

Studies in Nuclear Structure, Reaction & Nucleosynthesis using low and Medium Energy Light Ions

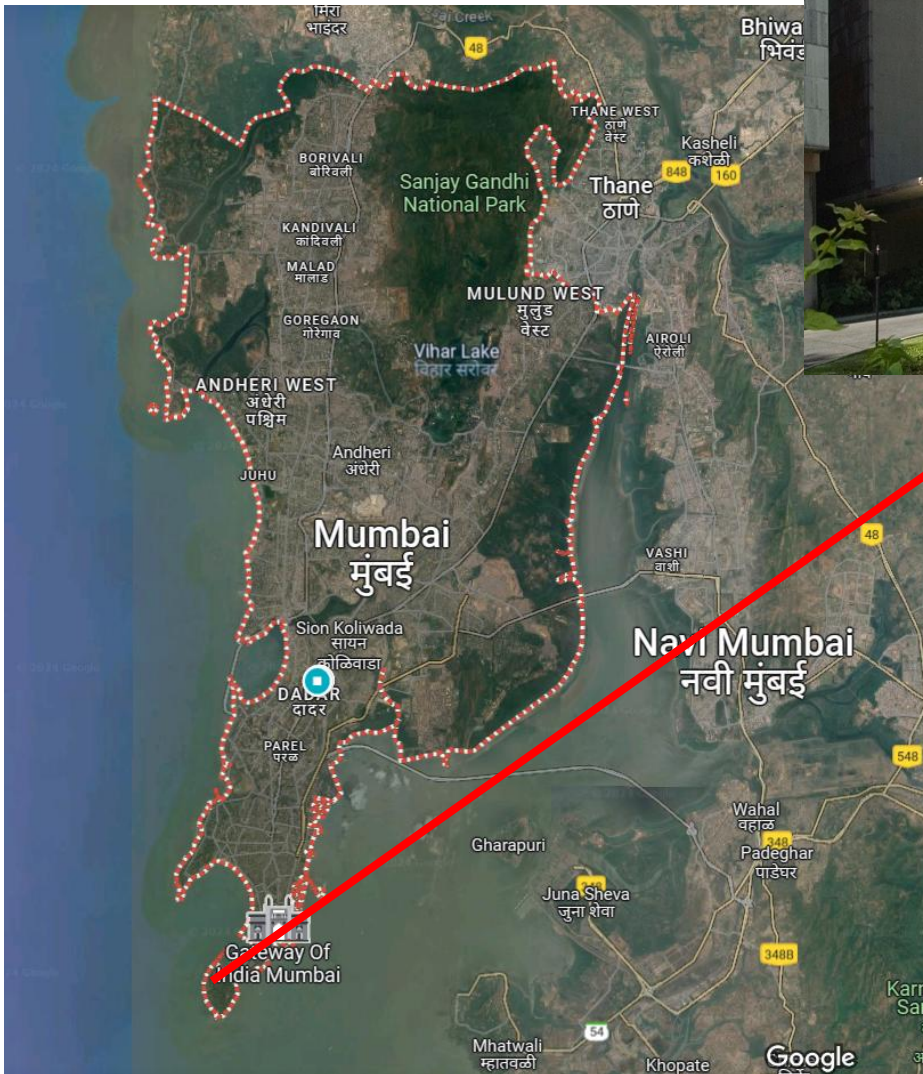
Indranil Mazumdar

*Dept. of Nuclear & Atomic Physics
Tata Institute of Fundamental Research, Mumbai*

IFJ PAN, Krakow
11th September, 2026



Tata Institute of Fundamental Research,
Mumbai



The Chronology of the talk:

- *Prefatory Comments:*
Raison d'être of the Programme
- *Tools & Techniques:*
Experimental, Theoretical
- *Inelastic Scattering of Light Ions:*
Structure, reactions
- *Capture reactions of Light Ions:*
Reactions of Nucleosynthesis
- *The road Ahead*
- *A very brief comment on Nuclear Spin Physics*
Need for a global consortium and an international hub

PART I

raison d'être of the programme

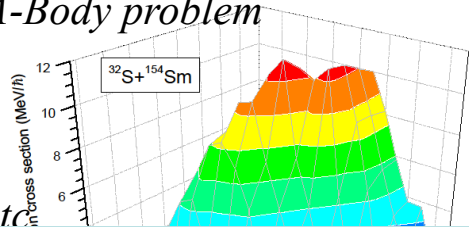
Or

Prefatory Comments

The World of Heavy Ion Nuclear Physics:

The Energy Scale:

- Low, Medium, Intermediate, Relativistic
- Probing many facets of the quantum *A*-Body problem
- SP & Coll. Excitations & interplays
- Rotation, Vibrations, collective flow etc
- Determining effective

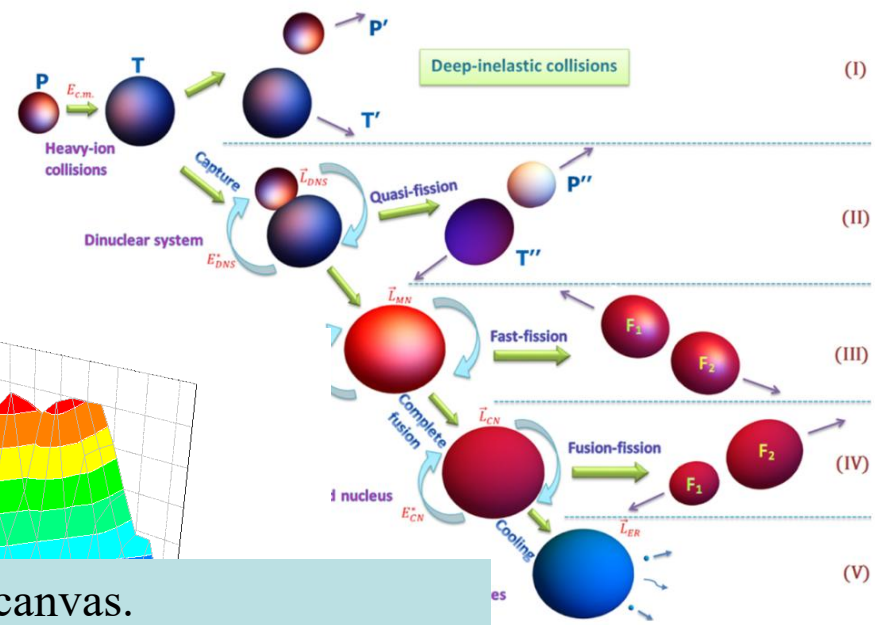


Nuclear Physics is a broad canvas.

Its charm lies from radioactivity to RHIC.

Major unsolved Issues across

- Elastic, Quasi-elastic, Inelastic, Fusion, Fission etc. at above, below and much below the barrier
- Equilibration and stability of the compound system
- Role of Shell effect
- Complete & Incomplete Fusion
- Role of Entrance Channel mass asymmetry
- Role of barrier height, viscosity etc.



Evolution of the Projectile System

Are we missing other interesting dimensions?

