Nuclear Physics Reactions of Astrophysical Importance

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July 27, 2012

Outline

- Nuclear Physics and Astrophysics

- The Big Bang
  - ^{7}Li abundance problem
    - Observations
    - Model predictions

  - Search for ^{7}Be+d resonance
    - Experimental Setup
    - Results

  - Conclusions

Origin of Elements

- Big Bang?
  - What formed and how?
- Stellar Nucleosynthesis?
  - What processes form what elements?
- Heavy Elements
  - r-process?
  - rp-process

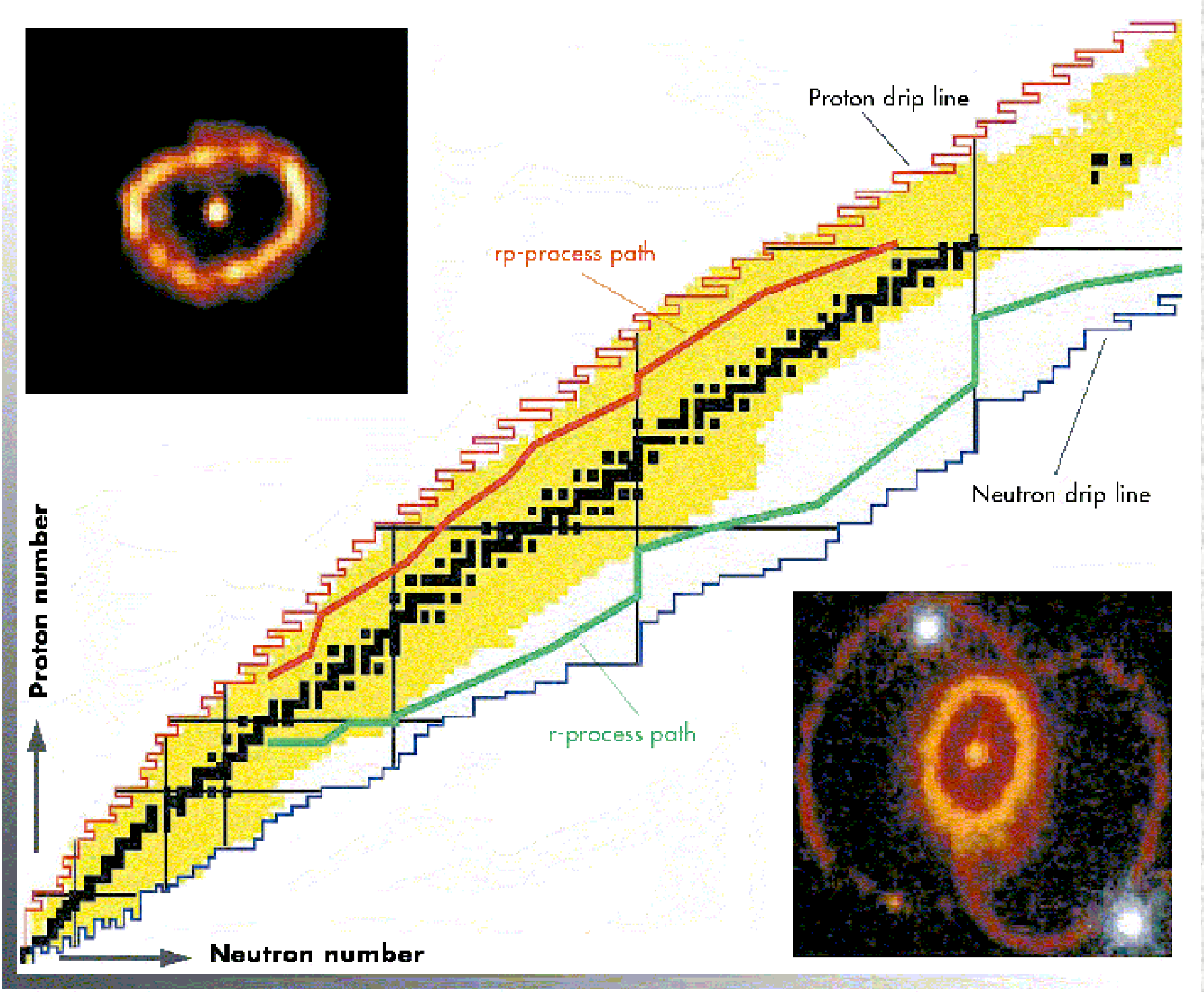
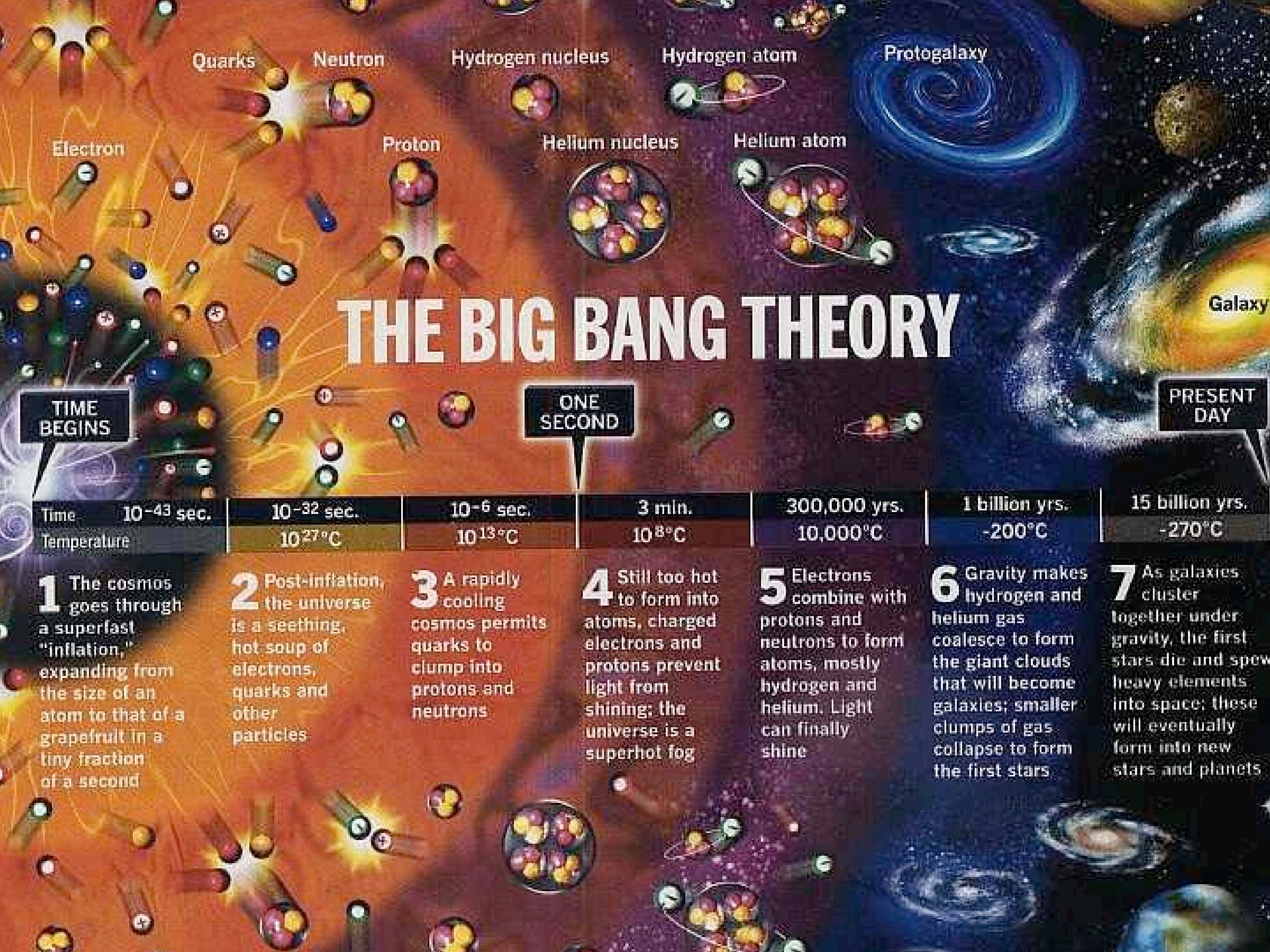


