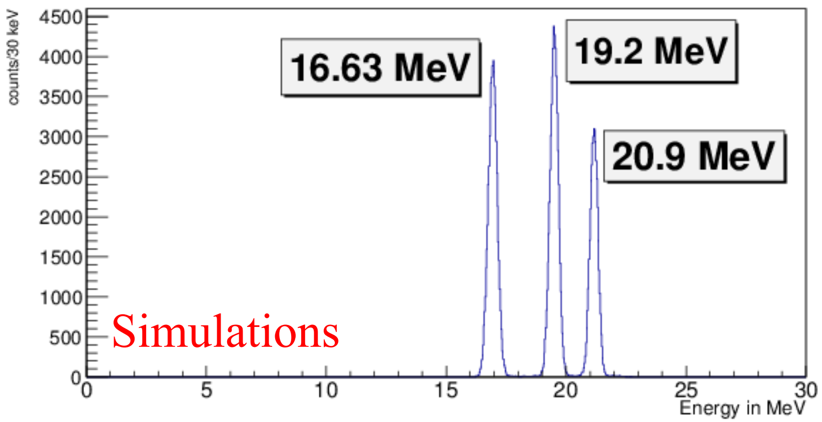
^{7}Be + ^{12}C elastic scattering



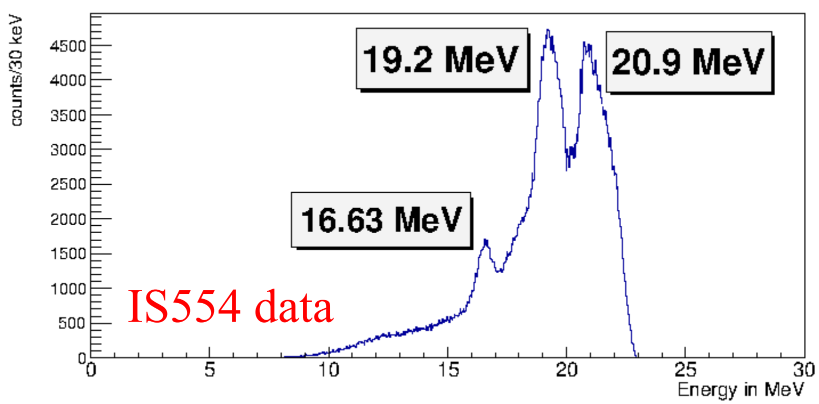
Data only from S3 detector

Transfer channels from ^{7}Be + d reaction

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



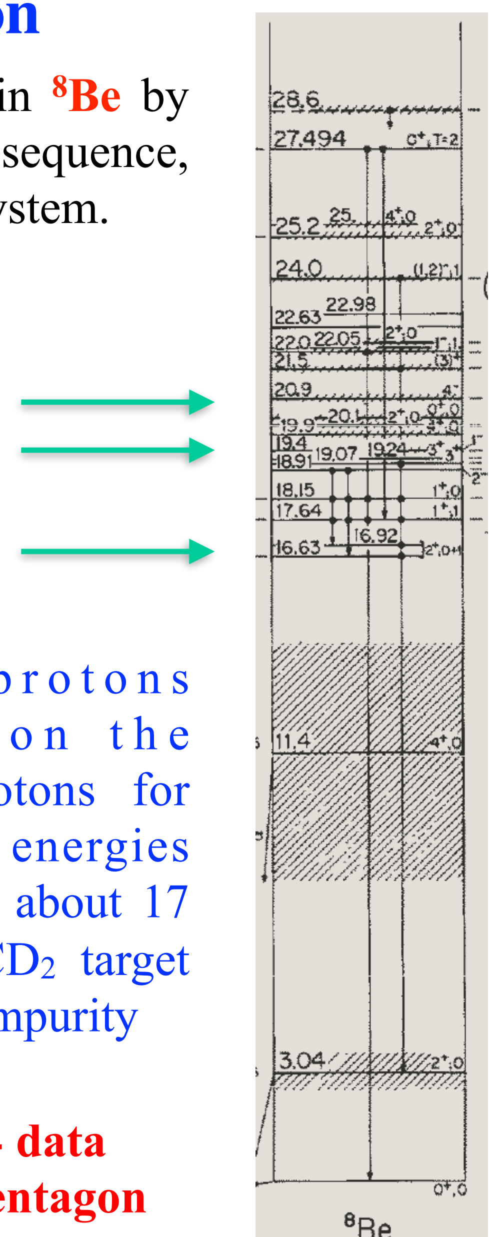
Excitation energy of ^{8}Be (simulations)



