Study of $d(p,\gamma)^3$He Reaction Relevant to Big Bang Nucleosynthesis

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NuSPRASEN Workshop on Nuclear Reactions
Heavy Ion Laboratory, Warsaw
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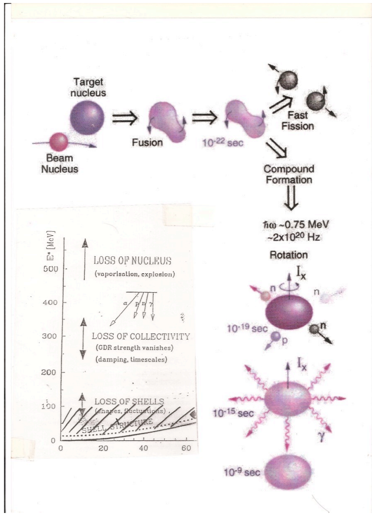
raison d’etre of the talk

Nuclear Physics Research in India in a nutshell:



Heavy-Ion Physics at low and medium energy :

- *Fusion-evaporation reaction*
- *Fusion-fission*
- *Deep inelastic reaction*
- *Transfer reactions*
- *Elastic and quasi-elastic processes*

The universal goal: **1) Nuclear structure and structural evolution with T, J**
2) Reaction dynamics below, above and around Barrier

Relativistic Heavy-Ion Nuclear Physics & QGP:

(International collaboration, Theoretical activities)

Major existing accelerators

1. *Delhi*
2. *Bombay*

3. *Calcutta*

Nuclear Physics is a broad canvas.

Its charm lies from radioactivity to RHIC.

Are we missing other interesting dimensions?

Probing the Atomic Nucleus with:

Light ions *Neutrons* *Photons* *Electrons*

Nuclear structure, N-N interactions, Nuclear Astrophysics, Application

e-ion Scattering:

- **SLAC** *Hofstadter et al. Phys. Rev. 92. 78 (1953)*
- **J-Lab (CEBAF) 12 GeV**
- **e-RI scattering (RIBF) (150 – 700 MeV)**
- **e-Ion collider (US) (BNL & JLAB)**

Continued importance of low energy proton beams

1. **N-N interaction:**
   Measurements with polarised beam and targets, cross sections, angular disctributions, analysing powers

2. **Nuclear astrophysics:**
   Precision measurements of cross sections & Astrophysical S factors through capture reactions of low energy light-ions

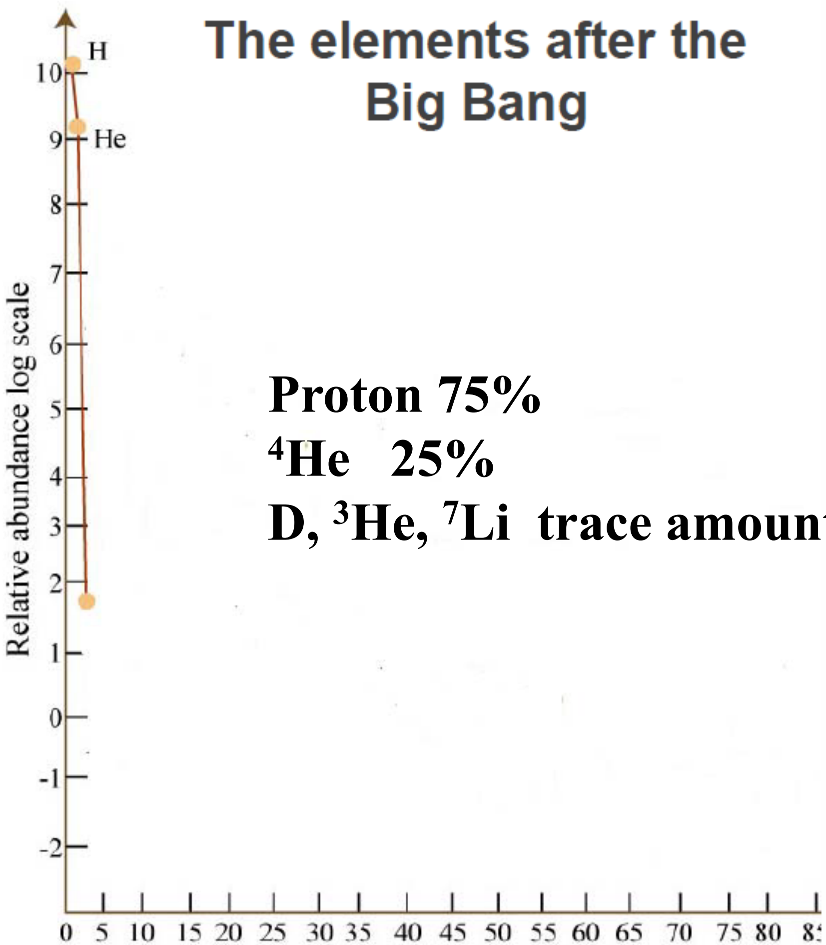
3. **Capture cross sections of great practical use.**
   High energy calibration and measurement of detector response function in continuum γ-ray spectroscopy

4. **Nuclear structure studies:**
   Giant resonances based upon low lying states

5. ***Application in production of monochromatic neutron beams.***
   (n, n')γ spectroscopy; medical imaging

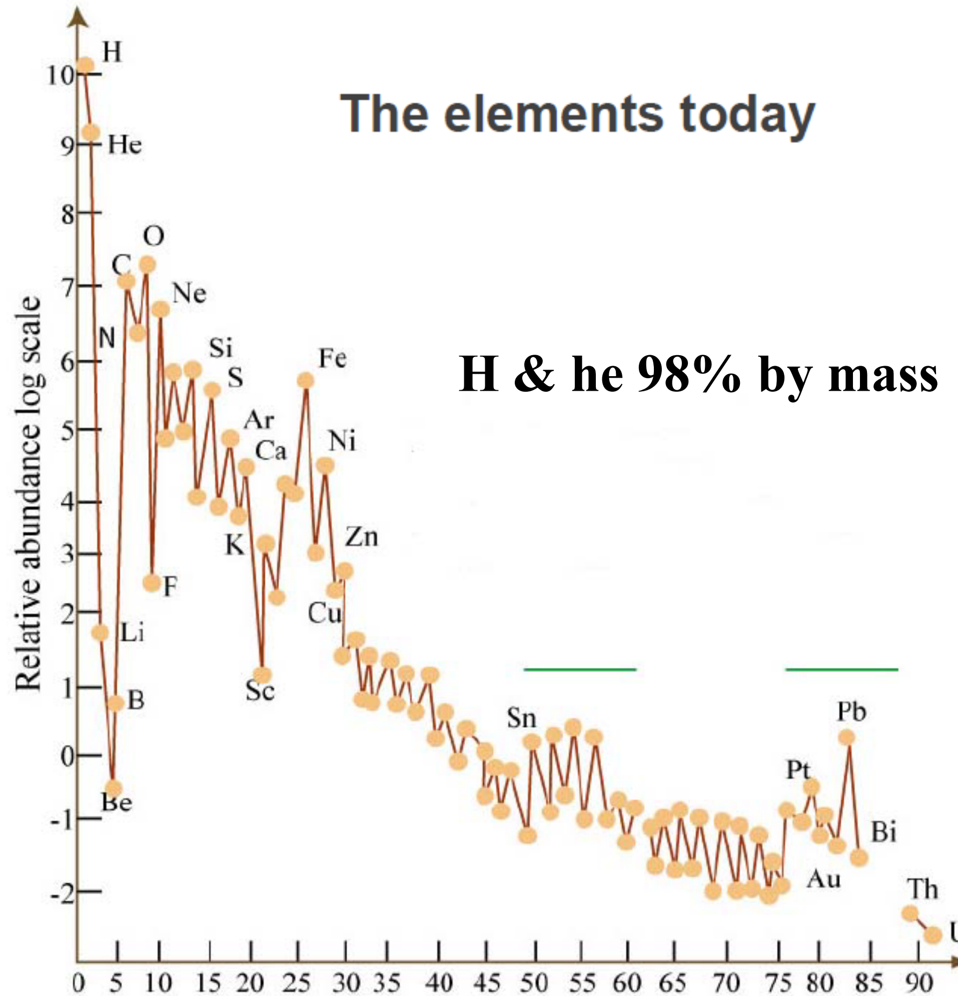
Elements relative abundances

The elements after the Big Bang



Proton 75%
^{4}He 25%
D, ^{3}He, ^{7}Li trace amount

The elements today



H & he 98% by mass

Atomic number →

Nuclear astrophysics: goals, challenges, requirements

➢ Goals:

- ✓ To understand the birth and death of stars
- ✓ production of energy that powers stars
- ✓ Synthesis of the elements

➢ Challenges:

- ✓ **Very low cross section**
- ✓ **reduction of background**
- ✓ **reactions involving unstable nuclei**

What can we do with

1) **Existing facilities**
2) **Detection systems**
3) **Intelligent techniques**

➢ Requirements:

- ✓ **Low energy, high current accelerator**
- ✓ **High efficiency detection systems (preferably 4π geometry)**
- ✓ **Purity of the target**
- ✓ **Radioactive ion beams**
- ✓ **Reducing and estimating the background**

$p(d,{}^3He)\gamma$ reaction

(BBN reaction & Stellar reaction)

Motivation

- ✓ Proton deuteron radiative capture process is important for Few-Body Nuclear Physics & Nuclear Astrophysics.