Figure taken from http://ns.ph.liv.ac.uk/~mc/my_research/mass_measurements.html

THE BIG BANG THEORY



Time	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature		10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

Support for the Big Bang

- The universe does in fact exist
- Hubble's Law – galaxies are moving away at speeds proportional to their distance from us
- Cosmic microwave background - ~2.7 K

Big Bang Nucleosynthesis

- Standard Model of Particle Physics
- General Relativity
- Homogeneity and Isotropy
- Nuclear Cross Sections

→ Light Elements

single free parameter: Baryon Density
(or η = baryon-to-photon ratio)

Goals:

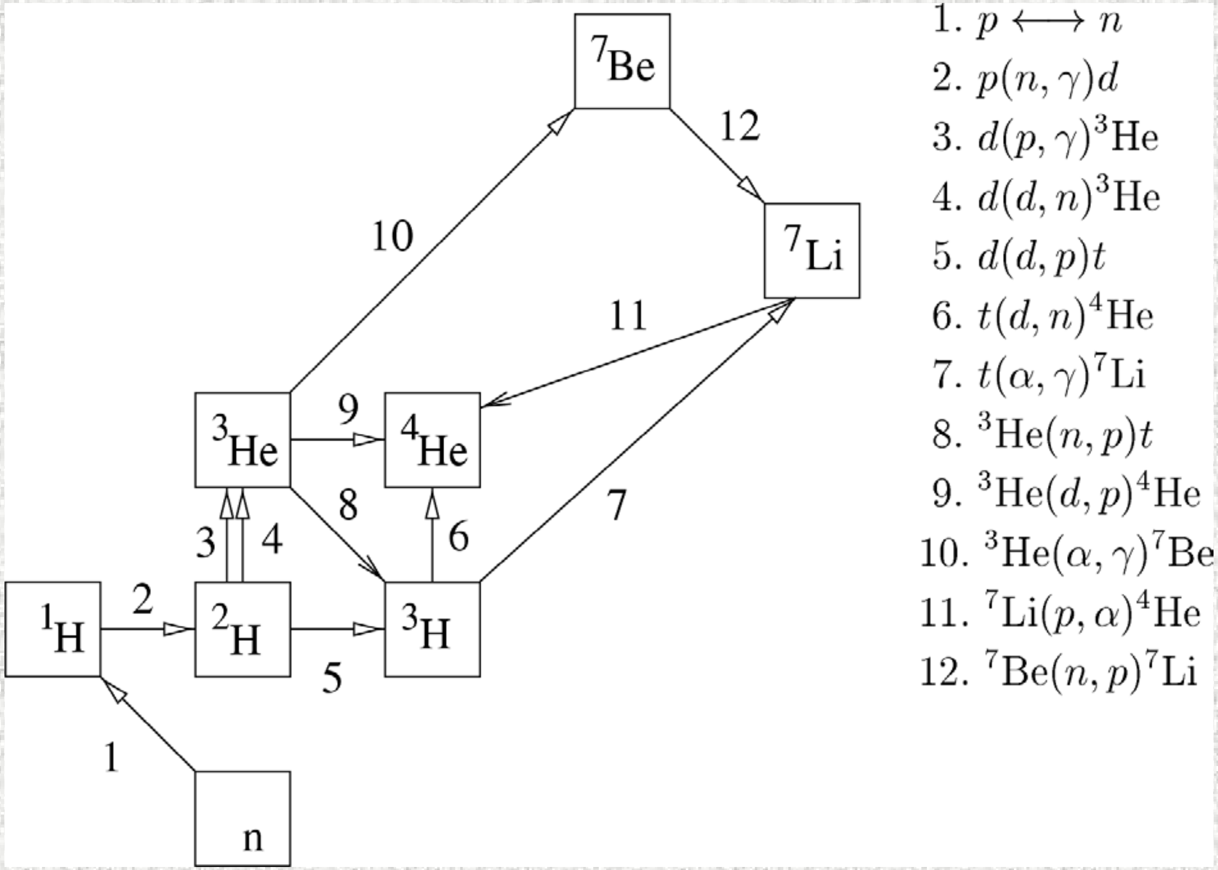
- Determine **η**
- Compare to astronomical observations of abundances
- Compare to other cosmological studies (e.g. CMB)

courtesy of Carl Brune, private communication

The Canonical Reaction Network

- 11 cross sections
- neutron lifetime
- E ~ 100 keV

Measure in the lab!



1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

Inverse reactions also included

courtesy of Carl Brune, private communication

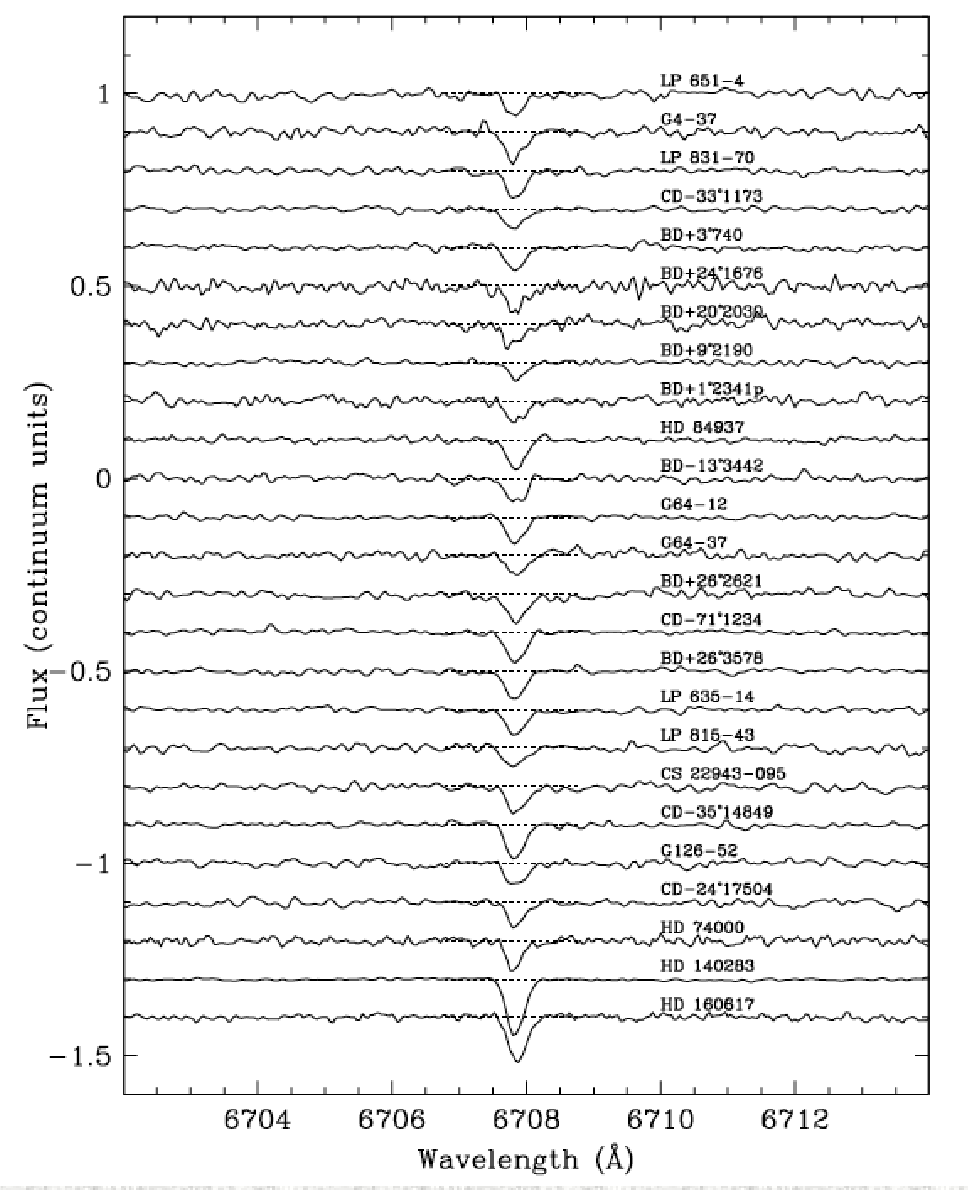
Observations?

