High-energy break-up of ^{6}Li as a tool to study the BBN reaction d(α,γ)^{6}Li

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1. **Introduction:**
   - ^{6}Li observations in old halo stars?
   - BBN Network
   - Previous results from d(α,γ)^{6}Li and ^{6}Li Coulomb-breakup experiments

2. **Theory of ^{6}Li high-energy break-up**
   - Modeling nuclear and Coulomb break-up
   - Predictions for differential cross sections and angular distributions

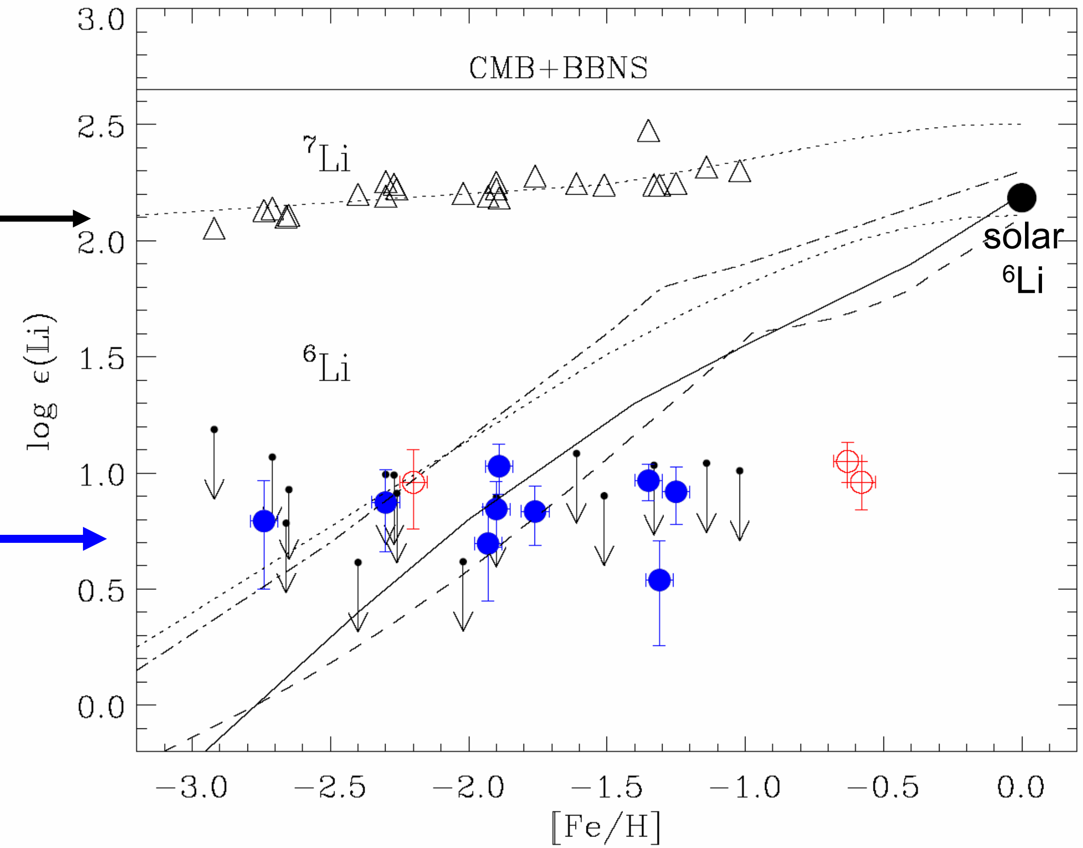
3. **^{6}Li high-energy break-up experiment at GSI**
   - Experimental set-up at KaoS
   - Evidence for nuclear-Coulomb interference
   - Extraction of S_{24}

4. **Conclusions**

GSI

Astronomy: Observation of $^{6,7}Li$ in old halo stars

Li has been observed in old halo stars ("Spite plateau")



Asplund et al. (2006):
Observation of ^6Li shoulders in Li lines from old stars!
➔ similar plateau for ^6Li!

The d(α,γ)^{6}Li reaction in the Big Bang

Small amounts of ^{6}Li are produced during the Big Bang via the **d(α,γ)^{6}Li** reaction:

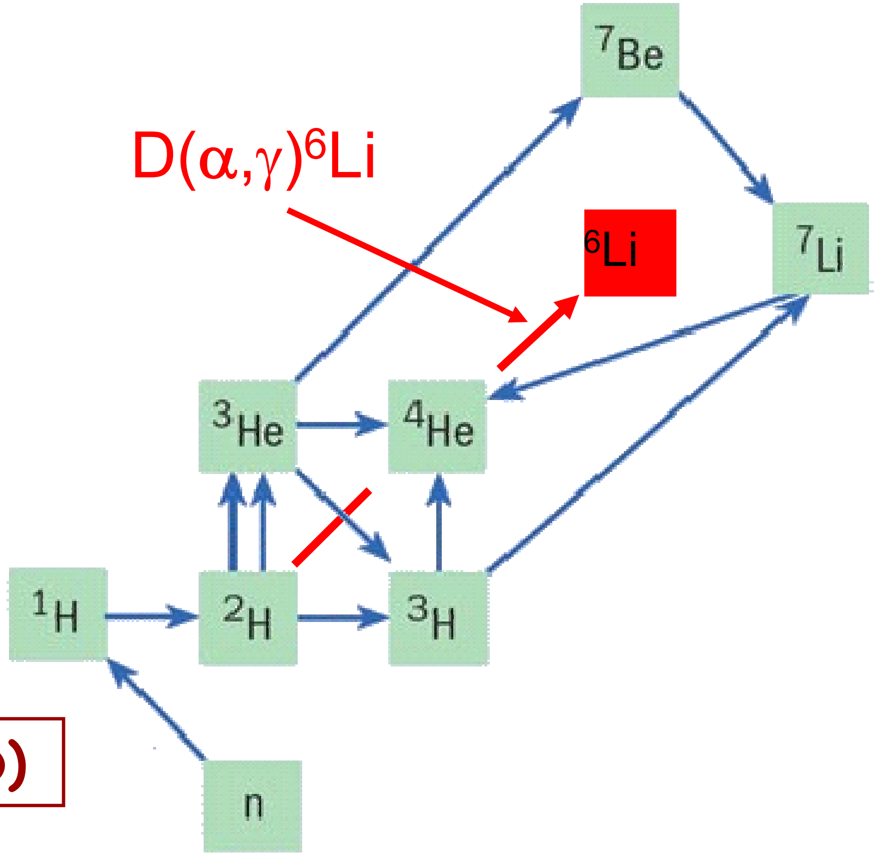
Direct measurements done, but only for E_{cm} > 700 keV

The cross section at Big Bang energies (E_{cm} ~50-400 keV) is extremely small and therefore difficult to measure directly:

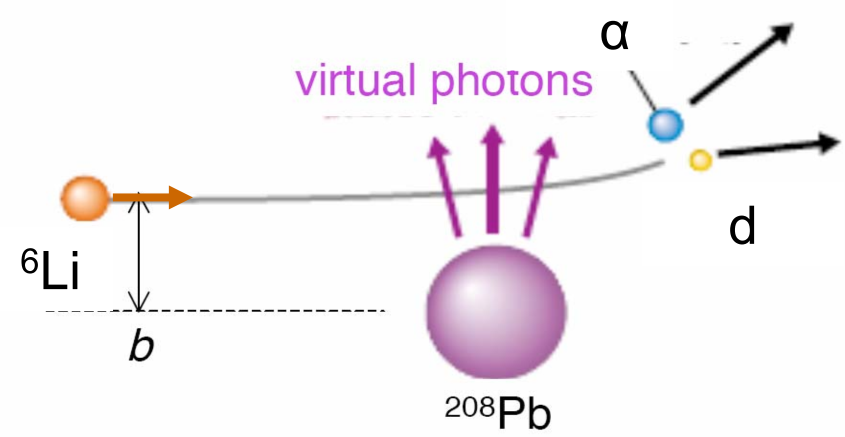
$$\sigma_{\alpha,\gamma}(100\ \text{keV}) \approx 30\ \text{pb}$$

Will be undertaken soon at LUNA!