  Beam energy: Varies over wide range depending upon the exact nature of the problem
  For Nuclear Astrophysics: few keV to few hundred keV

- ✓ Three scenarios for production of ^{3}He:
  Three different temperatures (Beam Energies)

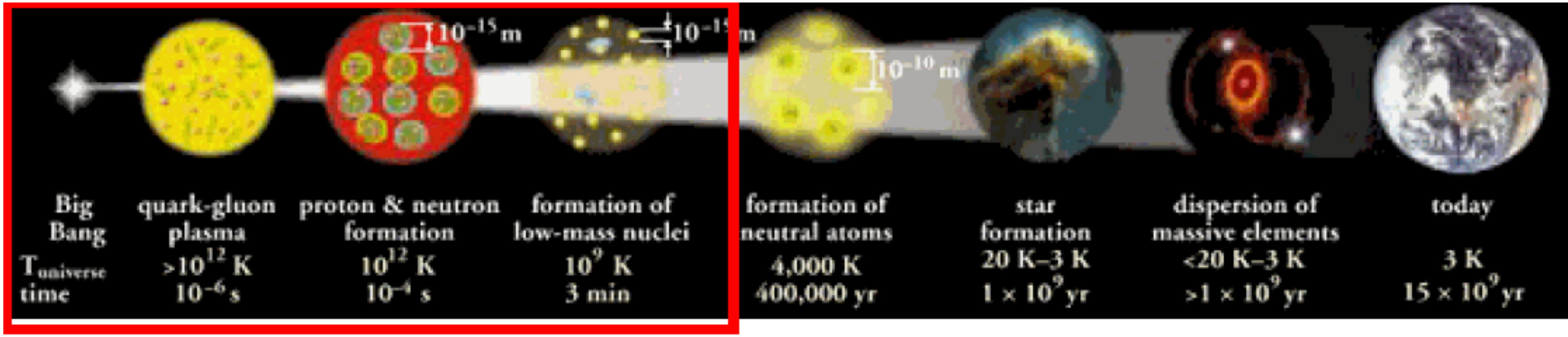
- ✓ All processes lead to depletion of deuteron. *D/H ratio governed by the reaction rates.*

- ✓ $d(p,\gamma)^3He$ reaction is also of paramount importance to study the nuclear 3-body problem. (Need for polarised beam/target)

C. Casella *et al*. (LUNA expt.)
Nucl. Phys. A 706 (2002)
High quality data for cross sections & S factors from 22 down to 2.5 kev energy

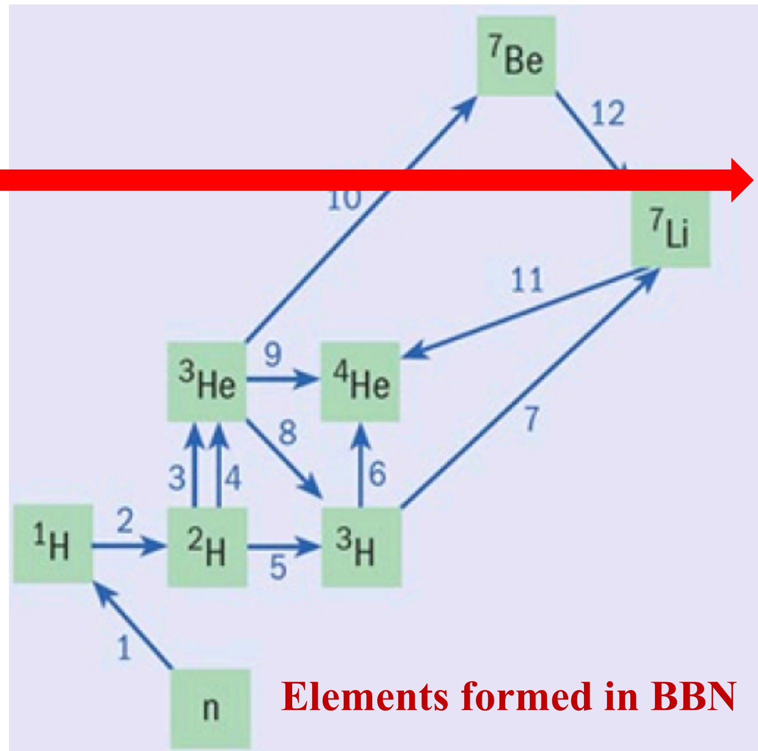
- **C. Rolfs and W. S. Rodney, Cauldrons in the Cosmos (The University of Chicago Press, Chicago, 1988).**
- **K.M. Burbidge et al., Rev. Mod. Phys. 29, 4 (1952).**
- **D. Tytler et al., Nature (London) 381, 207 (1996).**

BBN Scenario



Big bang Nucleosynthesis(BBN) → **T ~10^9K , Δt ~ 3min**

d +p→ ^{3}He + γ →



Elements formed in BBN

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

Very limited data in the BBN region

Suitable beam energy. Accessible using existing facilities in India

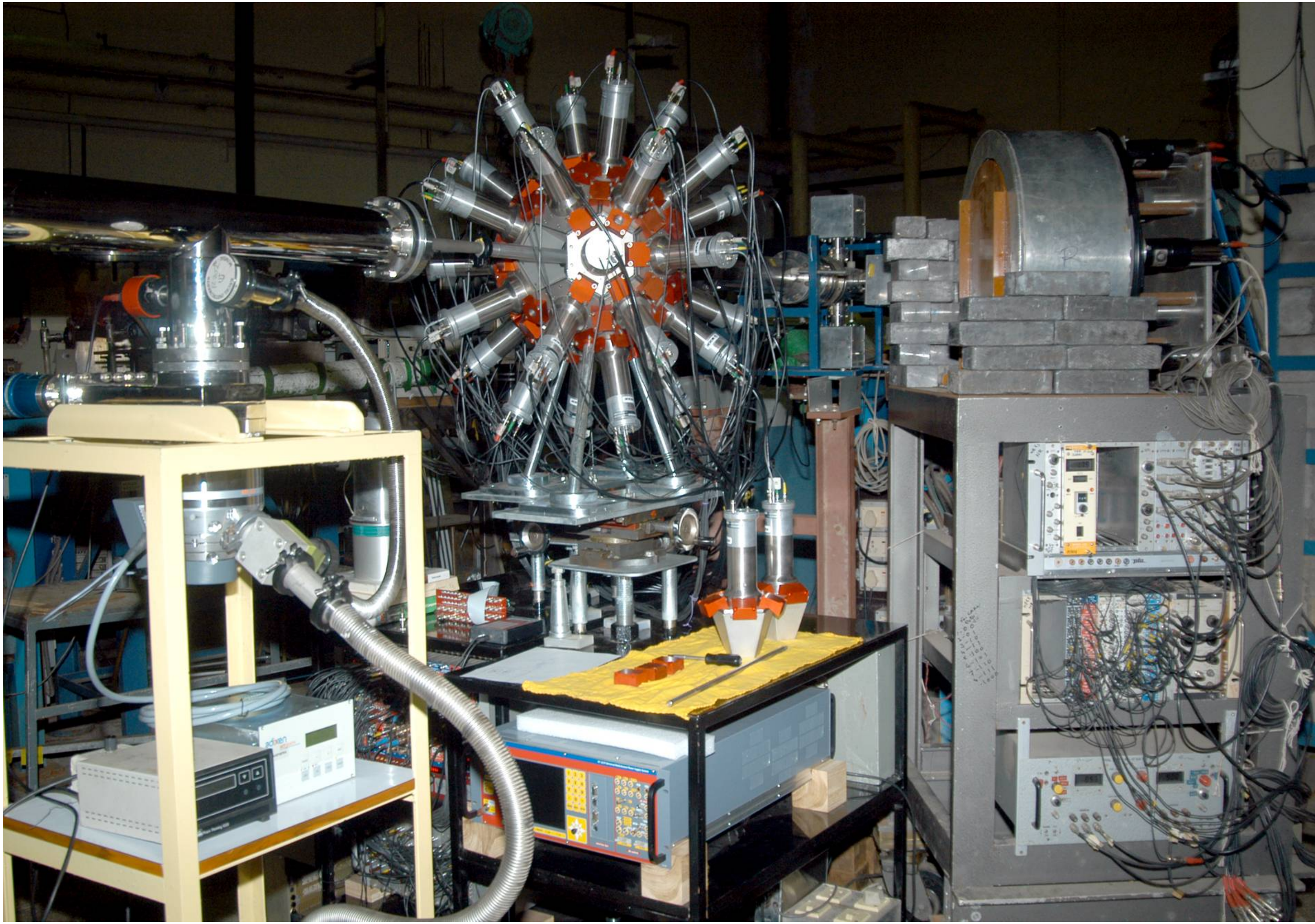
Very recent calculations by Marcucci et al. PRL (2016)