- Lithium abundances are measured for Population II stars
    - Stars with low metallicity formed from gases representative of the post big bang universe

- Look for a doublet peak around 670.7 nm
    - Characteristic atomic lithium line

- ^{6}Li and ^{7}Li differentiated only for a few stars
    - Location of centroid of doublet determines relative abundances

- Abundances fit as a function of metallicity
    - Extrapolate to 0 metallicity for BB abundance



S.G. Ryan, J.E. Norris, T.C. Beers, Astrophys. J. 523 1999

WMAP

- Wilkinson Anisotropy Probe (WMAP) is a deep space satellite used to measure the tiny fluctuations in the CMB
    - Fluctuations in the CMB correlate to fluctuations in the quark-gluon plasma

- WMAP was able to further constraint the baryonic density from the previously used range of $0.0044<\Omega_b h^2<0.025$:

$$\Omega_b^{WMAP} h^2 = 0.0227 \pm 0.0006$$

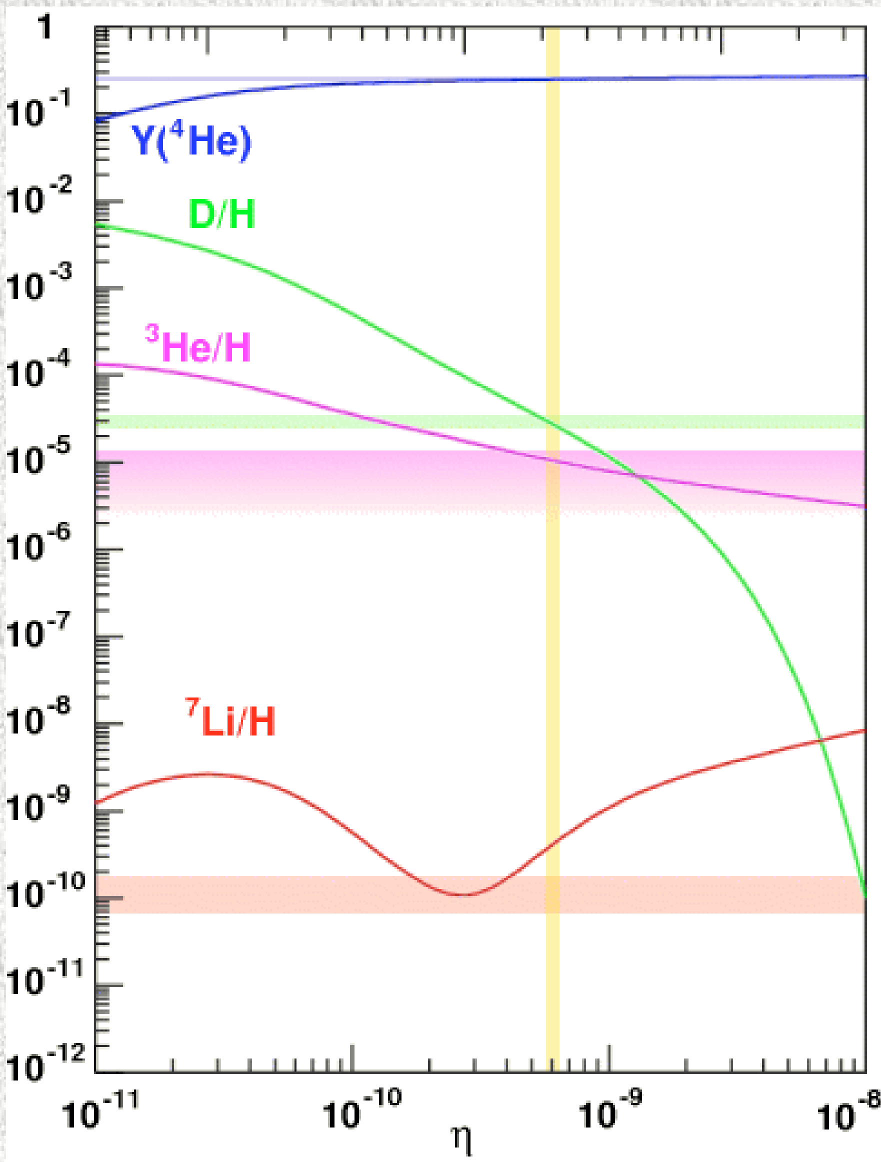
$$\eta = 6.23 \pm 0.17 \times 10^{-10}$$

    - Hydrogen and helium abundances were reproduced well by BBN calculations
    - Lithium abundances are not
        - Extrapolated observations yield:

$$^7Li/H = 1.23^{+0.34}_{-0.16} \times 10^{-10}$$

        - WMAP constrained BBN calculations yield:

$$^7Li/H = 5.24^{+0.71}_{-0.67} \times 10^{-10}$$



from http://www.einstein-online.info/en/spotlights/BBN/index.html

Why?

- Several explanations for this have been proposed:
  - Cosmological abundance of lithium is altered in the subsequent evolution
    - Perhaps convection in the layers of the star are pulling the lithium to lower levels where it gets destroyed

