Laboratory
Underground
Nuclear
Astrophysics

The D(^{4}He,γ)^{6}Li at LUNA and BBN

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For the LUNA collaboration

- LUNA and the Big Bang Nucleosynthesis
- The Lithium problem
- The D(^{4}He,γ)^{6}Li measurement at LUNA
- Conclusions

Vulcano, 28 May-2 June 2012

LUNA Vs BBN

In the standard scenario, the primordial abundance of light elements depends ONLY on:

- Barionic density ω_b (measured by CMB experiments at the level of %)
- Standard Model (τ_n, ν, α..)
- Nuclear astrophysics, i.e. cross sections of nuclear reactions in the BBN chain

The LUNA measurements are performed at LNGS, with the unique accelerator in the world operating underground.

Here, the background induced by cosmic rays is orders of magnitude lower than outside. The Low background at LNGS makes possible to study Nuclear reactions well below the coulomb barrier.

In particular, the BBN reactions can be studied in the region of interest, giving a direct experimental footing to calculate the abundances of primordial isotopes.

Already measured by LUNA:

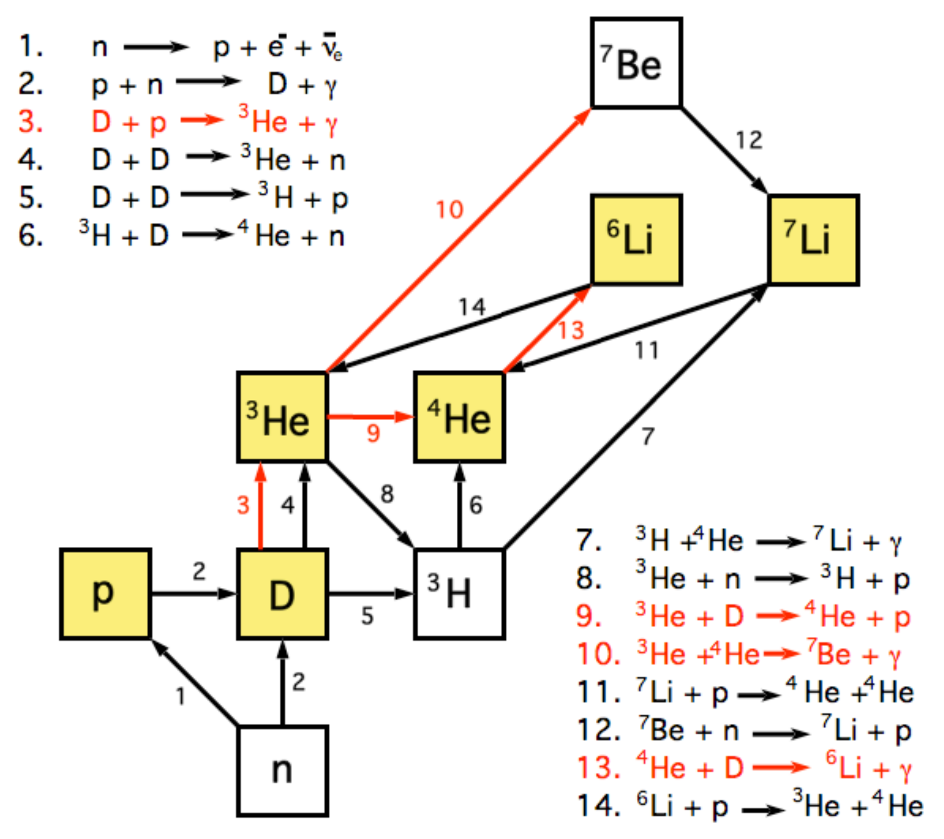
$P(D,\gamma)^3He$ (Deuterium abundance)

$^3He(^4He,g)^7Be$ (^7Li abundance)

$^3He(D,p)^4He$ (^3He abundance)

This talk:

$D(^4He,\gamma)^6Li$ (^6Li abundance)



1. $n \longrightarrow p + e^- + \bar{\nu}_e$
2. $p + n \longrightarrow D + \gamma$
3. $D + p \longrightarrow {}^3He + \gamma$
4. $D + D \longrightarrow {}^3He + n$
5. $D + D \longrightarrow {}^3H + p$
6. $^3H + D \longrightarrow {}^4He + n$
7. $^3H + {}^4He \longrightarrow {}^7Li + \gamma$
8. $^3He + n \longrightarrow {}^3H + p$
9. $^3He + D \longrightarrow {}^4He + p$
10. $^3He + {}^4He \longrightarrow {}^7Be + \gamma$
11. $^7Li + p \longrightarrow {}^4He + {}^4He$
12. $^7Be + n \longrightarrow {}^7Li + p$
13. $^4He + D \longrightarrow {}^6Li + \gamma$
14. $^6Li + p \longrightarrow {}^3He + {}^4He$

The Lithium Problem(s)

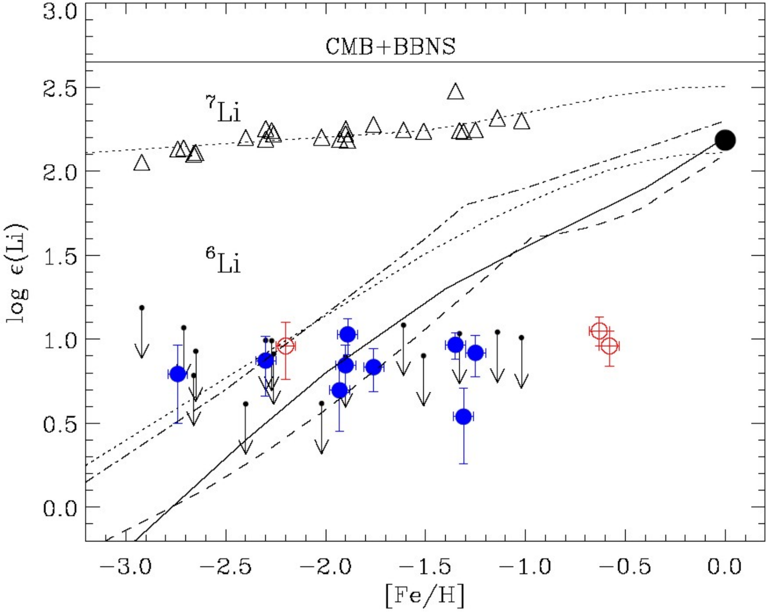
Basic Concepts to unfold primordial abundances

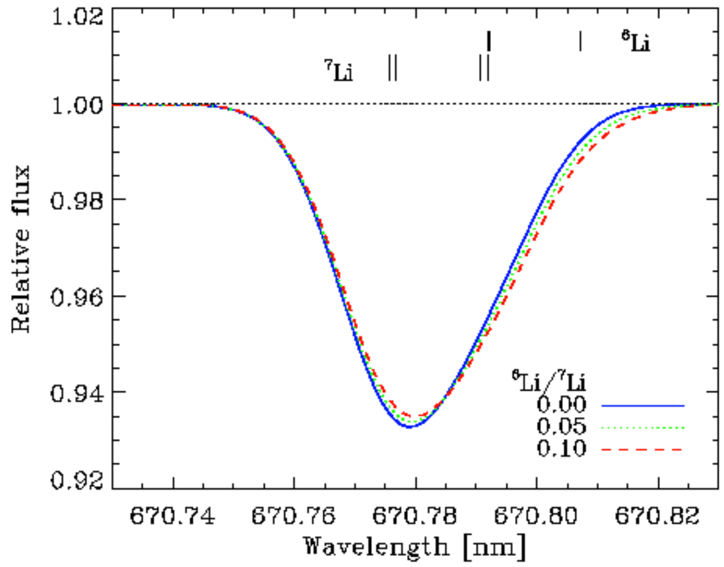
- Observation of a set of primitive objects (born when the Universe was young)
- Extrapolate to zero metallicity:

Fe/H, O/H, Si/H -----> 0

Lithium observations

- ^{7}Li primordial abundance: observation of the absorption line at the surface of metal-poor stars in the halo of our Galaxy
- ^{6}Li abundance : observation of the asymmetry of the ^{7}Li absorption line.





Line strength: ^{7}Li abundance
Line Profile: ^{6}Li/^{7}Li ratio

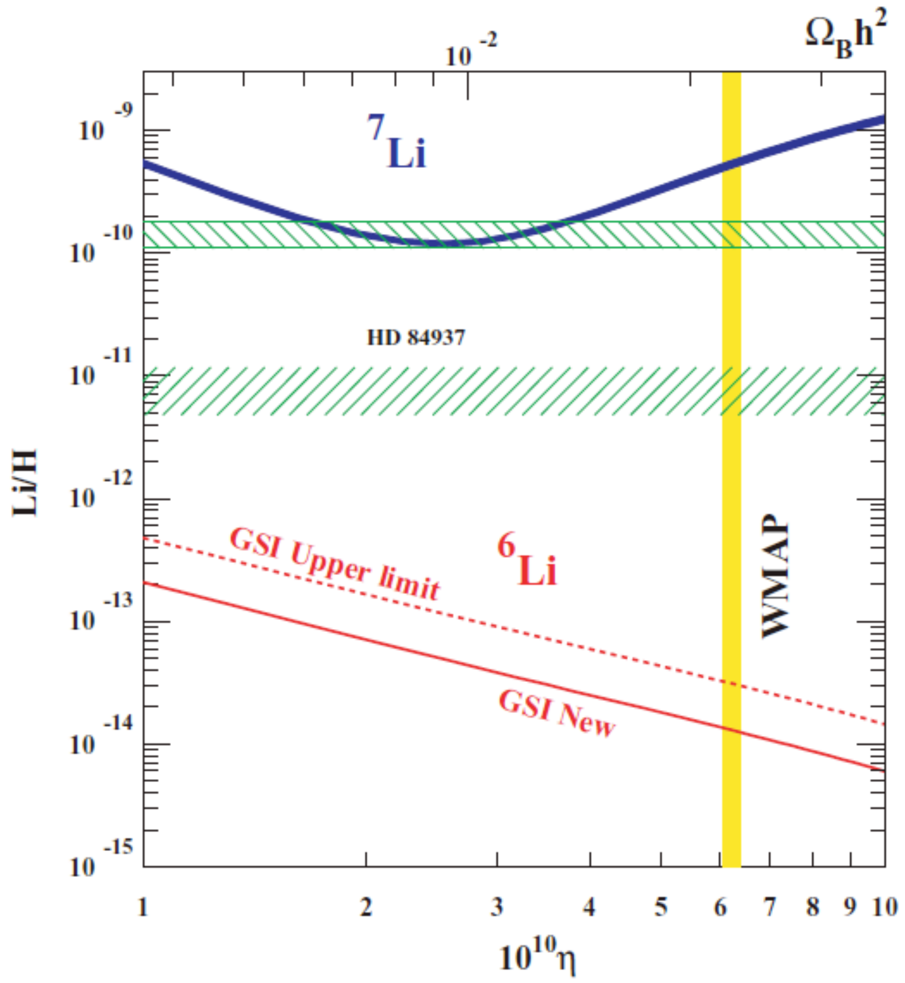
The Lithium Problem(s)

Observational Results:

- Observed ^{7}Li abundance is 2-3 times lower than foreseen (Spite Plateau): Well established "^{7}Li problem".