Cross section measurement of d(p,γ)^{3}He at low energies

Experimental Details

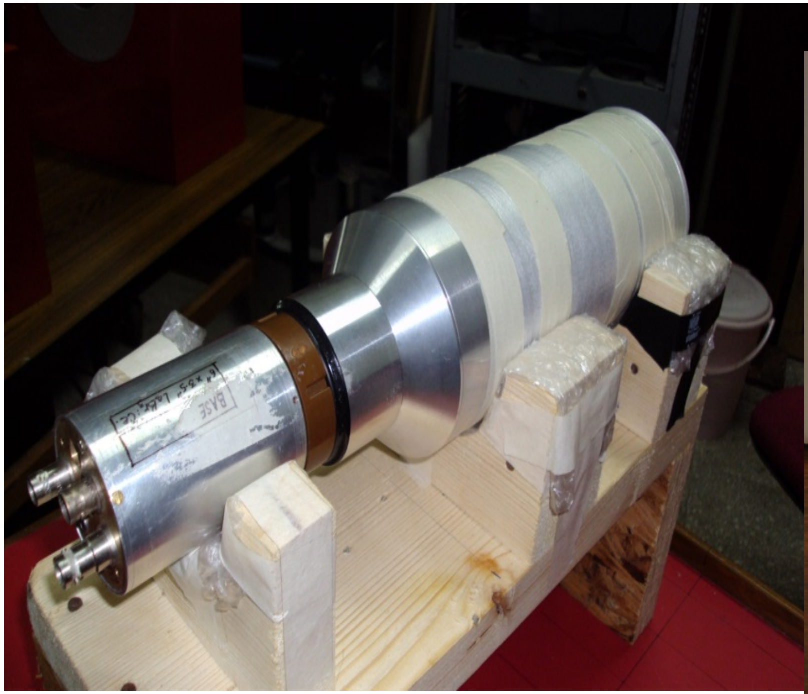
Top view

- Accelerator facility- ECR ion source facility at TIFR (Upto 400 keV proton energy)
- Proton Beam Energy used: E_p= 250, 175, 100 keV
- Current ~ 200 nA
- Target- CD_2 ~ **10^{17} atoms/cm^2**
- Detector facility- 3.5 "× 6" cylindrical $LaBr_3$ and array(2x2) of **$LaBr_3$**
- **Q of reaction = 5.493 MeV**



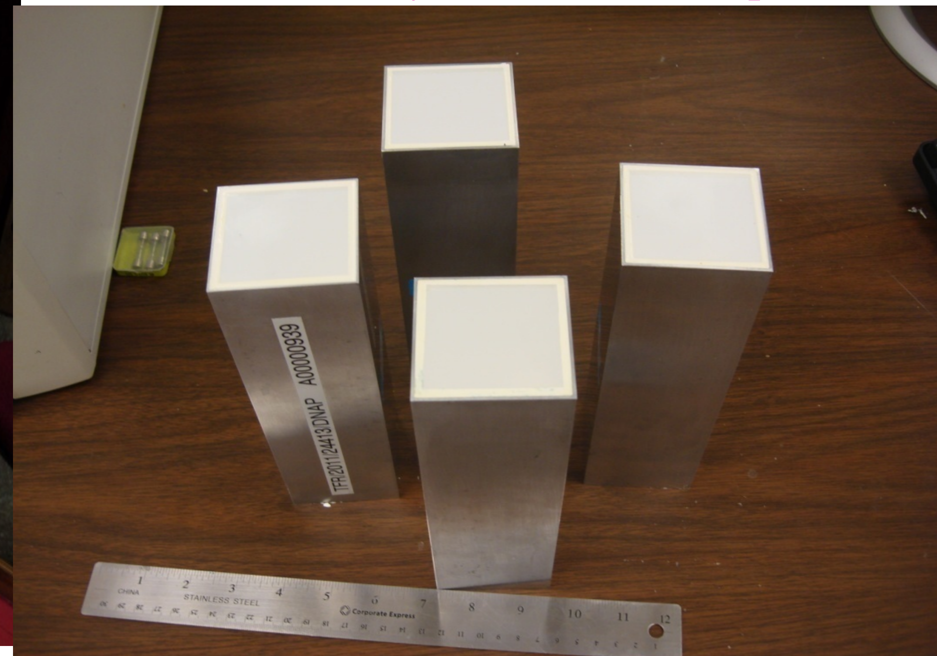
The 4π <u>Sum</u>-Spin Spectrometer at TIFR

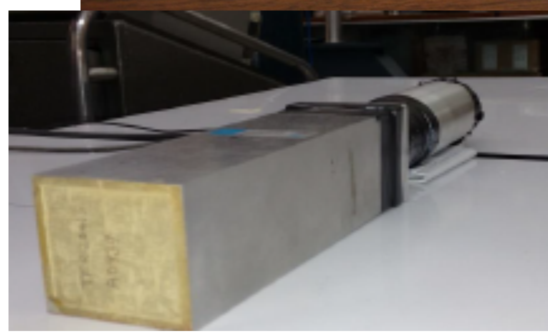
Kumar, Mazumdar, Gothe, NIM-A 611 (76) (2009)



3.5"× 6" cylinder

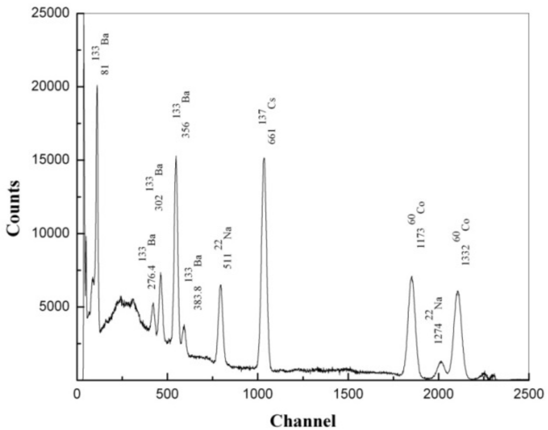
2x2 array of (2"×2"× 8") square bar



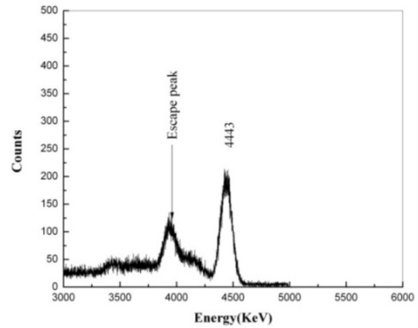


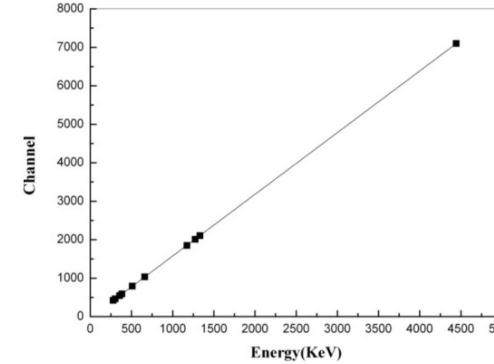
1. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 609 (2009)
2. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 610 (2009)
3. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 611 (2009)
4. I. Mazumdar, G. Anil Kumar, Gothe, Manchanda, Nucl. Instr. Meth. (2010)
5. I. Mazumdar, Gothe, Chavan, Yadav, G. Anil Kumar, Nucl. Inst. Meth.A 705 (2013
6. M. Dhibar, D. Mankad, I. Mazumdar and G. Anil Kumar. App. Rad. & Iso. (2016).
7. M. Dhibar, I. Mazumdar, G. Anil Kumar, S. M. Patel, P. B. Chavan. NIM-A (2018)