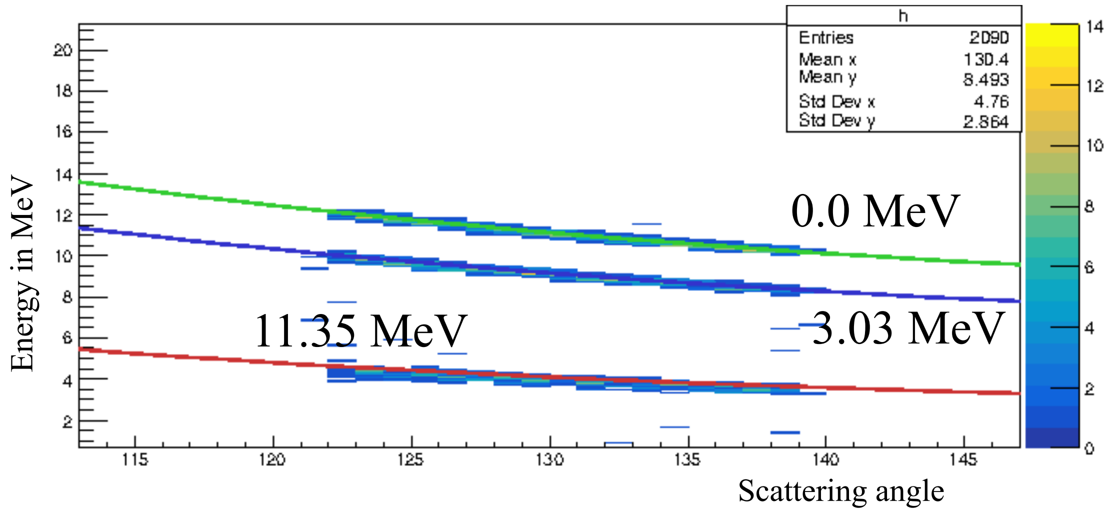
Excitation energy of ^{8}Be (after subtracting the contribution of elastic protons)

Elastic protons overlap on the transfer protons for excitation energies greater than about 17 MeV as CD_2 target has proton impurity