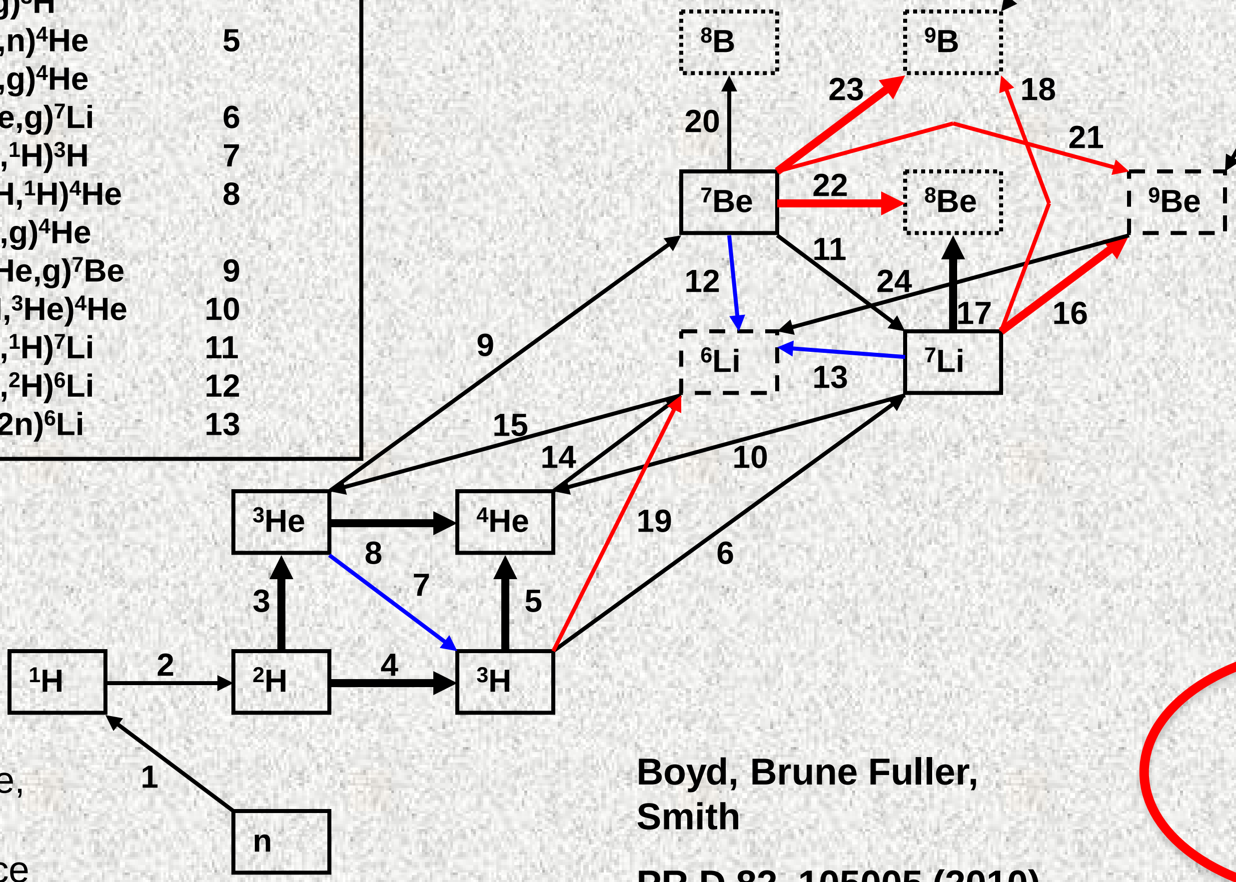
  - New Physics
    - Variation of the strong interaction in the early universe over time

    - Decays of heavier meta-stable particles that inject additional neutrons which could increase the rates of ^{7}Be+n

  - Nuclear Physics
    - Resonant enhancement of known reaction rates
    - A more complete system of reactions should be included

Extended BBN Reaction Network

Reaction Key	
n → ^{1}H	1
^{1}H(n,g)^{2}H	2
^{2}H(^{2}H,n)^{3}He	3
^{2}H(^{1}H,g)^{3}He	
^{2}H(^{2}H,^{1}H)^{3}H	4
^{2}H(n,g)^{3}H	
^{3}H(^{2}H,n)^{4}He	5
^{3}H(^{1}H,g)^{4}He	
^{3}H(^{4}He,g)^{7}Li	6
^{3}He(n,^{1}H)^{3}H	7
^{3}He(^{2}H,^{1}H)^{4}He	8
^{3}He(n,g)^{4}He	
^{3}He(^{4}He,g)^{7}Be	9
^{7}Li(^{1}H,^{3}He)^{4}He	10
^{7}Be(n,^{1}H)^{7}Li	11
^{7}Be(n,^{2}H)^{6}Li	12
^{7}Li(n,2n)^{6}Li	13



Completely unstable

Some stable states

Reaction Key	
^{4}He(^{2}H,g)^{6}Li	14
^{6}Li(^{1}H,^{4}He)^{3}He	15
^{7}Li(^{3}H,n)^{9}Be	16
^{7}Li(^{3}He,^{1}H)^{9}Be	
^{7}Li(^{2}H,n)^{8}Be	17
^{7}Li(^{1}H,g)^{8}Be	
^{7}Li(^{3}He,^{2}H)^{8}Be	
^{7}Li(^{3}He,n)^{9}B	18
^{3}He(^{3}H,g)^{6}Li	19
^{7}Be(^{1}H,g)^{8}B	20
^{7}Be(^{3}H,^{1}H)^{9}Be	21
^{7}Be(^{2}H,^{1}H)^{8}Be	
22	
^{7}Be(^{3}H,^{2}H)^{8}Be	
^{7}Be(^{3}He,^{1}H)^{9}B	23
^{7}Be(^{3}H,n)^{9}B	
^{9}Be(^{1}H,^{4}He)^{6}Li	24

Boyd, Brune Fuller, Smith

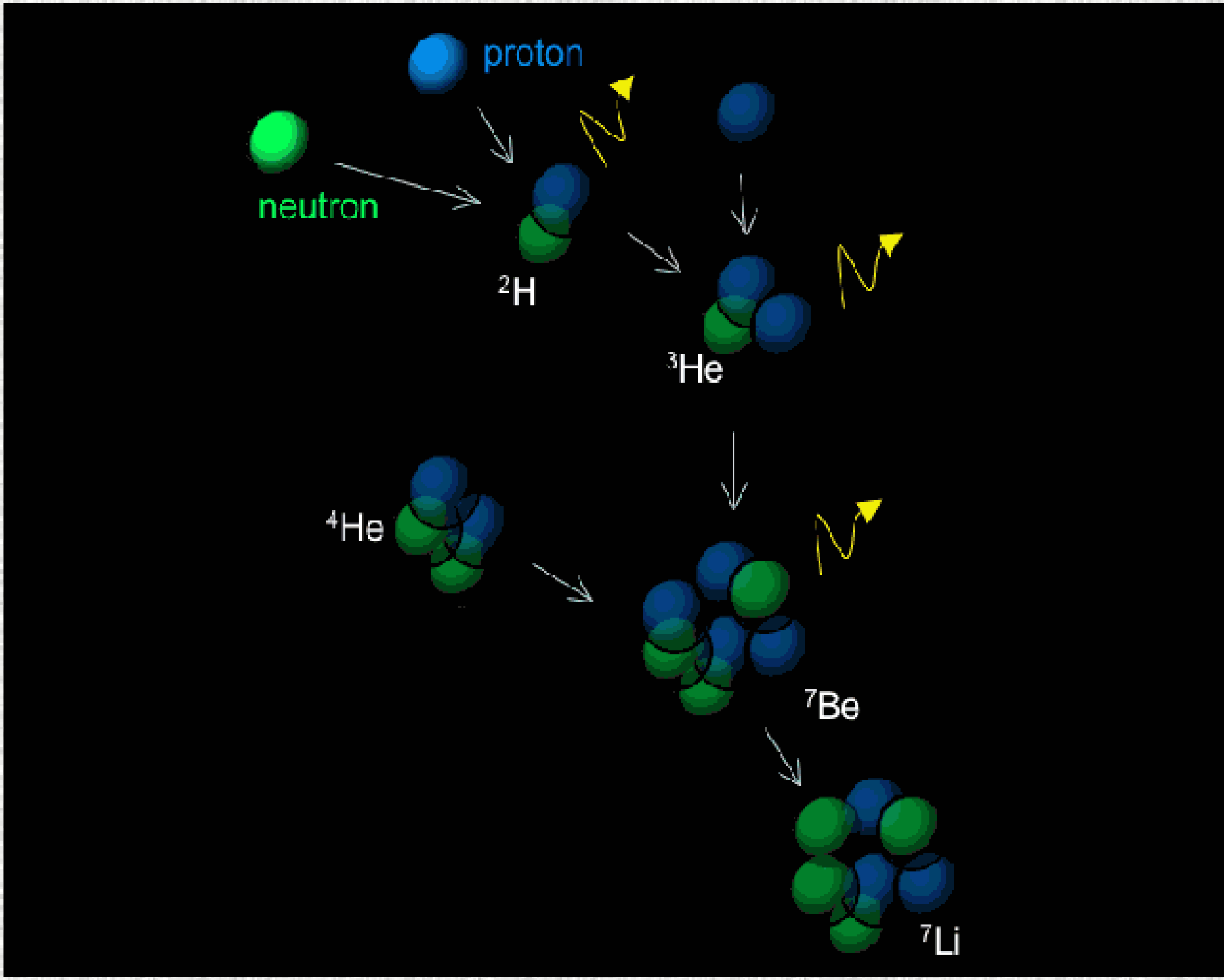
PR D 82, 105005 (2010).