- Observed ^{6}Li abundance is orders of magnitude higher than expected (Asplund 2006)

- However the "Second Lithium problem" is debated, because convective motions on the stellar surface can give an asymmetry of the absorption line, mimicking the presence of ^{6}Li.



For more details: "Lithium in the Cosmos", 27-29 february, Paris

D(^{4}He,γ)^{6}Li

The ^{6}Li abundance in metal-poor stars is very large (Asplund et al. 2006) compared to BBN predictions (NACRE compilation). The possible reasons are:

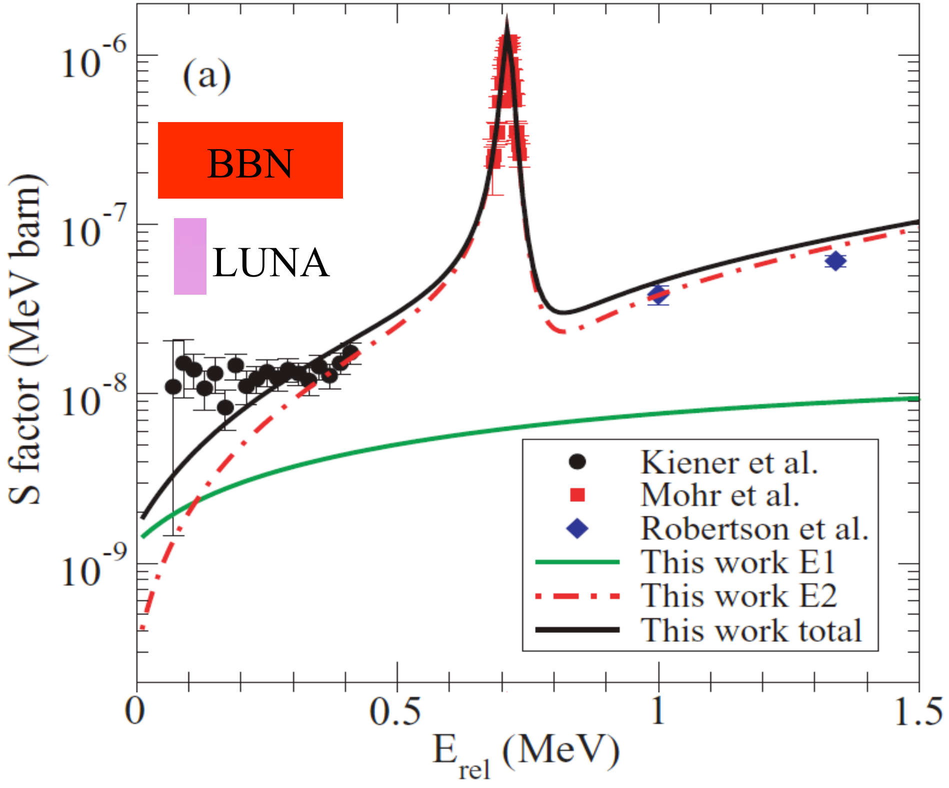
- Systematics in the ^{6}Li observation in the metal-poor stars
- Unknown ^{6}Li sources older than the birth of the galaxy
- New physics, i.e. sparticle annihilation/decay (Jedamzik2004), long lived sparticles (Kusakabe2010),…
- …Lack of the knowledge of the D(^{4}He,γ)^{6}Li reaction.

IN FACT:

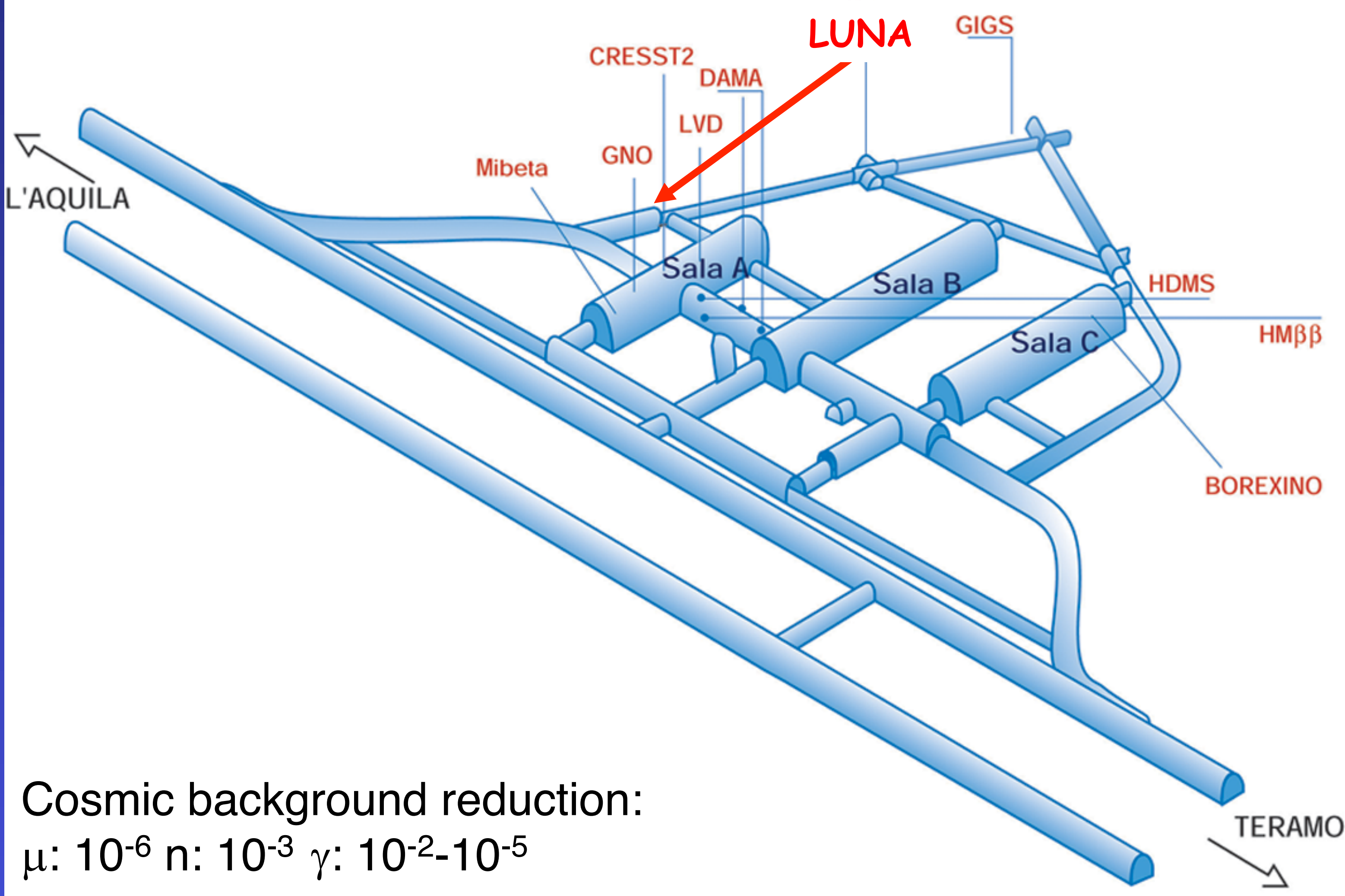
NO DIRECT MEASUREMENTS in the BBN energy region in literature (large uncertainty due to extrapolation)

INDIRECT coulomb dissociation measurements (Kiener91, Hammache2010) are not reliable because the nuclear part is dominant.

FOR FIRST TIME, LUNA has studied the D (^{4}He,γ)^{6}Li reaction well inside the (most interesting part of) BBN energy region.



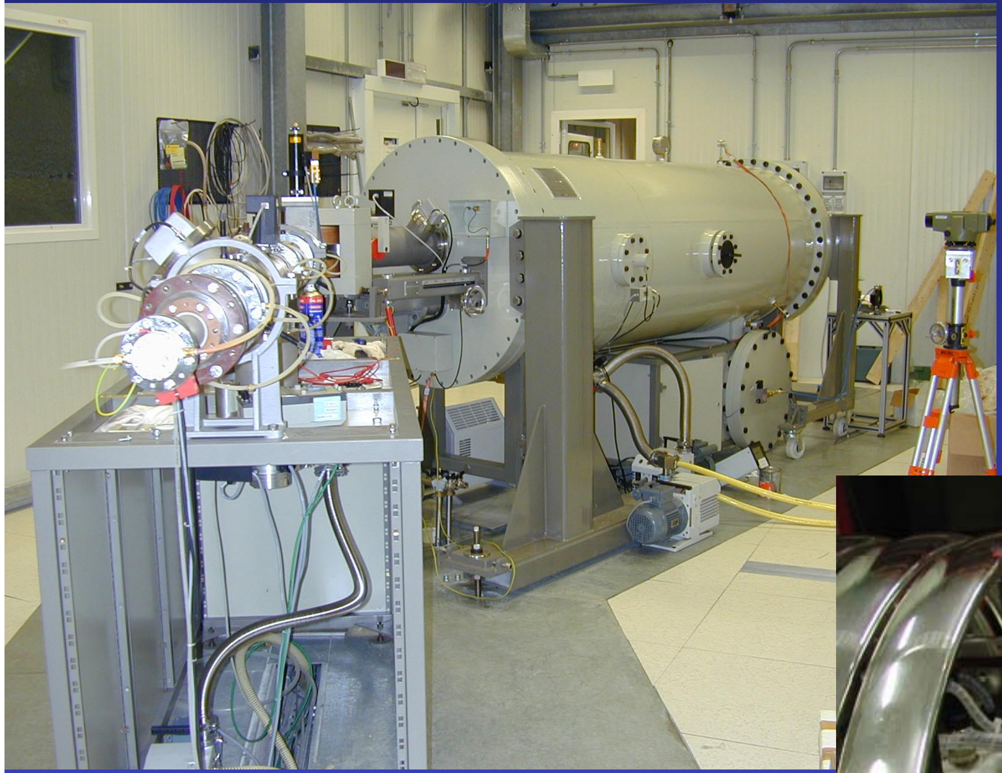
Gran Sasso National Laboratory (LNGS)