Alternative: Coulomb dissociation (CD)



Coulomb Dissociation of ^{6}Li



^{6}Li + ^{208}Pb → α + d + ^{208}Pb (CD)

↓ virtual photon theory

$$d\sigma_{CD}/dE_{cm} = 1/E_{cm}\, dn_\gamma/dE_{cm}\, \sigma_\gamma$$

↓ detailed balance

$$\sigma_\gamma = 3\, k^2/k_\gamma^2\, \sigma_{rc}$$

$k_\gamma = (E_{cm}+Q)/\hbar c$

$k^2 = 2\mu E_{cm}/\hbar^2$

$k^2/k_\gamma^2 \approx 1000$

<u>Necessary conditions for obtaining $\sigma_{p\gamma}$ from Coulomb dissociation:</u>

– multipole contributions must be known

– negligible nuclear contributions (l ≥ 2)

Ideal cases:

- pure E1 multipolarity!
- small Q-value!

e.g. ^{8}B → ^{7}Be+p

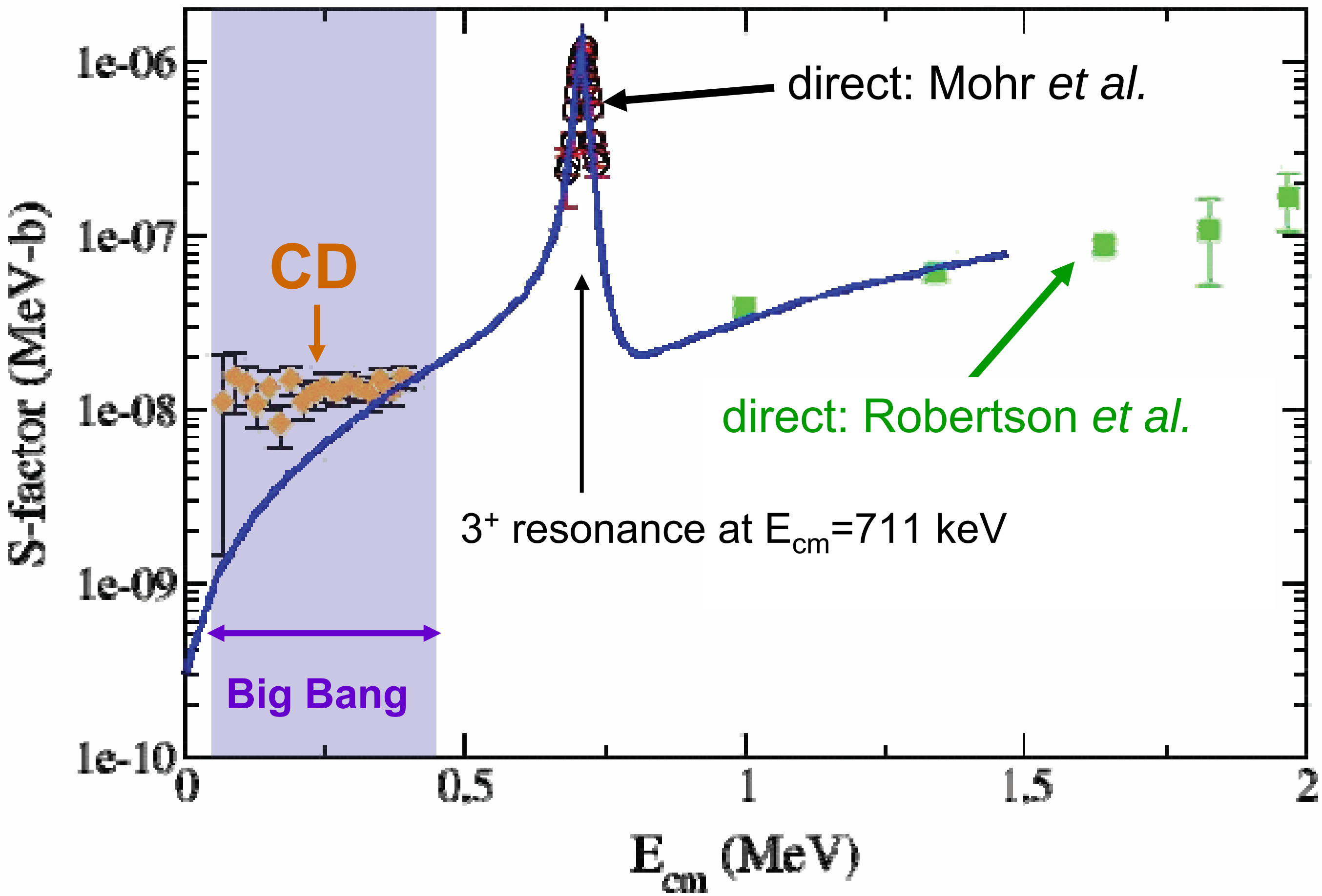
Here: l=2 multipolarity!

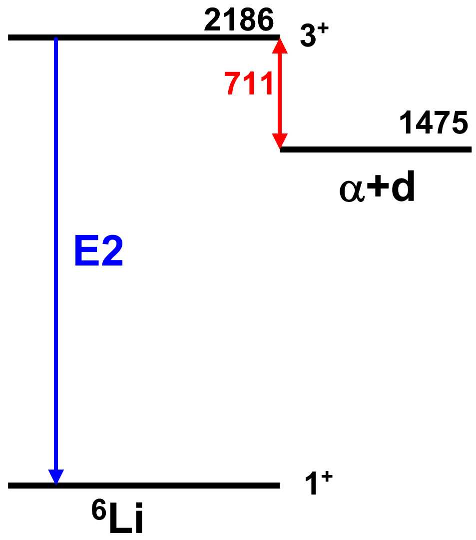
- **profit from large number of E2 photons**
- **but: nuclear contribution?**

Previous d(α,γ) Experiments

- Direct measurements at higher energies available.
- Pioneering CD experiment at 26 A MeV by Kiener *et al.* (Karlsruhe, 1991)

