The ^{7}Be + d reaction in the context of the cosmological lithium problem

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Plan of talk

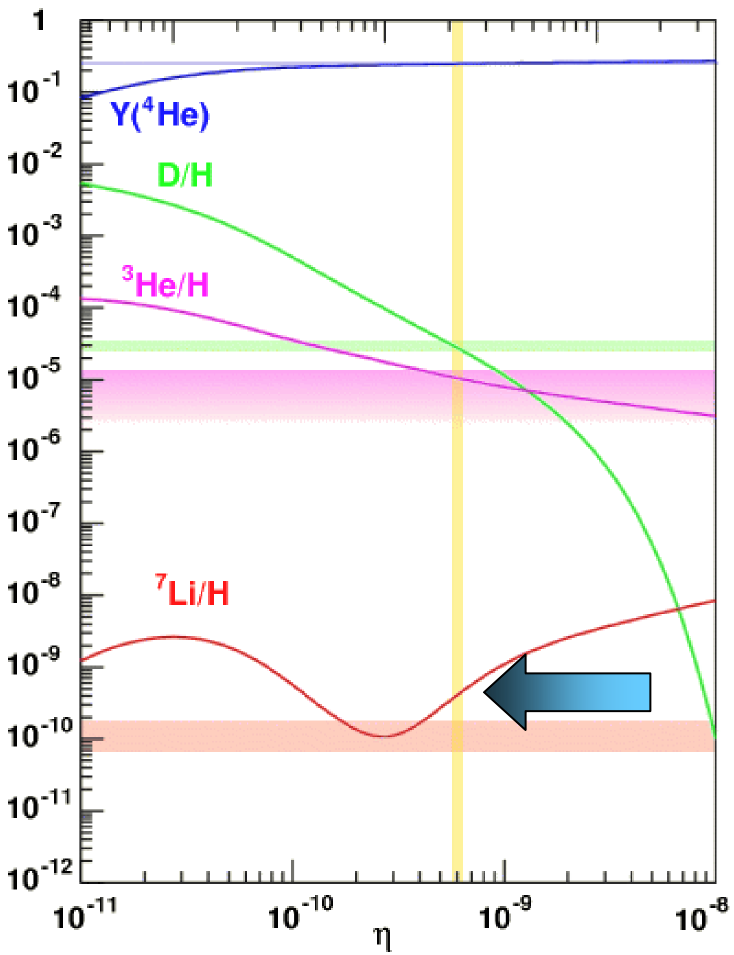
- CLiP
- Possible solutions: Nuclear Physics ?
- Resonance excitations in $^{7}Be + d$ channel
- IS 554: $^{7}Be + d$ @ 5 MeV/u
- Results: $^{7}Be(d,p)^{8}Be^{*}$, $^{7}Be(d,^{3}He)^{6}Li$, second Li problem
- Outlook

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



Observed (predicted) values : bands (lines)

$\eta = n_B/n_\gamma = 6.104 \pm 0.058 \times 10^{-10}$

baryon-to-photon ratio

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** (**WMAP / PLANCK**).

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

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

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

Possible Solutions

Astrophysical solutions tried to reconcile the difference on the basis of stellar processing of ^{7}Li, it may be destroyed in metal-poor stars through diffusion and turbulent mixing. Improvements in observationally inferred primordial lithium abundance, found to be very difficult to justify enough destruction. *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 aspects of the primordial lithium problem

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 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 ?

^{3}He(α,γ)^{7}Be has an uncertainty of < 5%
^{7}Be(n,p)^{7}Li, **^{7}Be(n,α)^{4}He** have failed to solve the Li anomaly

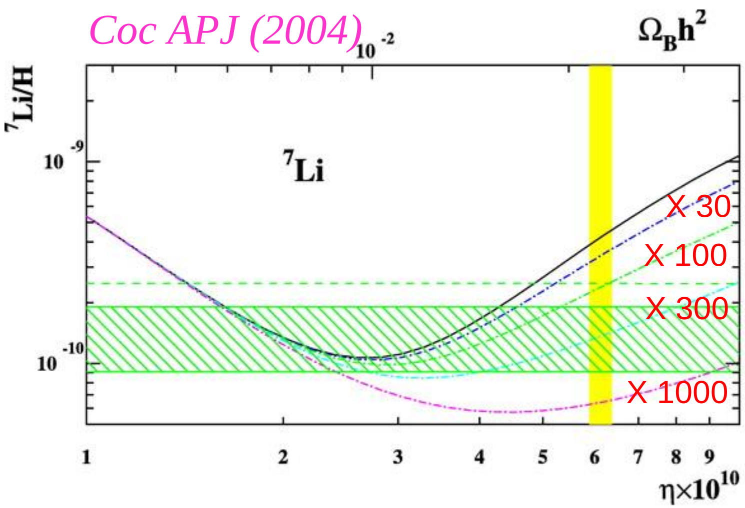
Broggini JCAP(2012)
Damone PRL (2018)
Barbagallo PRL (2016)

Increased mass-7 destruction via novel reaction pathways or by resonant enhancement of otherwise minor channels.

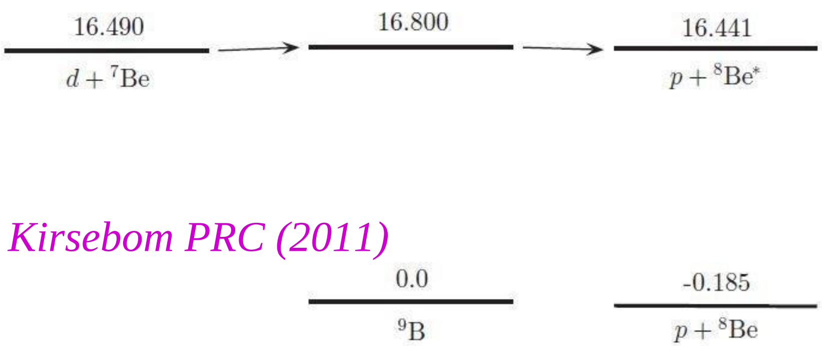
The ^{7}Li discrepancy resolved, if the **^{7}Be(d,p)^{8}Be*(2α)** Q = 16.674 MeV reaction rate larger by a factor **~ 100**, **Resonant enhancement in ^{7}Be + d?**

IJMPE (2012)

Coc APJ (2004)

