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Resonance excitation in ^{7}Be + d reaction to study ^{7}Li abundance anomaly

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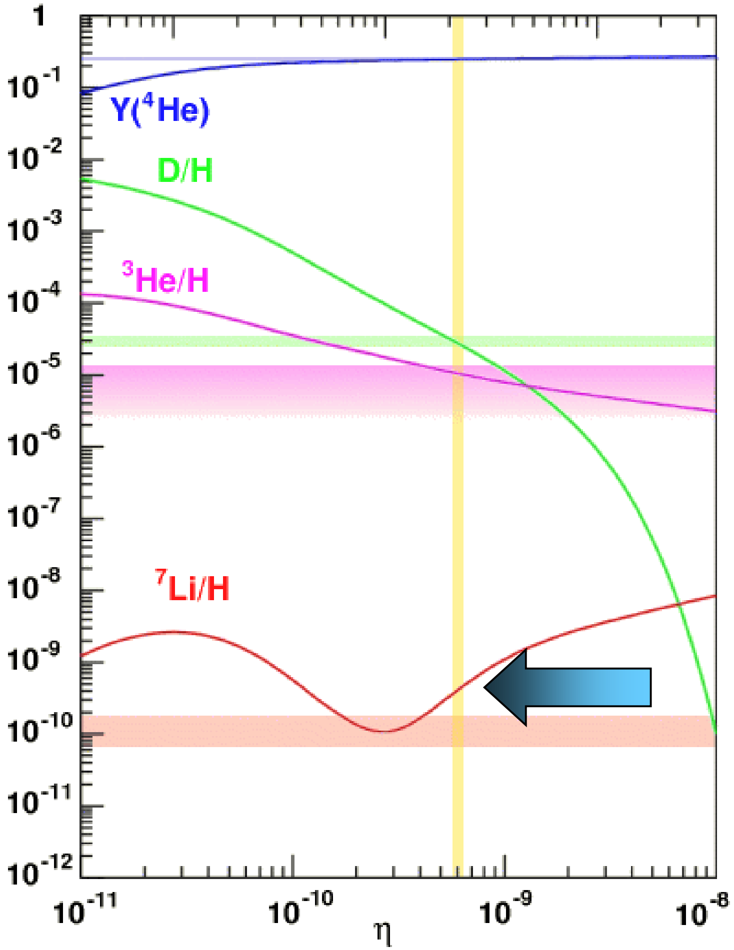
HIE-ISOLDE Experiments Workshop, CERN, February 1, 2016

Physics case



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

$\eta_b^{WMAP} = n_B/n_\gamma = (6.23 \pm 0.17) \times 10^{-10}$
ratio of the baryon and photon number densities

Serious discrepancy of a factor of about 4 in primordial ^{7}Li abundance, while good agreement of D, ^{3,4}He abundances

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

Observationally extracted: $^7\mathrm{Li/H} = 1.23\,^{+0.34}_{-0.16} \times 10^{-10}$

The Cosmological ^{7}Li problem

Aim of the experiment:

Study discrepancy of ^{7}Li abundance in the context of **resonance enhancement** of nuclear reactions

Importance:

One of the **important unresolved problems** of present-day astrophysics.
Existing data: nuclear/astrophysical/new effects beyond standard BBN- inconclusive

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

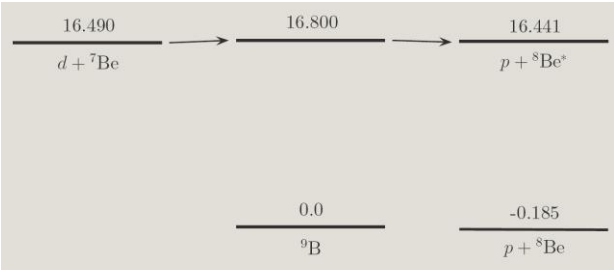
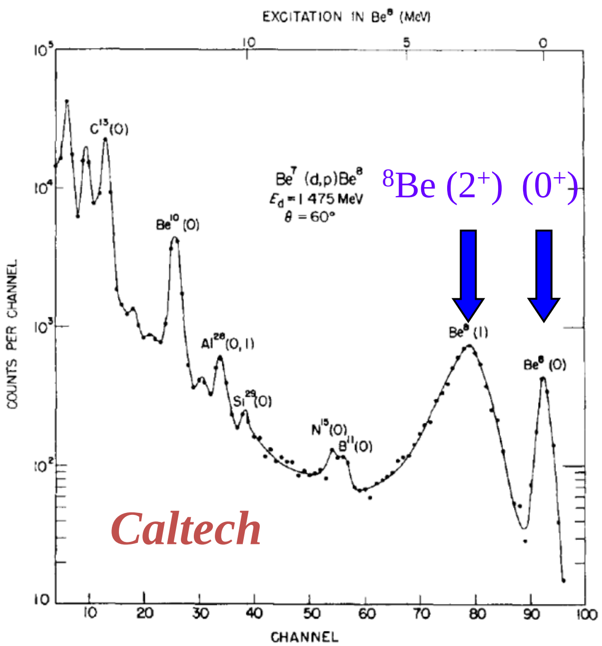