IS554 data from pentagon detectors

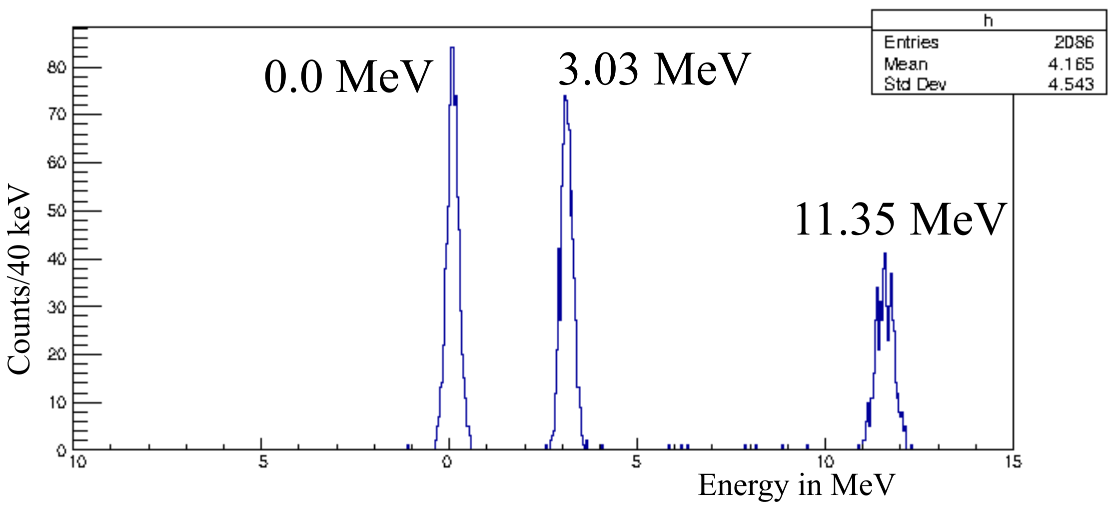


Back angle data from BB7 detectors



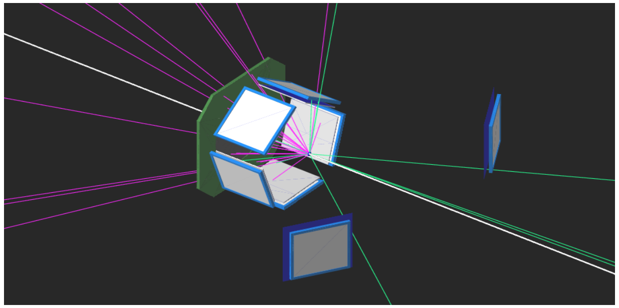
Energy vs theta of the protons of $^{7}Be(d,p)^{8}Be^{*}$