➔ new CD measurement at higher energy (150 A MeV) at GSI



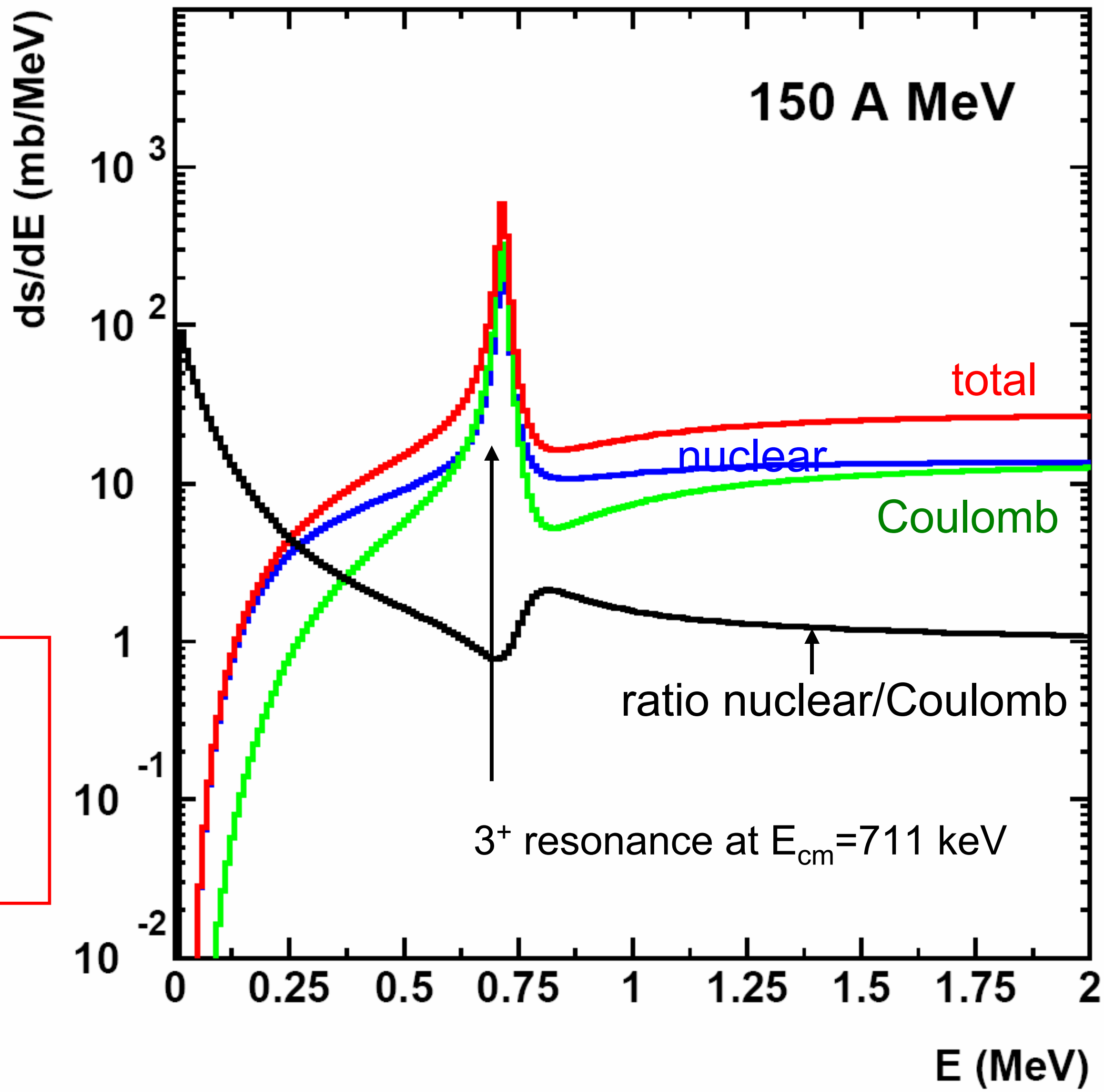


New theoretical calculations for ^{6}Li break-up (1)

Calculations by Stefan Typel (Code CDXS+):

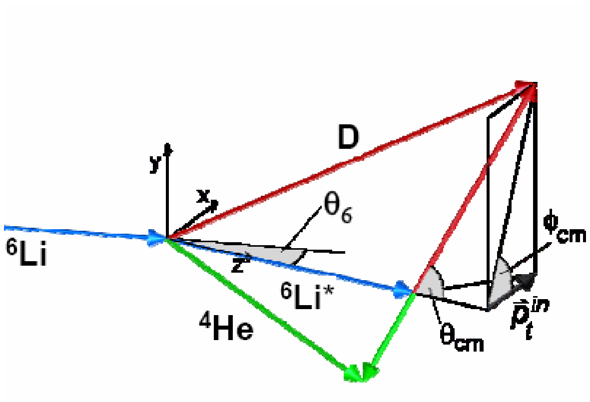
- Strong nuclear contribution at low c.m. energies!

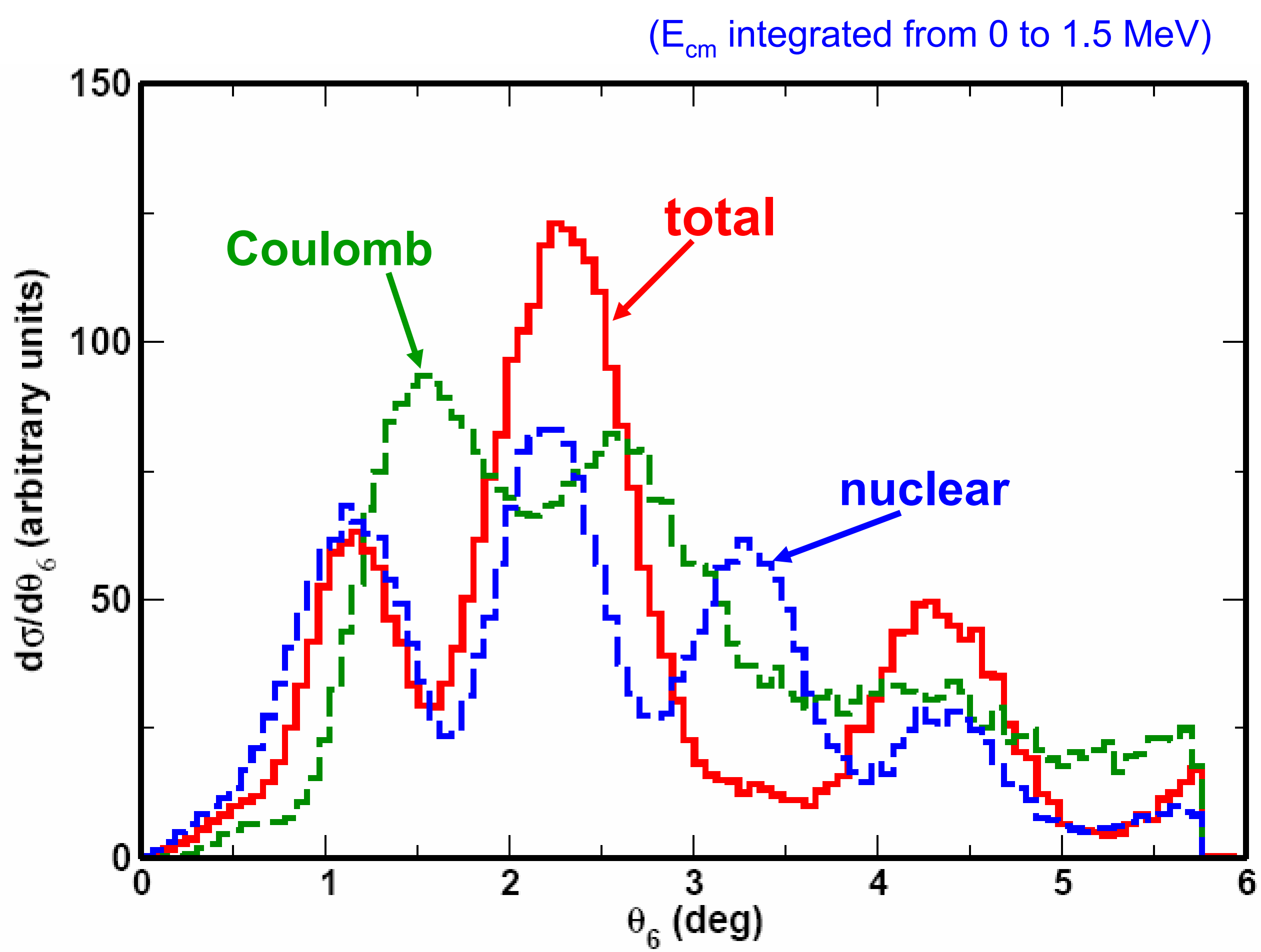
Can angular distributions help to disentangle CD and nuclear contributions?



New theoretical calculations for ^{6}Li break-up (2)

Scattering-angle θ_6:

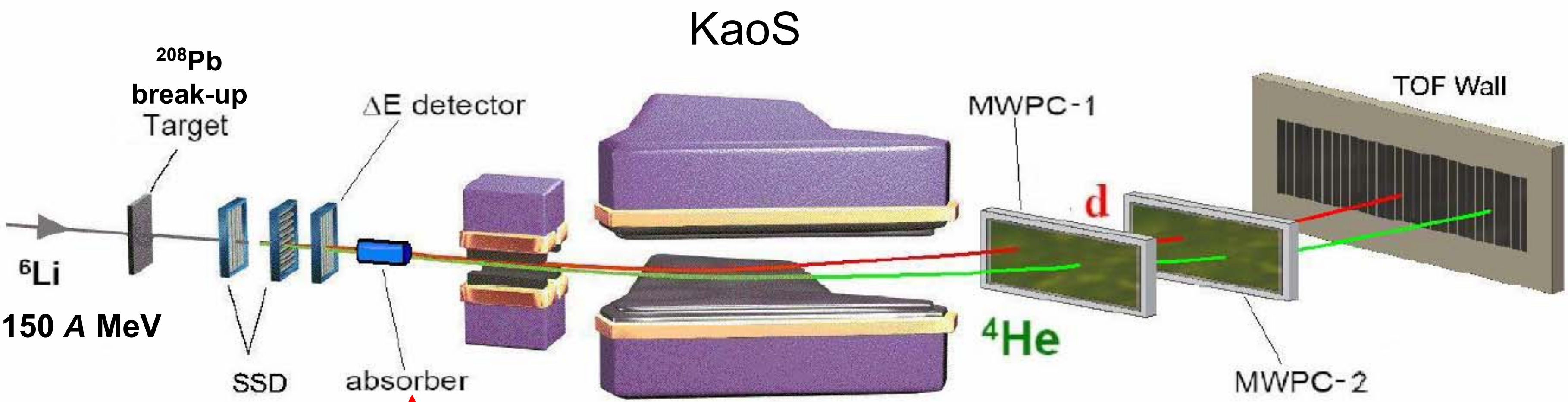




Same area
under all curves!
Pure theory,
no experimental filter!