- Dynamics of Decay of the System
- Statistical Theory
- Dynamical Theory
- Microscopic Formalism
- Semi –classical formalisms

Light ion probes, photons, electrons, neutrons

Both polarized and un-polarized projectiles and targets

N-N Interaction is spin dependent, hence it is absolutely imperative to do measurements with polarized beam and target and in few body systems

e-ion Scattering:

Most precise information about nuclear size and charge distribution

- 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)

Importance of stable LI induced reactions:

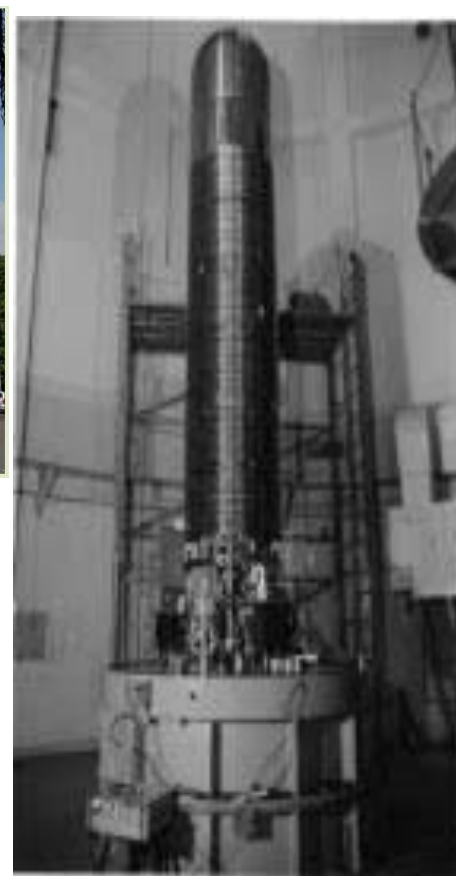
- Nuclear Structure & reaction information:
low lying excited states, GR on low lying states, role of channel couplings, resonances, calibrating theoretical formalisms (reducing the parameter spaces in Optical Model Analysis)
- Information on N-N to N-A to A-A interaction
- γ -ray astronomy:
Isotopic abundances in astrophysical sites and Inter Stellar Medium
- Nucleosynthesis: proton/alpha capture reactions of Nuclear Astrophysics
- Practical application: *surface composition analysis using PIGE, Calibration of detectors at high energies*

The modes of reactions:

- *Elastic Scattering* $(p, p), (\alpha, \alpha)$ etc.
- *Inelastic scattering* $(p, p'), (p, p'\gamma), (\alpha, \alpha), (\alpha, \alpha'\gamma)$ etc.
- *Capture reaction* $(p, \gamma), (\alpha, \gamma)$ etc.
- *Knock out reaction* & *Charge exchange reaction* (p, n)

Part II

Tools & Techniques





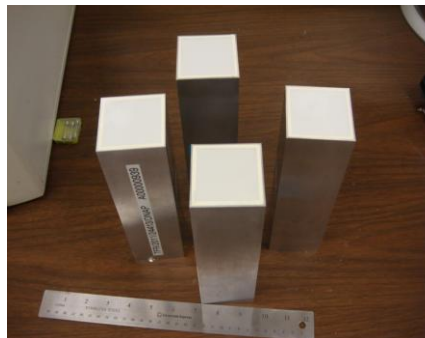
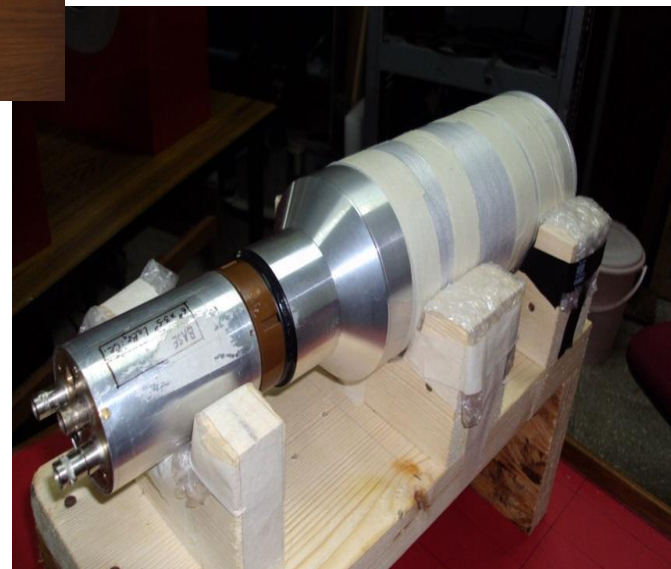


Our Arsenal

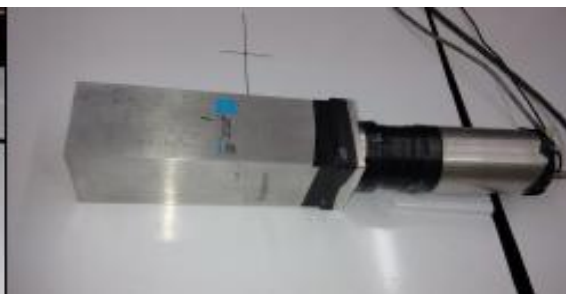
Inorganic Scintillation γ -ray Detectors Nal(Tl), LBC, CeBr₃, CsI(Na) etc.

2x2 array of (2"×2"× 8") square bar

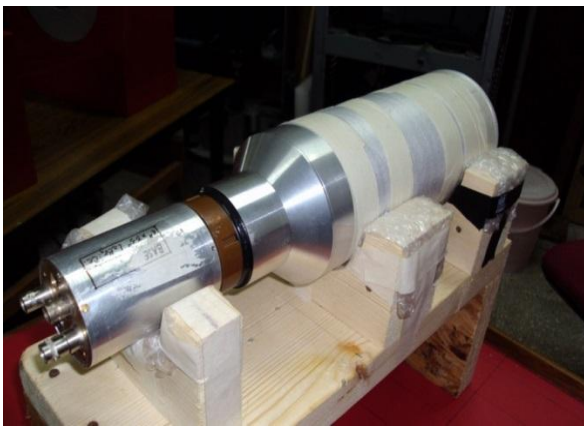
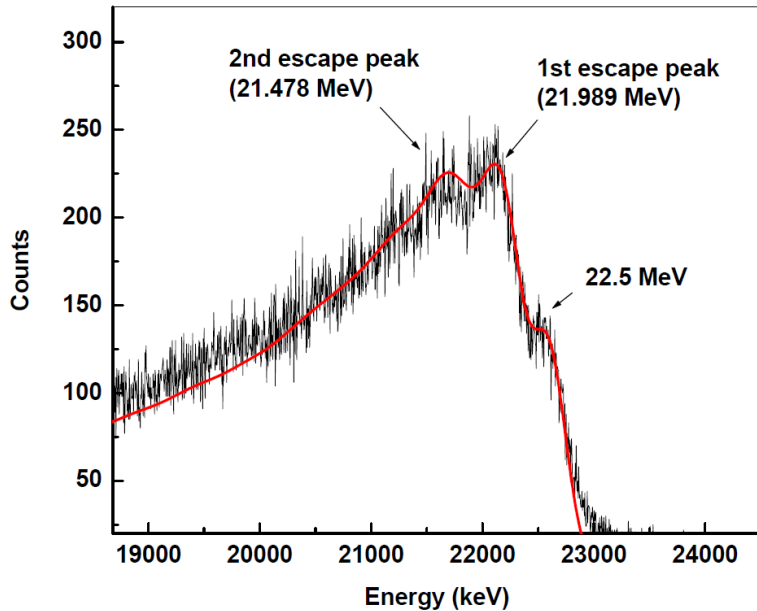
- *Large Volume NaI(Tl) detectors*
- *Large Array of NaI(Tl) detectors in 4π configuration*
- *Large Volume (Cylindrical) LaBr₃:Ce Detectors*
- *Array of Large Volume (square bars) LaBr₃:Ce detectors*