Carl Brune,
Gordon Conference
June 12-17 2011

^{7}Li's parent

- A proposed nuclear physics solution is a possible resonance in ^{9}B that would enhance the burning of ^{7}Be in ^{7}Be(d,p) and ^{7}Be(d,γ) reactions and reduce the number of ^{7}Li from ^{7}Be decays.
  - If ^{7}Be were destroyed faster then it may explain the discrepancy between calculations and observation

- If the known ^{9}B 5/2^{+} level at E_x=16.7 MeV has a resonance energy and deuteron decay width in the range (E_r,Γ_d)=(170-220,10-40) keV, it could be a candidate for such a resonance.



Carl Brune, private communication

^{7}Li's parent

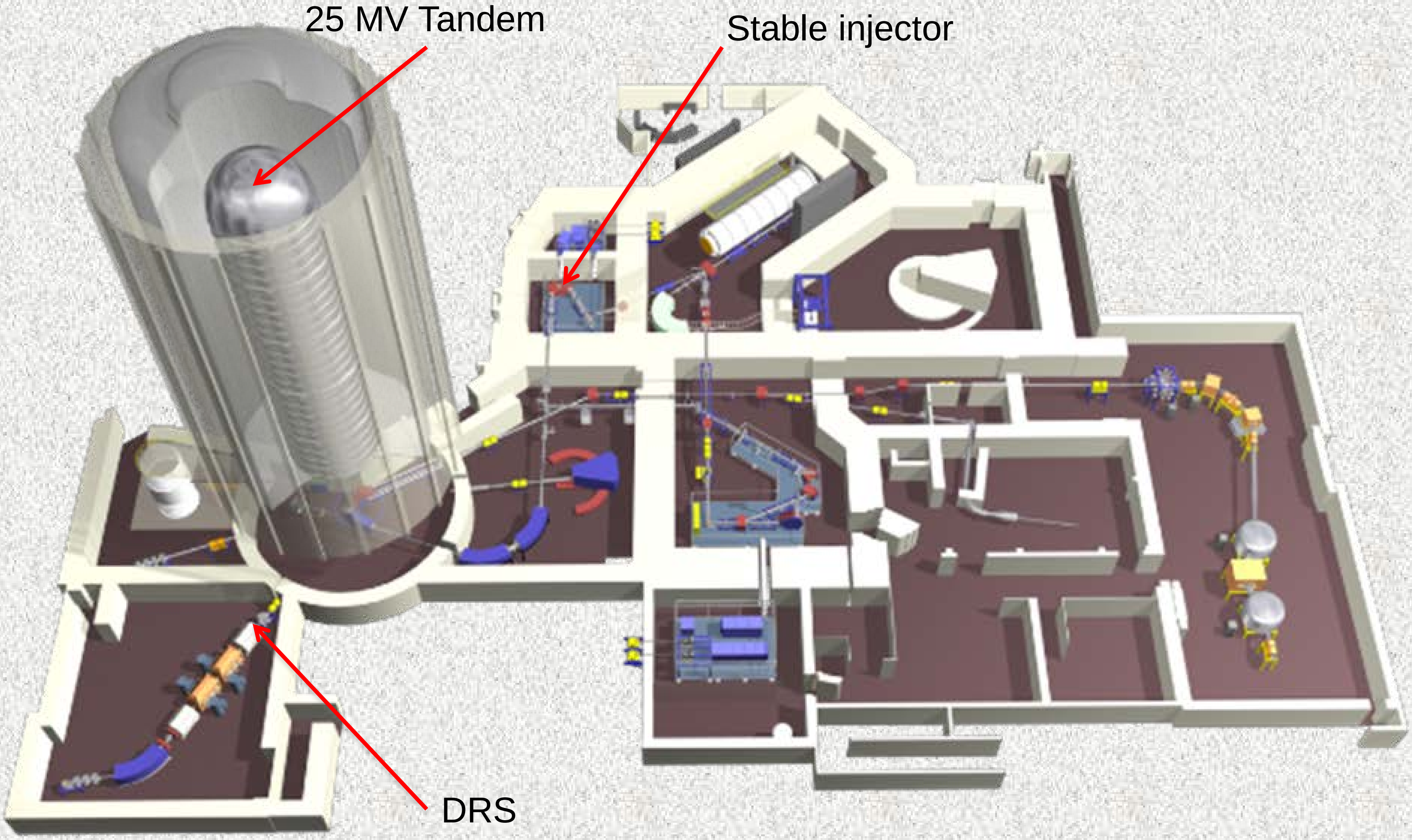
- ^{7}Be(d,p)2α rate was directly measured before by C Angulo *et. al.*
  - C. Angulo et al., Astrophys. J. 630, L105 (2005).

- Assumptions in prior work may not have been valid and experiment may not have been sensitive to protons in the range of importance
  - R. H. Cyburt and M. Pospelov, astro-ph/0906.4373, C. Angulo et al., Astrophys. J. 630, L105 (2005)

- A new measurement
  - Elastic scattering of deuterons could measure properties of such a resonance

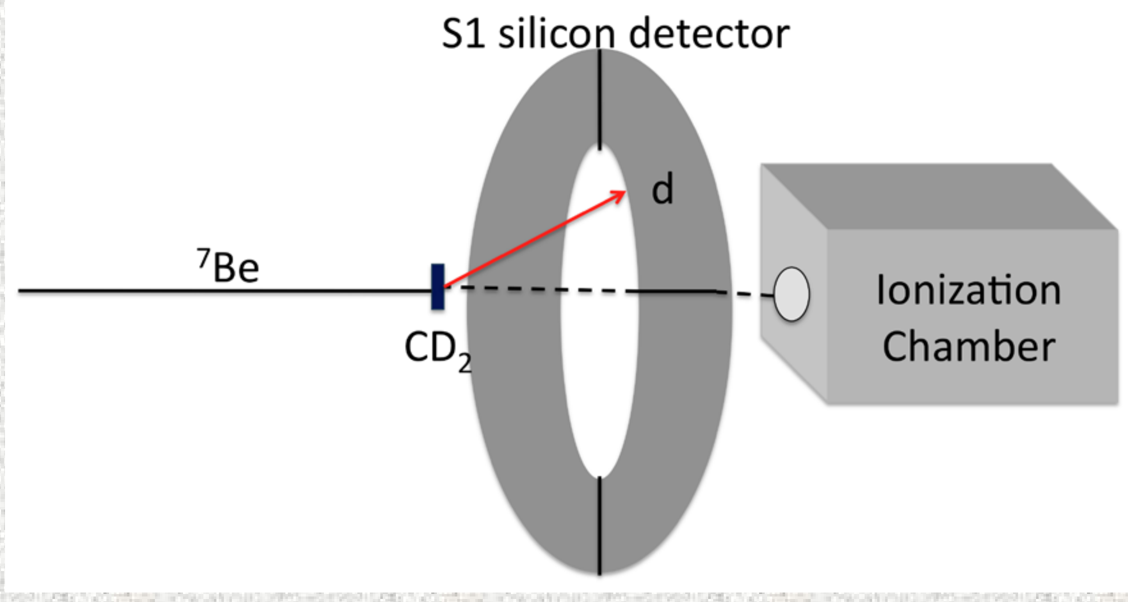
- Bombarding a thick target CD_2 target with a ^{7}Be beam will allowed energies around the proposed resonance to be studied