FIG. 1. Schematic illustration of the proposed ^{7}Be destruction mechanism, $d + {}^7\mathrm{Be} \to {}^9\mathrm{B}^* \to p + {}^8\mathrm{Be}^*$. The energies are in MeV relative to the ground state of ^{9}B. Subsequently, ^{8}Be* breaks up into two α particles.

^{7}Li mostly produced as ^{7}Be during Big Bang. One narrow nuclear level in ^{9}B, $E_{5/2+} \approx 16.7$ MeV, not sufficiently studied experimentally, and just ~ 200 keV above the ^{7}Be+d threshold, may lead to resonant enhancement of ^{7}Be(d,γ)^{9}B and ^{7}Be(d,p)^{8}Be reactions.

Cyburt et al
arXiv:0906.4373v1 (2009)



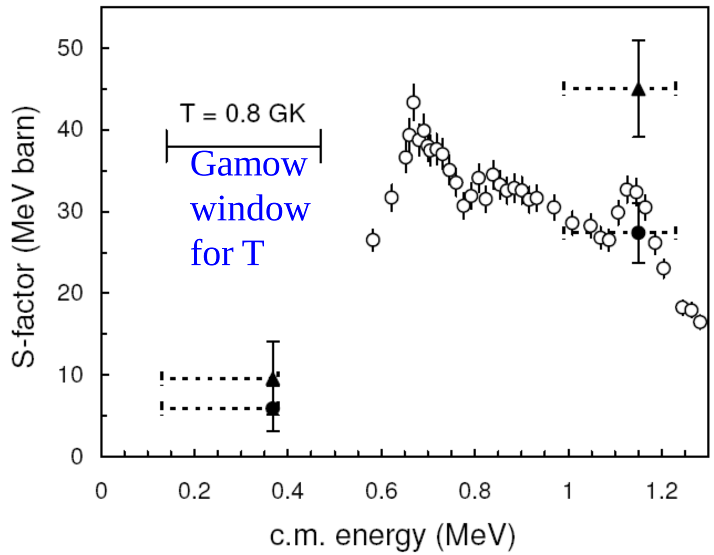
^{7}Be(d,p)^{8}Be*$\rightarrow 2\alpha$ (Q = 16.490 MeV)

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

upto E_x= 11 MeV

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

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



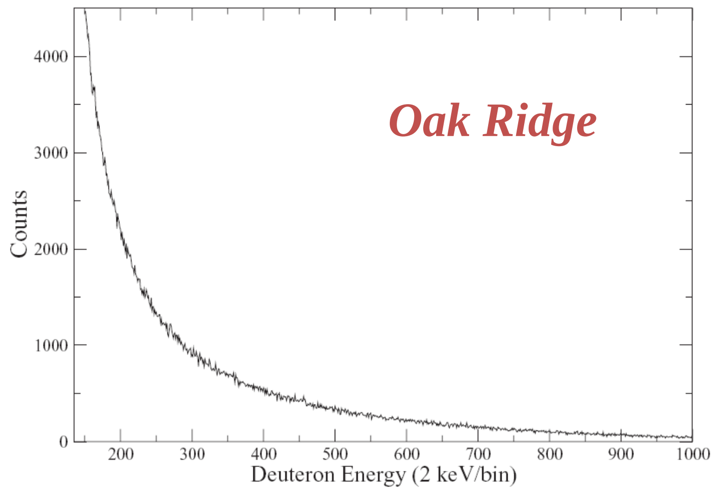
^{7}Be(d,p)^{8}Be*→2α (Q = 16.490 MeV)