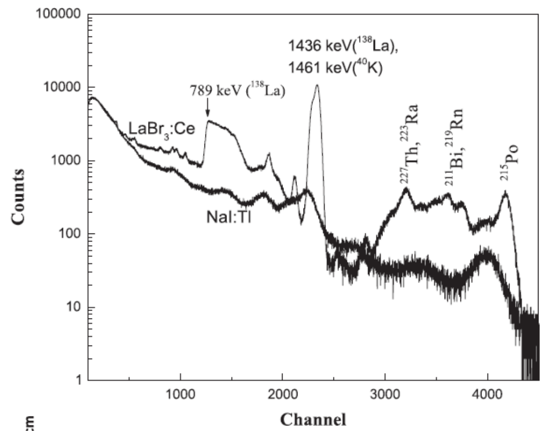
3.5" X 6" $LaBr_3$:Ce

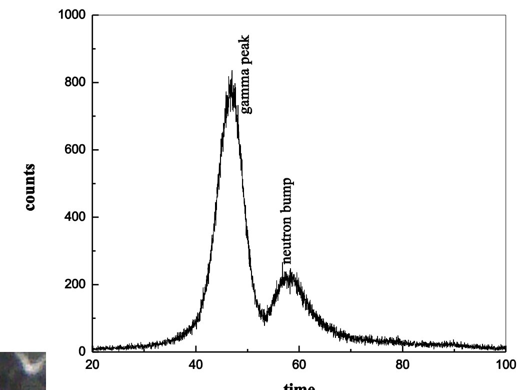


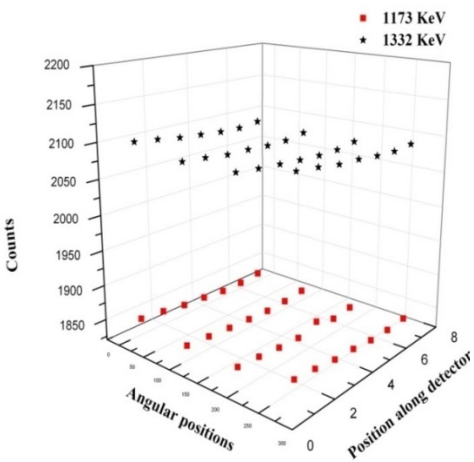
AmBe (4.433 MeV)

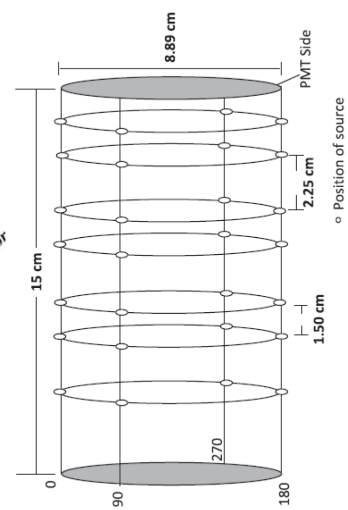


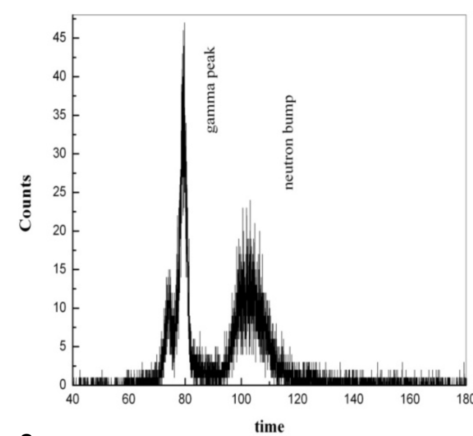












Mazumdar et al
NIM-A 705 (2013)

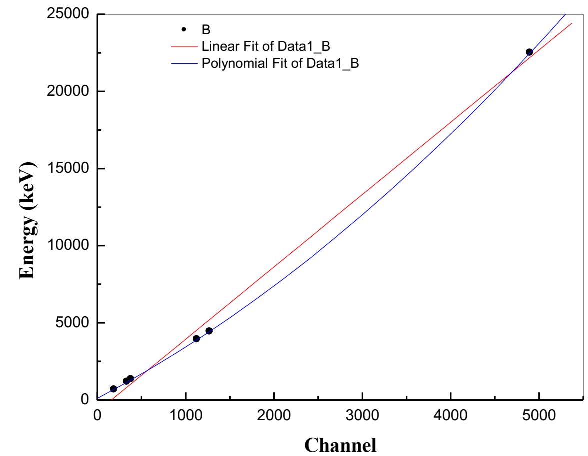
Internal radioactivity of the $LaBr_3$:Ce ~ 3 cts/s/cm^3

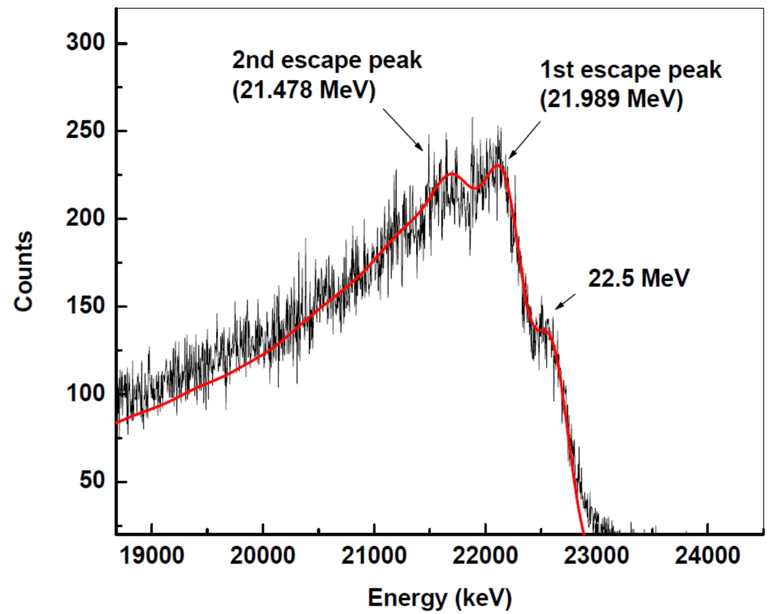
Reactions:

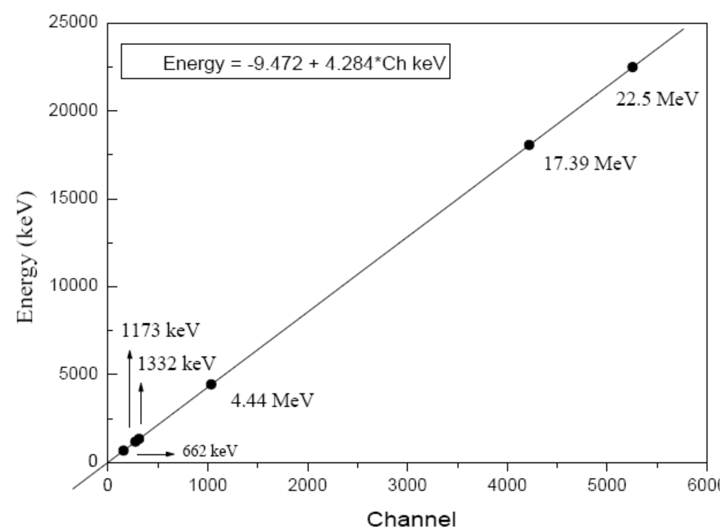
$^{11}B(p,\gamma)^{12}C$ (Capture Reaction)

$^{12}C(p,p')^{12}C,\gamma$ (inelastic scattering reaction)

Mazumdar, Schmidt, Maj, PARIS Collaboration Web site







22.5 MeV γ-rays measured at TIFR with the large cylindrical $LaBr_3$:Ce.

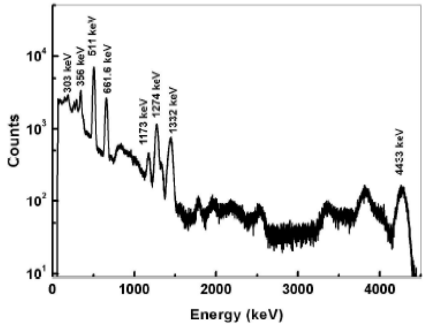
E_p = 7.2 MeV proton beam from TIFR Pelletron