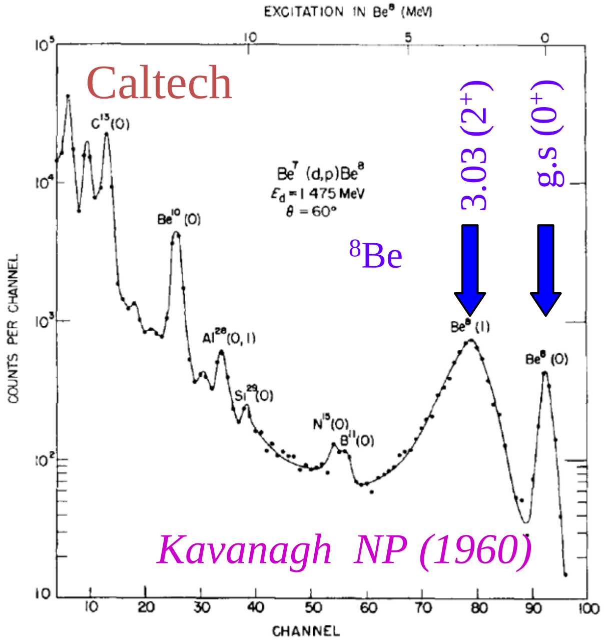


Proposed ^{7}Be destruction mechanism
d + ^{7}Be → ^{9}B* → p + ^{8}Be*



Kirsebom PRC (2011)

The ^{7}Be + d reaction leads to the 16.8 MeV state in ^{9}B, which 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.

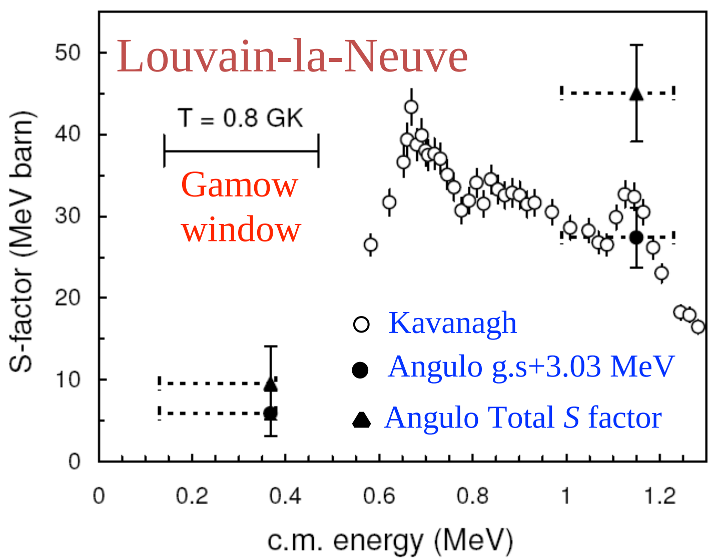


E_{cm} = 0.6–1.3 MeV, up to E_x = 11 MeV in ^{8}Be, protons detected for **^{8}Be g.s(0^+) and 3.03 MeV(2^+)**

Lacking complete angular distributions, data were converted to total cross section by multiplying by 4π and ~ 3 to take in to account contributions from **higher excited states in ^{8}Be.** A constant *S* factor ~ 100 MeV b 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.

Angulo APJ (2005)



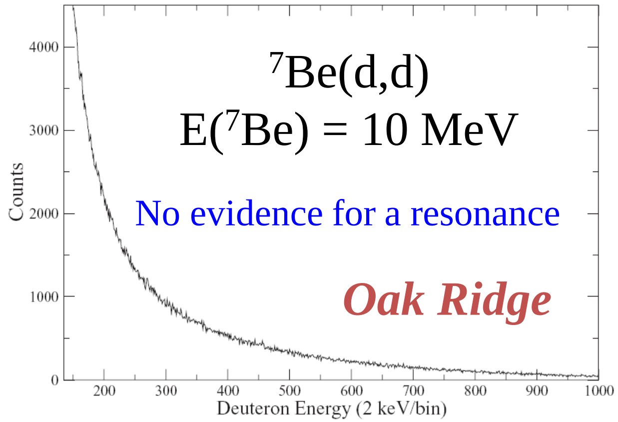
E_{cm} = 0.38, 1.23 MeV, up to E_x = 13.8 MeV in ^{8}Be. Observed also **11.4 MeV(4^+) higher energy level**

Higher energy states not observed by *Kavanagh* contribute about 35% of 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.

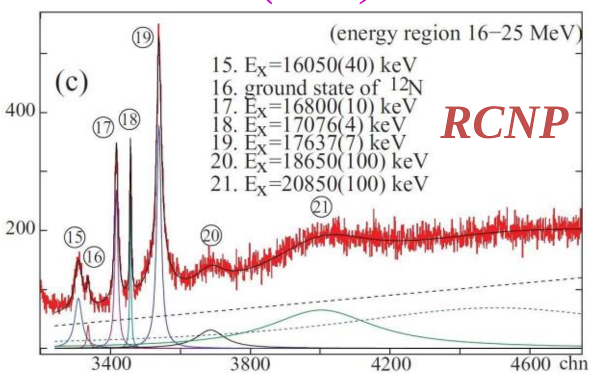
The ***S* factor** at BBN energies was not underestimated by Parker but **overestimated.**

Other works suggested **resonant enhancement** through a high lying resonance state in ^{9}B *Cyburt (2005), Chakravorty (2011)*

O'Malley PRC (2011)



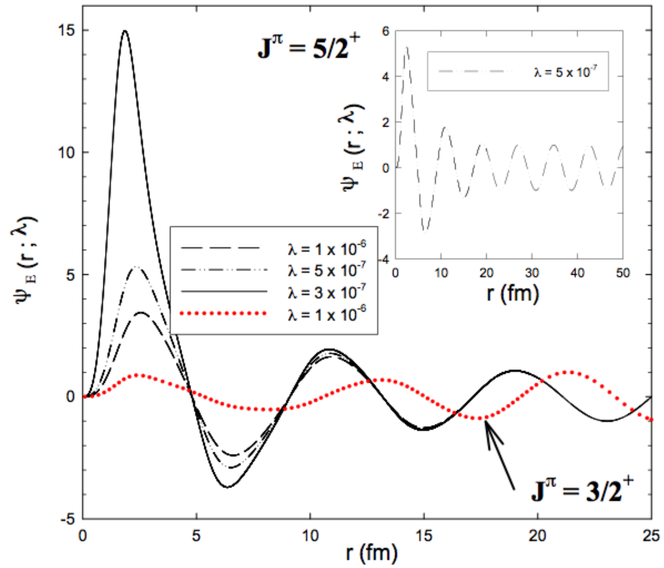
Scholl PRC (2011)



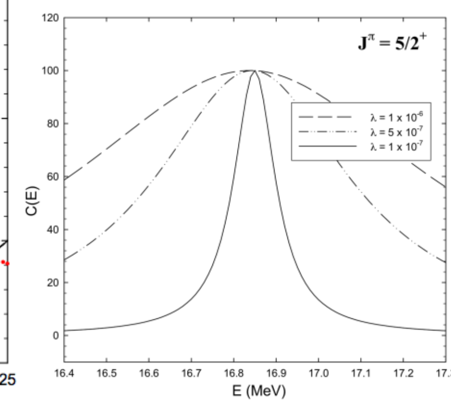
High resolution study of ^{9}Be(^{3}He,t)^{9}B
E= 140 MeV/A, the state is strongly excited.