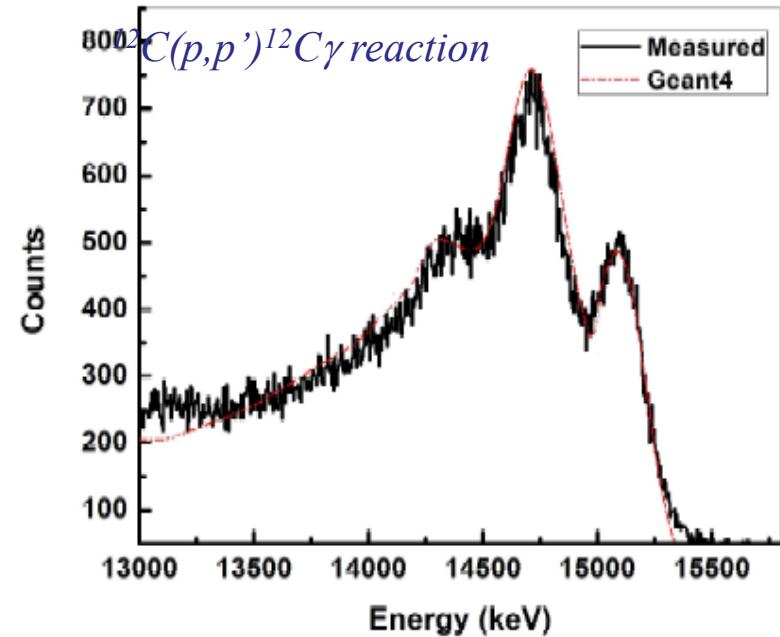
3.5"× 6" cylinder



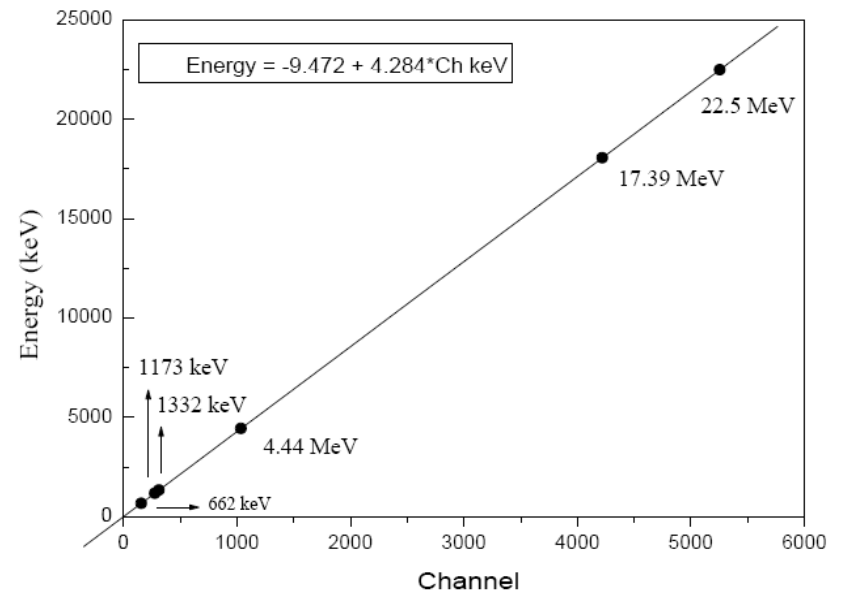
1. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 609 (2009)
2. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 610 (2009)
3. G. Anil Kumar, Mazumdar, Gothe, Nucl. Instr. Meth. A 611 (2009)
4. I. Mazumdar, G. Anil Kumar, Gothe, Manchanda, Nucl. Instr. Meth. (2010)
5. I. Mazumdar, Gothe, Chavan, Yadav, G. Anil Kumar, Nucl. Instr. 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)
8. R. Sariyal, I. Mazumdar et al J. Instr. (2021) 11) Ranga, Mazumdar, et al NIMA (2024)
9. S. Panwar, I. Mazumdar et al., NIM-A (2020) 12) Ranga, Mazumdar et al NIMA (2022)
10. R. Sariyal, I. Mazumdar et al. J. Instr. (2021) 13) A. Srivastava et al NIM-A (2023)



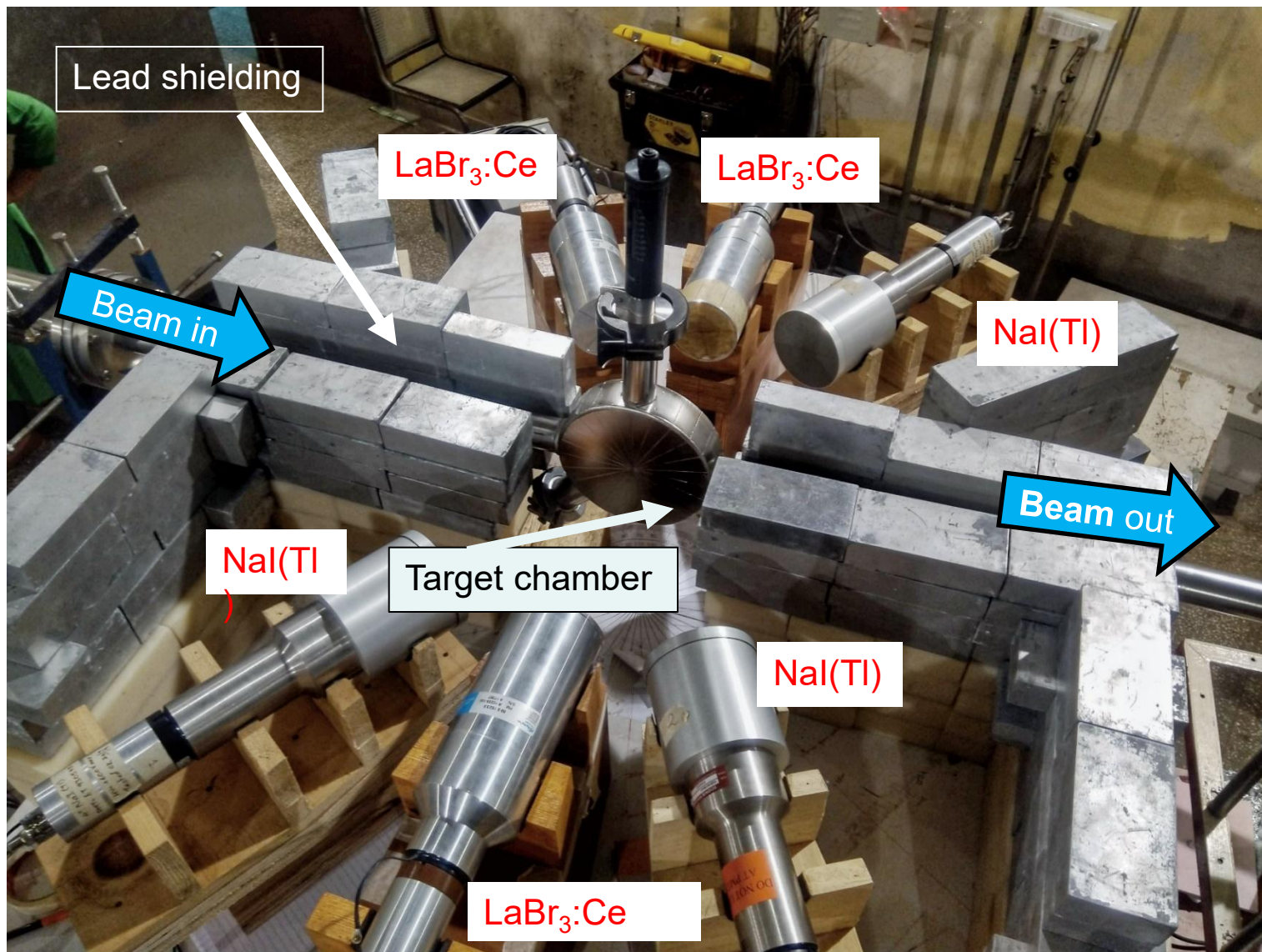
First measurement of 22.5 MeV γ -rays using
 Large $\text{LaBr}_3:\text{Ce}$, $E_p = 7.2$ MeV
Mazumdar et al. Nucl. Instr. Meth. A (2013)