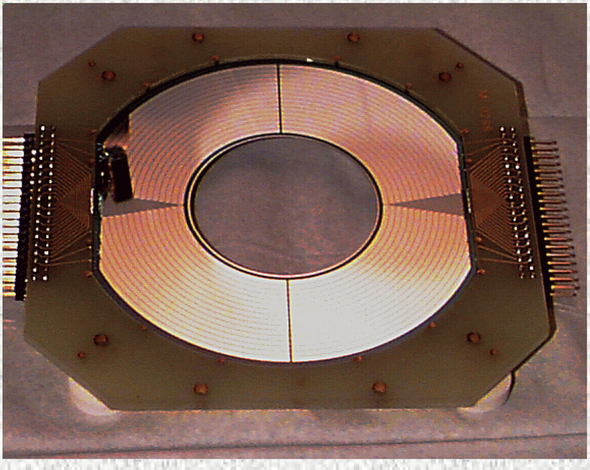
Holifield Radioactive Ion Beam Facility



^{7}Be(d,d)

This reaction could measure the width of the ~200 keV resonance

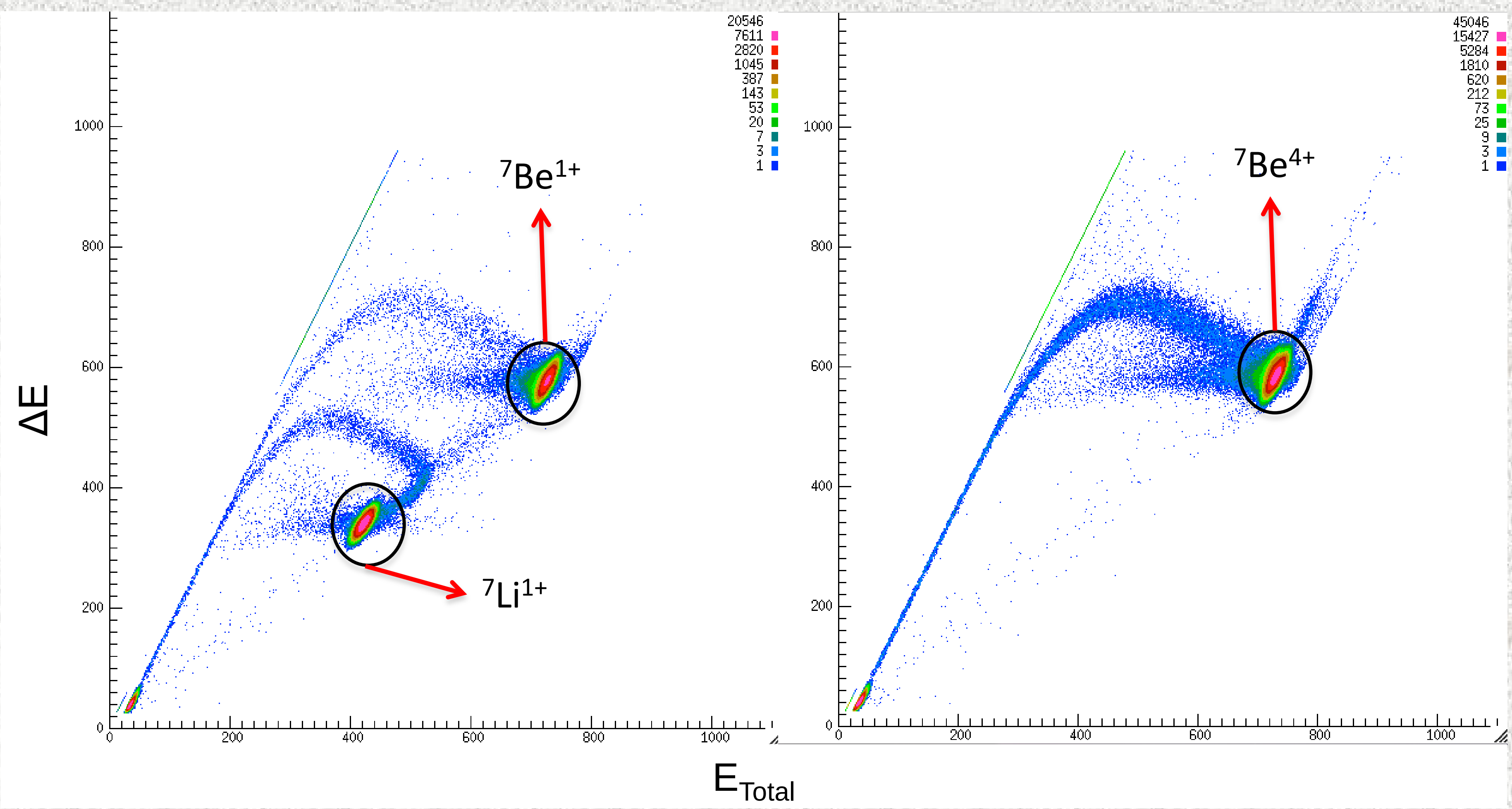




- ^{7}Be beam was bombarded a CD_2 target at an average intensity of 50,000 pps
  - The target was rotated to 50° making it effectively 2.52 mg/cm^2 thick

- Outgoing particles were detected in the MINI silicon detector covering lab angles 6° -12°
  - 12.9 – 25.8 in the center of mass

^{7}Be(d,d)



- An ionization chamber was utilized downstream to measure the beam purity/rate
  - By stripping to charge state 4^{+}, a pure beam of ^{7}Be was achieved

R-Matrix in a nutshell

- Main aim of R-matrix theory is to describe scattering states result from interactions of particles

- Divides space into two regions, internal and external regions
  - The boundary of these regions is defined the “channel radius”

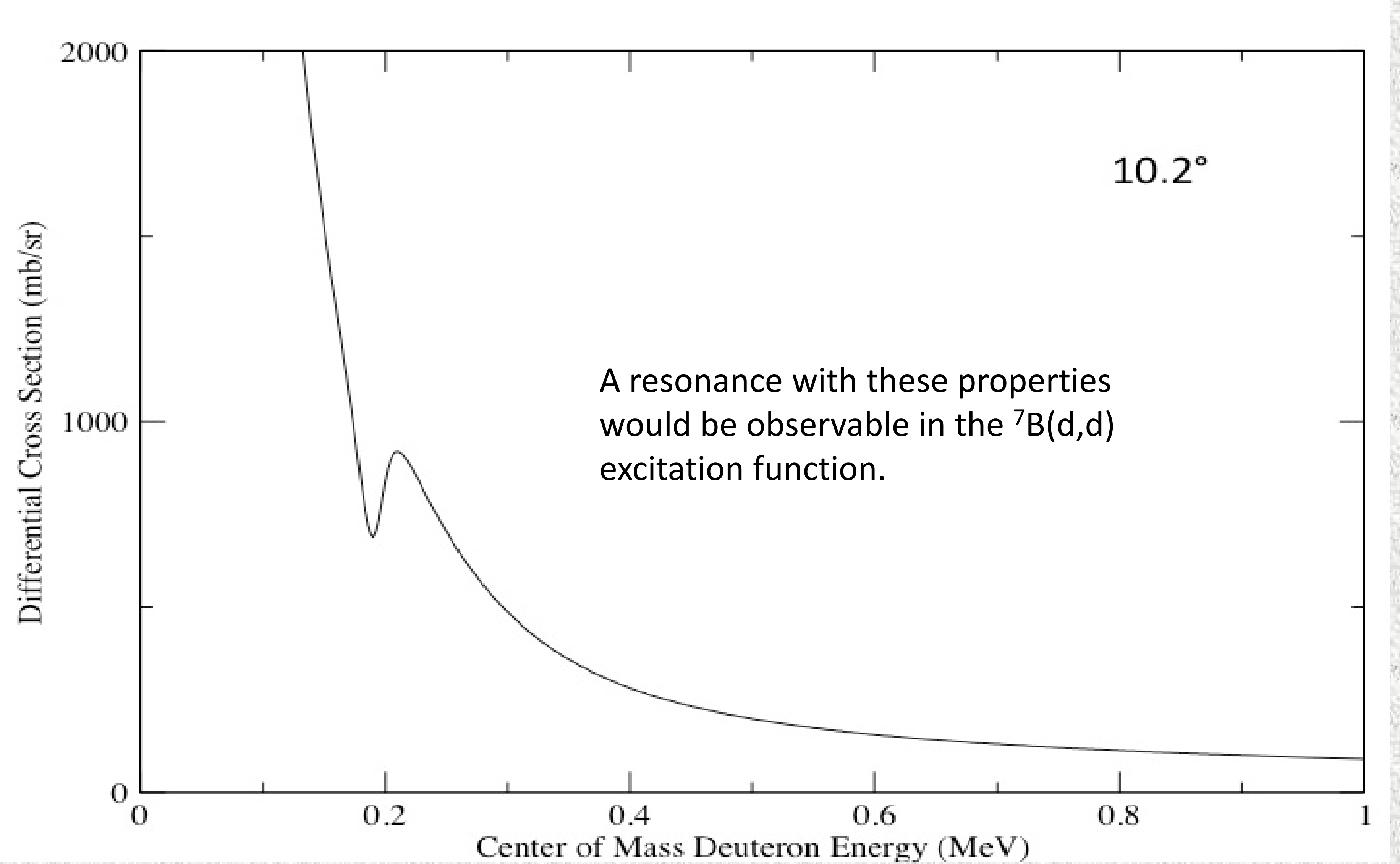
- In the external region, only known long range interactions are considered
  - Scattering wave function is approximated by its asymptotic expression
  - Interaction matrices are diagonal