Energy: **16.800(10) MeV** ($5/2^+$) , width: **81(5) keV**

Supersymmetric quantum mechanics to study the ^{9}B resonance



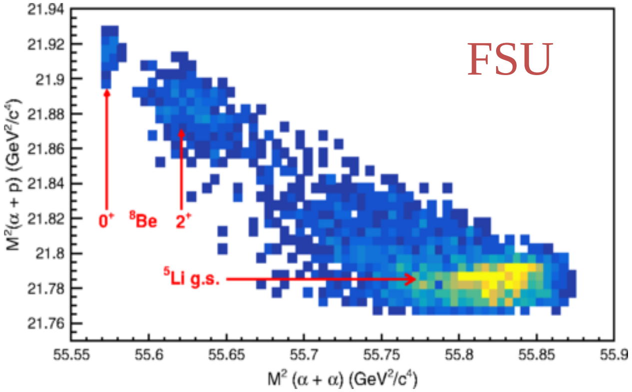
Dutta arXiv (2020)
PLB (2018)



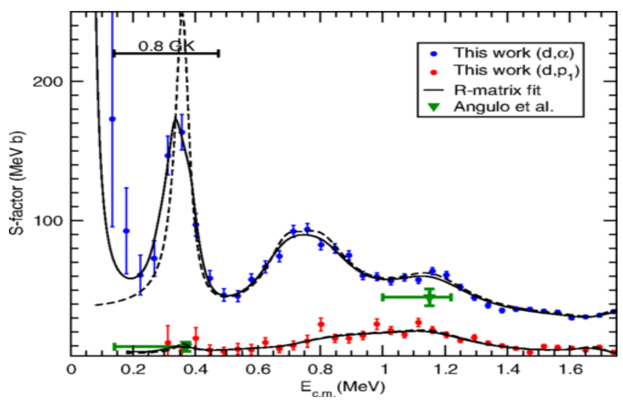
Resonance energy E_R=**16.84 MeV ($5/2^+$)**
Width Γ = **69 keV**

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

Rijal PRL (2019)



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

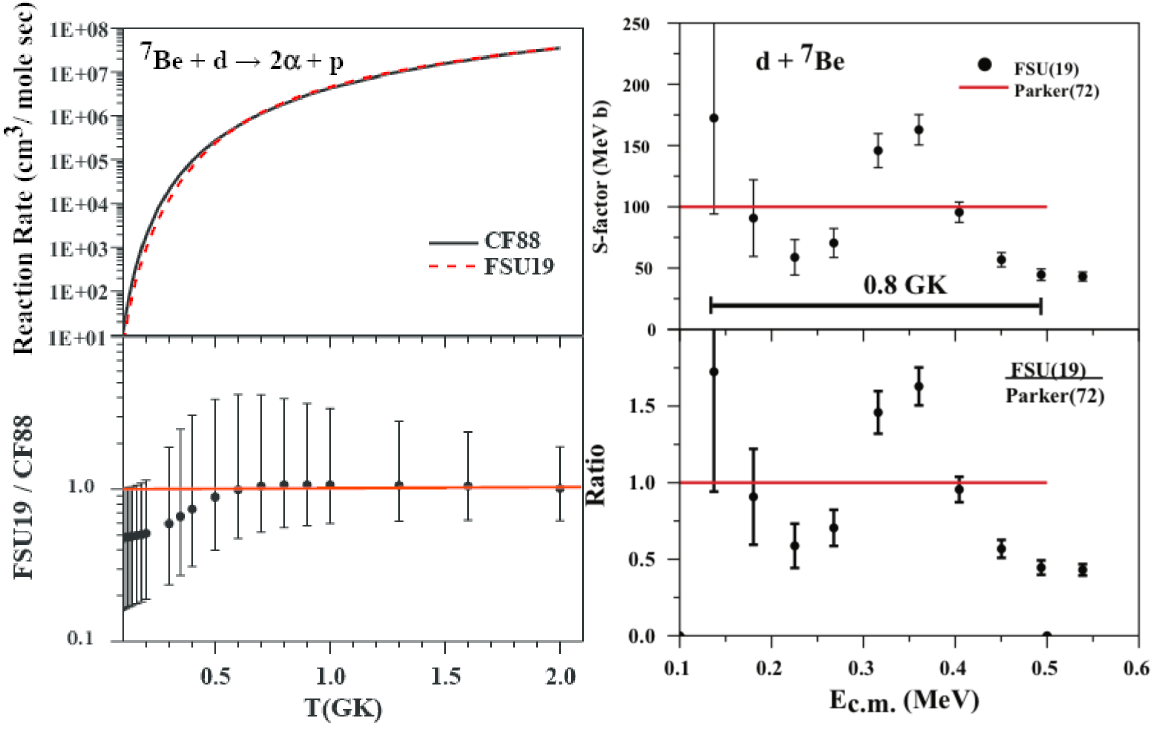


A new resonance at 0.36(5) MeV observed, claiming to **reduce predicted abundance** of primordial ^{7}Li.

R-matrix analysis: **16.849(5) MeV(5/2^{+})** state in ^{9}B? Speculation: ^{9}B resonance at **16.80 MeV?** *Scholl (2011)*

Additional experiments with improved statistics needed to reduce the **uncertainty in the resonance energy**.

Gai Mem. S.A.It (2019)



FSU rate uncertain by a factor of 10, due to uncertainty of the resonance energy. Old BBN d + ^{7}Be rate (CF88) and Rijal (FSU) rates are **nearly identical**.

Since no state is known in ^{9}B at the proposed "new resonance" energy of 16.85 MeV, resolving such a major systematical uncertainty is required.