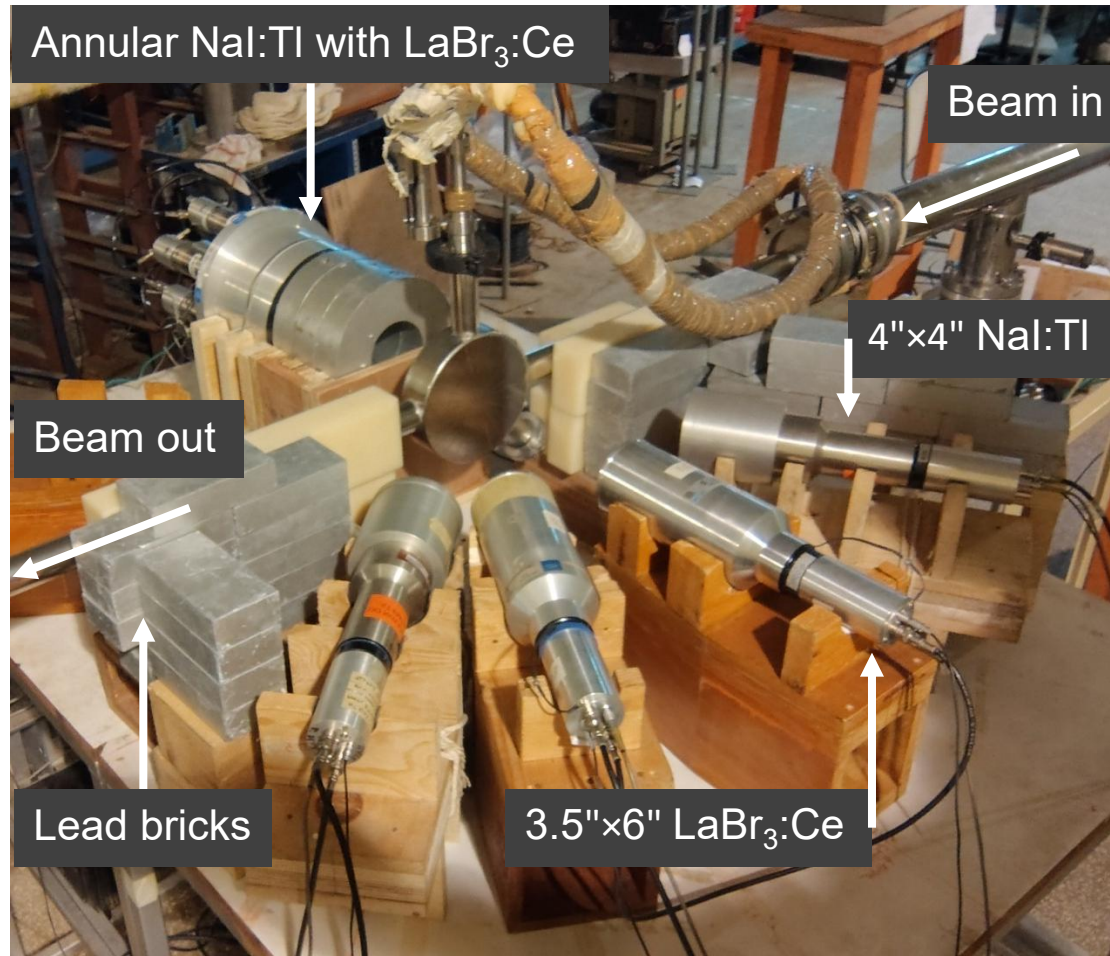
Taming the non-linearity up to 22.5 MeV



Typical Experimental Setup for $(p, p'\gamma)$

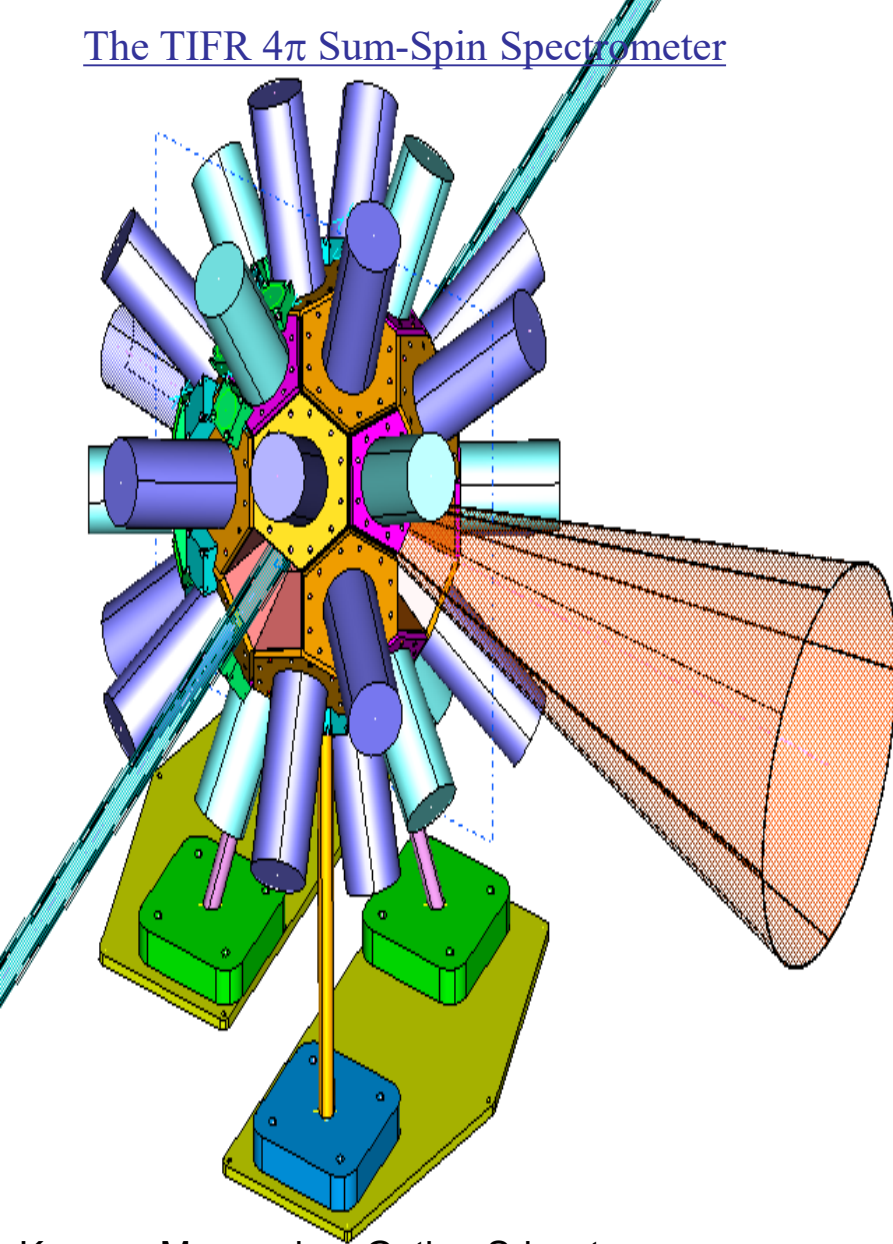


Experimental Setup (TIFR Pelletron)



Target: Self supporting CD₂ 1.38 mg cm⁻³(Prepared by: John Green, Argonne National Lab)
Beam: 4, 5 MeV (FOTIA), 8-20 MeV(TIFR)
Detectors: Two 3.5"x6" LaBr₃:Ce, two 4"x4" NaI:TI, One 3.5"x6" LaBr₃:Ce inside Annular NaI:TI