Simulations

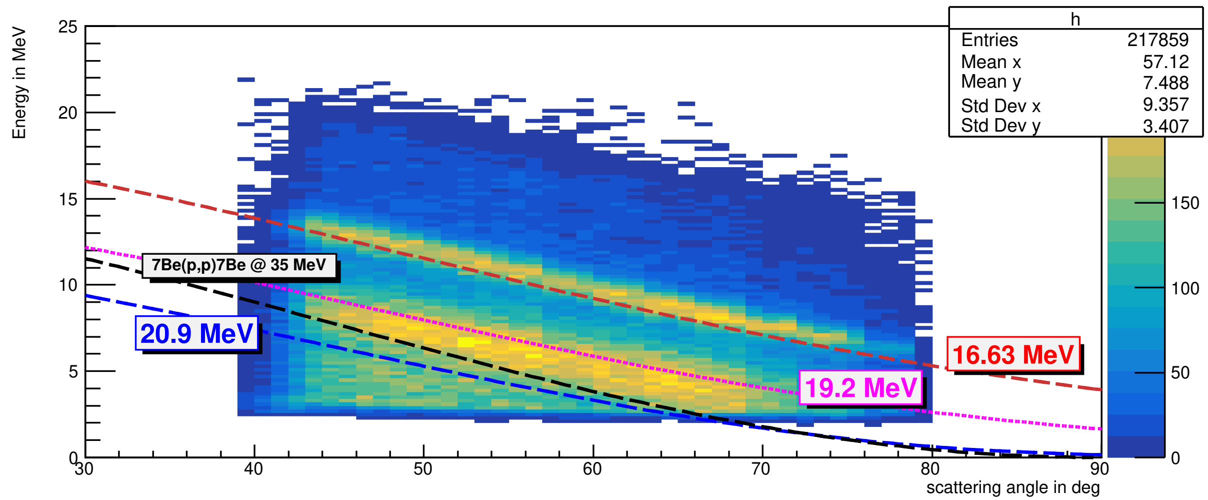


Excitation energy of $^{8}Be^{*}$

Analysis of back angle data going on

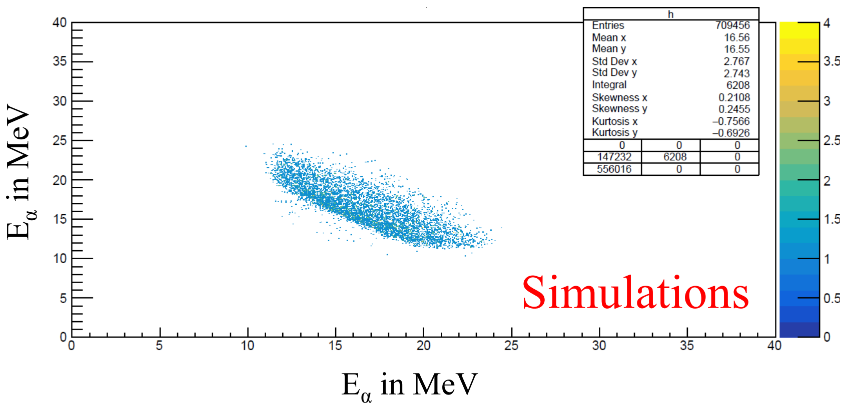


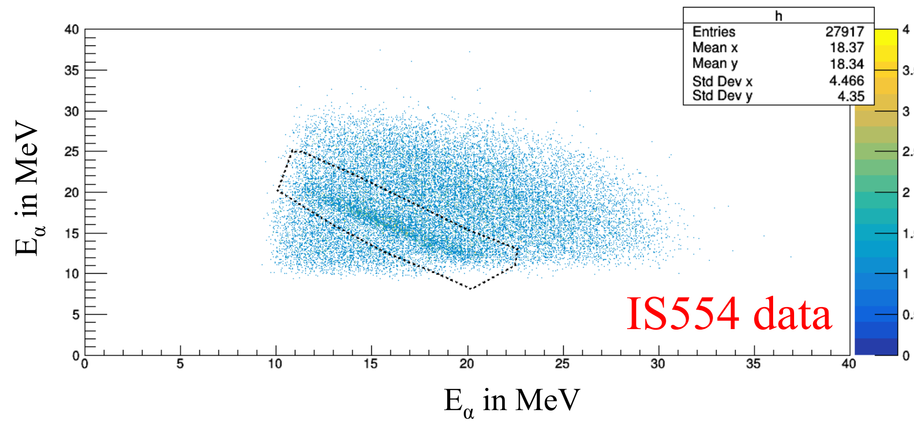
α-p coincidence

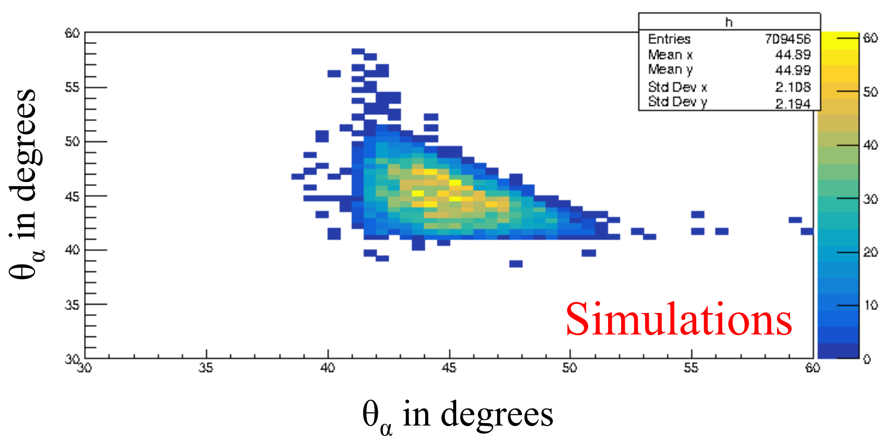


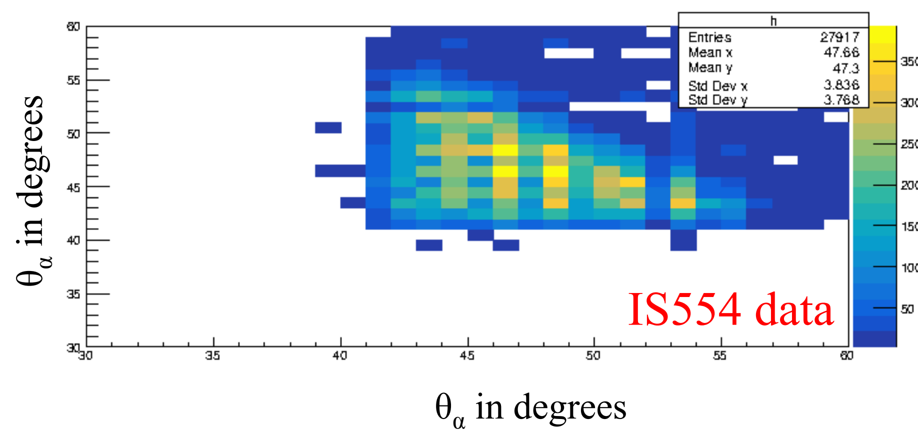
Energy vs theta spectrum for protons detected in coincidence with alphas at the pentagon