Cosmic background reduction:

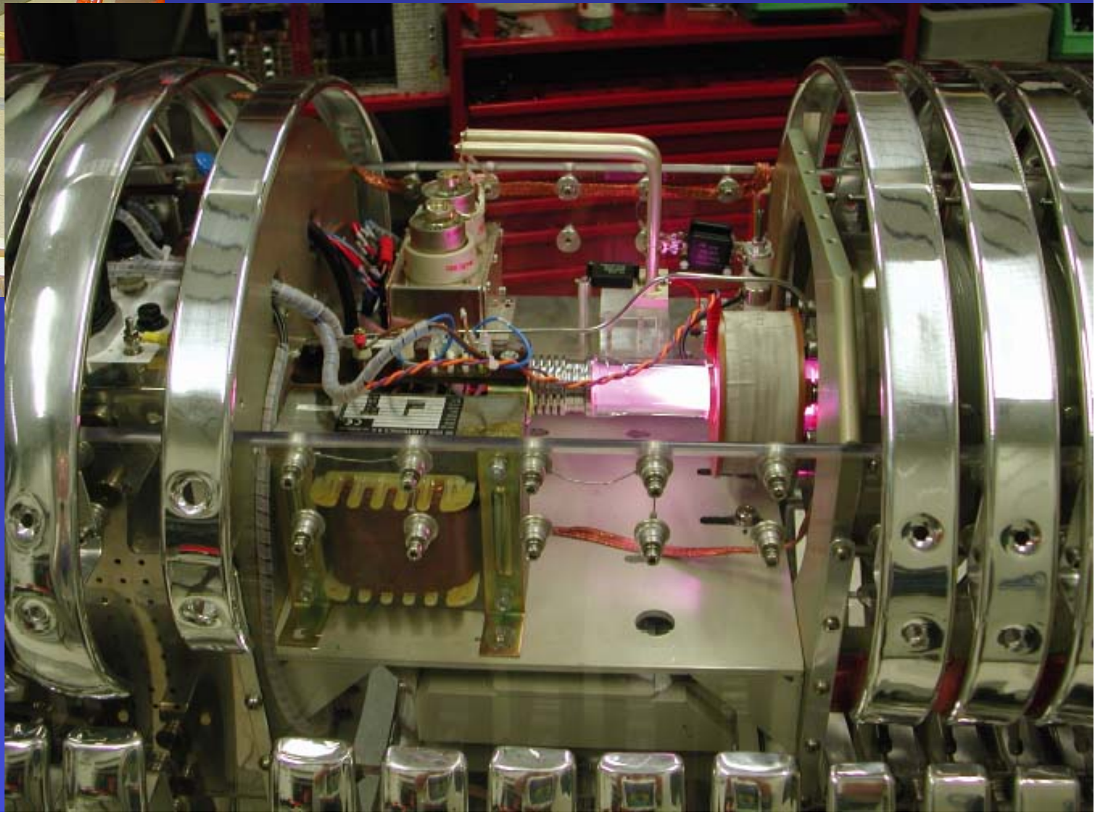
μ: 10^{-6} n: 10^{-3} γ: 10^{-2}-10^{-5}

The LUNA (400 kV) accelerator



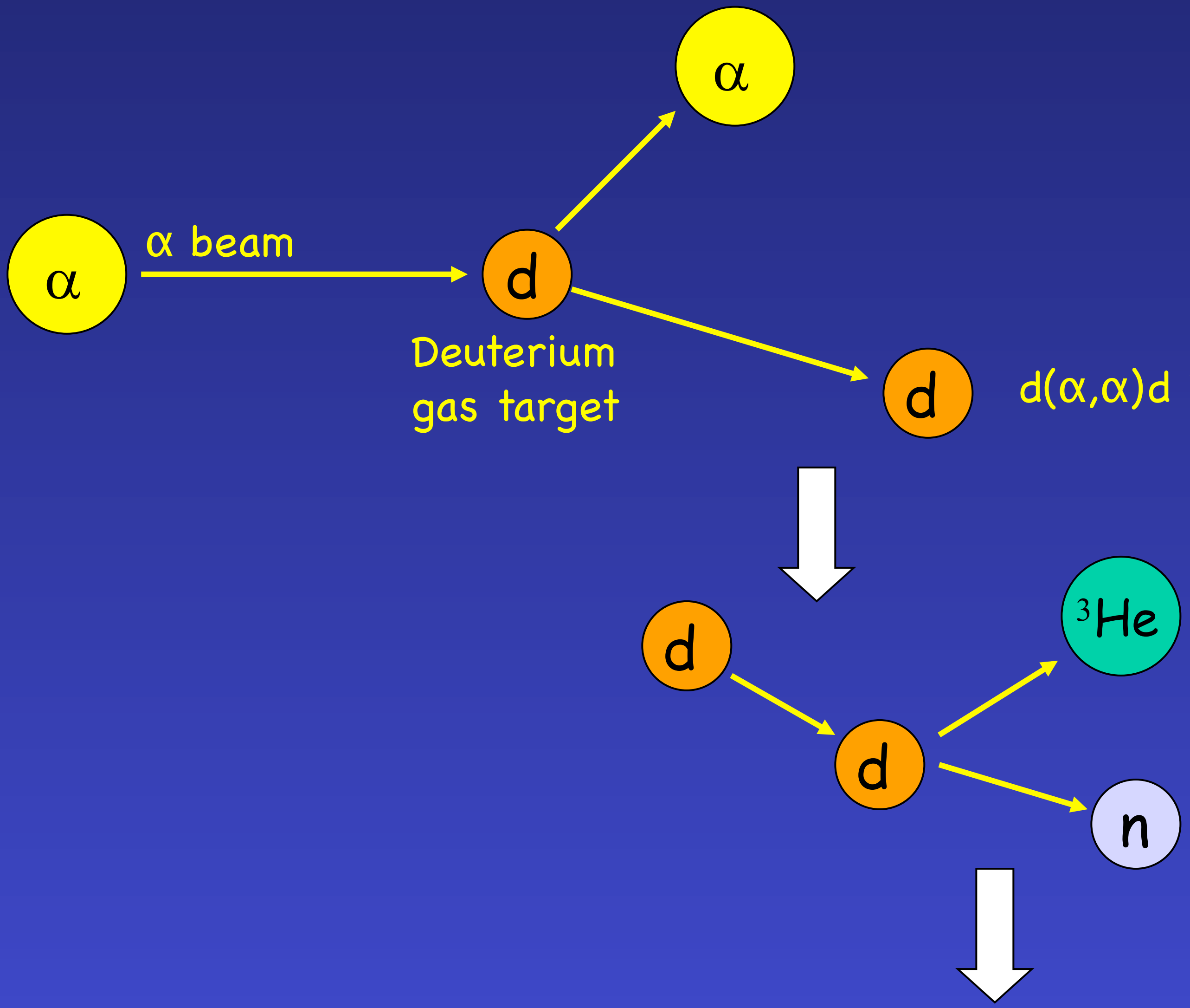
Voltage Range: 50-400 kV
Output Current: 1 mA (@ 400 kV)
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability (1 h) : 5 eV
Terminal Voltage ripple: 5 Vpp

A. Formicola et al., NIMA 527 (2004) 471.



$^{14}N(p,\gamma)^{15}O$
$^{3}He(^{4}He,\gamma)^{7}Be$
$^{25}Mg(p,\gamma)^{26}Al$
$^{15}N(p,\gamma)^{16}O$
$^{17}O(p,\gamma)^{18}F$
$D(^{4}He,\gamma)^{6}Li$
$^{22}Ne(p,\gamma)^{23}Na$