(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
Due to Coulomb barrier, contributions of the higher states were negligible. Small angular range covered (~ 7-17 deg) and full isotropy for proton angular distribution **assumed** in calculating average cross section

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



Resonance enhancement of the ^{7}Be(d,p)2α reaction through the 5/2$^+$ 16.7 MeV resonance state in ^{9}B ? ^{2}H(^{7}Be,d)^{7}Be (E_{7Be}= 10 MeV)

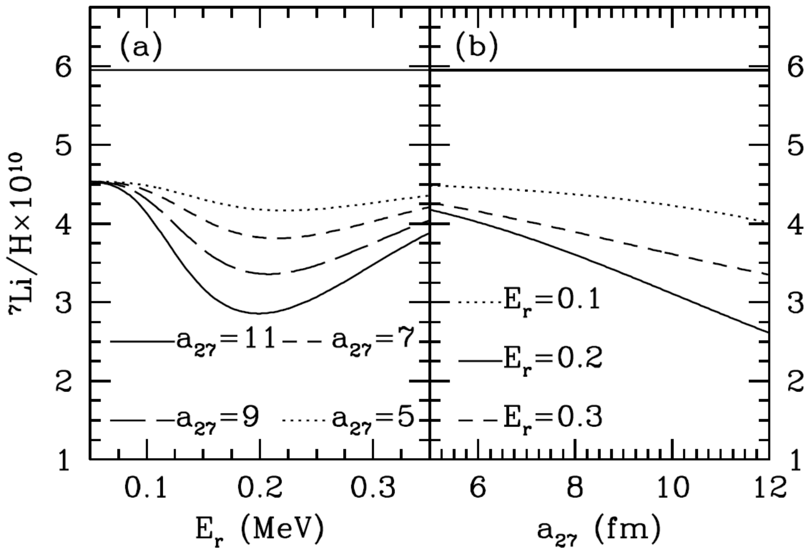
No evidence for a resonance observed

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

^{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

Cyburt et al
arXiv:0906.4373v1 (2009)



Reaction rates of the ^{7}Be destruction by deuterons could be large, owing to a narrow resonance 16.7 MeV ($5/2^+$) in ^{9}B. **This resonance may be very strong**, and at the very limit of the quantum mechanically allowed value for the deuteron separation width. This would be responsible for a factor of ~ 2 suppression of the primordial ^{7}Be yield, ***resolving ^{7}Li problem***.

(Resonant energy E_r, deuterium separation width Γ_d) ≈ **(170-220, 10-40) keV** can **eliminate current discrepancy**. Such a large width at this resonant energy can only be achieved if the interaction radius for the deuterium entrance channel is very large, $a_{27} \geq 9$ fm

Chakraborty et al
Phys. Rev. D 83, 063006 (2011)

16.7 MeV ($5/2^+$) in ^{9}B, a large channel radius (a>10 fm) needed to give sufficiently large widths

Clearly more study of possible resonances in ^{7}Be + d reactions and the 16.7 MeV state in ^{9}B needed. This state has the potential to significantly influence ^{7}Be destruction.

Merit of the experiment

Measurements of the 16.7 MeV (5/2+) resonance in ^{9}B at HIE-ISOLDE offering higher beam energies and intensity of ^{7}Be can resolve the ^{7}Li issue. Direct experimental information about its p and α decay properties unknown. Dominant single proton-decay branch to the 16.626 MeV (2^{+}) state in ^{8}Be ?

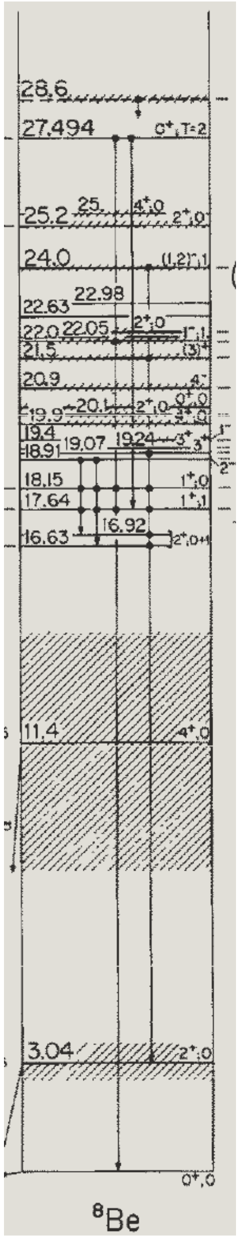
FIRST TIME

higher beam energy : measure higher excitation energies in ^{8}Be up to about **20 MeV**