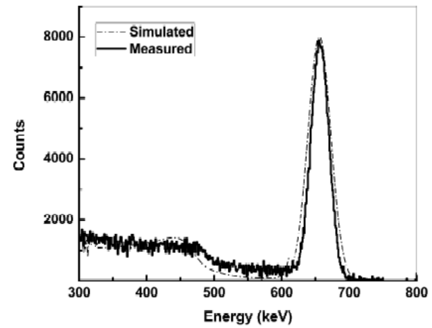
Taming the non-linearity up to 22.5 MeV

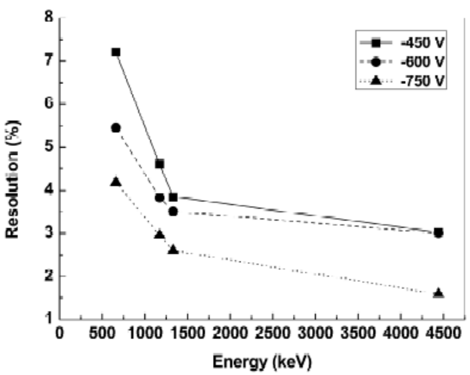
Mazumdar et al. Nucl. Instr. Meth. A (2013)

Characterisation of 2”X2”X8” bar & 2x2 array

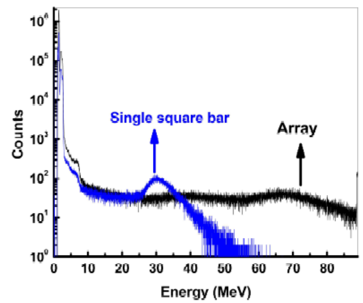
Dhibar, Mazumdar et al. NIM-A (2018)

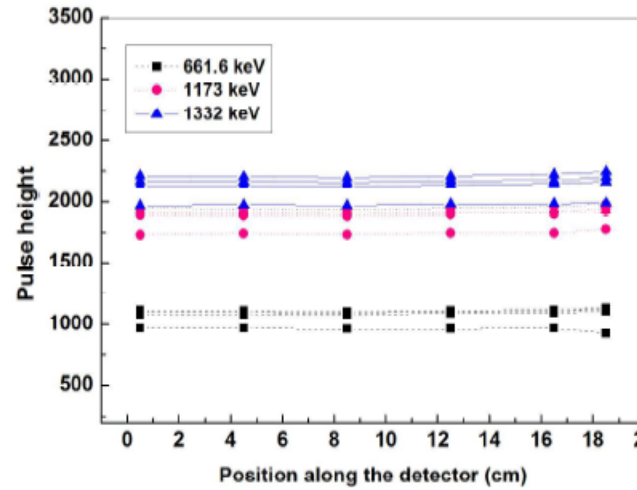




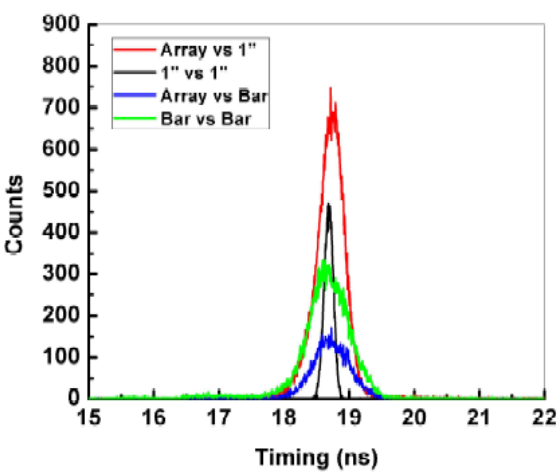


Energy Resolution

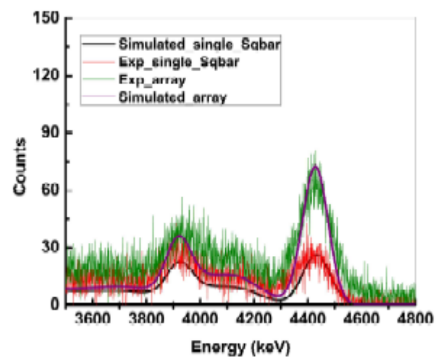




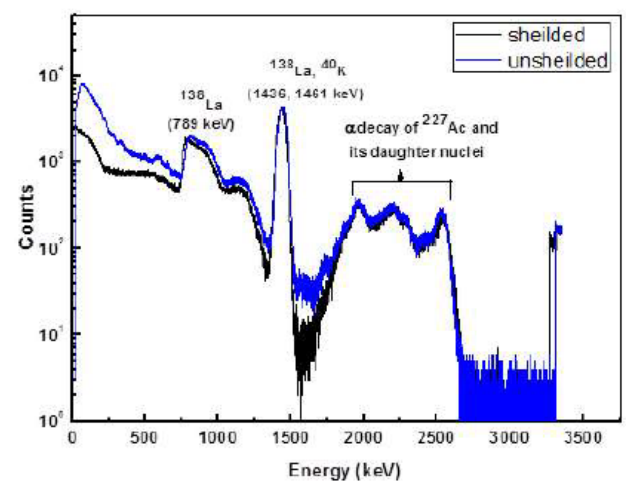
Uniformity



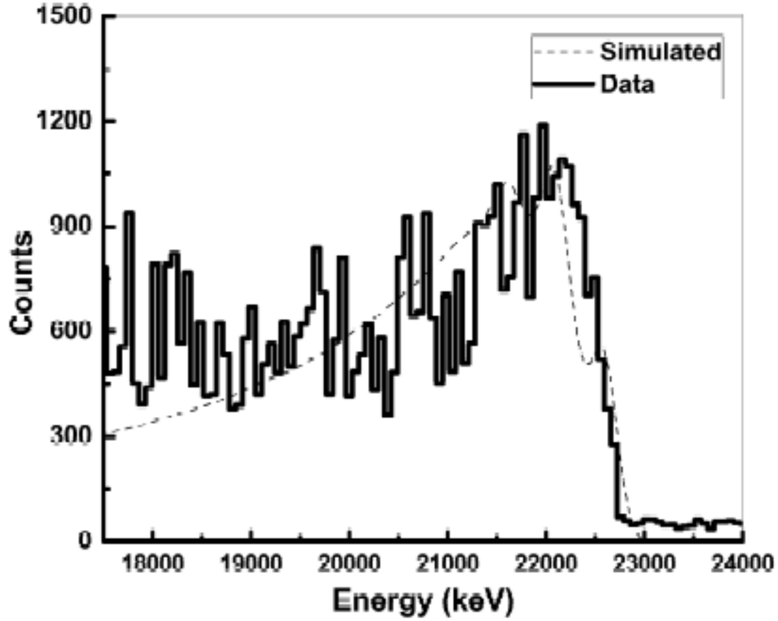
Timimg Resolution



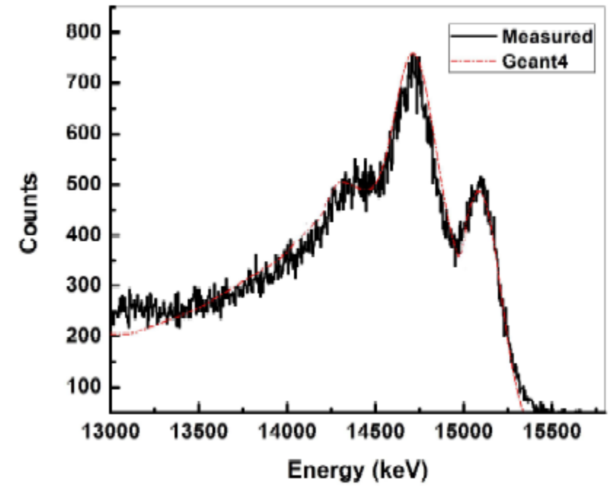
Detector geometry	Efficiency(%)	
	Experimental	Simulated
Single square bar	34.88 (0.03)	34.13 (0.05)
Array	40.50 (0.15)	41.00 (0.11)