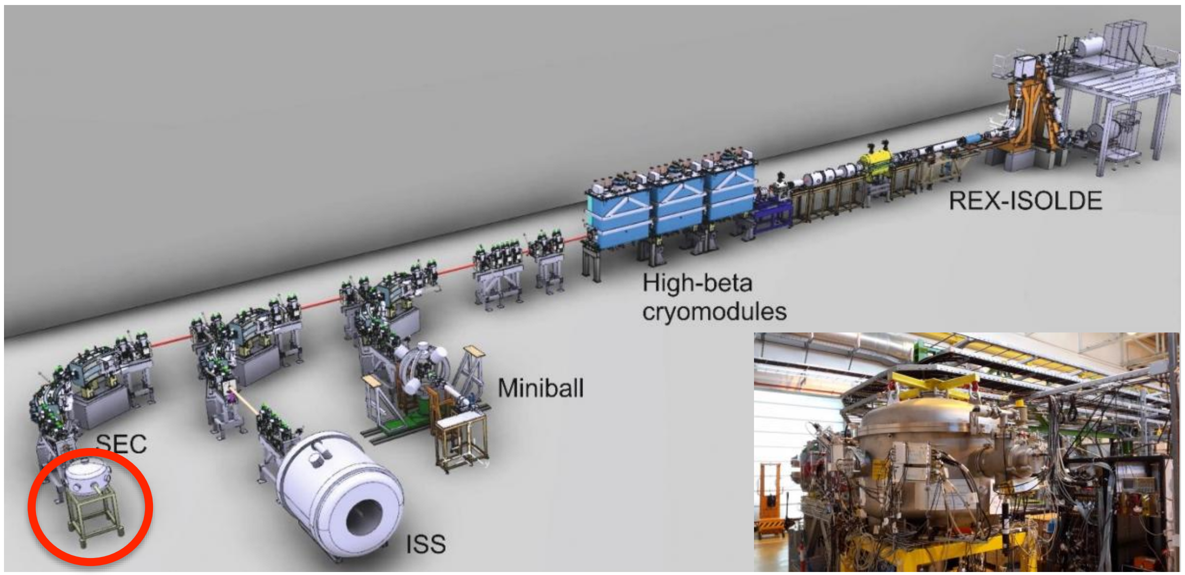
No reduction in ^{7}Li abundance.

There are carefully measured cross-sections, but still **^{7}Be destruction could be enhanced by unknown or poorly measured resonances.** To determine fully the contribution of the **^{7}Be(d,p)^{8}Be** reaction to the ^{7}Li abundance, it needs to be measured for ^{8}Be excitations around 16 MeV.

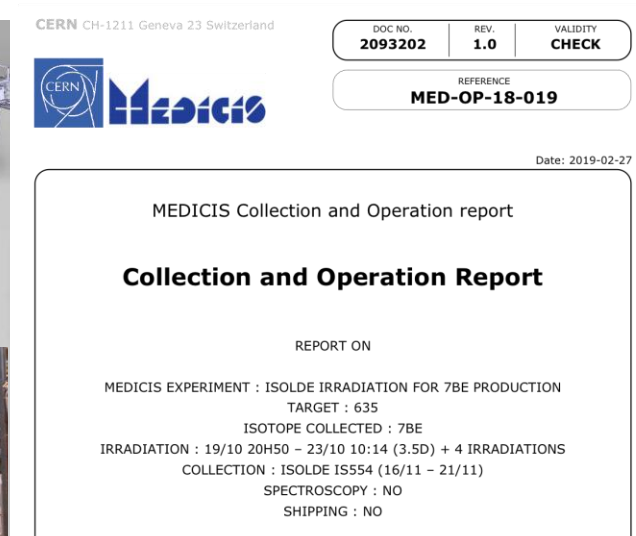
Experiment IS 554 @

^{7}Be : E = 5 MeV/u , I ~ 5 x 10^{5} pps

Targets: CD_2 (15 μm), CH_2 (15 μm), ^{208}Pb (1 mg/cm^2)



Scattering Chamber (SEC)



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DOC NO.	REV.	VALIDITY
2093202	1.0	CHECK