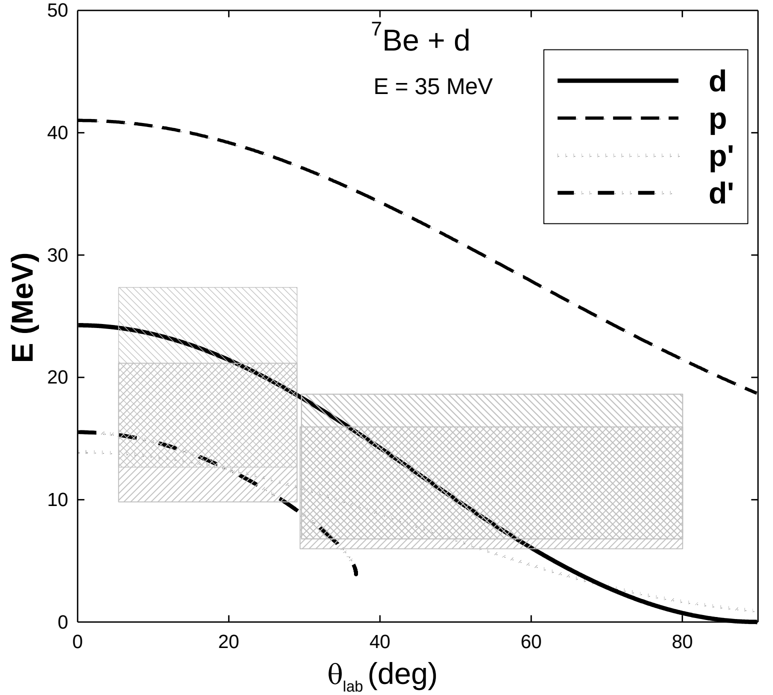
wider angular coverage : Improved average cross section measurements without assuming isotropy done in earlier works

POSSIBLE AT HIE-ISOLDE (beam energy and intensity)

35 MeV ^{7}Be : measure (d,p) (d,d) with T-REX
CD_2 target of thickness 1 mg/cm^2, I = 10^8 pps
Estimated cross section ~ 500 mb
Expected count rate ~ 1000/s