The TIFR 4π Sum-Spin Spectrometer

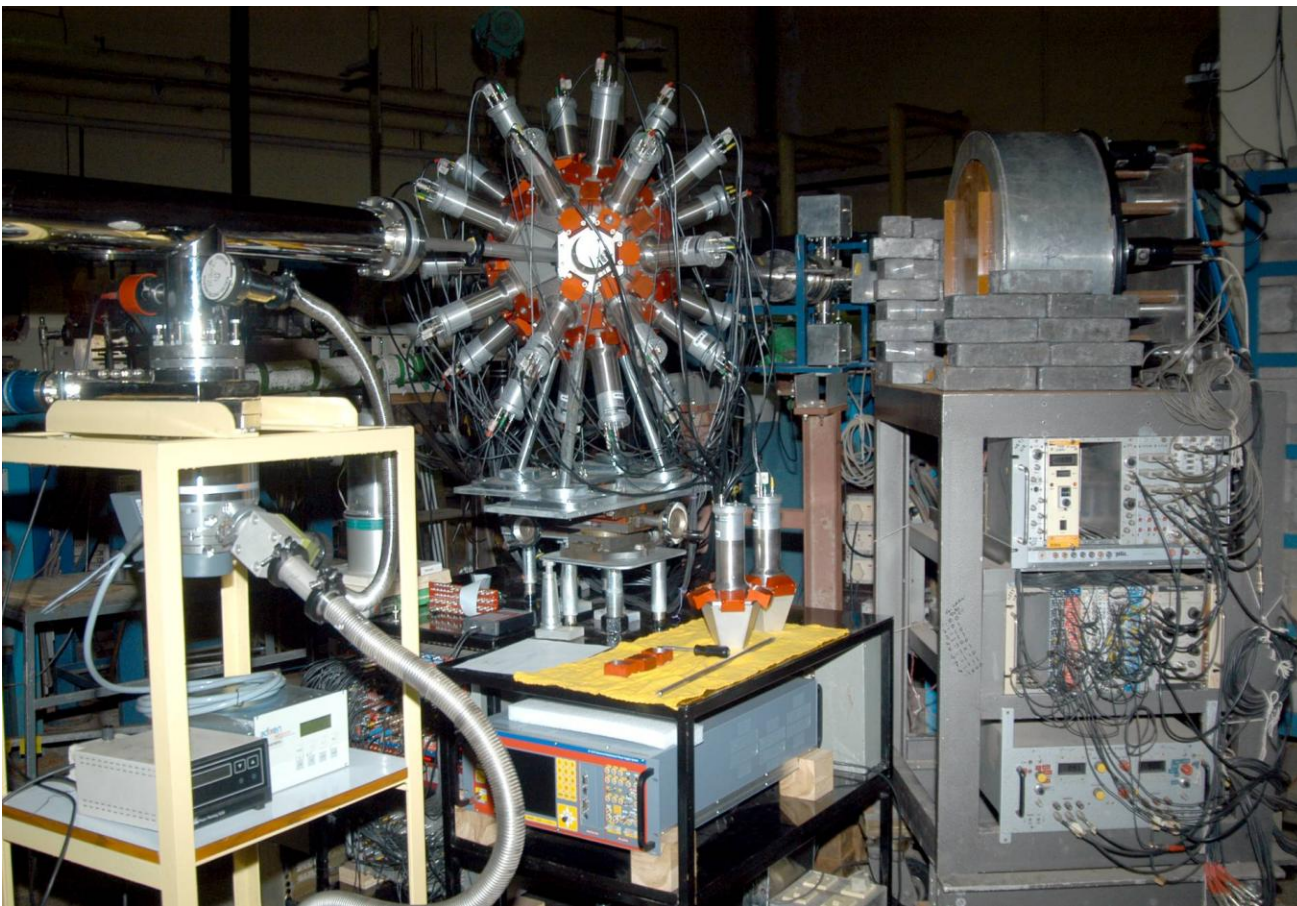


Kumar , Mazumdar, Gothe, Srivastava
Nucl. Instr. Meth. A 611 (2009)
Nucl. Instr. Meth. A 609 (2009)
Nucl. Instr. Meth. A (2023)

32 Conical NaI(Tl) detectors.
12 Pentagonal & 20 Hexagonal



TIFR 4π Sum-Spin Spectrometer



- *Nucl. Phys. A* 890, 62 (2012)
- *EPJ Web of Sc.*(2011,2013)
- *Phys Rev. C* 88 024312 (2013)
- *Phys Rev C* 88 034606 (2013)
- *Jour. Phys. G* 41 (2014)
- *Phys. Rev. C* 95 (2017)
- *Phys. Rev. C* 96 (2017)
- *Phys. Rev. C* 99 (2019)
- *Phys Rev C.* 101 ,(2020)
- *Phys Rev C* (2024)
- *Phys. Lett B* under review)
- *Phys Rev C* (under review)

Kumar , Mazumdar, Gothe, Srivastava
Nucl. Instr. Meth. A 611 (2009)
Nucl. Instr. Meth. A 609 (2009)
Nucl. Instr. Meth. A (2023)

Theoretical Analysis:

- 1) Macroscopic Phenomenological Analysis: The OM Framework, Weppner et al, PRC80 (2009)
- 2) Semi-microscopic Folding Model Analysis: L. Trache et al., PRC 61, 024612 (2000)
- 3) Microscopic Optical Potentials: M. vorabbi et al., PRL 135, 172501 (2025)

Part III

Inelastic Scattering of Light Ions

$(p, p'\gamma)$ & $(\alpha, \alpha'\gamma)$ reactions

- The measurements of $(p, p' \gamma)$ cross sections are important for both fundamental and applied nuclear physics

Nuclear Structure:

- Is the state excited in collective mode or SP excitation?
- Role of α -particle clustering (Physics of Hoyle State)
- Influence of GR states in ^{12}C and ^{16}O and energy levels of ^{13}N and ^{17}F in the analysis
- No OM theory that explains the states (4.43, 9.64, 12.71, 15.1 MeV) in low energy region
- Lowest energy discussed in literature for microscopic p -nucleus collision is 40 MeV [1]
- Microscopic p -nucleus theories have been successful only for elastic channels [2,3,4]
- OM works well in higher energy but not in lower energy

(Validation of optical model parameters over wide range of energy is required)

- [1] Amos, Dortmans, von Geramb, Karataglidis: Adv. Nucl Phys. 2002
- [2] Jeukenne, Lejeune, Mahaux: Phys. Rep. 25 (1976)
- [3] Brieva, Rook: Nucl. Phys. A 291 (1977)
- [4] Peter, Islam, Finlay, Dietrich: Phys. Rev. C 32 (1985); Kato et al. Phys. Rev. C 1616 (1985)

Motivation Continues

The Experimental scenario:

Considerable data on 4.43 MeV state (very well studied, both p, p' and $p, p' \gamma$)

- Very little data for the $(p, p' \gamma)$ cross section measurements for 12.71, 15.1 MeV
- No data on 9.64 MeV state
- *Inelastic proton scattering at 30 - 40 MeV from ^{12}C*

R. De Leo et al., Phys. Rev. C28 (1983) 1443

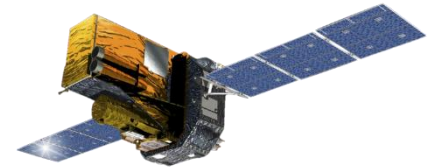
A) Nuclear Astrophysics:

Occurrence of γ -ray lines (4.43, 15.1 MeV) from solar flares

may provide information on acceleration mechanism,

interaction of charged particles (protons, ions) with solar flares,
abundance of elements, temperature, density etc.

flux ratio $f_{15.1}/f_{4.43}$ is important relative abundance of ^{12}C and ^{16}O



Satellite based γ – ray astronomy : RHESSI & INTEGRAL observed prominent nuclear lines of 2.2, 4,4, 6,1 MeV with good statistics in Oct – Nov 2003,