- In the internal region, the system is confined
  - Eigenstates form a discrete basis which can be calculated
  - The scattering wave is expanded over these eigenstates

- R-matrix accounts for all interactions within the nucleus (non diagonal)
  - Also depends on set of boundary conditions
  - Matching with solution in the external region yields scattering matrix

P. Descouvemont and D Baye, Rep. Pro. Phys. **73** 036301 (2010)

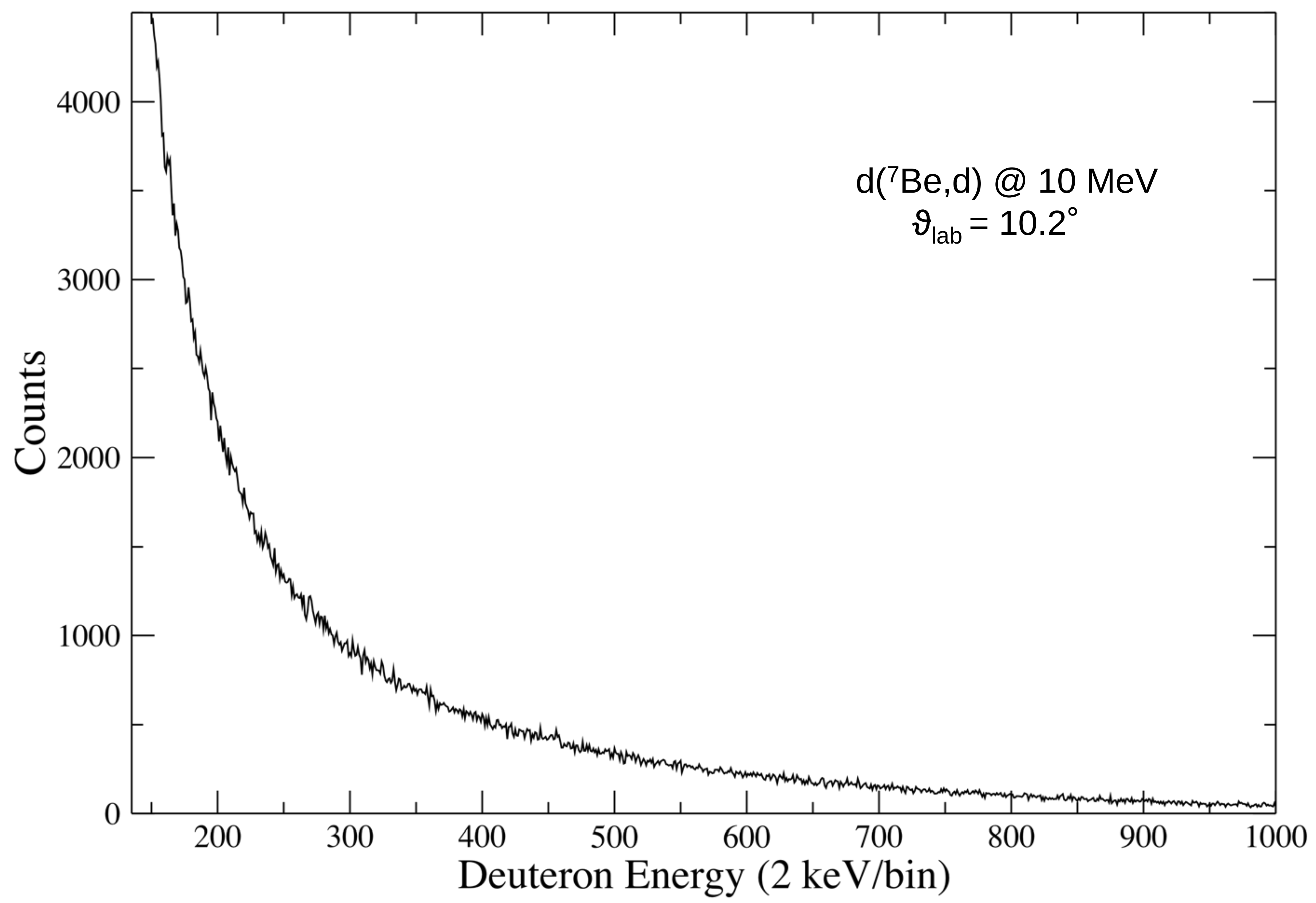
R-Matrix with MULTI



A resonance with these properties would be observable in the ^{7}B(d,d) excitation function.

R.O. Nelson, E.G. Bilpuch, and G.E. Mitchell, Nucl. Inst. and Meth. in Phys. Res. **A236**, 128 (1985).

Data


d(^{7}Be,d) @ 10 MeV
ϑ_{lab} = 10.2°
Counts
4000
3000
2000
1000
0
200
300
400
500
600
700
800
900
1000
Deuteron Energy (2 keV/bin)

Corrections

- Several corrections need to be made before comparisons can be made to theoretical calculations
  - Energy loss of deuterons in target
    - Estimated using kinematics code RELKIN in conjunction with STOPIT