Experiment: ^{6}Li break-up at 150 A MeV at KaoS/GSI

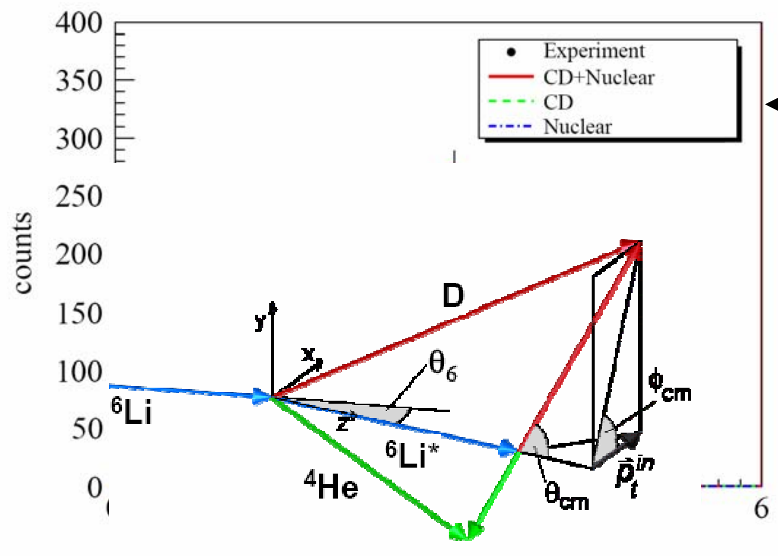
Problem: ^{2}H, ^{4}He and ^{6}Li have about the same magnetic rigidity!



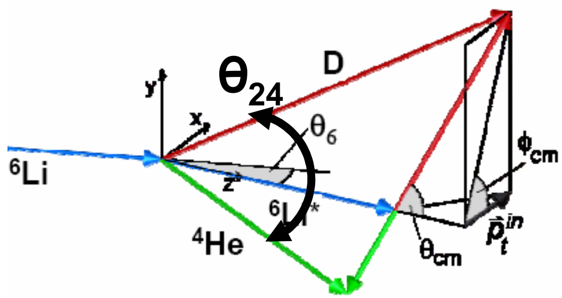
Intercept ^{6}Li with Ta absorber.

How to set MWPC voltages to detect d, He and Li with the same efficiency without discharging the MWPC with ^{6}Li?
How to identify d and He in MWPC?

Comparison between experiment and simulation



α-d opening angles θ_{24}

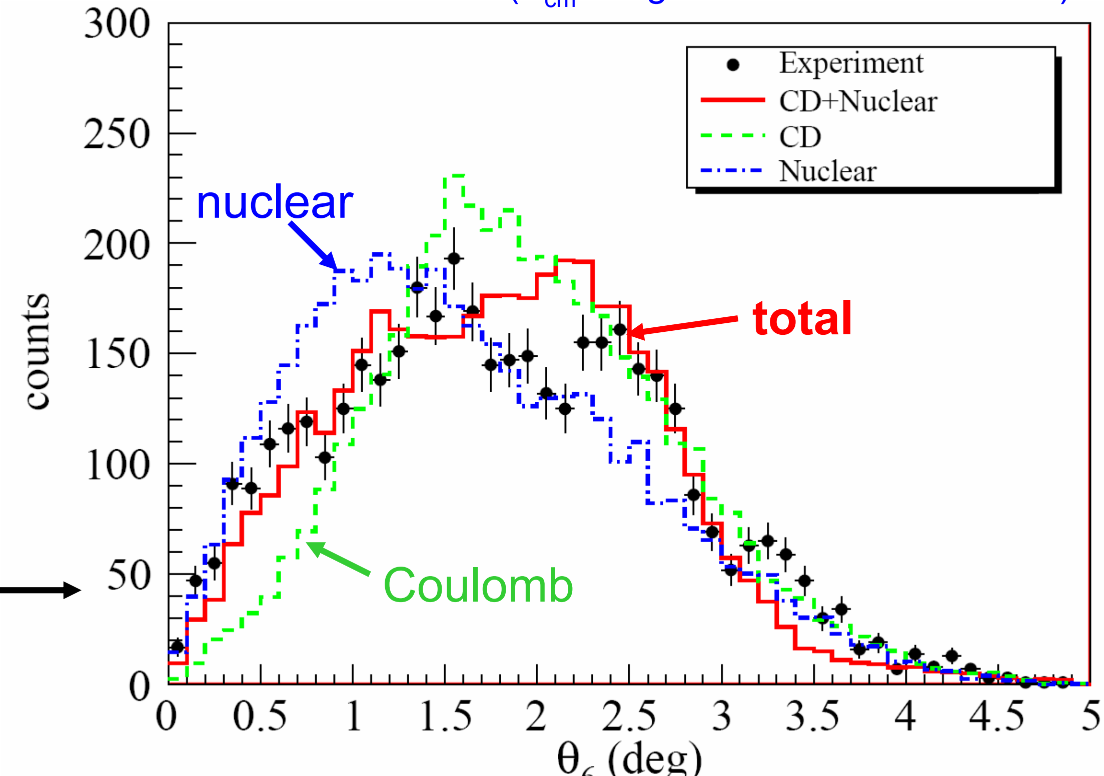


(E_{cm} integrated from 0 to 1.5 MeV)

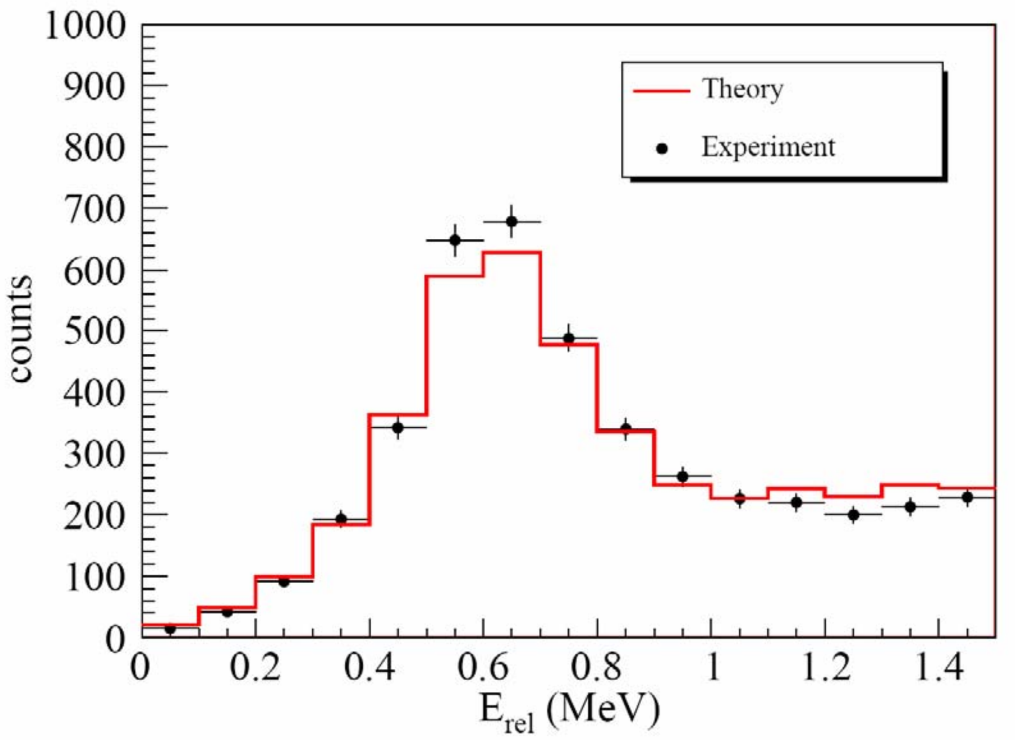
Simulations account for acceptance and resolution!