J. Kiener et al 2006

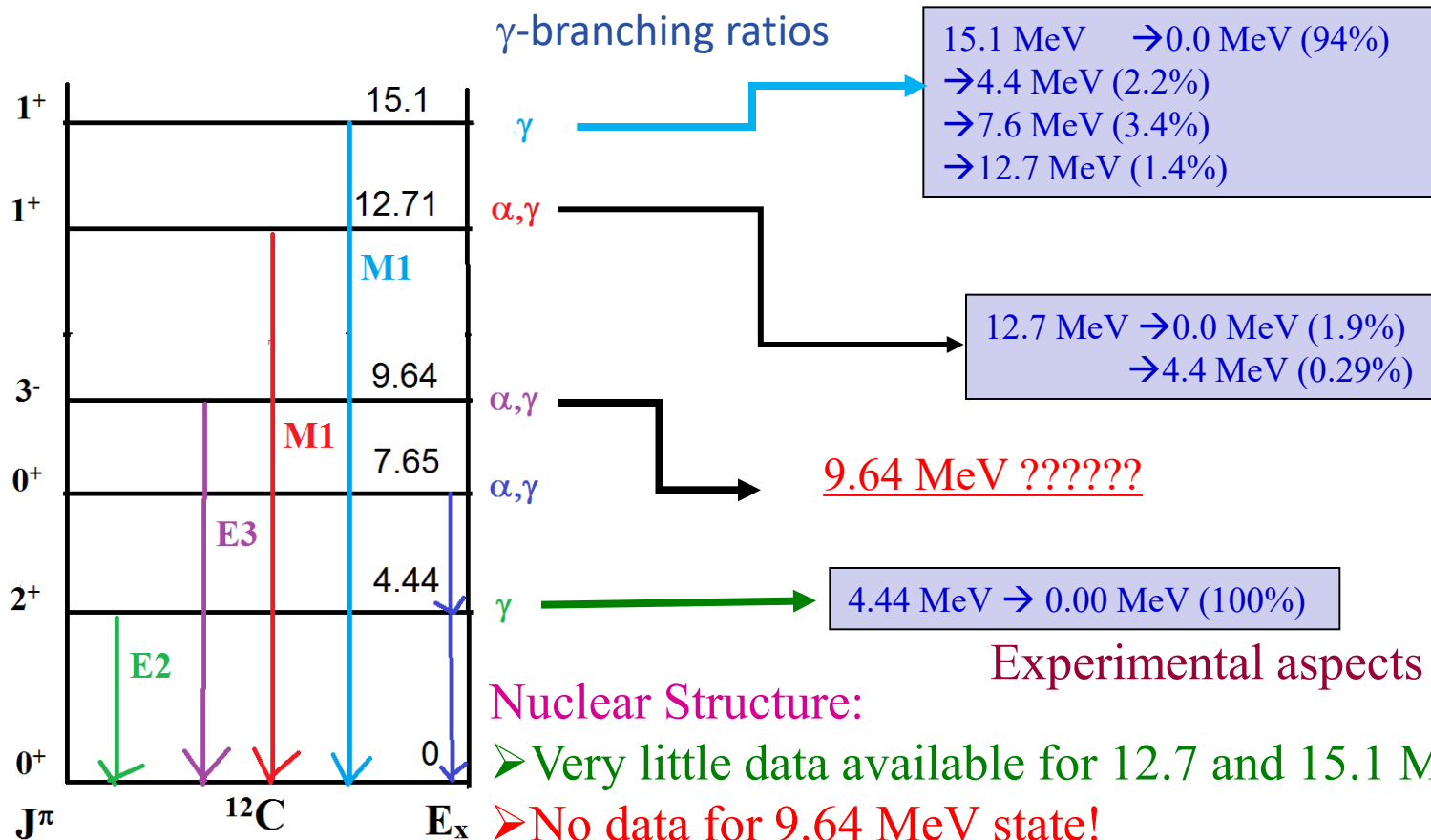
Lang et al. Phys. Rev. C 35,1214 (1987); Kiener et al. Phys. Rev. C 58, 2174 (1998);

Chupp et al., Astr. Phys. Jour. 318, 913, (1987); Murphy et al., Astr. Phys. Jour.331,(1988)

Belhout et al 2007, P. Dyer et al 1985

Ramaty et al. APJ 229 (1979), Murphy et al APJ Supp. Series 215, 2014

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



^{12}C energy level diagram

Experimental Details

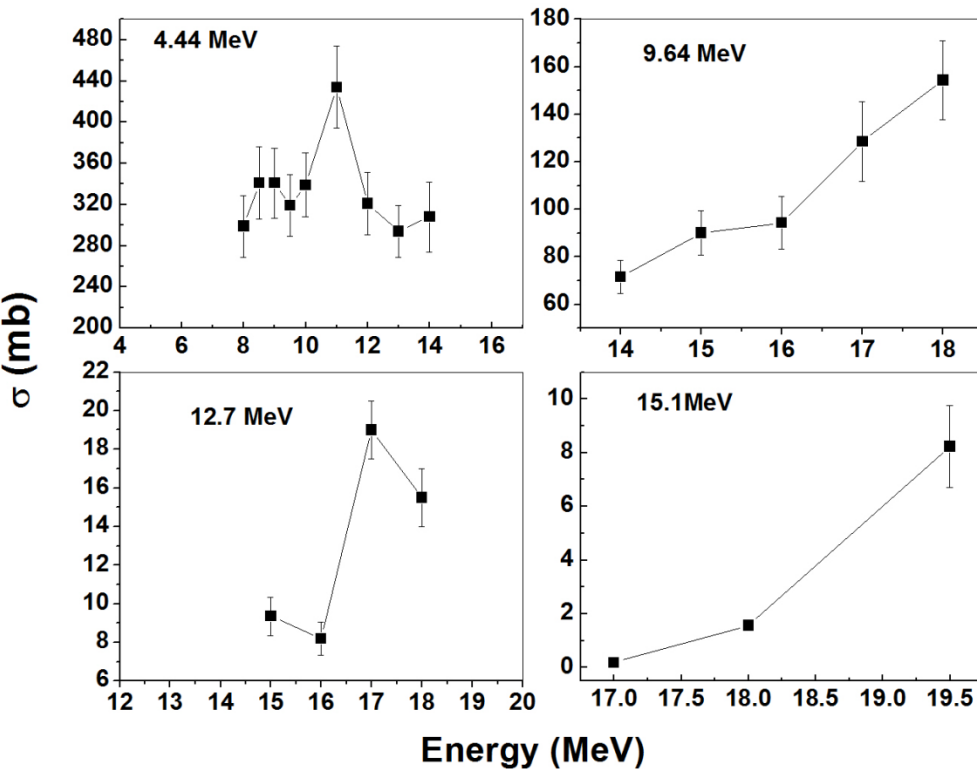
- Accelerator facility- Pelletron, TIFR, Mumbai
- Proton Beam Energy $E_p = 8 \text{ MeV to } 22 \text{ MeV}$
- Current: 7-8 nA
- Target: Carbon 1.34 g/cm³
- Detector facility- 3.5 m
- 1. Cylindrical LaBr₃ (-4)
- 2. Square bars of LaBr₃
- Angles: 45°, 60°, 75°, 135°

130 Data Points

State (MeV)	Beam Energy (MeV)	Angle(θ)
4.44	8	60°, 75°, 90°, 105°, 120°, 135°
	8.5	60°, 75°, 90°, 105°, 120°, 135°
	9	60°, 75°, 90°, 105°, 120°, 135°
	9.5	60°, 75°, 90°, 105°, 120°, 135°
	10	60°, 75°, 90°, 105°, 120°, 135°
	11	60°, 75°, 90°, 105°, 120°, 135°
9.64	12	60°, 75°, 90°, 105°, 120°, 135°
	13	60°, 75°, 90°, 105°, 120°, 135°
	14	60°, 75°, 90°, 105°, 120°, 135°
	14	60°, 75°, 90°, 105°, 120°, 135°
	15	60°, 75°, 90°, 105°, 120°, 135°
	16	60°, 75°, 90°, 105°, 120°, 135°
12.7	17	60°, 75°, 90°, 105°, 120°, 135°
	18	60°, 75°, 90°, 105°, 120°, 135°
	15	60°, 75°, 90°, 105°, 120°, 135°
	16	60°, 75°, 90°, 105°, 120°, 135°
	17	60°, 75°, 90°, 105°, 120°, 135°
	18	60°, 75°, 90°, 105°, 120°, 135°
15.1	17	60°, 75°, 90°, 105°, 120°, 135°
	18	60°, 75°, 90°, 105°, 120°, 135°
	19.5	60°, 75°, 90°, 105°, 120°, 135°
	20	90°
	21	90°
	21.5	90°
	22	90°



Total γ -Cross sections and Branching ratios



Energy Level (MeV)	14 MeV	18 MeV	19.5 MeV
9.64	$.0035 \pm .0003$		
12.7		$0.021 \pm .0025$	
15.1			0.79 ± 0.19

$$\text{Branching Ratios} = \sigma_{\gamma} / \sigma_{pp}'$$

9.64 MeV σ_{pp}' 70 mb $\pm$ 0.2

HARADA *et al.*, Journal of Nuclear Science and Technology, 36(4), 313, 1999.