REFERENCE
MED-OP-18-019

Date: 2019-02-27

MEDICIS Collection and Operation report

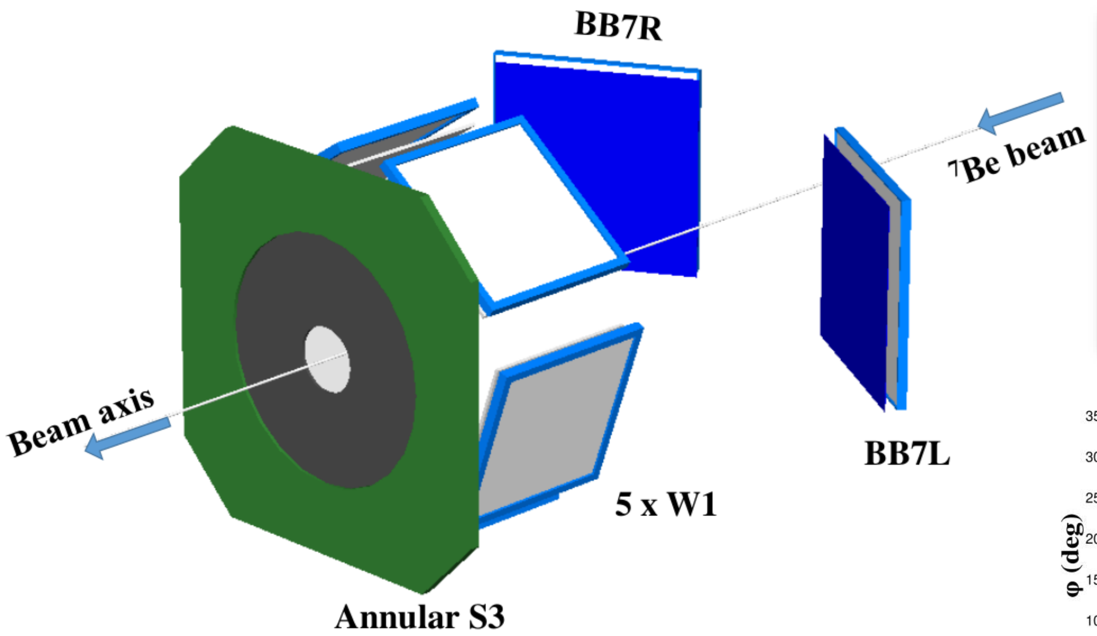
Collection and Operation Report

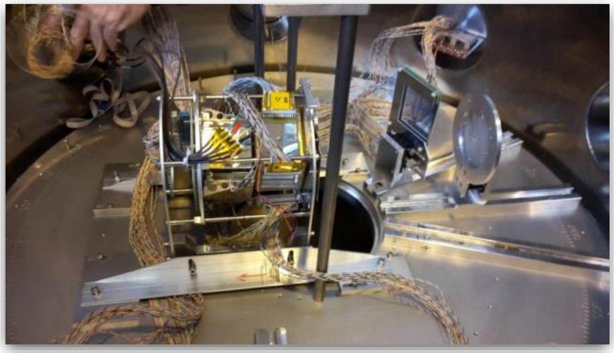
REPORT ON

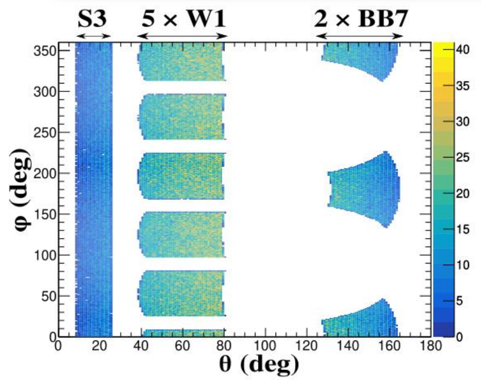
MEDICIS EXPERIMENT : ISOLDE IRRADIATION FOR 7BE PRODUCTION
TARGET : 635
ISOTOPE COLLECTED : 7BE
IRRADIATION : 19/10 20H50 – 23/10 10:14 (3.5D) + 4 IRRADIATIONS
COLLECTION : ISOLDE IS554 (16/11 – 21/11)
SPECTROSCOPY : NO
SHIPPING : NO

The target (UCx) was irradiated with 0.37 μA of 1.4 GeV **protons from the PS-booster offline during 3 days**. The activated target was then mounted on the GPS target station, heated and the ^{7}Be was extracted using the **RILIS laser ion-source**, and accelerated using the HIE-ISOLDE post accelerator. A stripping foil and a dipole before the experimental station was used to clean the beam to **$^{7}Be^{4+}$**.

Experiment IS 554 @







The total solid angle coverage of the detectors is **~32% of 4π.**

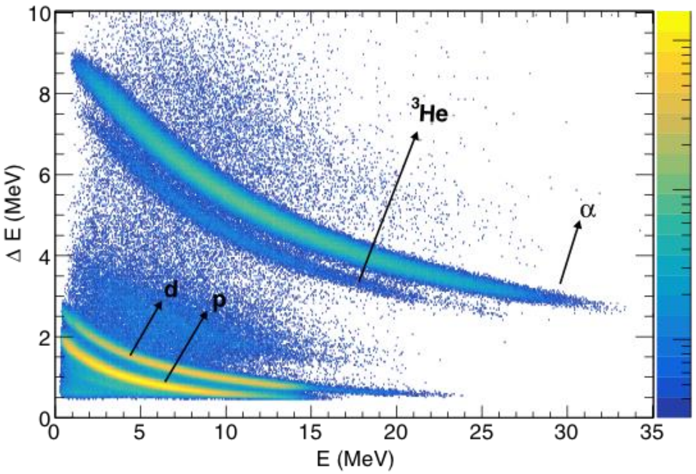
Charge particle detector setup

1 x S3 annular DSSD (24 x 32 strips, 1000 μm) covering front angles 8º – 25º
5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40º – 80º
2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 127º – 165º
The W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads MSX25/MSX40

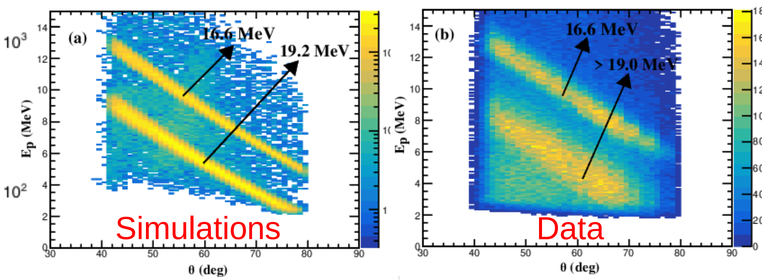
Experiment IS 554 @

Measured excitation energy of ^{8}Be from **0-22 MeV** in the **^{7}Be(d,p)^{8}Be*** channel, events identified from E vs θ plot of protons detected in coincidence with $\alpha-$particles.

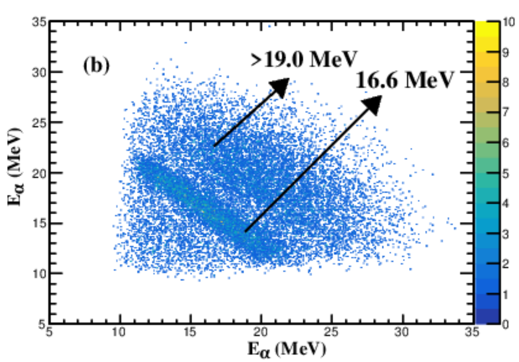
Ali et al., PRL (2022)



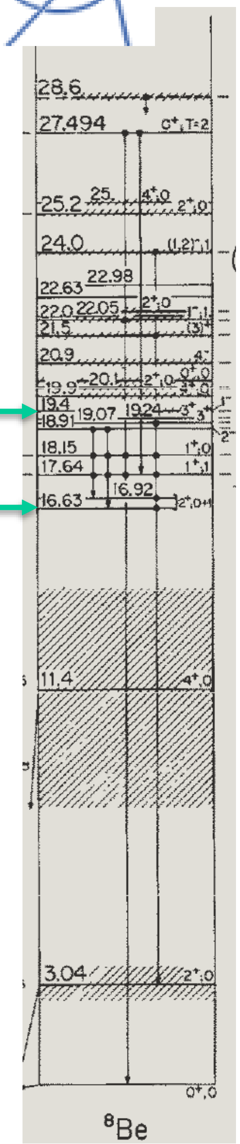
ΔE-E spectrum of p, d, ^{3}He, and α, detected at W1 + MSX25 telescopes



Two distinct bands for **higher excitations of ^{8}Be**, one corresponds to states **16.63 MeV** and 16.922 MeV, other to states in 17-22 MeV. Earlier works suggest that 16.63 MeV state populated considerably more than 16.92 MeV. Hence, we refer to this doublet as 16.63 MeV.