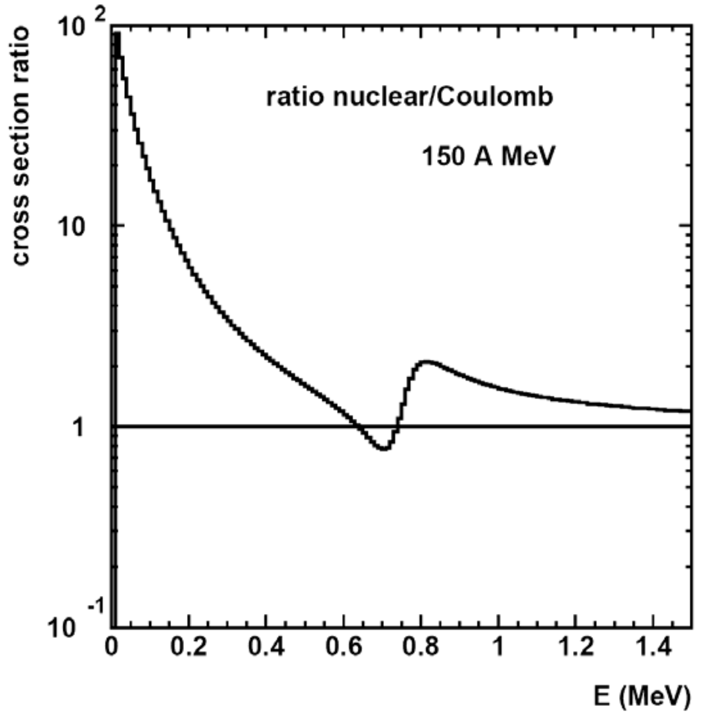
But: same shape for CD and nuclear contributions!

scattering angles θ_6



Differential cross sections: Experiment and simulation

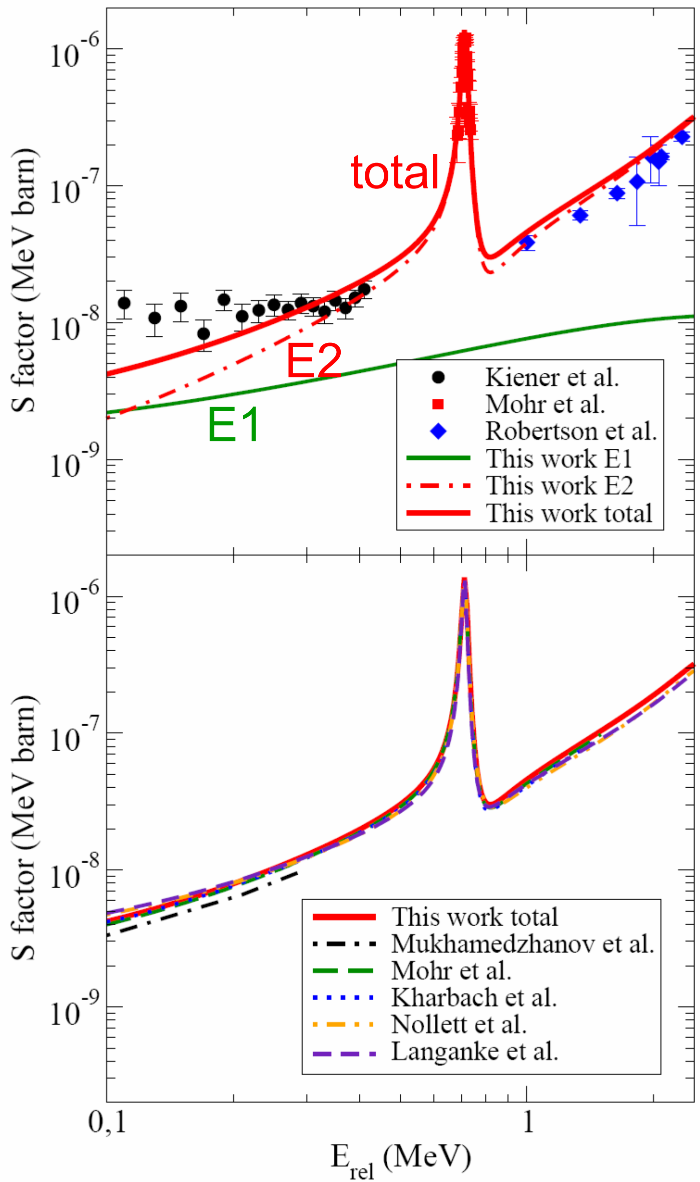




Simulation with theoretical Coulomb and nuclear component fits measured cross sections well!

But: **Coulomb part cannot be separated experimentally from total!**
➔ S-factor S_{24} derived from theory!

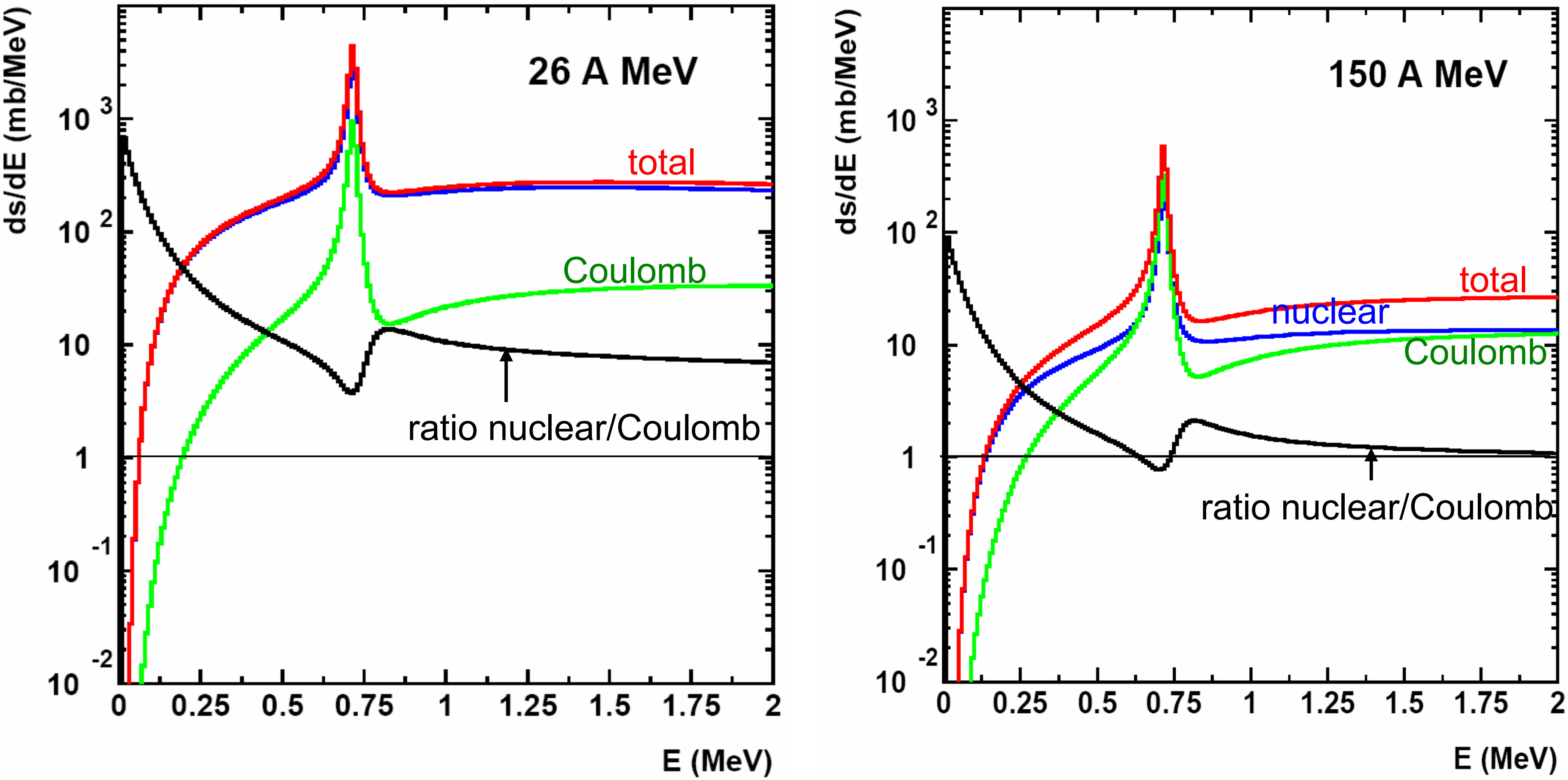
Final results for S_{24}



Our theory fits well also
to direct measurements
at and above the resonance!

All theories (with very different models)
predict very similar S-factors!