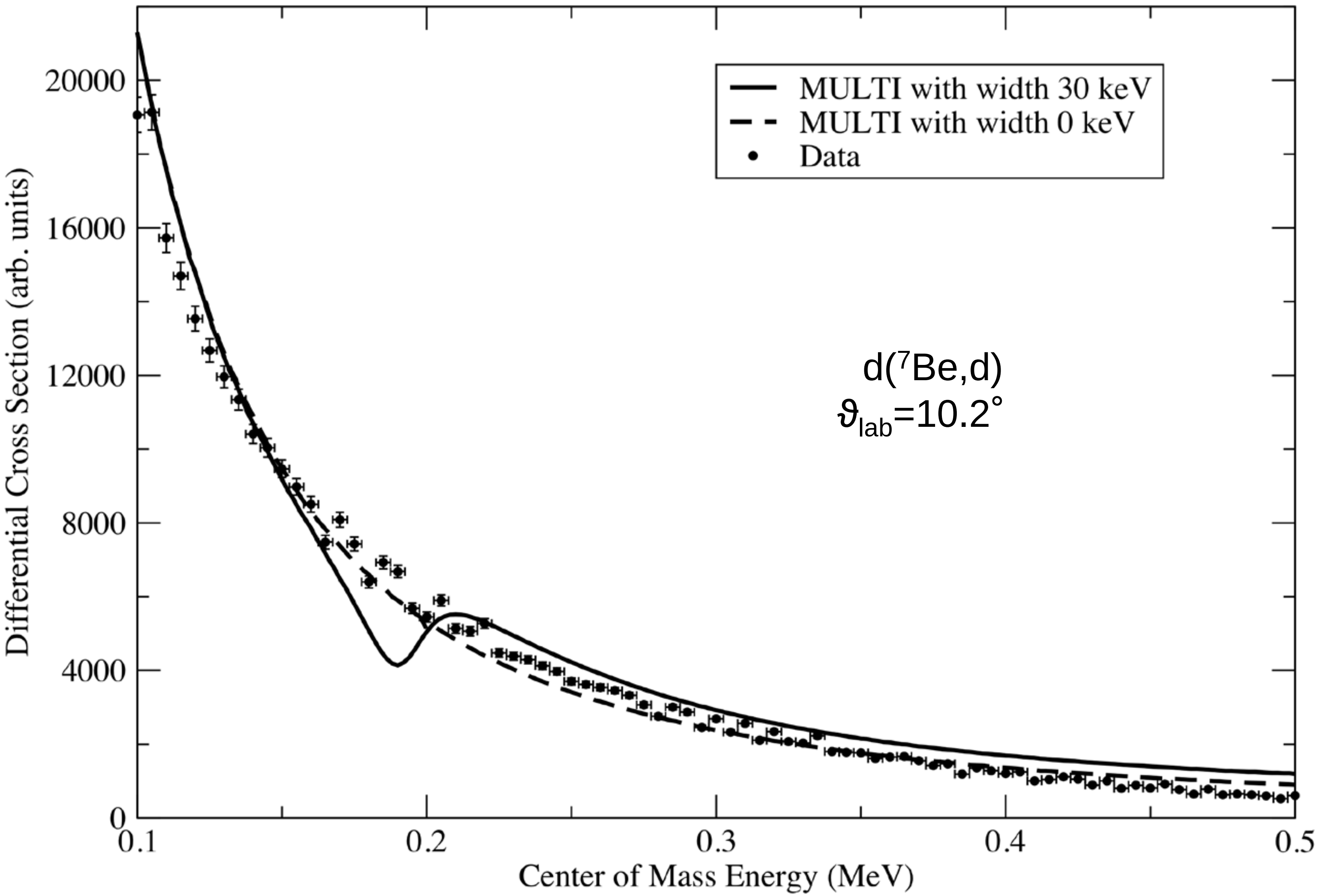
$$\frac{d\sigma}{d\Omega}=\frac{\overset{\text{Detection rate}}{R}}{\underset{\text{Target density}}{\rho}\times\underset{\text{Target thickness}}{\Delta x}\times\underset{\text{Beam intensity}}{I}\times\underset{\text{Solid angle}}{\Delta\Omega}}=\frac{R}{\rho\times\left(\Delta E\times\frac{dx}{dE}\right)\times I\times\Delta\Omega}$$

- In this experiment the effective target thickness is energy dependent
  - Could use energy bins and stopping power instead
  - dE/dx Estimated using SRIM

$$=\frac{R\times\frac{dE}{dx}}{\rho\times\Delta E\times I\times\Delta\Omega}$$

- Center of mass conversion:

$$E_{c.m.}=\frac{m_d+M\left({}^{7}Be\right)}{4M\left({}^{7}Be\right)\cos^2\vartheta_{lab}}E_{d,\,lab}$$



d(^{7}Be,d)

ϑ_{lab}=10.2°

Strategy

- For each strip, perform a least X^2 normalization to MULTI calculations for ~0 keV width
- Slowly increase width until X^2 increases by 6.17 to get an upper bound for the width within a 95% confidence level
- The upper limit was determined to be the average of that determined from each strip

Laboratory Angles (degrees)	Upper Limit Γ_d (keV) for 3/2 entrance	Upper Limit Γ_d (keV) for 5/2 entrance
6.9	1.1	1.1
7.3	0.4	0.5
7.7	0.6	0.7
8.0	1.1	1.2
8.8	0.8	0.8
9.1	0.8	0.9
10.2	1.5	1.6
11.0	2.4	2.4

Averaging these strips yields an upper limit of **1.06 keV** and **1.10 keV** with a 95% confidence level for the entrance channels of 3/2 and 5/2 respectively

Conclusion

- A proposed solution to the ^{7}Li mystery was the existence of a 16.7 MeV resonance in ^{9}B
  - In order to resolve the discrepancy the resonance width should be greater than 10 keV.

- At ORNL a study of this “resonance” was performed using the ^{2}H(^{7}Be,d)^{7}Be reaction
  - A thick target technique was used with a 10 MeV beam of ^{7}Be

- No such resonance was observed and an upper limit was placed on this resonance of ~1 keV with a 95% confidence level

- Since this upper limit is much smaller than the minimum necessary for this proposed resonance to resolve the discrepancy, this is clearly not the solution

- Other possible solutions need to be studied
  - understanding of the stellar processes that deplete lithium need to be improved.
  - physics beyond the standard BBN model

- **Phys. Rev. C 84, 042801(R) (2011)**

^{7}Be+d Thanks!

A. Adekola, J.A. Cizewski, M. Howard, S Strauss
Rutgers University

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University of Tennessee

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Oak Ridge Associated Universities

S. Graves, R.L. Kozub, J.F. Shriner, J. Wheeler
Tennessee Technological University

J. Blackmon, L. Lindhardt, M. Matos, B. Moazen
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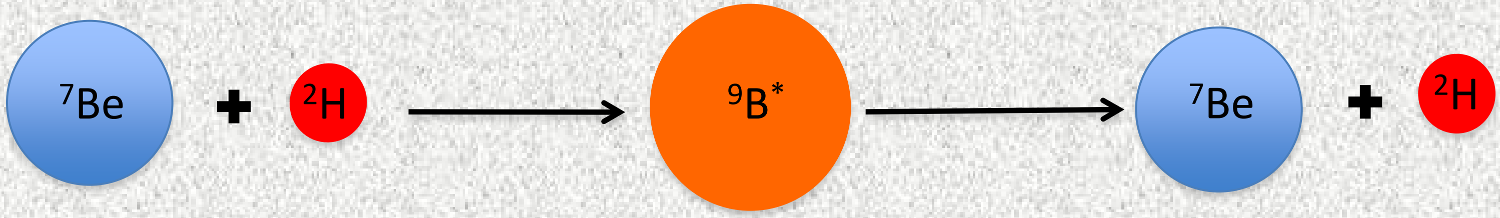
*Work supported in part by DOE and NSF

Questions?

Entrance Channel Spin



$^{7}\mathrm{Be} + {}^{2}\mathrm{H} \rightarrow {}^{9}\mathrm{B}^{*} \rightarrow {}^{7}\mathrm{Be} + {}^{2}\mathrm{H}$

$3/2^{-} + 1^{+} \rightarrow 5/2^{+}$

(1/2, 3/2, 5/2)

- 3/2 and 5/2 entrance spins would require a p-wave transfer to populate this 5/2 resonance
- 1/2 needs an f-wave transfer, which would be much less probable at these energies so it was neglected in the final analysis
- Need to consider both possible entrance channel spins (3/2 and 5/2) in R-matrix calculations

Energy Loss

1. Determined beam energy for various depths in target
2. For each depth and detector angle, calculate expected deuteron energy
3. Determine energy loss for these deuterons in remaining target thickness
4. Plot “measured” energy against energy loss to determine eloss correction function