12.7 MeV σ_{pp}' 15 mb $\pm$ 1.1

Daehnick *et al.*, Phys. Rev., 133, B934, Feb 1964.

15.1 MeV σ_{pp}' 8.3 mb $\pm$ 1.2

Warburton *et al.*, Phys.Rev.128, 4, 1962.

- Mazumdar *et al.* Act. Phys. Pol B,(2019)
- Mazumdar, Asro Particle Physics (2020)

Optical Model Analysis:

The principal Stages:

The depths of the central and surface optical potential (real and imaginary terms) obtained from the fittings are as follows,

$$V_0 = -60.37 + \frac{9.059(E - 5.000)^4}{(E - 5.000)^4 + 4.000^4}$$

$$W_0 = -0.410 + \frac{0.293(E - 20.00)^4}{(E - 20.00)^4 + 4.000^4}$$

$$V_s = 6.342 - \frac{4.254(E - 8.248)^6}{(E - 8.248)^6 + 4.255^6}$$

$$W_s = 6.336 - \frac{7.324(E - 20.00)^4}{(E - 20.00)^4 + 10.085^4}$$

where the subscript 0 refers to the central potential and is multiplied by a Woods-Saxon function

$$f(r) = \frac{1}{1 + \exp((r - r_0 \times A^{\frac{1}{3}})/a_0)}$$

The radii r and the diffusive parameters a of the central and surface terms are given the same structural form

$$r_0 = 1.163 - \frac{0.115(E - 20.00)^4}{(E - 20.00)^4 + 8.939^4}$$

$$a_0 = 0.5496 + \frac{0.08252(E - 5.000)^4}{(E - 5.000)^4 + 10.4558^4}$$

$$r_s = 1.429 - \frac{0.03529(E - 18.734)^4}{(E - 18.734)^4 + 9.744^4}$$

$$a_s = 0.358$$

Next are the energy-dependent equations for the real and imaginary spin-orbit depths

$$V_{so} = 5.603 + \frac{1.286(E - 11.090)^4}{(E - 11.090)^4 + 4.000^4}$$

$$W_{so} = -0.02447 - \frac{1.3757(E - 10.366)^4}{(E - 10.366)^4 + 4.7934^4}$$

and their respective radii and diffusion parameters

$$r_{so} = 0.9815 - \frac{28.39(E - 9.893)^4}{(E - 9.893)^4 + 30.00^4}$$

$$a_{so} = 0.4596 - \frac{0.1230(E - 17.068)^4}{(E - 17.068)^4 + 6.056^4}$$

Next are the energy-dependent equations for the real and imaginary spin-orbit depths

$$V_{so} = 8.67746 - \frac{1.95582(E - 17.777)^4}{(E - 17.777)^4 + 3.000^4} + \sum_i^{res.} \frac{\mathcal{A}_{soi}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i^6}$$

$$W_{so} = -0.01782 - \frac{1.3537(E - 10.381)^4}{(E - 10.381)^4 + 4.707^4}$$

and their respective radii and diffusion parameters

$$r_{so} = 0.5538 + \frac{0.31743(E - 20.442)^4}{(E - 20.442)^4 + 3.00^4} + \sum_i^{res.} \frac{\mathcal{R}_{soi}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i^6}$$

$$a_{so} = 0.3440 + \frac{0.11343(E - 6.8494)^4}{(E - 6.8494)^4 + 4.344^4}.$$

The coulomb radius is where the structure of the coulomb interaction changes from short-range to long range

$$r_c = 1.490 + \frac{0.170(E - 5.000)^4}{(E - 5.000)^4 + 4.000^4}$$

Effect of Target Deformation

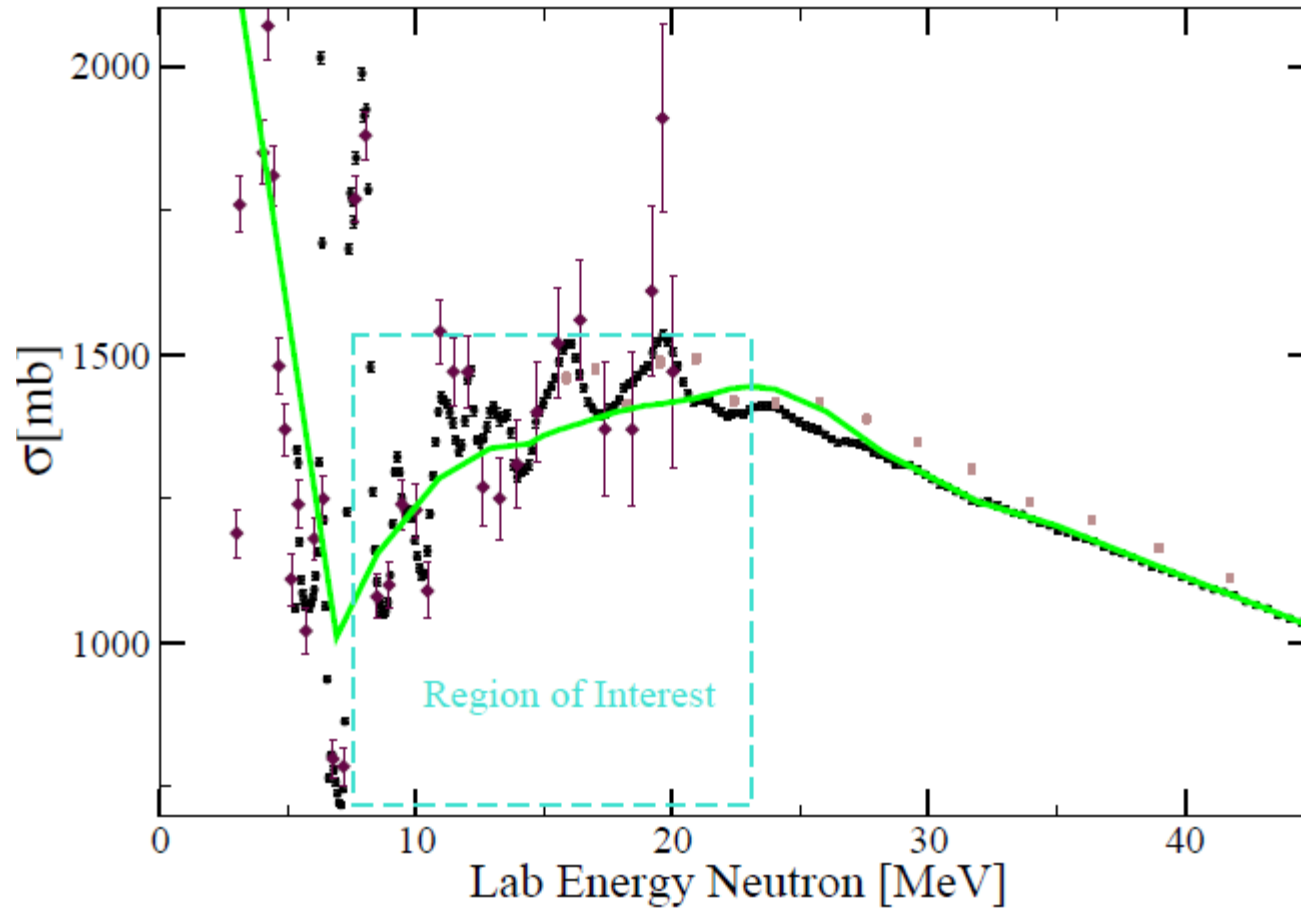
Expanding the radius, assuming a series of deformations