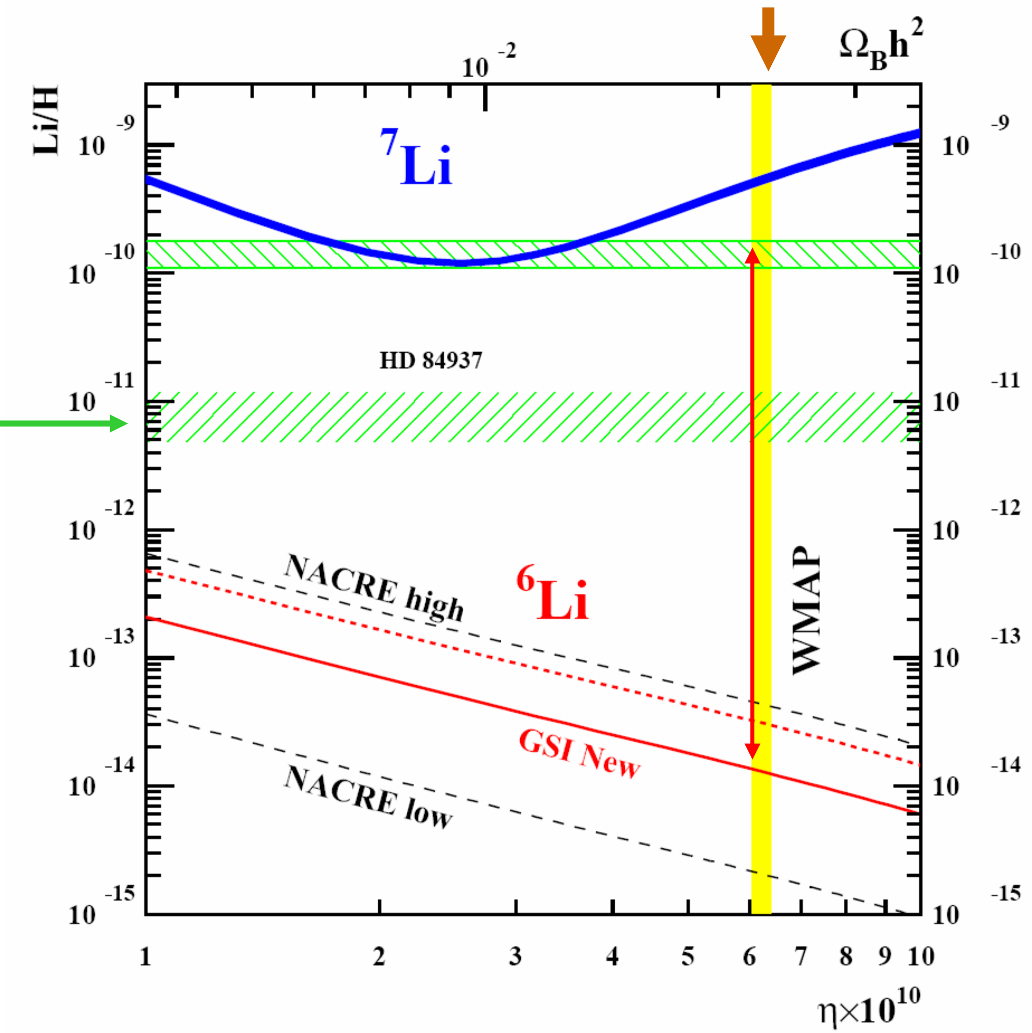
Theory: Break-up at 26 and 150 A MeV



- Nuclear and Coulomb break-up have very similar shapes!
- At 26 A MeV, nuclear break-up dominates!

The Big Bang and the ^{6,7}Li problem

WMAP



Observed ^{6}Li/^{7}Li is ~ 4%
(if observation can be confirmed!)

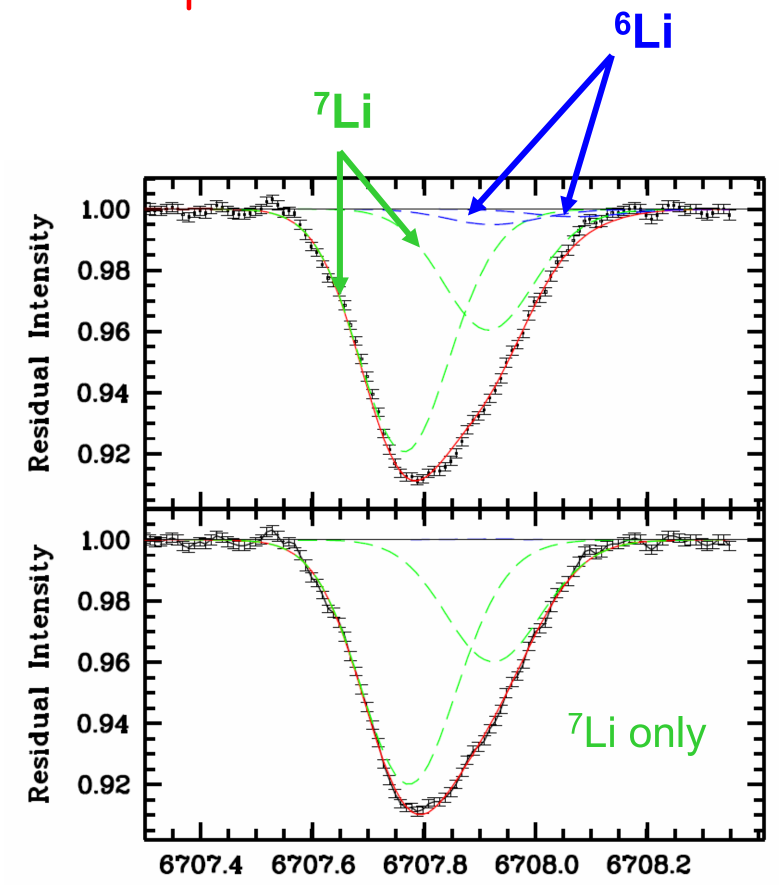
Primordial ^{6}Li/^{7}Li should be around 10^{-4}!

Problem with ^{6}Li observation?

Current status of ^{6}Li observations in old stars

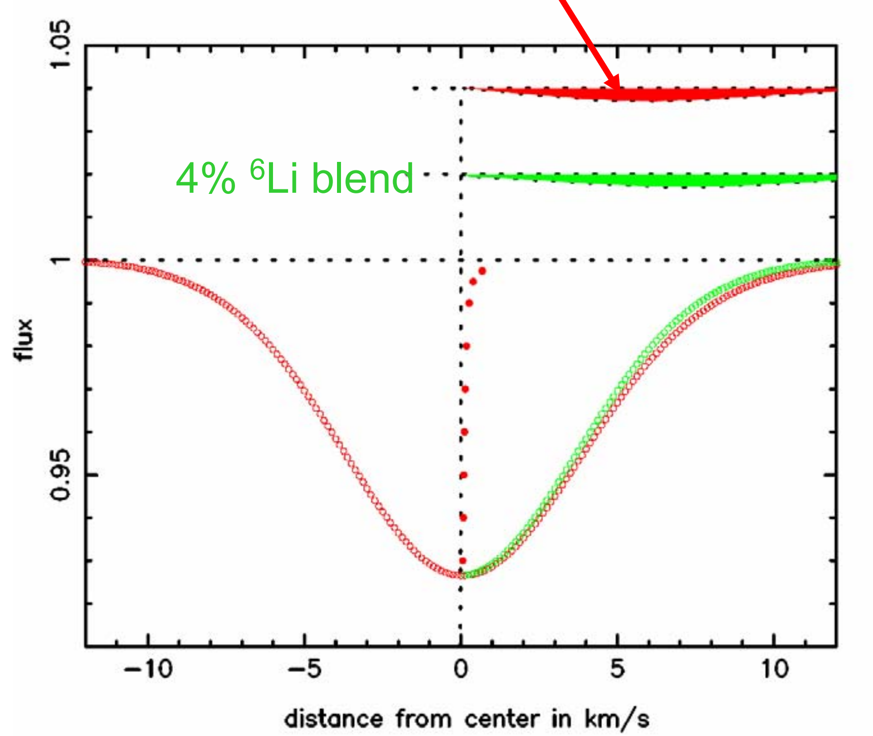
Cayrel *et al.* A&A 473, L37 (2007):

Li absorption line can be fitted without ^{6}Li component!