DSSDs. The band corresponding to **16.63 MeV state** which was earlier very faint is now clearly seen.

α-α coincidence



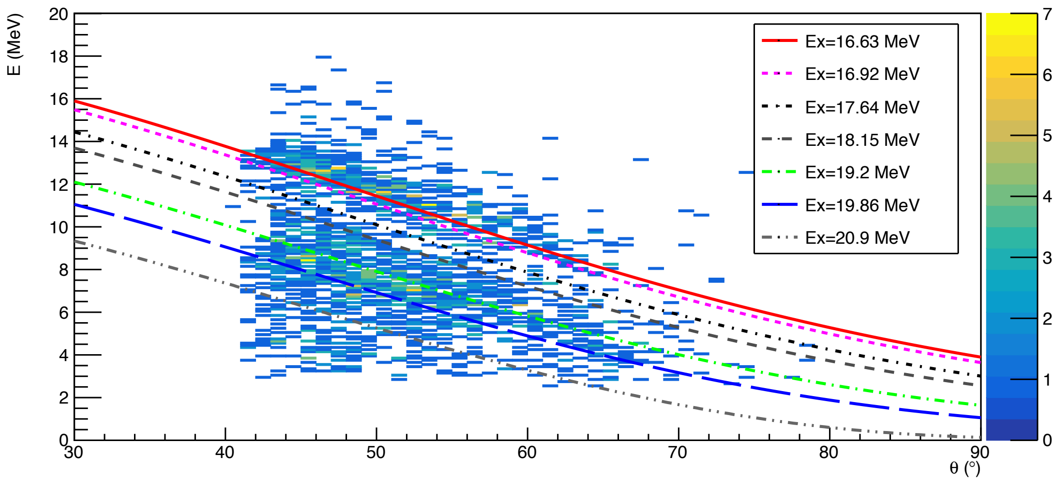


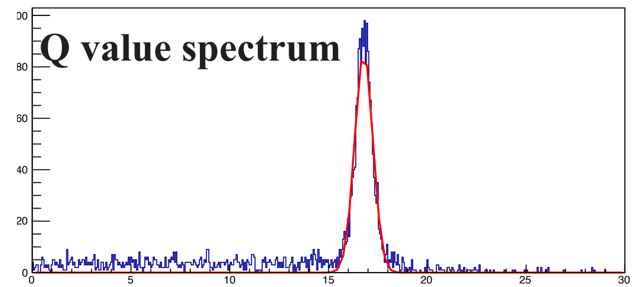




Energy and angular correlations of coincident alphas detected by the pentagon DSSDs. Simulations correspond to the correlation of the alphas emitted from the **16.63 MeV state of ^{8}Be**.