Beam Induced Background origin



α beam

Deuterium gas target

d(α,α)d Rutherford scattering

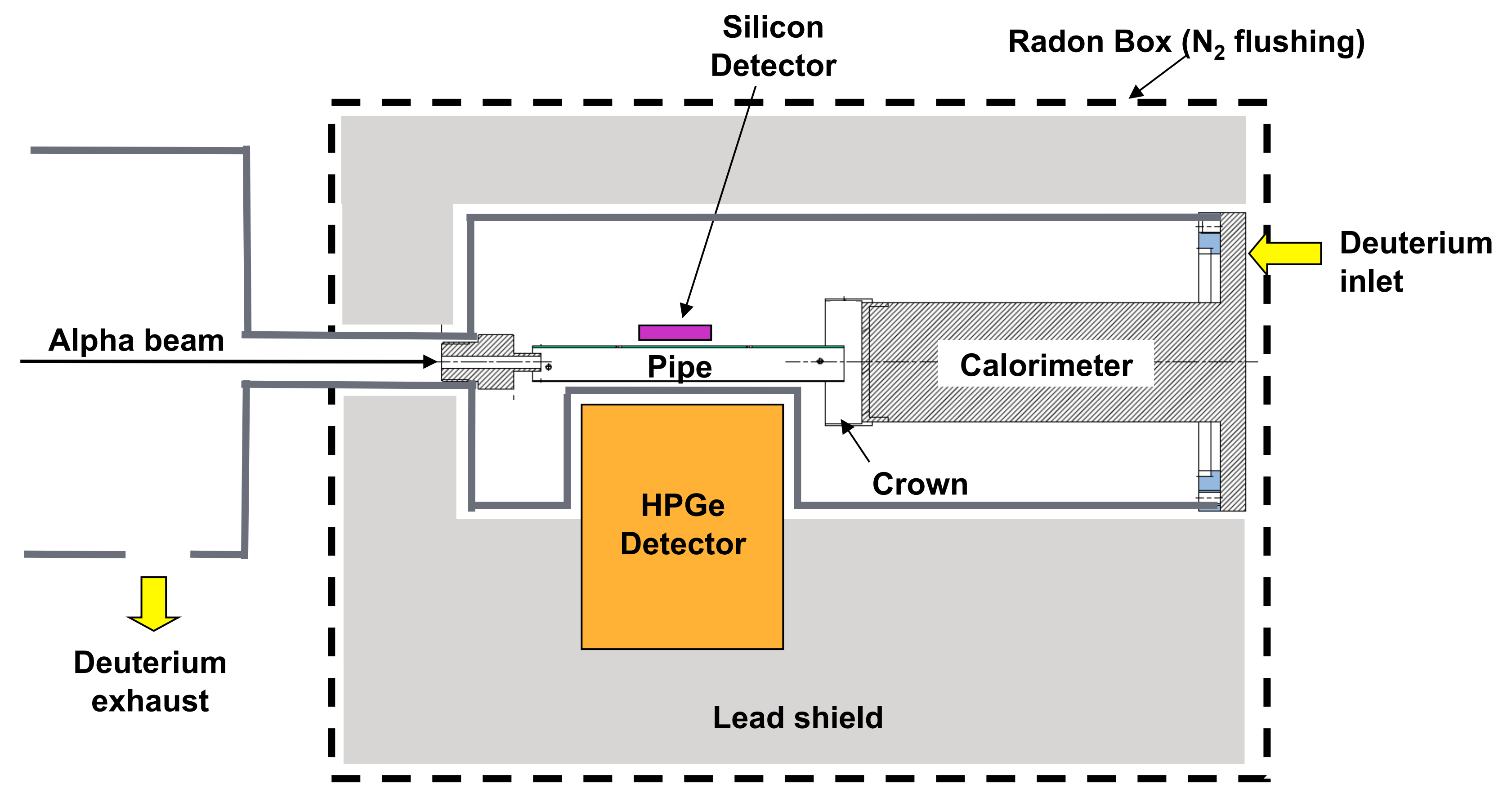
d(d,n)^{3}He reaction

(n,n'γ) reaction on the surrounding materials (Pb, Ge, Cu).

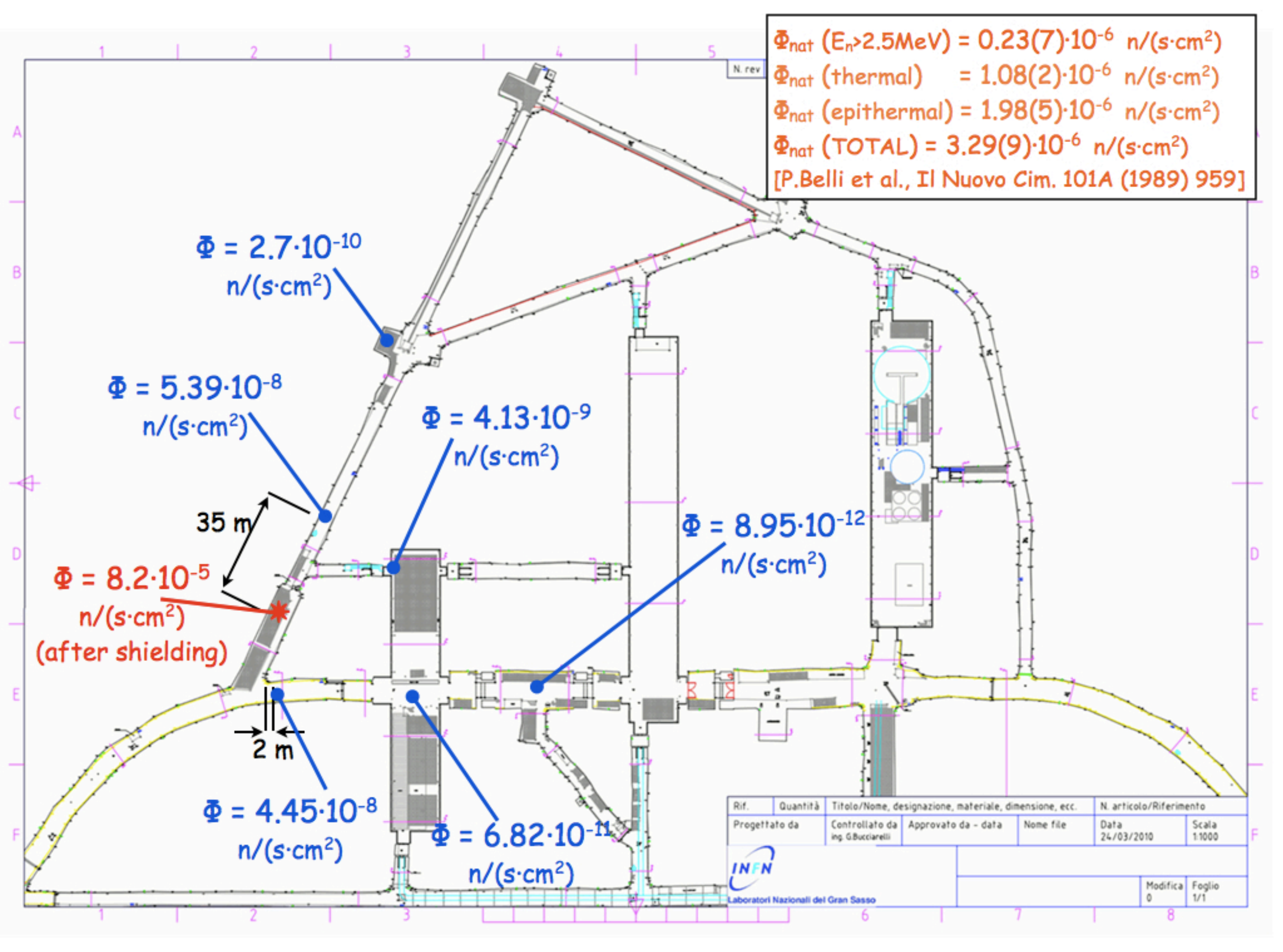
γ-ray background in the RoI for the D(α,γ)^{6}Li DC transition (~1.6 MeV)

D(^{4}He,γ)^{6}Li set-up

- Germanium detector close to the beam line to increase the detection efficiency
- Pipe to reduce the path of scattered deuterium, to minimize the d(d,n)^{3}He reaction yield
- Target length optimized
- Copper removal
- Silicon detector to monitor the neutron production through the d(d,p)^{3}H protons
- Lead, Radon Box to reduce and stabilize Natural Background



Neutron flux inside LNGS (GEANT Calculation)



Φ_{nat} (E_n>2.5MeV) = 0.23(7)·10^{-6} n/(s·cm^2)

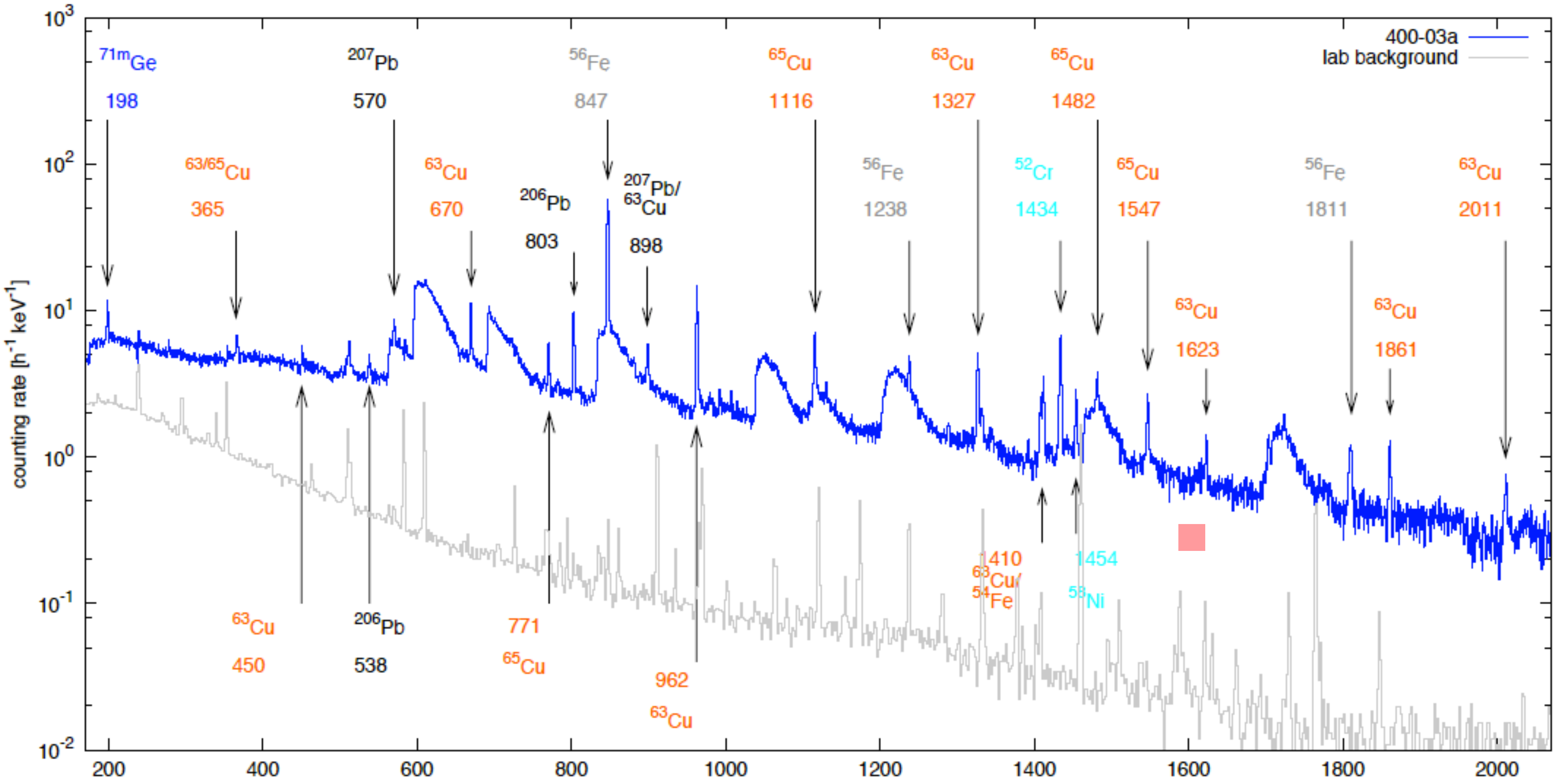
Φ_{nat} (thermal) = 1.08(2)·10^{-6} n/(s·cm^2)