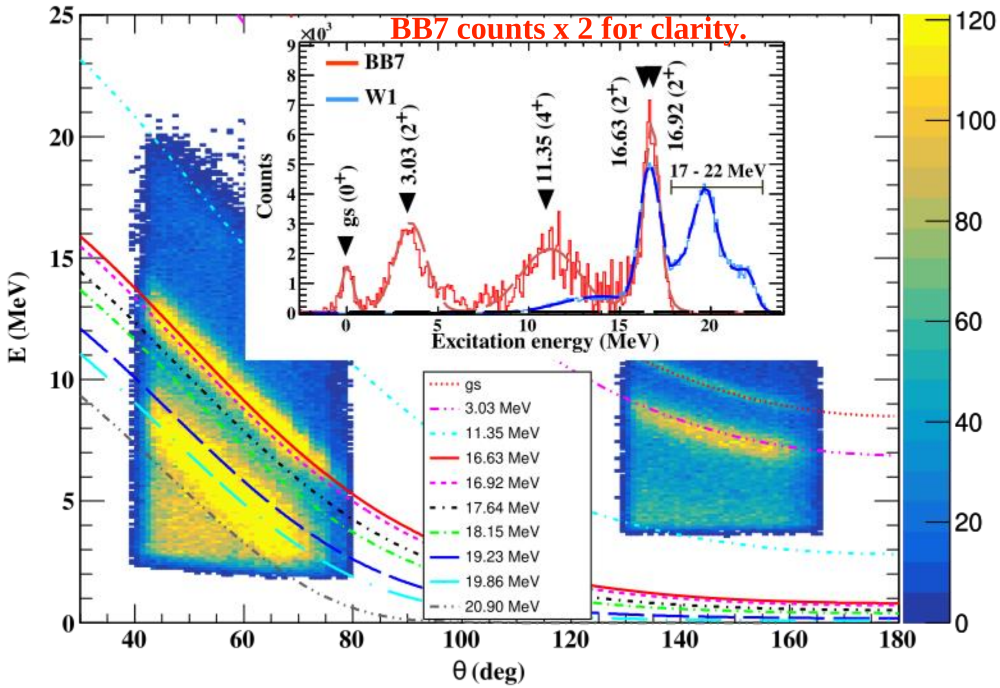


The ^{7}Be(d,p)^{8}Be* events for forward scattered protons to S3 were clearly identified from energy-energy correlations of two coincident α-particles at W1.

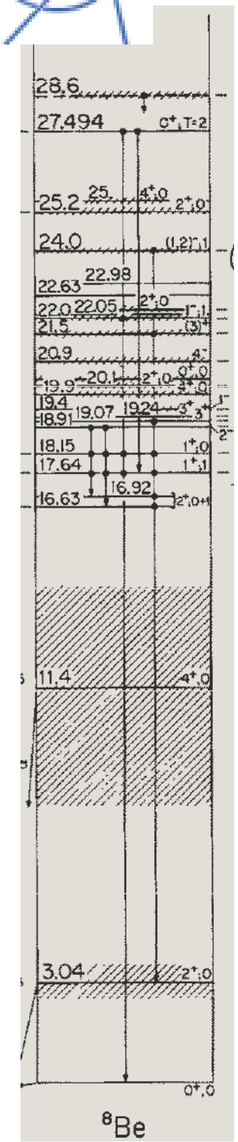


Experiment IS 554 @

Ali et al., PRL (2022)



E vs *θ* for protons at W1 and BB7. The kinematic lines for different excited states of ^{8}Be are shown and the inset shows the **excitation energy** spectrum of ^{8}Be from **0-22 MeV.**



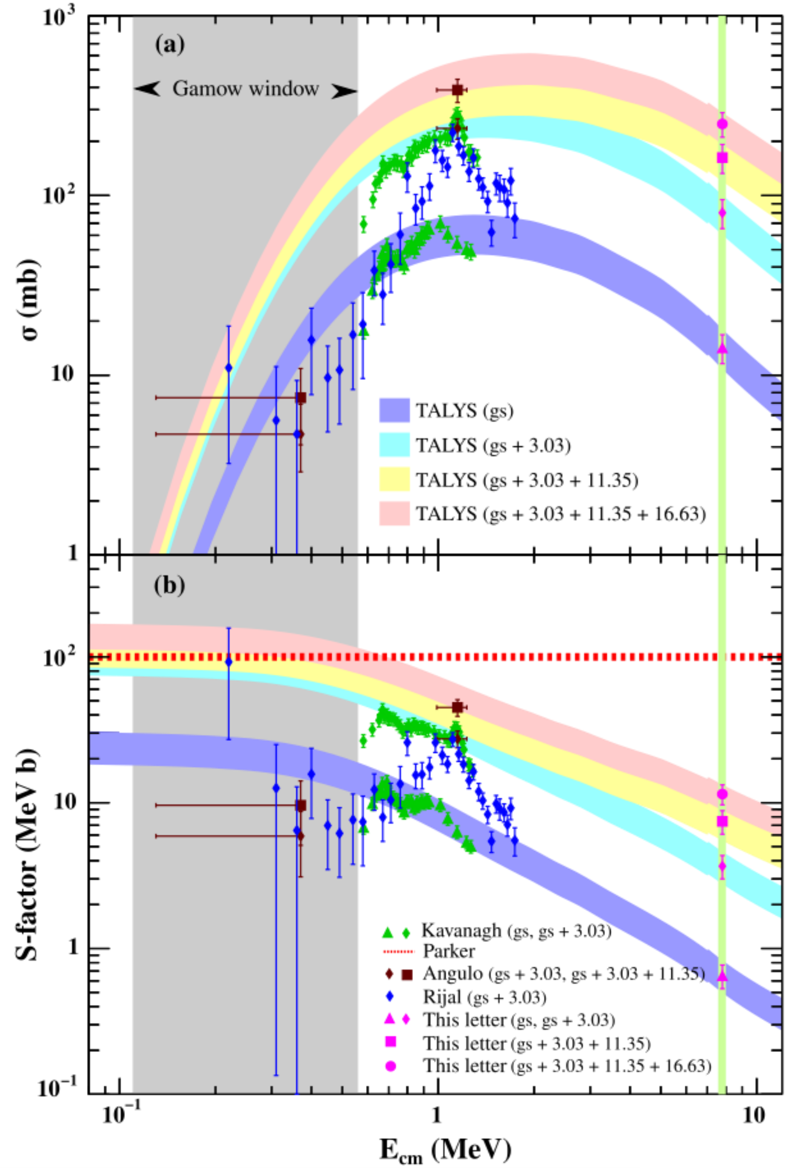
The energy resolution **~660 keV** due to beam, target straggling and detectors, limits the separation of narrowly spaced high lying states at **16.63** and **16.92 MeV**, and around **17–22 MeV**. The errors in cross sections mainly arise from statistical uncertainties, systematic uncertainties in target thickness (~10%) and beam intensity (~10%).