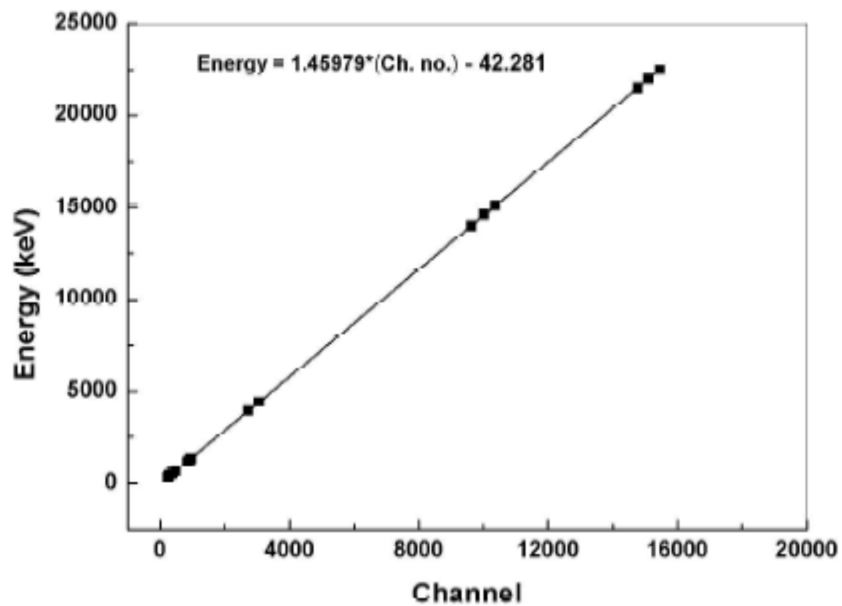
Internal activity



22.5 MeV from $p(^{11}B,\gamma)$ reaction



15.1 MeV from $^{12}C(p,p'),\gamma$ reaction



Linearity up to 22.5 MeV

Dhibar, Mazumdar et al., NIM-A (2018)

Capture reaction cross section measurement

$$d + p \rightarrow {}^{3}He + \gamma$$

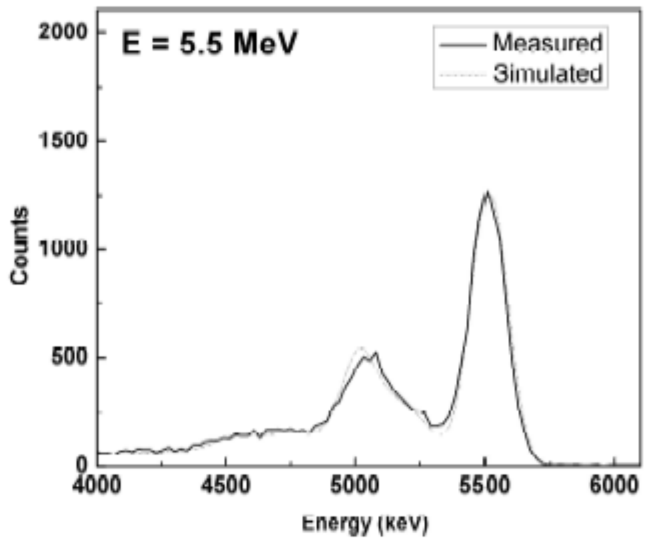
$$\sigma = \frac{Yield}{n_1 n_2 \left(\varepsilon_{\text{int}\, rin}\, \varepsilon_{\Omega}\right)}$$

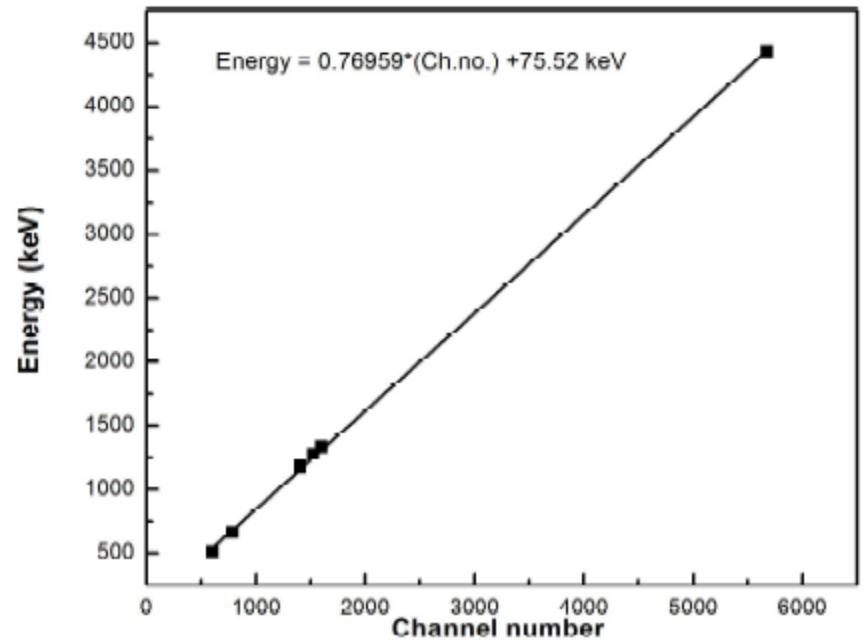
$\varepsilon_{\text{int}\, rin}\, \varepsilon_{\Omega}$ **= Efficiency correction factor** → **Using Geant4 Simulation**

$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta)\, S(E)$$

"Probability for barrier tunneling"

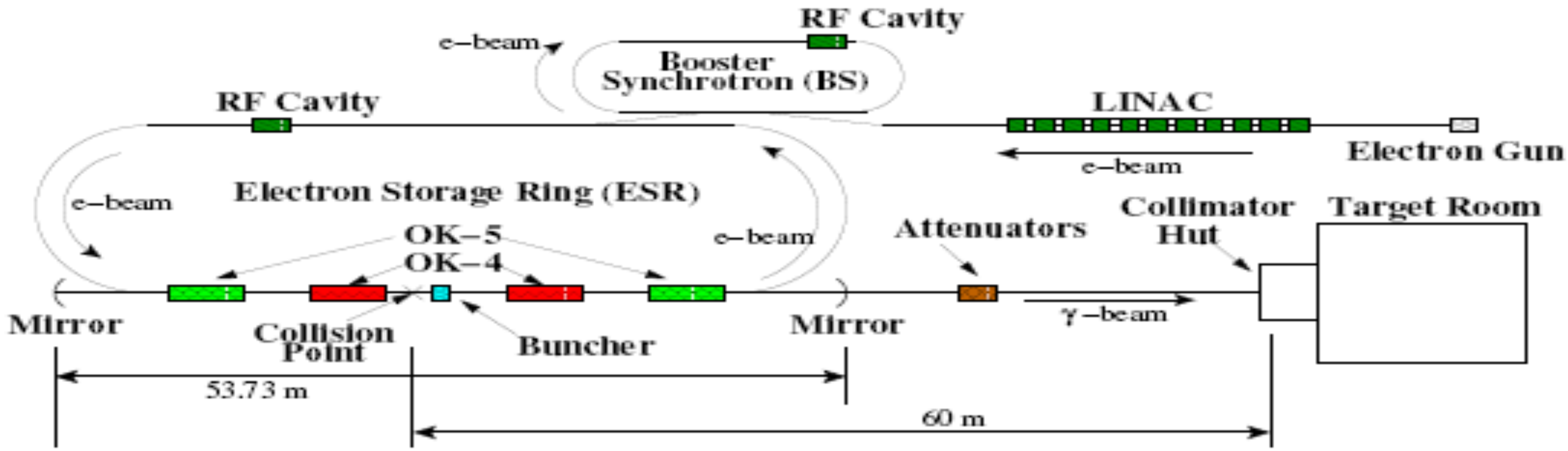
$\eta = 31.29 Z^{1} Z^{2} (\mu/E)^{1/2}$