Kinematics

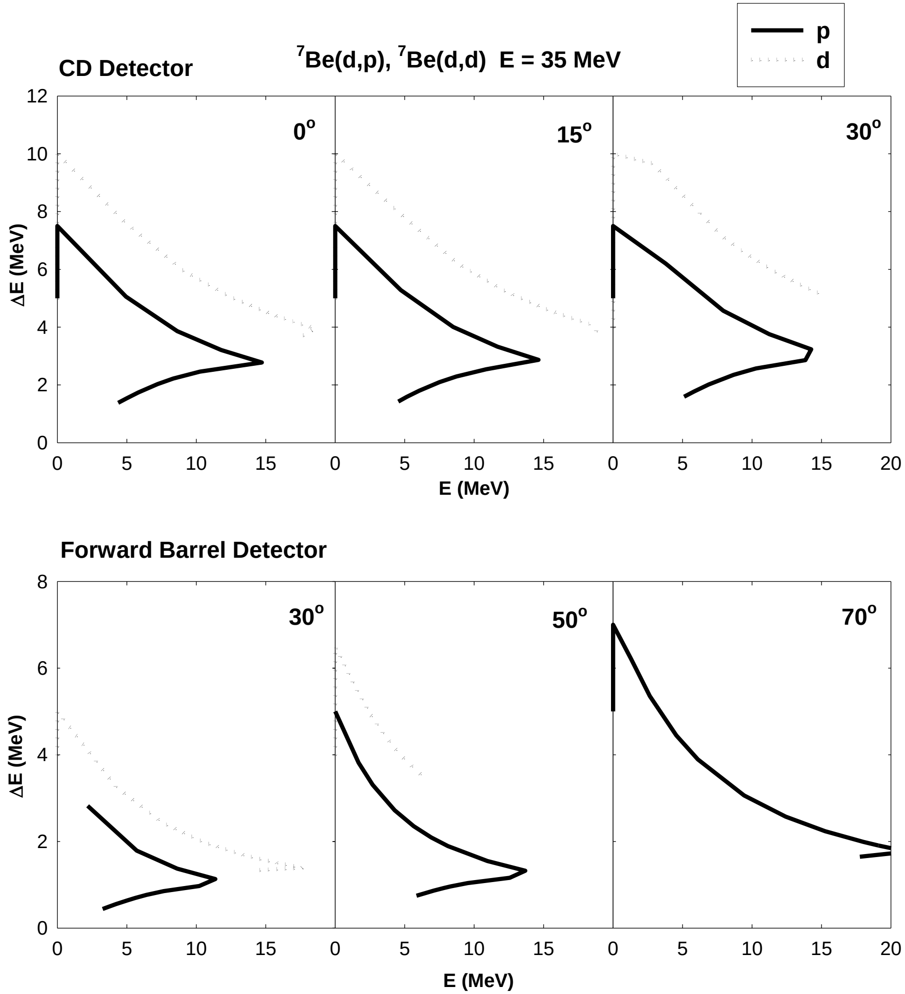


Kinematics of the 7Be(d,d), 7Be(d,p) reactions for ground state (d) (p), excitation of 20 MeV (p'), 5 MeV (d') respectively. The forward hashed (backward hashed) areas cover the detected p (d) energies and angles in CD and barrel detectors of T-REX.

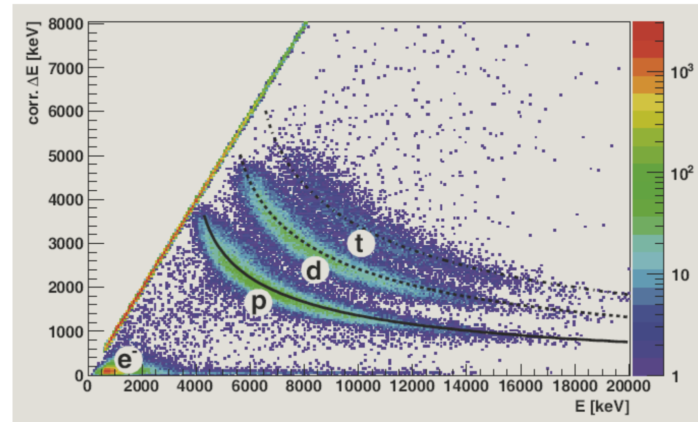
CD (ΔE=500 μm, E = 1.5 mm), Forward Barrel (ΔE=140 μm, E = 1.0 mm)

Protons : E_x =0, E_p = 20-40 MeV, do not stop

E_x =20 MeV, E_p = 4-14 MeV at 5 – 50 deg, corresponding α-particles stop in ΔE



Bildstein et al
Eur. Phys. J. A 48, 85 (2012)