Φ_{nat} (epithermal) = 1.98(5)·10^{-6} n/(s·cm^2)

Φ_{nat} (TOTAL) = 3.29(9)·10^{-6} n/(s·cm^2)

[P.Belli et al., Il Nuovo Cim. 101A (1989) 959]

Beam Induced Background and Natural Background



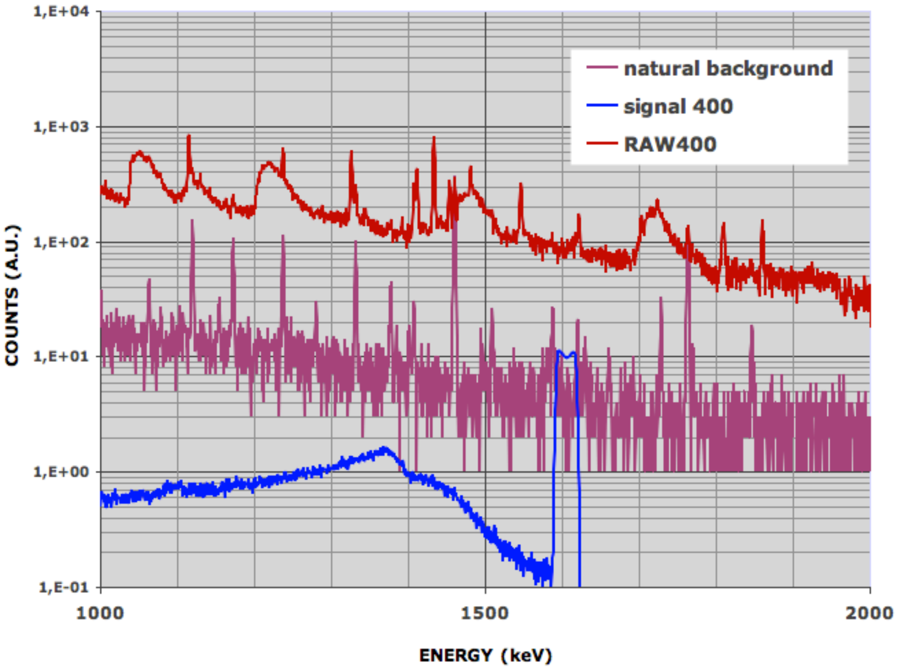
Measurement strategy:

-The shape of Beam Induced Background spectra weakly depends on the α-beam energy.
-The Energy of γ's coming from D+alpha reaction are kinematically constrained by the following relationship:

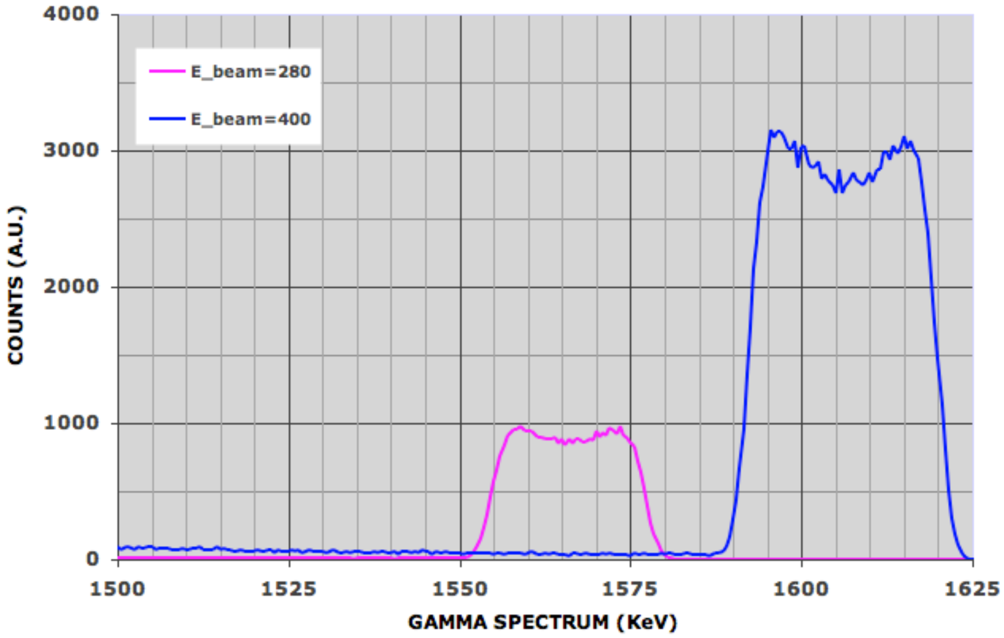
$$E\gamma=1473,48+E_{cm}\pm\Delta E_{doppler}$$

1. Measurement with E_{beam}=400 keV on D_2 target. The Ge spectrum is mainly due to background induced by neutrons interacting with the surrounding materials (Pb, Ge, Cu). The $D(\alpha,\gamma)^6Li$ signal is expected in a well defined energy region (1587-1625 keV) .
2. Same as 1., but with E_{beam}=280 keV. The Ge spectrum is essentially the same as before, while the gammas from the $D(\alpha,\gamma)^6Li$ reaction are expected at 1550-1580 keV.

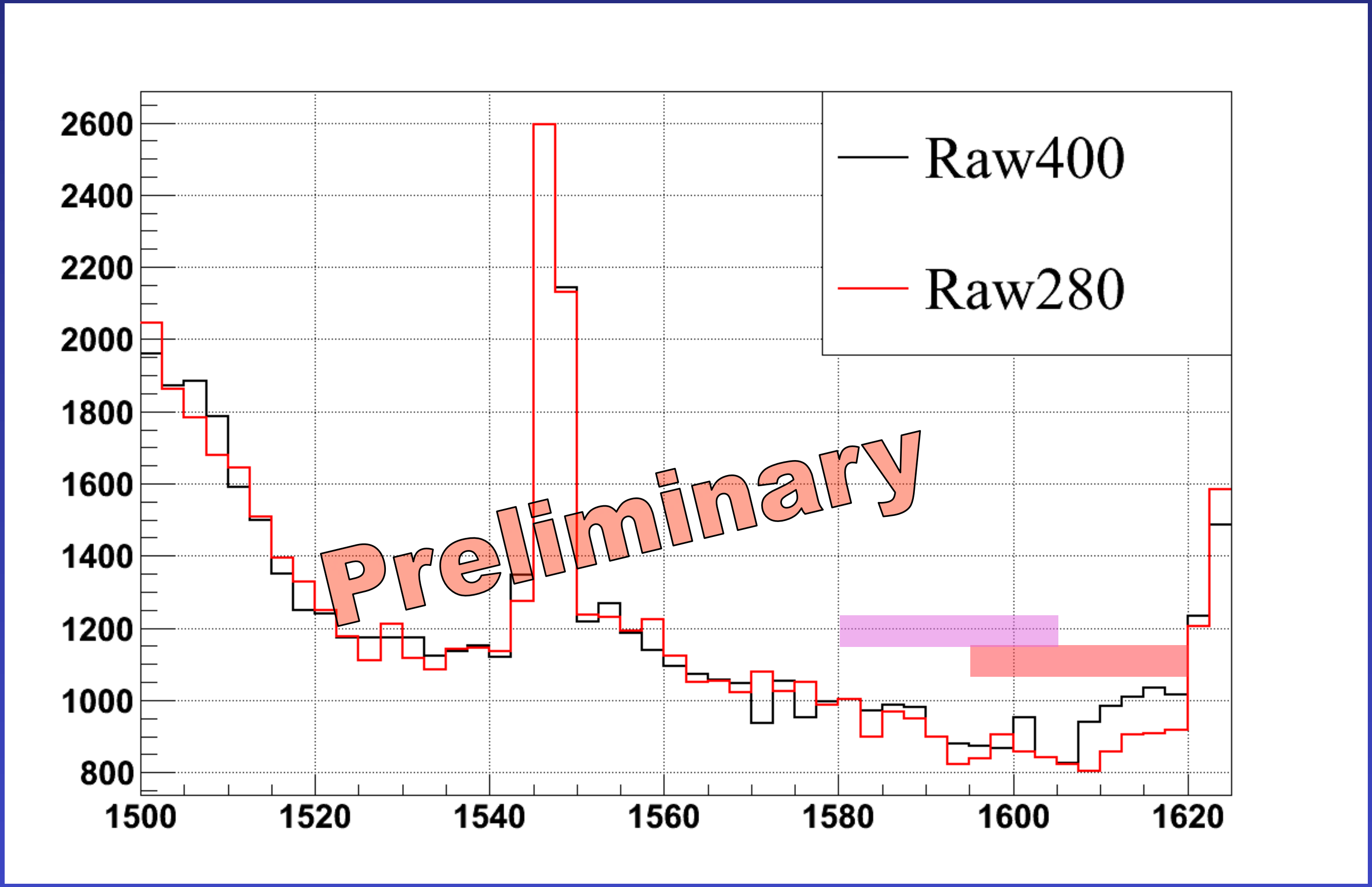
$D(\alpha,\gamma)^6Li$ Signal is obtained by subtracting the two spectra