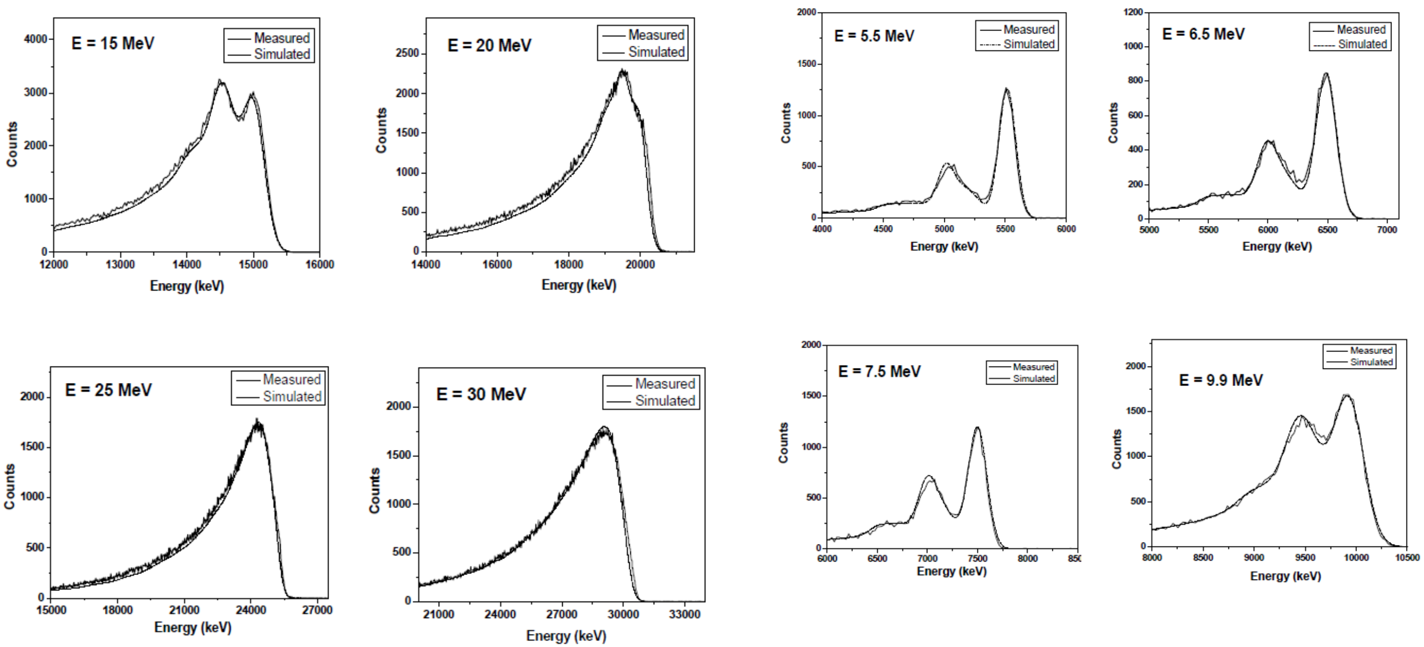




Measured spectrum using HIγS photon beam

Energy (keV)	Photo-peak (%)	Total detection (%)
662	46.1±0.95	71.1±1.24
1000	38.8±0.92	69.2±1.32
4433	16.8±0.83	61.4±1.41
5000	14.8±0.95	56.3±1.09
5500	13.6±0.87	52.5±1.12





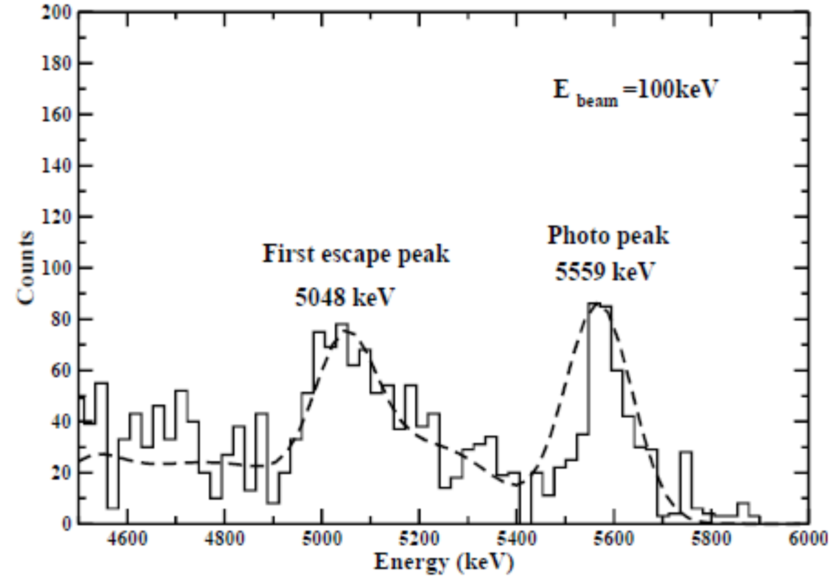
Mazumdar et al.

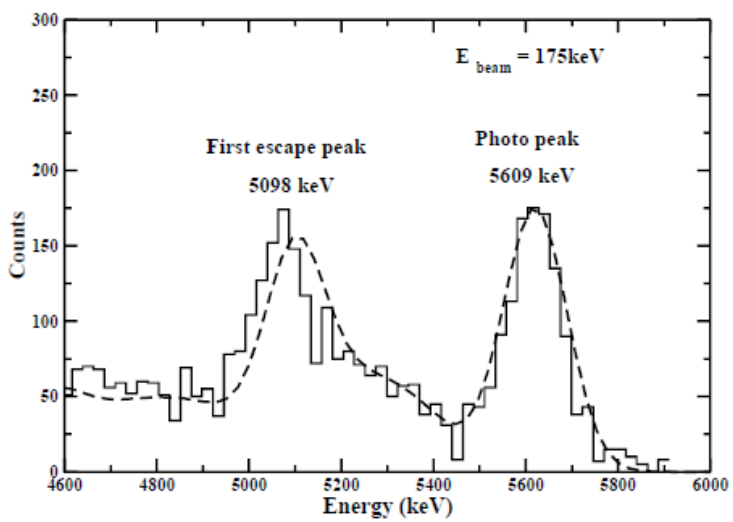
$p + d \rightarrow {}^3He + \gamma$

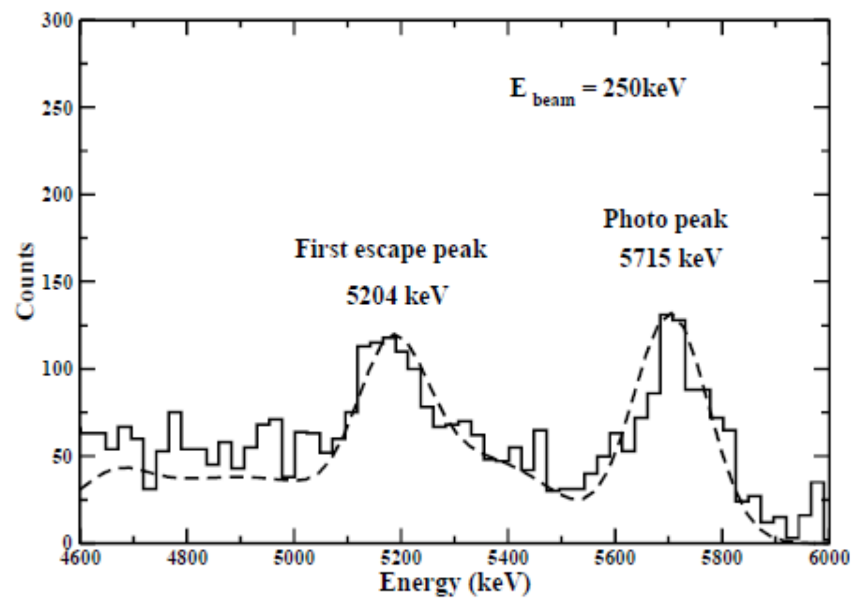
Experiment performed at TIFR ECR facility

Extraction voltage range 30 to 400 kV
CD_2 target of ~ 10^{17} atoms/cm^2
Large volume cylindrical $LaBr_3$ detector