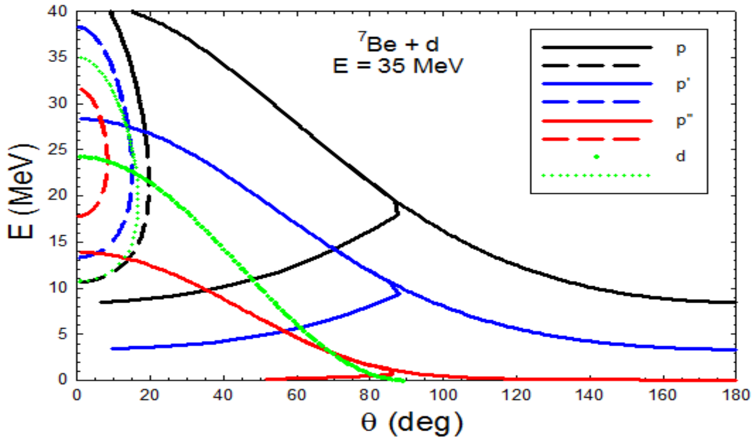


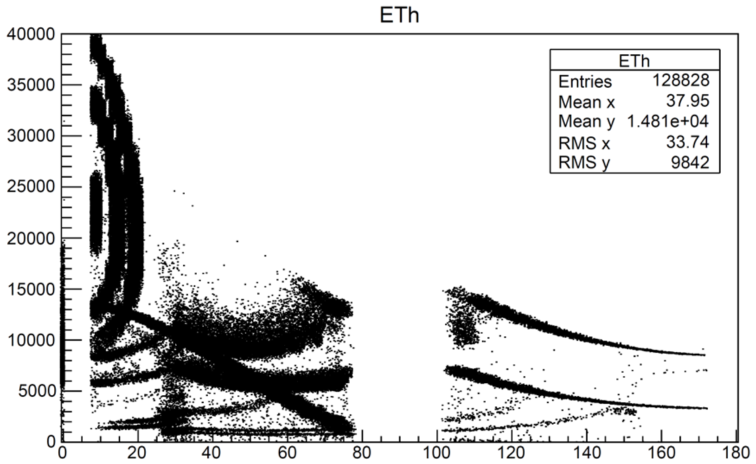
Energy resolution of T-REX would be sufficient for particle identification in this experiment

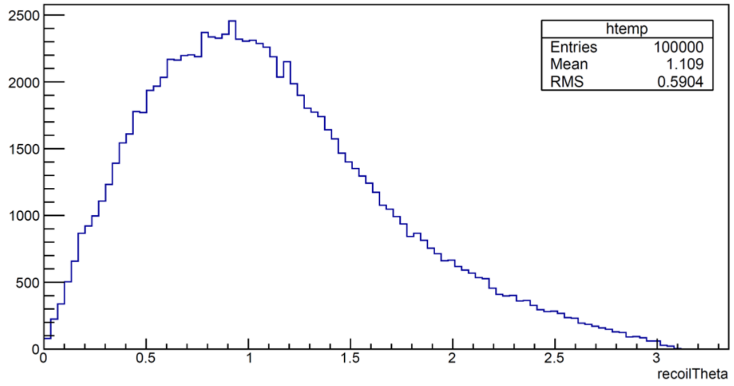
Excitation energies of the populated states of interest can be reconstructed from deposited energies in various detectors for stopping particles. Breakup of ^{8}Be → 2α particles that stop in ΔE detectors of T-REX, can be identified by using a multiplicity trigger.

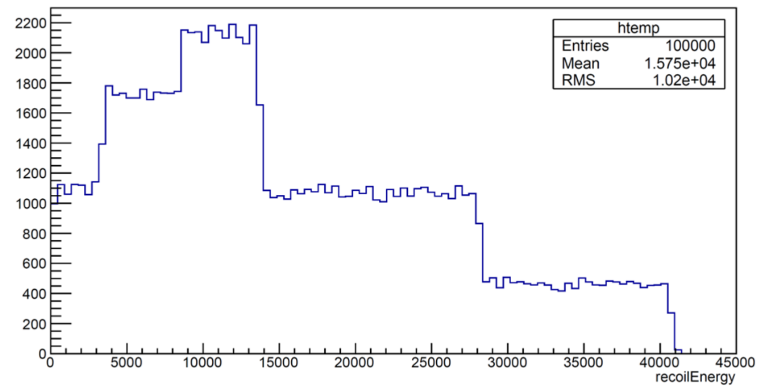
Geant4 simulations

35 MeV 7Be beam on a 1 mg/cm2 CD2 target
7Be(d,p)8Be reaction simulated
Standard T-REX setup : FCD, FBarrel, BCD, Bbarrel