D+ALPHA SIMULATED SPECTRA

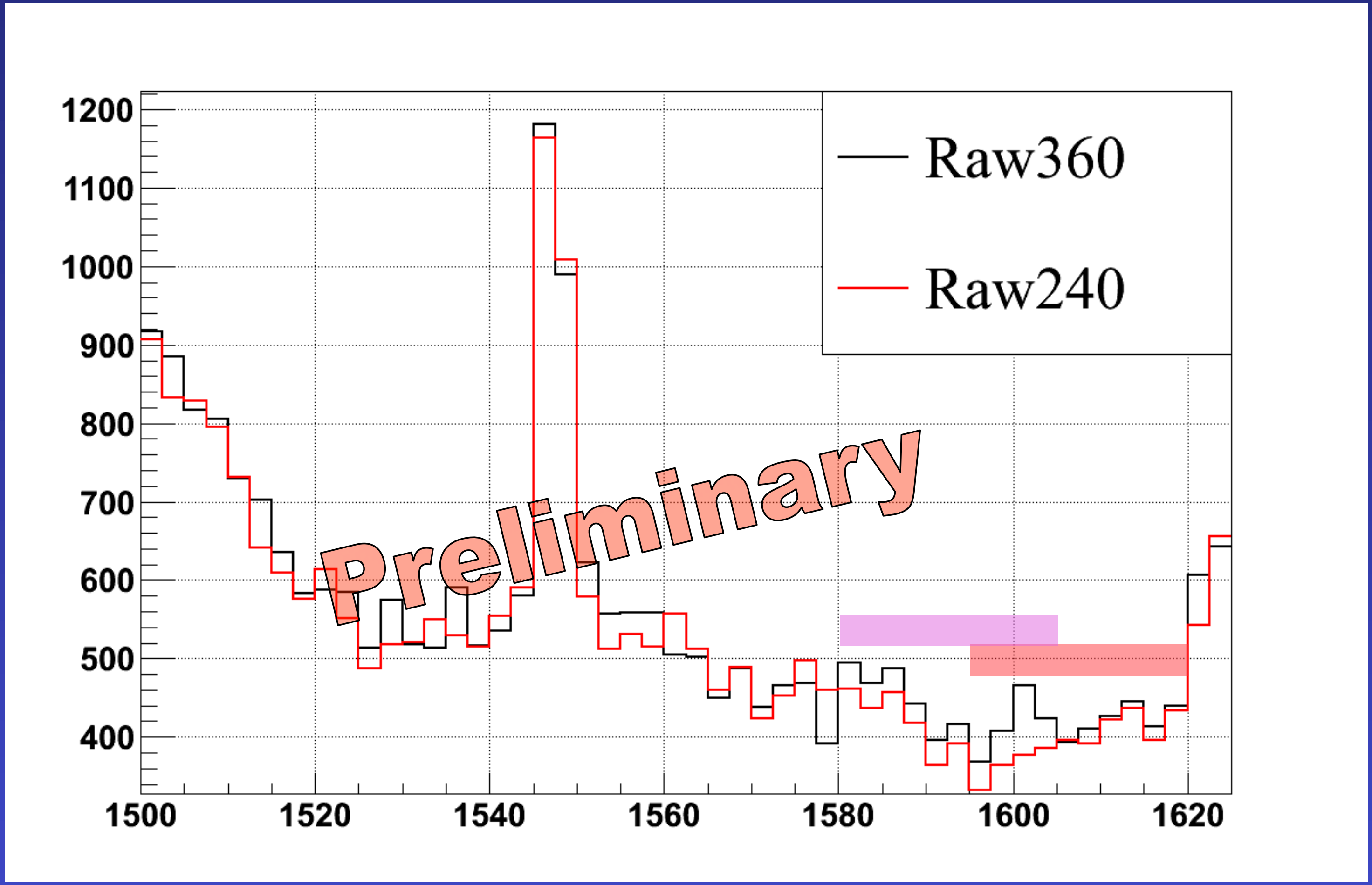


Preliminary Results (E_{lab}=400/280 keV)



Counting excess observed in the E_{cm}=134 keV ROI (red band)

Preliminary Results (E_{lab}=360/240 keV)



Counting excess shifted to the E_{cm}=120 keV ROI (violet band)

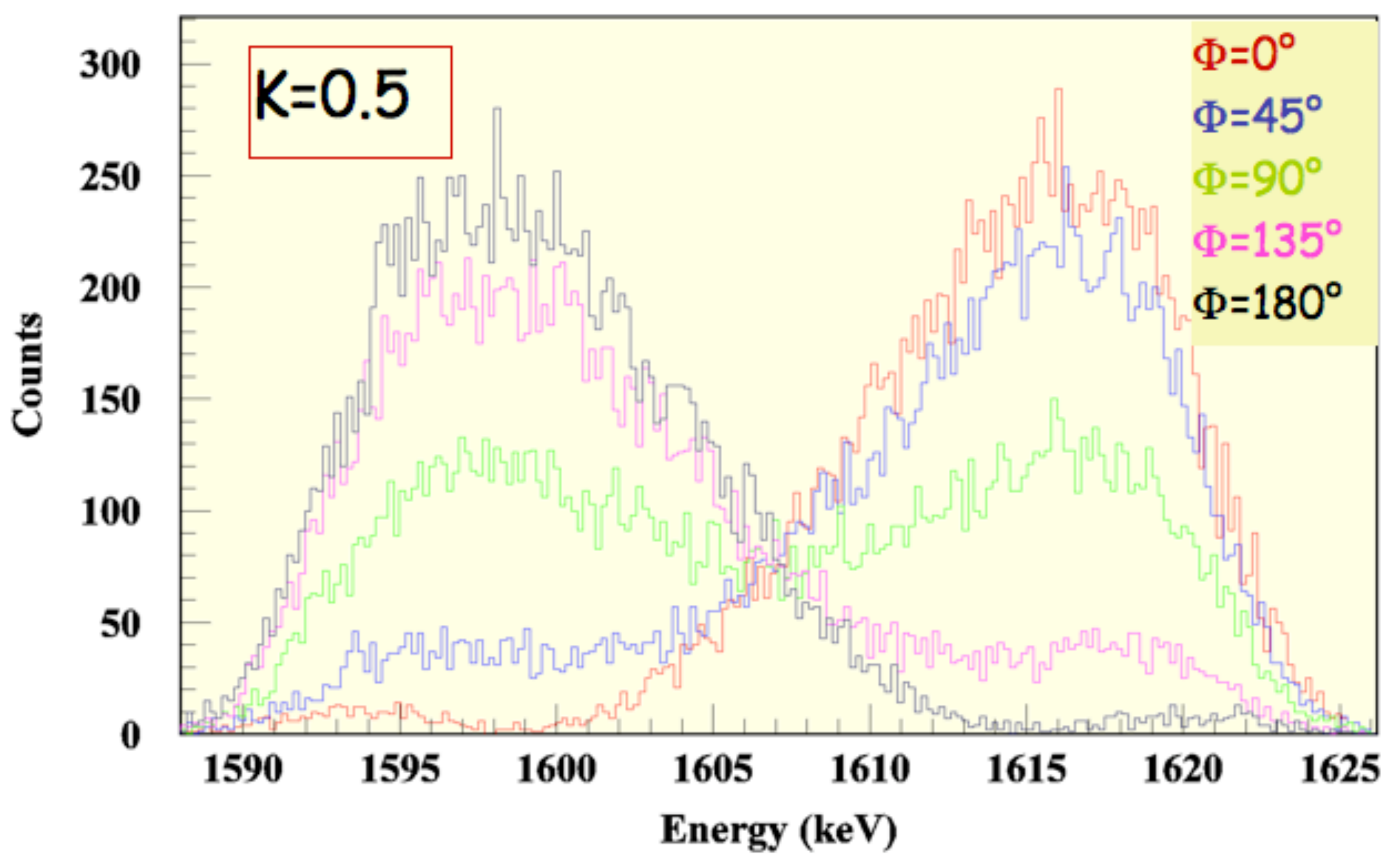
Conclusion

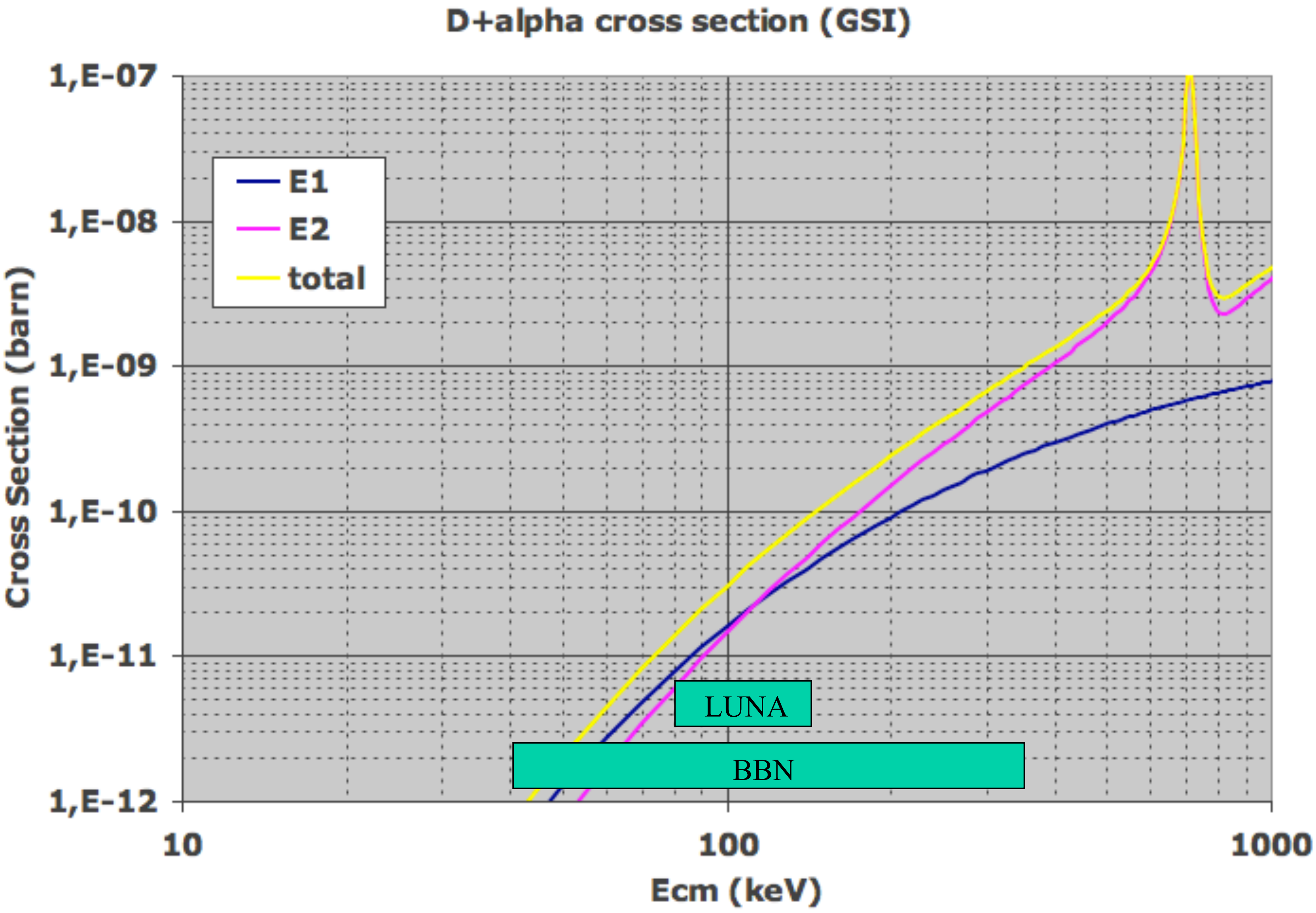
Three independent analysis are now in progress, showing a counting excess compatible with the D+alpha signal.