α-α-p coincidence



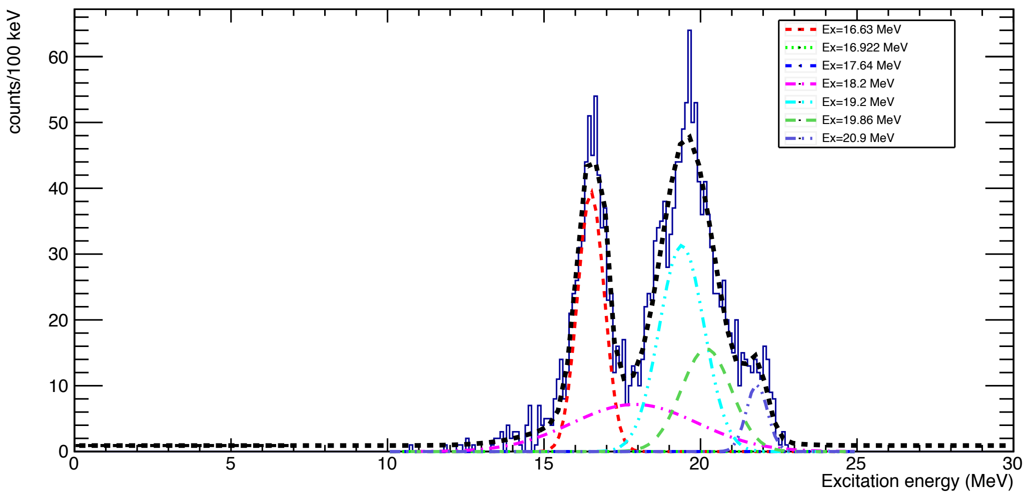


Mean : 16.786 MeV
FWHM : 1.0788 MeV

Energy (E) vs Theta (θ) of detected protons in coincidence with the detected alphas

Two distinct bands. The upper band corresponds to the two isospin mixed states **16.63 MeV** and 16.922 MeV of ^{8}Be whereas the lower band corresponds to the narrowly spaced **higher excitations of ^{8}Be** in the 18-20 MeV range.

Excitation energy spectrum of ^8Be



Excitation energy level (MeV)	Fitted value (MeV)	FWHM (MeV)=2.355 σ
16.626	16.5	1.0075
16.922	16.951	1.034*10-3
17.64	17.349	5.435*10-4
18.15	17.9	4.71
19.2	19.4	1.689
19.86	20.86	1.88
20.9	21.8	0.793

The **$^7Be(d,p)^8Be^*$** events have been identified clearly from E vs θ plot of protons from α–p and α-α-p coincidences.

For lower excited states of ^8Be from $^7Be(d,p)^8Be^*$, analysis for back angle data going on.

We measured excitation energy of ^8Be from **0-20 MeV** and would soon have the **angular distributions** of the excited states in the **$^7Be(d,p)^8Be^*$** channel.

Outlook

Search for standard nuclear physics solution to the Cosmological Lithium problem

A number of experiments were carried out to measure the destruction of ^{7}Be. The destruction of ^{7}Be involving neutrons ^{7}Be(n,p)^{7}Li, ^{7}Be(n, α)^{4}He yield a decrease of the lithium abundance but insufficient to solve the anomaly. *Damone (2018), Barbagallo (2016)*

The destruction channel ^{7}Be(*d,α*)*αp* leads to speculation of a new resonance at **0.36 MeV** corresponding to the **16.8 MeV state of ^{9}B** *Rijal (2019)*. The decay properties of the state remains unknown. No reduction of the abundance of ^{7}Li can be deduced from the data *Gai (2020).*

The cosmological lithium problem persists!

Our data (IS 554) are dominated by the **(d,p)** channel for **higher ^{8}Be states** unto 20 MeV, instead of (d,α). At present we can not firmly conclude about the anomaly from our data, as analysis is still going on. All alternative physics and astronomical scenarios to solve the anomaly is still open.

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

IS 554 collaboration

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