V_{coul} = 600 keV
Gamow Window ~ 8 – 24 keV
Q of reaction = 5.493 MeV

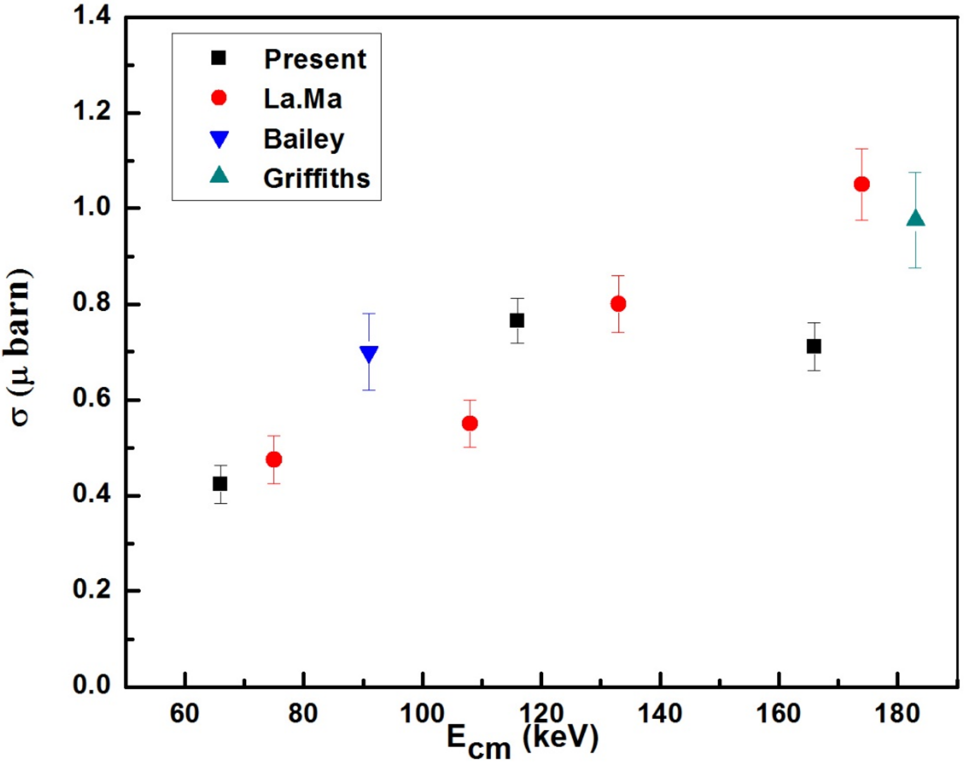


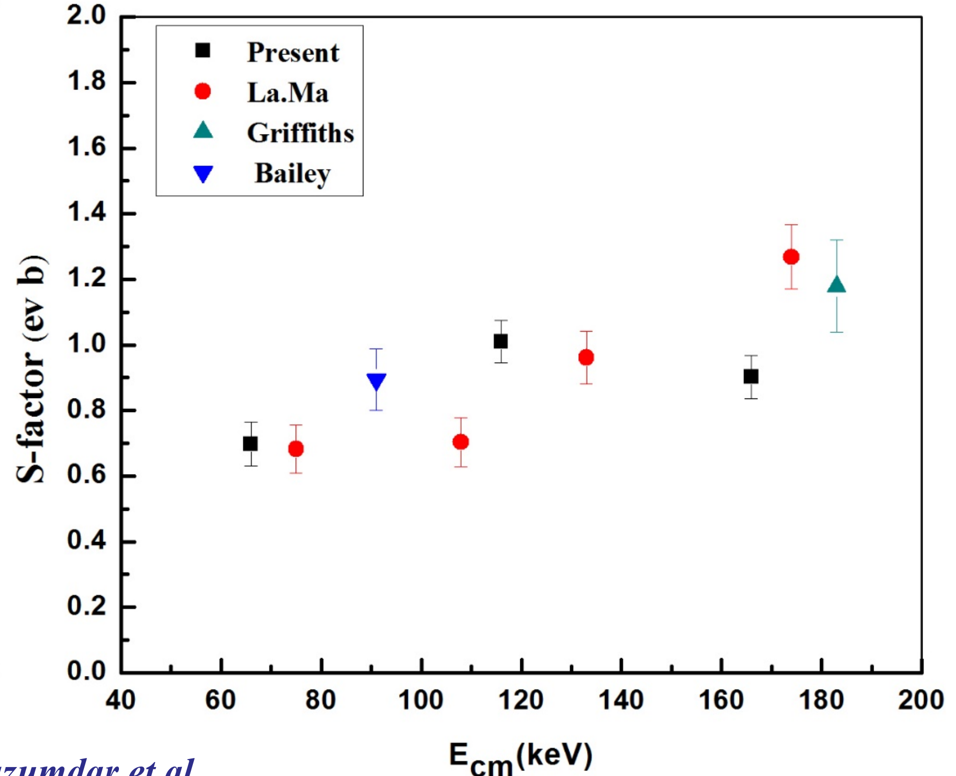




Cross section and S-factor

$$d + p \rightarrow {}^{3}He + \gamma$$





Dhibar, Mazumdar et al, under review

E_{cm} (keV)	σ (μb)	S-factor (eV-b)
166.66	0.71±0.05	0.902±0.066
116.66	0.73±0.04	0.967±0.064
66.66	0.42±0.04	0.698±0.067

Grifffths *et al.*, Can. J. Phys. 41 ,724 (1963).
Balliey *et al.*, Can. J. Phys. 48 , 3059 (1963).
Ma *et al.*, Phys. Rev. C 55, 2 (1997).

Implication of the Proton-Deuteron Radiative Capture for Big Bang Nucleosynthesis

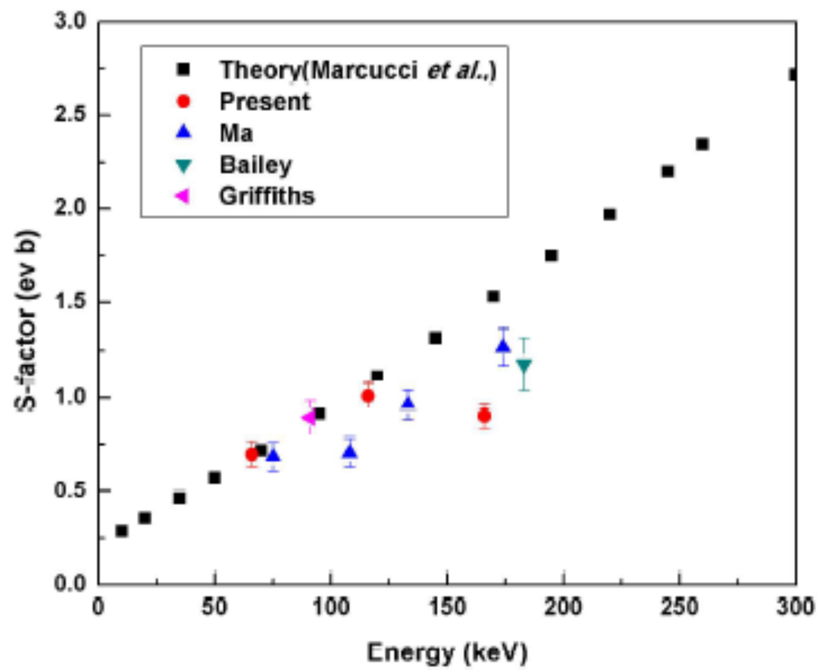
L. E. Marcucci,[1,2] G. Mangano,[3] A. Kievsky,[2] and M. Viviani[2]

PRL 116, 102501 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

way is to increase the value of the $d(p,\gamma)^3$He astrophysical S factor. This possibility was first explored in Ref. [9] and then analyzed in detail in Ref. [5], using the Planck 2013 data release, and in Ref. [3]. The conclusion of these studies is that increasing the $d(p,\gamma)^3$He thermal rate in the BBN temperature range by a factor of order 10% leads to a very good agreement between CMB anisotropy results and primordial deuterium abundance. Thus, a better determination of this S factor with a reduction of the corresponding uncertainty in the BBN energy range, $E \simeq 30$–300 keV, would be very important.

The astrophysical S factor at low energy, around the solar Gamow peak $E_G \simeq 9$ keV, is well known, thanks to the results of the LUNA experiment [10]. However, for the BBN relevant energy range, the experimental situation is rather unclear, since the only available experimental data [11] are quite in disagreement with the polynomial best fit of $S(E)$ for $E \simeq 0$–2 MeV [7]. This gives rise to an uncertainty on the cross section at the level of 6%–10%. This is the main motivation of the experiment recently proposed by the LUNA Collaboration, with the goal of measuring the $d(p,\gamma)^3$He astrophysical S factor in the BBN energy range with a 3% accuracy. A feasibility test has already been performed [12].

On the other hand, the $d(p,\gamma)^3$He astrophysical S factor found to be 2%–10% higher than the central value for the polynomial fit of Ref. [7]. In the present Letter, our starting point is the work of Ref. [14], which, although very accurate, should be considered incomplete for two reasons: (i) no estimate of the theoretical uncertainty was given, in particular, that one arising from the solution of the p-d scattering problem with the HH method; (ii) the one-body terms beyond the leading order operator, of the order $1/m^3$, were found a few years later [18], essential in order to get a reasonable agreement between theory and experiment for a related process, the $d(n,\gamma)^3$H radiative capture. Given the similarities between the p-d and n-d radiative captures, it is to be expected that these $1/m^3$ one-body contributions might be important also for the process here under consideration. The goal of the present Letter is to address the two above-mentioned issues and to verify whether the new prediction for the $d(p,\gamma)^3$He astrophysical S factor goes in the direction of improving the consistency of theoretical BBN deuterium abundance prediction, the new Planck results, and the experimental data of Ref. [8]. We do not consider here ^{4}He primordial mass fraction Y_p, since it is insensitive to this reaction rate. For example, a change of the $d(p,\gamma)^3$He S factor by a factor of 2 affects Y_p at the level of 0.04%, too small to be appreciated with the present statistical and systematic uncertainties on its experimental



Summary:

Cross sections and S factors measured for three new beam energies in the BBN energy region for (pd)γ capture reaction.

Measured values are in very good agreement with the limited global data set.

Measured values are in excellent agreement with recent calculations of Marcucci *et al*.

Measurements for more beam energies [for (pd)^{3}Heγ]are underway.

Near future measurements: proton capture on ^{12}C, ^{10,11}B

Collaborators

- *M. Dhibar, A.K. Gourishetty, P.B. Chavan, S. M. Patel, A.K. Rhine Kumar, C.D. Bagdia, L.C. Tribedi*

  TIFR, Mumbai,

  IIT-Roorkee


Thank You