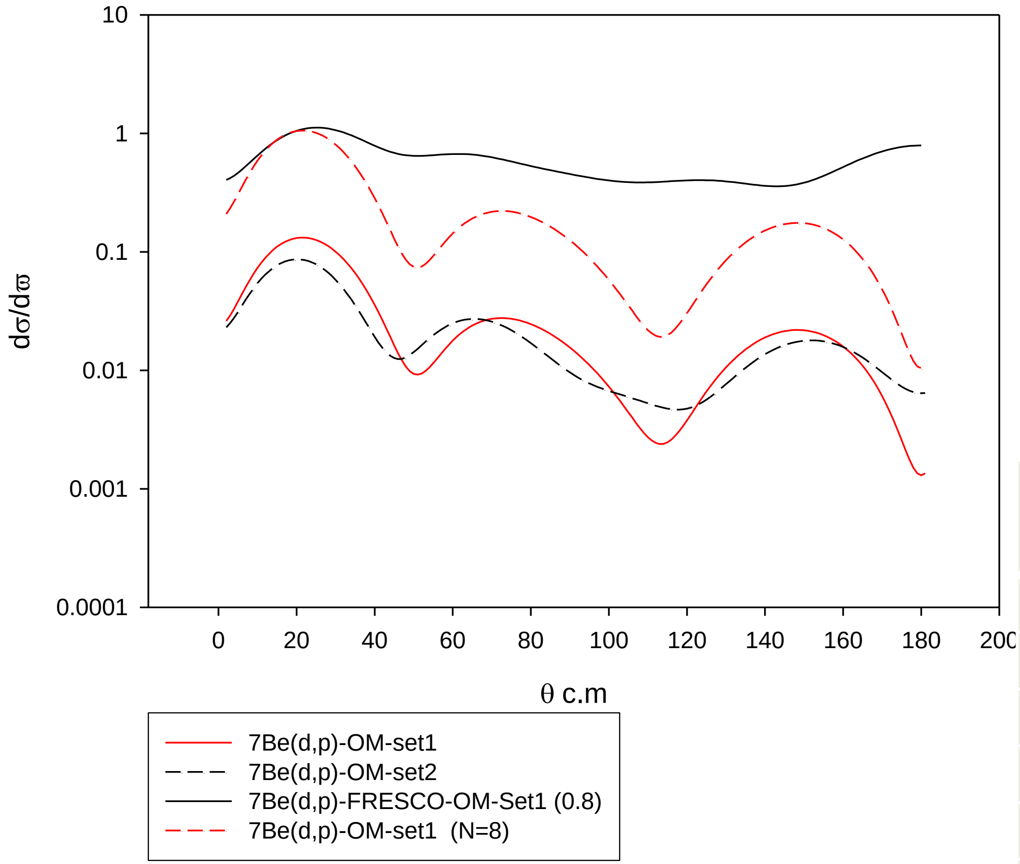






OM Potential for dwba

7Be(d,p)8Be 8Be gr state Ed=10MeV



OM Set-1

	Incident particle (deuteron) Set H[b]	Set C[c]	Set HII[d]	Captured particle (neutron)	Outgoing[e] particle (proton)
V_0 (MeV)	118	118	78		45
r_0 (F)	0.886	0.886	0.9	1.32	1.32
r_c (F)	1.3	1.3	1.3		1.3
a (F)	0.907	0.907	0.95	0.57	0.57
V_{so} (MeV)	5.8	5.8	5.8	$\lambda=25$	5.0
W' (MeV)	5.8	6.3	30		11
r_0' (F)	1.57	1.77	0.9		1.32
a' (F)	0.777	0.66	0.8		0.345

Ref. PRC 164,1274(1967) J. P. SCHIEZER et al .

OM Set-2

E_d=10 E_p=10 MeV	d+ ^{7}Be	p+^{8}Be
V_0	109	45.5
r_0	0.983	1.34
a_o	0.97	0.74
W_d	6.3	14
r_d	1.87	1.52
a_d	0.62	0.30
$V_{s.o.}$	8.8	4.9
r_c	1.3	1.3

NPA 173 (1971) 265-272; H. G. BINGHAM et al

Binding Potential for outer - n

	n+ ^{7}Be (Ref1)	p+n (Ref2)
V_0	50 (Adj)	50 (Adj)
r_0	1.6	1.25
a_o	0.6	0.65
$V_{s.o.}$	6	

Ref 1. Nuclear Physics A173 (1971) 213
Ref2. PRC 59,1545(1998)]

Outcome of the Experiment

- **Higher excitation energies in ^{8}Be -** measurement up to about **20 MeV** from (d,p)

- **Properties of the 16.7 MeV ($5/2^{+}$) resonance in ^{9}B** from (d,d)

Direct experimental determination of corresponding reaction rates might either support/refute a nuclear physics solution to the lithium problem. Other effects may include astrophysical effects, new effects (beyond standard BBN model) or a combination of all. Conventional solutions to the lithium problem ask for experimental testing.

While astrophysical solutions are not ruled out, they are increasingly constrained. Thus a serious and thorough evaluation of all possible nuclear physics aspects of primordial lithium production is urgent in order to determine whether the lithium problem truly points to new fundamental physics.

- **Possible at HIE-ISOLDE.**

At ISOLDE, ^{7}Be is produced with very high yields and even with a modest charge breeding efficiency 2-3% we should get plenty of beam at the end of the linac. Energy should be well above 5.5 MeV/A for this A/q.