^{7}Be(d,p)^{8}Be* *Ali PRL (2022)*

Excitation function of the different levels is calculated with the nuclear reaction code TALYS. The bands are TALYS calculations normalized to the measured cross section, giving an estimate of contributions of individual states of ^{8}Be up to the 16.6 MeV state for the **first time.**

The existing data within Gamow window (T = 0.5–1 GK, $E_{c.m.}$ = 0.11–0.56 MeV) has **large error bars**. Good agreement with data outside Gamow window.

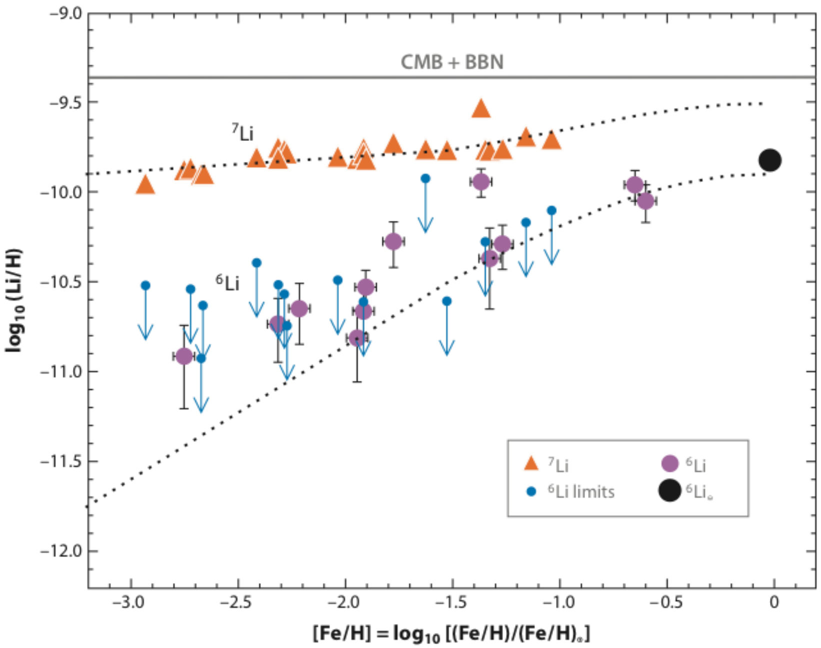
The ***S* factor** due to contribution of gs+3.03+11.35 MeV state agrees with Parker’s estimate of 100 MeV b. Addition of the **16.63 MeV** state leads to a **maximum value of 167 MeV b** but is **not adequate** to solve the Lithium anomaly. The **Li abundance is reduced by < 1%**.



Contribution of higher excited states in ^{7}Be(d,p)^{8}Be* do not solve the Cosmological lithium problem

Second Li problem ?

Fields ARNPS (2011)



^{6}Li production in standard BBN is very small: ^{6}Li/H $\simeq 10^{-14}$, ^{6}Li/^{7}Li □ $\lesssim 10^{-4}$, far below the ^{6}Li plateau.

Lithium abundances in selected metal-poor Galactic halo stars. For each star, both lithium isotopes are plotted versus the star's metallicity. The flatness of ^{7}Li versus iron is known as the **Spite plateau**; it indicates that the bulk of the lithium is unrelated to Galactic nucleosynthesis processes and thus is **primordial**. The horizontal band gives the CMB+WMAP prediction.

Points below the Spite plateau show ^{6}Li abundances; the apparent flatness of these points (suggesting a **primordial origin**) constitutes the **^{6}Li problem.** BBN predictions **underestimate the observed abundance** by a factor of ~1000. Curves show predictions of a Galactic cosmic-ray nucleosynthesis model.

^{6}Li observations remain controversial and only for a few halo stars, ^{6}Li detection is confirmed. **How to explain the ^{6}Li plateau**, if it exists.

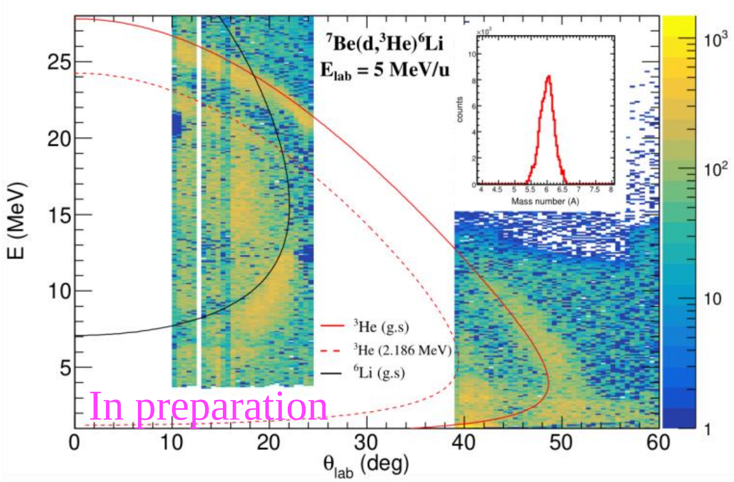
Are there novel reaction pathways or resonant enhancement of otherwise minor channels ?

$^7Be(d,^3He)^6Li$

This ^{7}Be destruction reaction **may impact both the lithium problems** simultaneously. It produces ^{6}Li and destroys ^{7}Be, thereby decreasing ^{7}Li abundance indirectly. If this reaction rate is artificially multiplied by 100, the BBN calculations result in a 45% decrease in abundance of ^{7}Li and 47% increase in abundance of ^{6}Li.