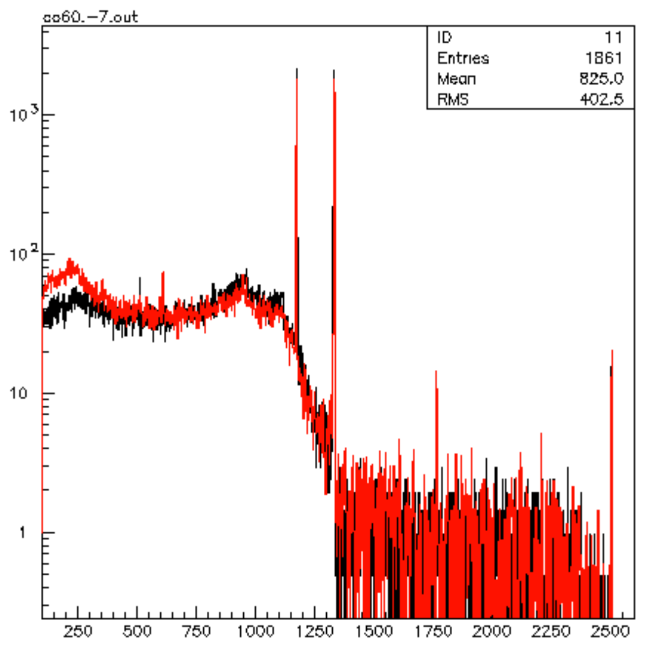
LUNA data exclude a nuclear solution for the ^{6}Li problem. The observation of a “huge” amount of ^{6}Li in metal-poor stars must be explained in a different way.

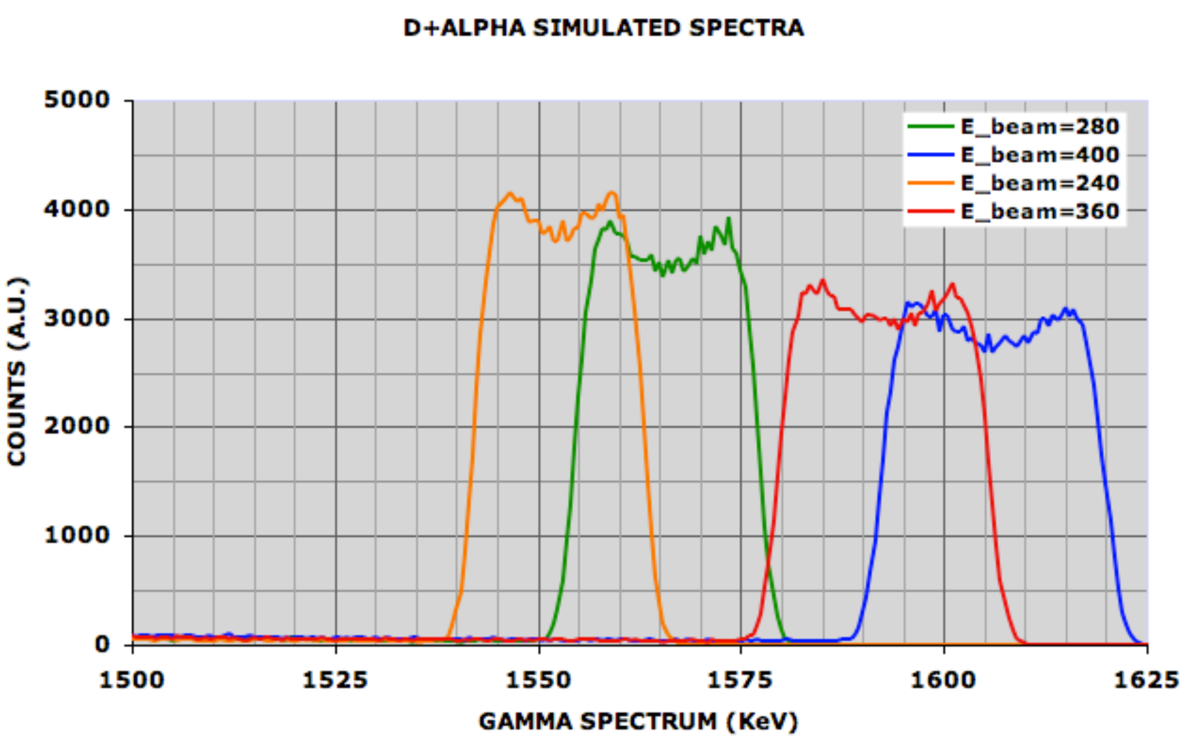
The D(α,γ)^{6}Li reaction has been studied at BBN energies. The LUNA measurement provides for the first time a solid experimental footing to calculate the ^{6}Li primordial abundance

Extra Slides


K=0.5
Φ=0°
Φ=45°
Φ=90°
Φ=135°
Φ=180°
Counts
0
50
100
150
200
250
300
1590
1595
1600
1605
1610
1615
1620
1625
Energy (keV)

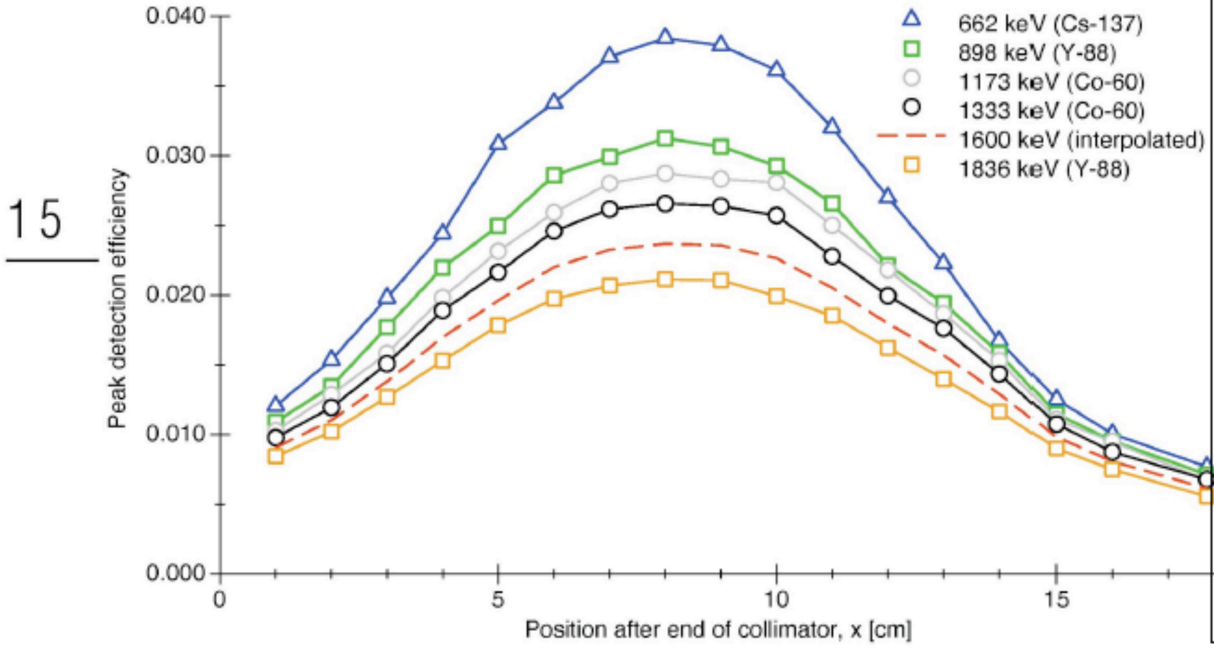

D+alpha cross section (GSI)
E1
E2
total
Cross Section (barn)
1,E-07
1,E-08
1,E-09
1,E-10
1,E-11
1,E-12
10
100
1000
Ecm (keV)
LUNA
BBN