Concerning contaminations of the beam, both **^{14}N** and **^{21}Ne** can be **suppressed completely** by selecting $^{7}Be^{4+}$ after a stripping foil inserted at the end of the linac ($^{7}Be^{3+}$ being accelerated up to the stripper foil).

As the halflife is long we will not reach saturation for the radiation level during the run. There are no restriction from a radiation protection point of view. If (for example) we take 10^{8} pps for 3 x 8 h shifts we will end up with ~ $9x10^{12}$ ions collected which lead to an activity of 0.2 MBq. Regarding the radiological hazards of radioactive nuclei produced at ISOLDE, the activity we need for our experiment is only a very small fraction of the authorization limit LA (**very small internal exposure risk**).

The hazard related to **external exposure**, assessed via the h10 quantity which for ^{7}Be = 0.008 (mSv/h)/GBq at 1 m quantity which give the dose rate at 1 m per GBq of activity.

Recent experiment with 7Be

1.. α-resonance structure in 11C studied via resonant scattering of 7Be + α and with the 7Be(α, p) reaction: Thick target method with inverse kinematics :(7Be beam stops in a thick ^{4}He gas target (200 mm-long, 1.6 atm). Recoiled a particles are detected by ΔE-E counter (10 mm and 500 mm Si detectors) at forward angle. NaI array for γ-ray measurement (to identify inelastic events).

..strong resonances were observed. The "thick target method with inverse kinematics" could be applied to many nuclides. We can study astrophysical reactions and alpha-clusterstructures. H. Yamaguchi et al., PRC (2013).

2..Experiments submitted at Tandem-ALPI-PIAVE accelerators
by May 31st, 2015 to be evaluated by PAC

Experimental study of the 7Be(n,α)4He at astrophysical energies by means of the Trojan Horse Method:
Lamia Livio from Dipartimento di Fisica e
Astronomia, UniCT

3..**Measurement of 7Be(n,a) and 7Be(n,p) cross sections for the Cosmological Li problem in EAR2@n_TOF :** Experimental program aiming at measuring at n_TOF-EAR2 for the first time the 7Be(n,p) and 7Be(n,a) cross sections in the whole range of interest for BBN, with the aim of reducing uncertainties in nuclear data used in calculations, thus setting stronger constraints to BBN theory and on CLiP.

nTOF INFN

4..Abstract Submitted for the DNP15 Meeting of The American Physical Society: Date submitted: 23 Jun 2015.

Measurements of 7*Li*+*d* $\rightarrow n+\alpha+\alpha$ *and 7Be+d* $\rightarrow p+\alpha+\alpha$ *nuclear* reactions and their implication in the Standard Big Bang Nucleosynthesis (SBBN) by Nabin Rijal et al (Florida State University).

We investigate the 7*Be + d reaction* at SBBN energies using a radioactive 7*Be beam and deuterium gas target inside* ANASEN (Array for Nuclear Astrophysics Studies with Exotic Nuclei). ANASEN is an active target detector system which tracks the charged particles using a position sensitive proportional counter and 24-SX3 and 4-QQQ position sensitive Silicon detectors, all backed up by CsI detectors. The experiment measures a continuous excitation function by slowing down the beam in the target gas down to zero energy.

Our set-up provides a high detection efficiency for all relevant reaction channels. We also performed an experiment for the mirror nuclear reaction 7*Li*+*d* $\rightarrow n+\alpha+\alpha$ with ANASEN in solid target mode using *CD2 target and a neutron detectors wall.* The results of the experiment along with details of ANASEN and plans for the 7*Be + d experiment using ANASEN in gas target mode will be presented.

5. Background Considerations for the 2H(7Be,3H)6Be Experimental Data II: Three-body Continuum:
K. Y. Chae, . V.Guimaraes, (Journal of the Korean Physical Society, 67,1533(2015)

The one-neutron transfer reaction was measured in inverse kinematics by using radioactive 7Be (*t1/2 = 53.2 days) beams at the Holifield Radioactive Ion* Beam Facility of the Oak Ridge National Laboratory in 2004 in order to search for the resonances in the unbound 6Be nucleus.
The observed spectrum was rather featureless indicating that direct transfer to 6Be levels was not particularly strong compared to other reactions that could produce tritons in their exit channels.

Moreover, as pointed out in Ref. [1], the observed cross sections were larger than the Distorted Wave Born Approximation calculations indicating that a mixture of reaction mechanisms is involved.

Thank You