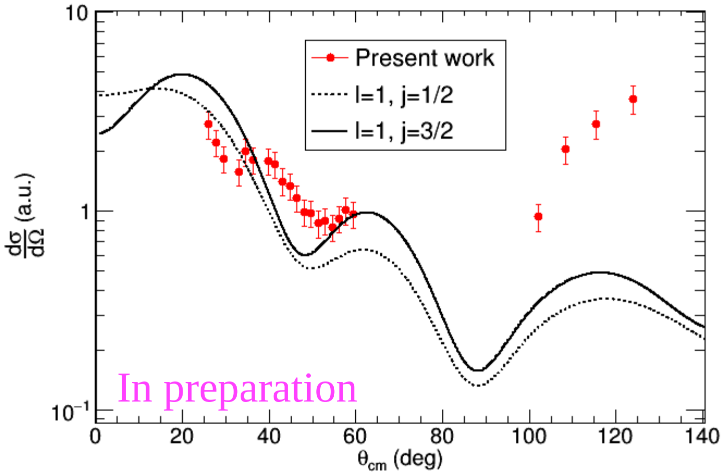
Existing measurement at $E_{cm} =$ 4.0 and 6.7 MeV Li et al. (2018). No kinematical identification, relied on MC simulations. Statistical uncertainty ~ 10% - 67%.

IS554 data



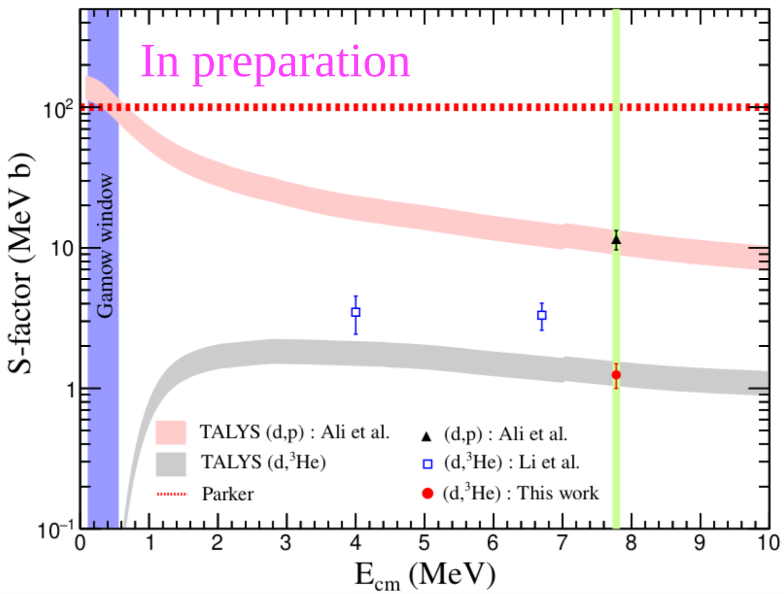
The p-transfer agree with forward angle data, α-transfer increases cross section at back angles, elastic-transfer effect in (d + ^{3}He) may cause back angle rise.

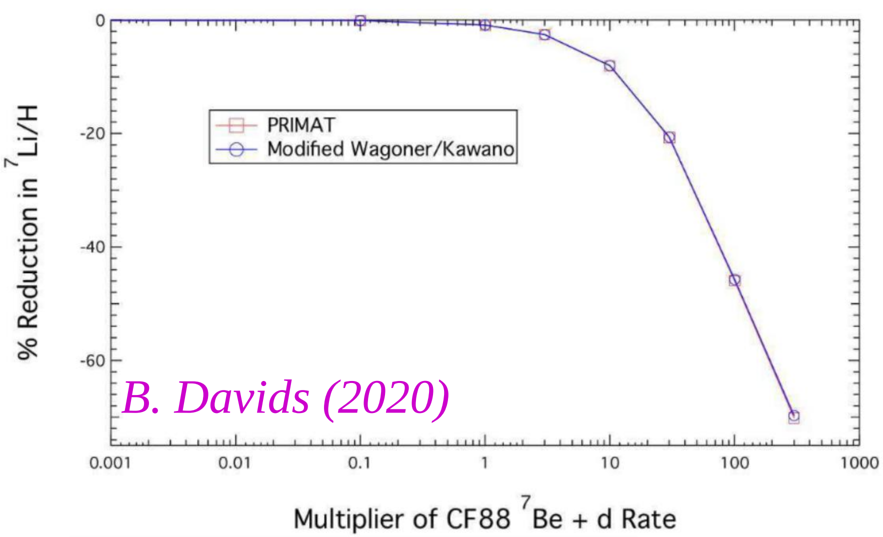
The coincident detection of ^{3}He and ^{6}Li from $^7Be(d, ^3He)^6Li$. Clear kinematic signatures are observed from E-θ plot. Missing mass spectrum by gating events on ^{3}He band.



Angular distribution of $^7Be(d, ^3He)^6Li$ at 5 MeV/u and DWBA calculations.

^{7}Be(d,p)^{8}Be* and ^{7}Be(d,^{3}He)^{6}Li





Excitation function calculated using **TALYS** by normalizing with present data at $E_{c.m.}$ = 7.8 MeV. *S* factor of (d, ^{3}He) is ~3 orders of magnitude less than (d,p) inside the Gamow window. It is almost 50% lower than Li et al data at nearby energies (may be due to lower statistics and contribution of other channels in Li et al data).

For (d,p), *S* factor of 167 MeV b, the ratio of reaction rate from the present work and CF88 at the relevant BBN energies is < **2** whereas for solving the Li problem this ratio ~ **100**. The ^{7}Be destruction by the (d, ^{3}He) is **negligible** compared to (d,p). **Both channels are not able to alleviate the Li anomalies.**

Outlook

Search for nuclear physics solution to the CLiP through the possible influence of resonances at higher excitation energies, that could enhance ^{7}Be destruction

Destruction channels ^{7}Be(n,p)^{7}Li, ^{7}Be(n, α)^{4}He decrease lithium abundance but are insufficient. *Damone (2018), Barbagallo (2016).* ^{7}Be(d,α)αp leads to speculation of a new resonance at E_{cm}= 0.36 MeV *Rijal (2019)* but no reduction of ^{7}Li abundance *Gai (2020).*

Contribution of ^{8}Be* higher excited states to the **^{7}Be(d,p)^{8}Be*** cross section is **reported for the first time**. Including contribution of the measured **16.63 MeV state**, the S factor is estimated to reach 167 MeV b inside Gamow window (60% higher than currently used 100 MeV b in BBN calculations). No substantial mitigation **(< 1%)** of the discrepancy. The ^{7}Be destruction by (d, ^{3}He) is **negligible** compared to (d,p).

The cosmological lithium problem persists!

Nuclear physics solutions are found to be inadequate. Solutions to ^{7}Li and ^{6}Li anomalies are difficult to find in reaction rates and may well require physics beyond the Standard Model, although deuterium and ^{4}He must remain unperturbed.

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

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