Synthetic line shape:

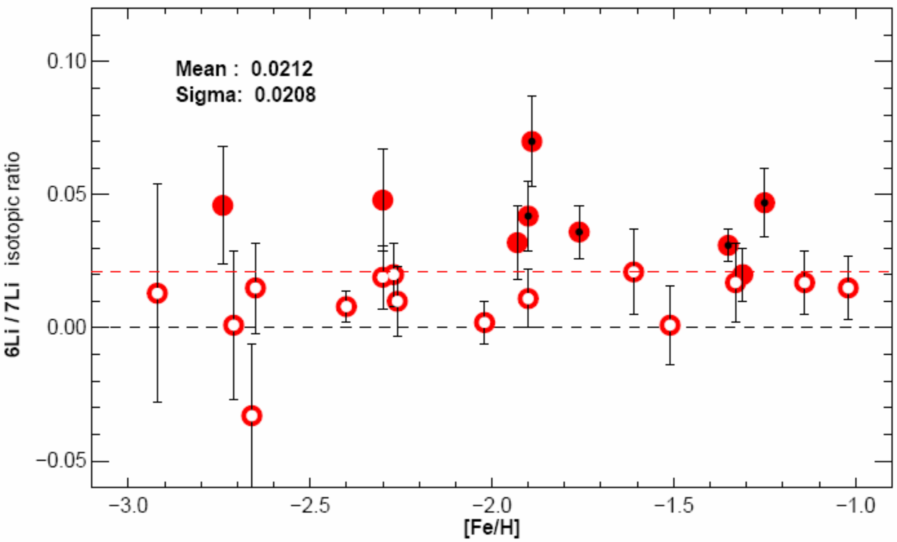
Asymmetry is due to Doppler shift (convection)



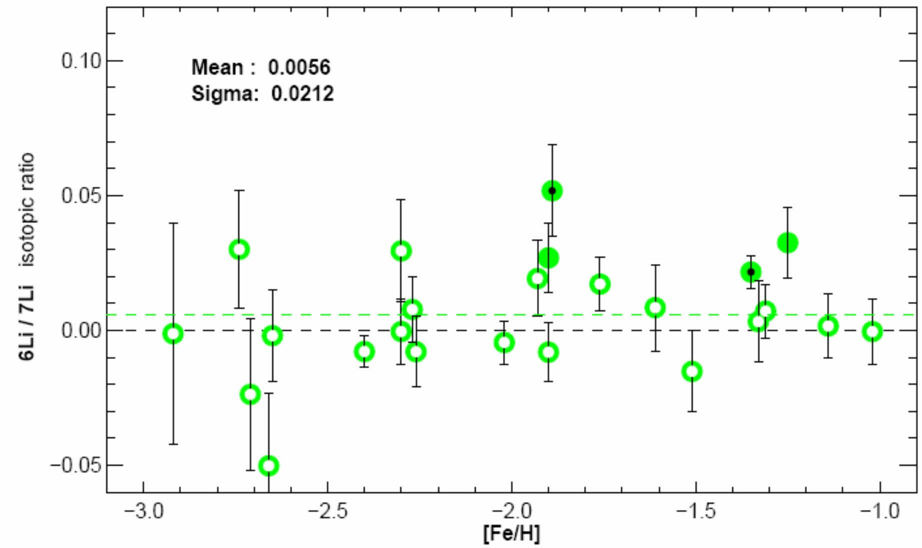
^{6}Li observations in old stars?

Steffen *et al.* have corrected the Asplund *et al.* (2006) ^{6}Li observations for convection-induced line asymmetries:

observations (2σ - criterion)



observations (3σ - criterion)



Steffen *et al.*, IAU Symposium 268 (2010)
arXiv 1001.3274

Conclusions

- ^{6}Li breakup: even at 150 A MeV, nuclear dissociation is strong
- Evidence for nuclear-Coulomb interference as predicted by theory
- Coulomb contribution cannot be extracted at low c.m. energies
- Low-energy S_{24}-factor relies on theory
- At 26 A MeV, nuclear dissociation dominates!
- Reanalysis of ^{6,7}Li lines in old halo stars casts some doubt on claimed primordial ^{6}Li abundances
- Probably no need to invent exotic particles to solve the "^{6}Li BBN puzzle"

Collaboration

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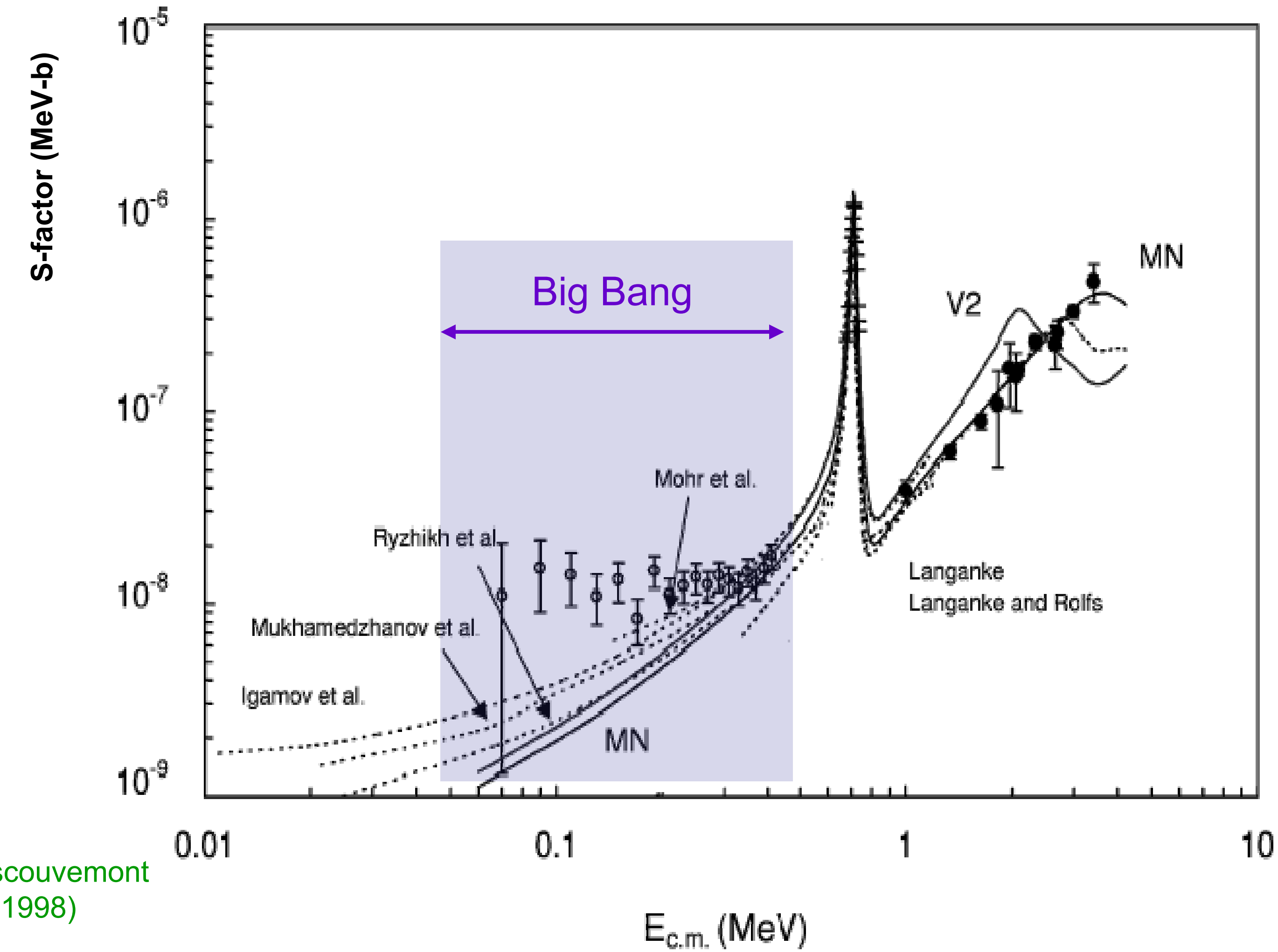
Old experiments *vs.* theoretical predictions