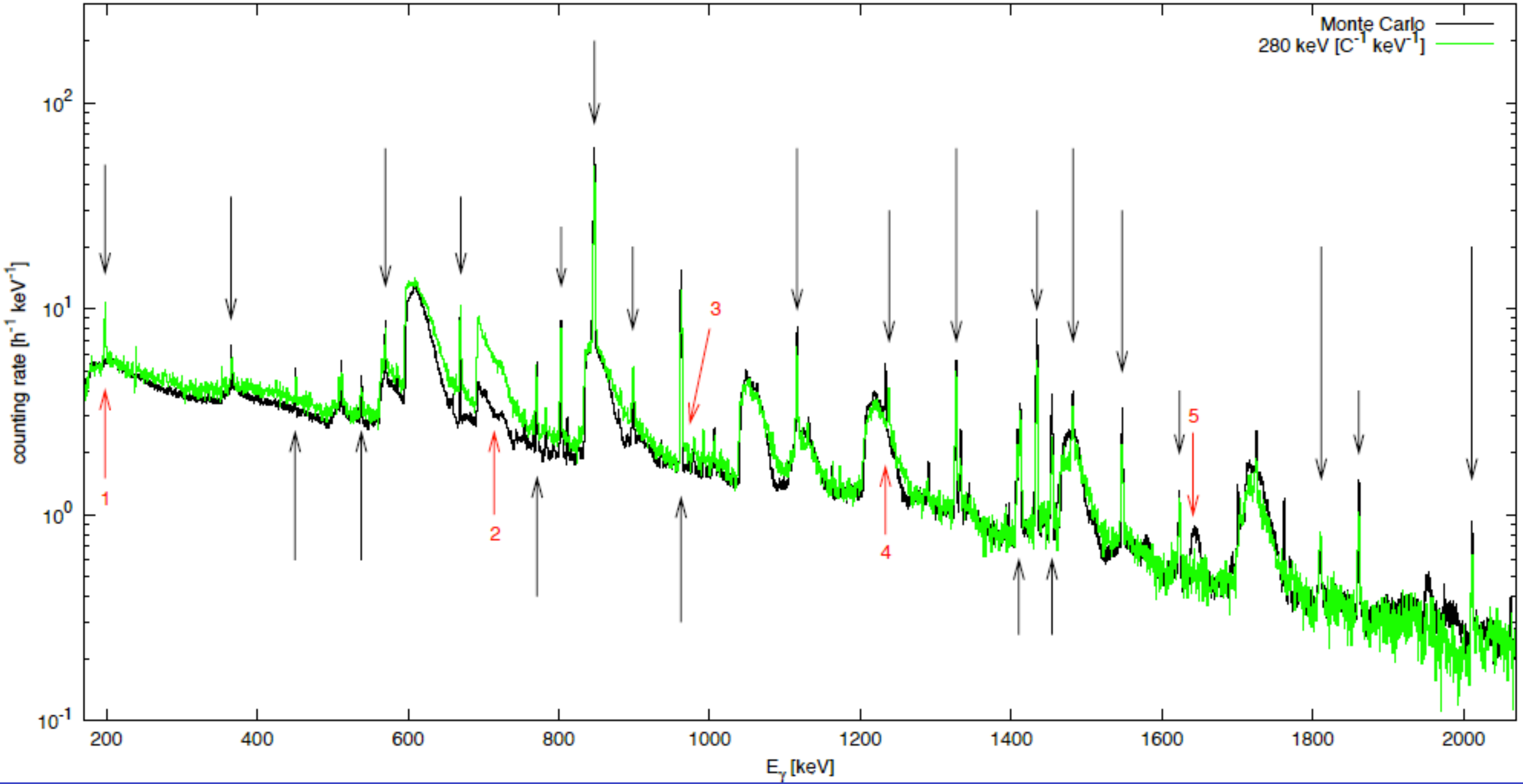


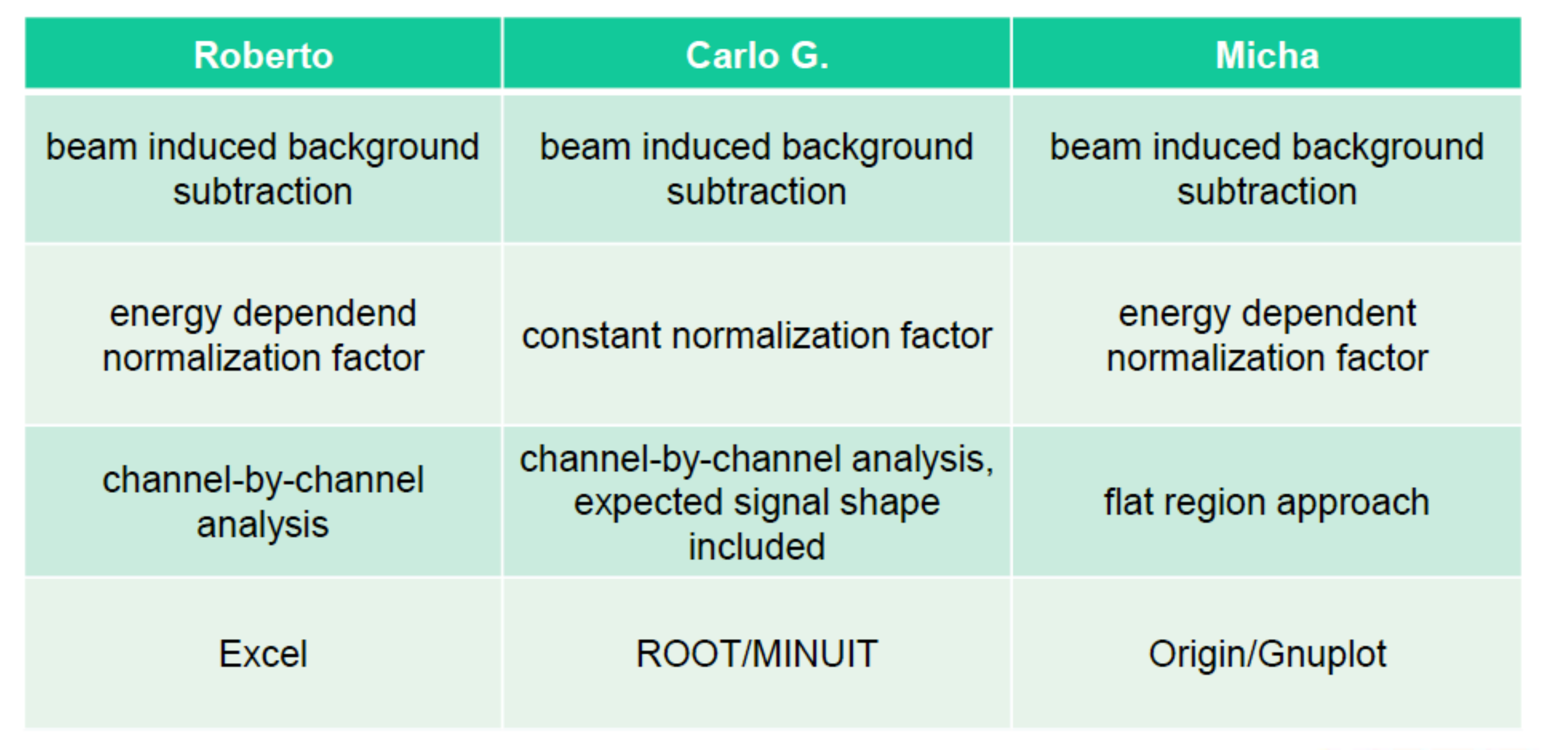
Energy (keV)	240 keV	280 keV	360 keV	400 keV
Efficiency (%)	1,661	1,658	1,635	1,633

- The D+alpha peak width depends on geometry: $E\gamma=1473{,}48+E_{cm}\pm\Delta E_{doppler}$
- Spectra of ^{137}Cs, ^{60}Co, ^{88}Y sources placed along the beam line to calibrate the Ge efficiency



- Sources calibrated to 0.5% (^{88}Y), 0.75% (^{60}Co), 1.5% (^{137}Cs)
- Interpolation between 1.333 and 1.836 MeV: $\eta_{1.333}/\eta_{1.836}$ ~ 1.25
- Estimated uncertainty for interpolated efficiency at 1600 keV: 5%
- Total efficiency, averaged over 17.7cm target length, 1600 keV: (1.63±0.08)%

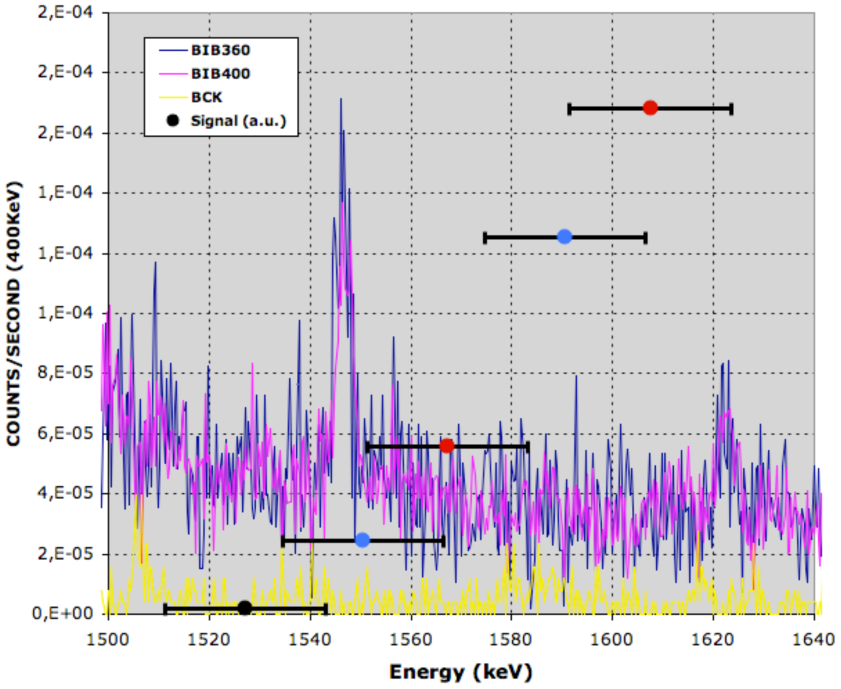

Monte Carlo
280 keV [C^{-1} keV^{-1}]
counting rate [h^{-1} keV^{-1}]
10^{2}
10^{1}
10^{0}
10^{-1}
200
400
600
800
1000
1200
1400
1600
1800
2000
E_γ [keV]
1
2
3
4
5



Roberto	Carlo G.	Micha
beam induced background subtraction	beam induced background subtraction	beam induced background subtraction
energy dependend normalization factor	constant normalization factor	energy dependent normalization factor
channel-by-channel analysis	channel-by-channel analysis, expected signal shape included	flat region approach
Excel	ROOT/MINUIT	Origin/Gnuplot

E_{lab}(keV)	ROIγ(keV)	S (counts/day)	Noise (counts/day) 35 keV window, 0,3mbar, 300uA	N/S
160	1527±17,5	0,45	848	1886
230	1550±17,5	6,09	896	147
280	1567±17,5	13,9	701	50
350	1590±17,5	31,3	609	19
400	1607±17,5	42	659	16

"GOOD" SIGNAL/NOISE RATIO AT E_{lab}=350 keV



YELLOW: NATURAL BCK
BLUE:BIB@400kV(natural BCK subtracted)
VIOLET: BIB@360kV (natural BCK subtracted)
POINTS: SIGNAL (A.U.) at 160,230,280,350,400 keV