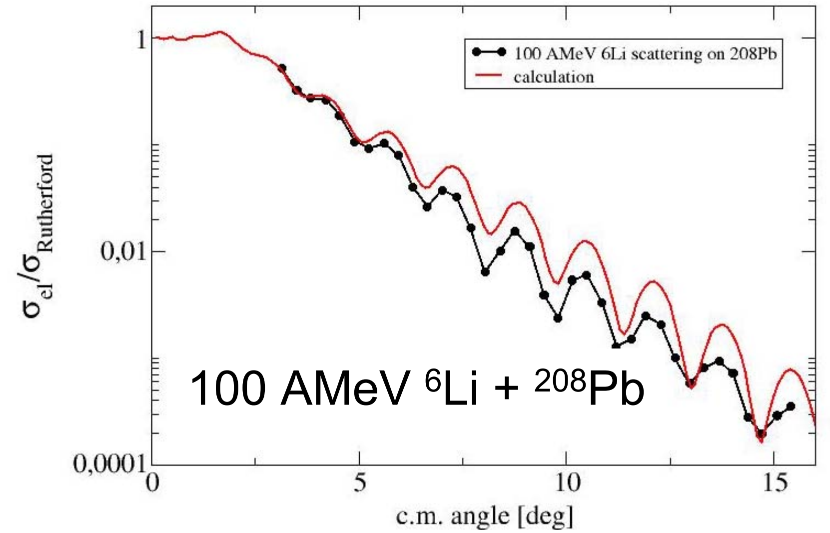
Theories have difficulties to reproduce the Karlsruhe data

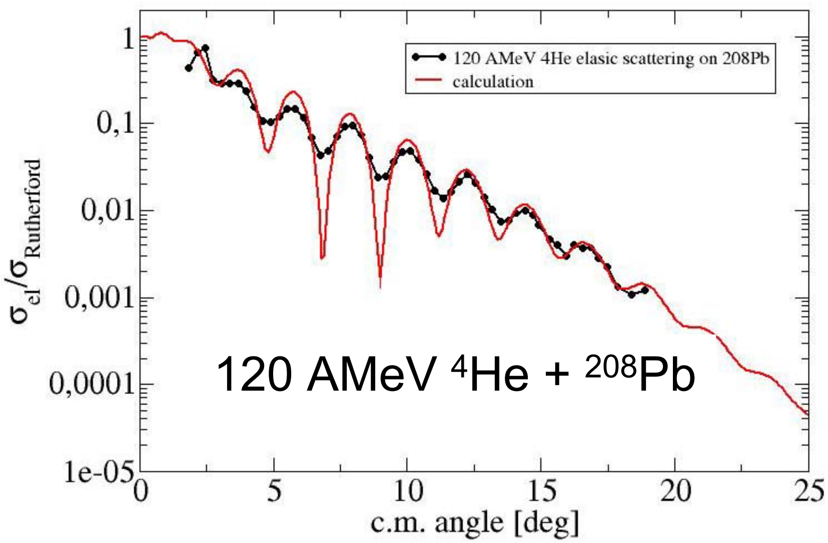


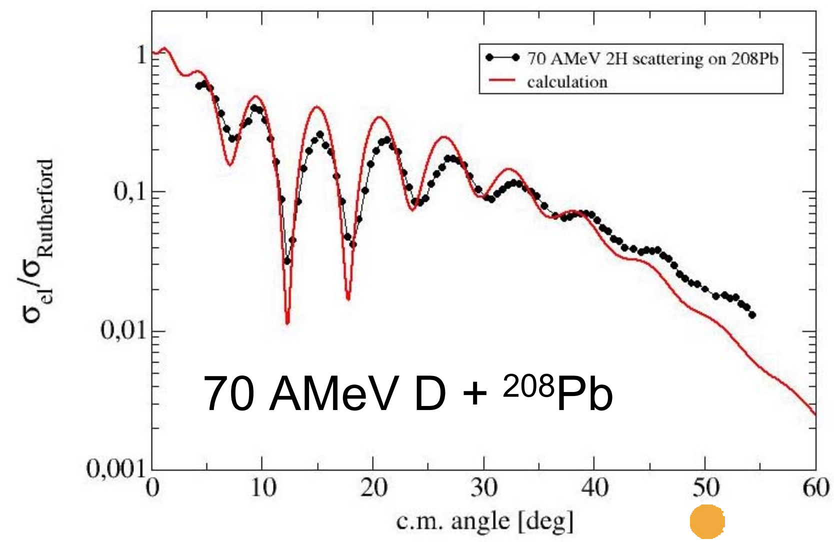
Kharbach & Descouvemont
PR C 58, 1066 (1998)

Elastic-scattering data

validate optical model parameters by comparison with elastic scattering data

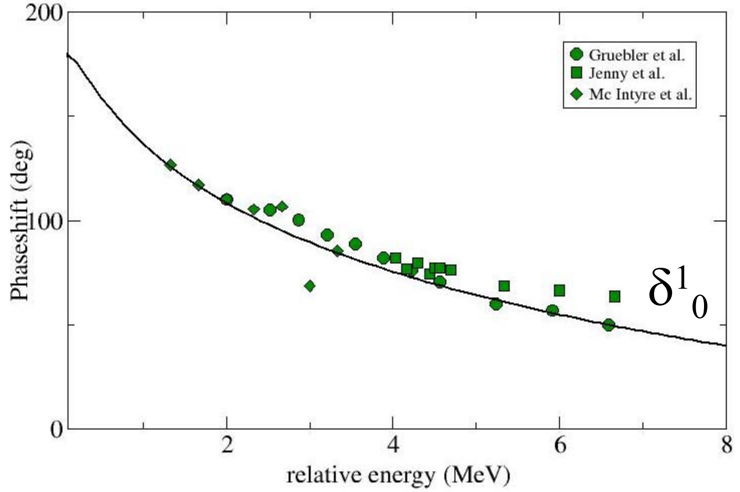


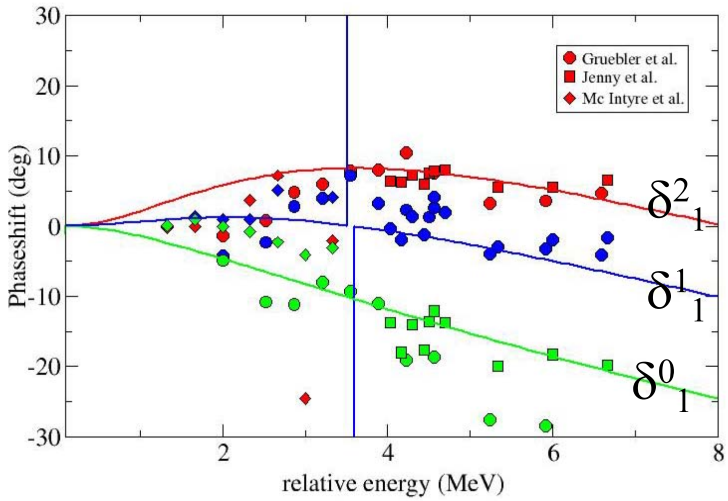


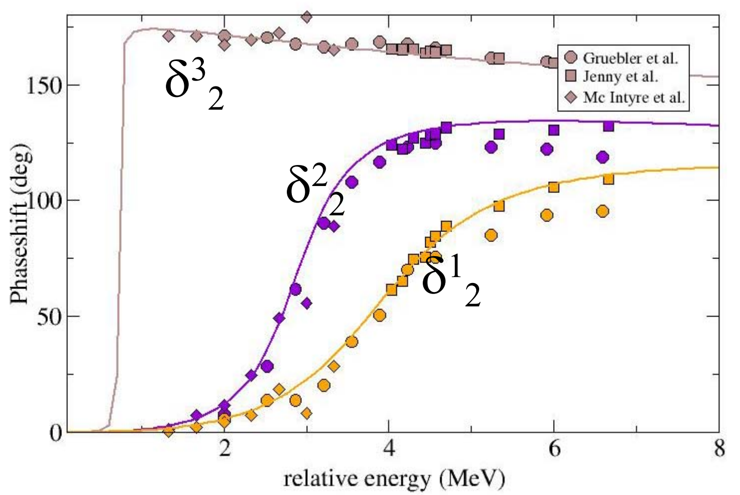


Phase shift analysis

Validate optical-model parameters by comparison with a+d elastic phase shift data.







LUNA: direct reaction

- α-beam (I~200 μA) on a D_2 gas target: $D(^4He,\gamma)^6Li$
- High Purity Germanium detector to detect the 1,6 MeV gamma's from $D(^4He,\gamma)^6Li$

C. Gustavino,
Vulcano,
May 2010

Solve background problem by subtracting γ-spectrum from $^3He(d,\gamma)$ reaction!