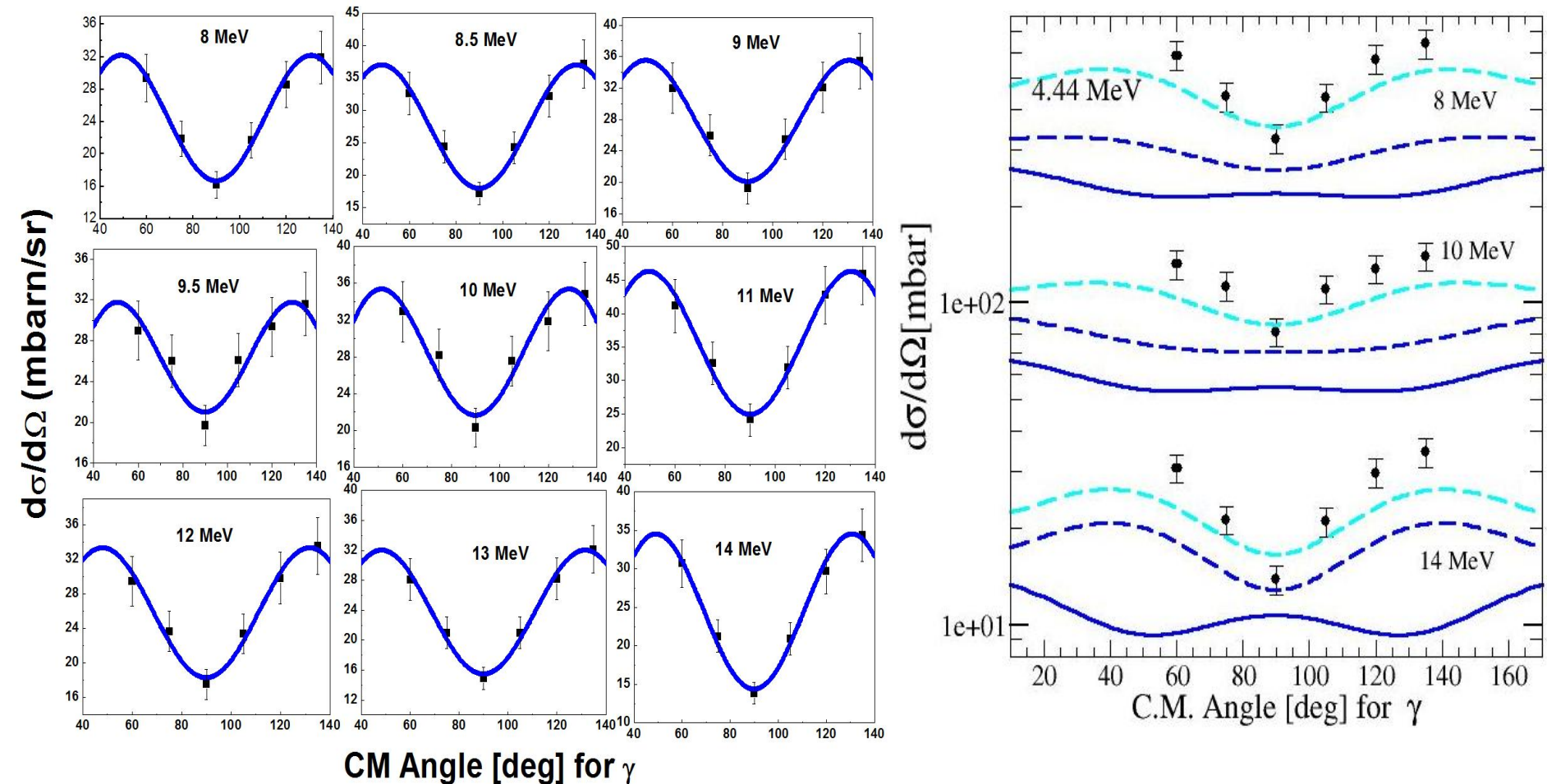
$$R(\theta) = R_0 \left[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta) + \beta_6 2Y_6^0(\theta) + \dots \right],$$

where the β_i 's are deformation parameters.

One can then expand the potential in a Taylor series to first order as:

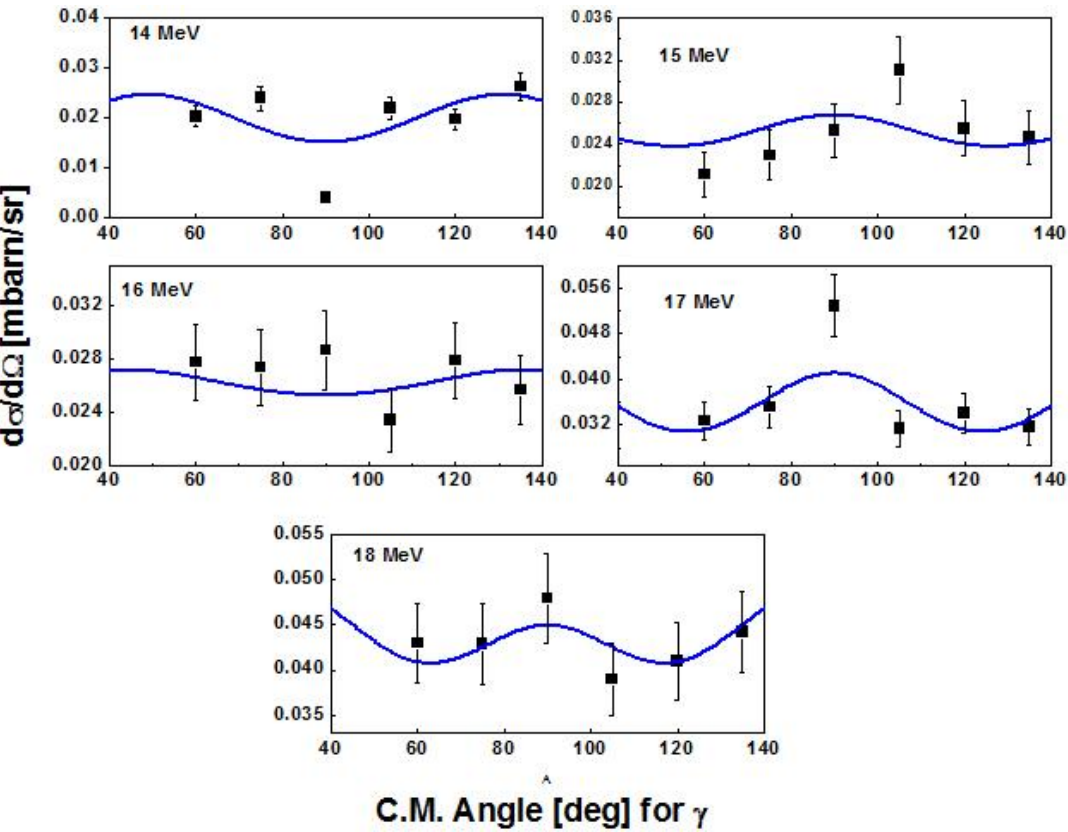
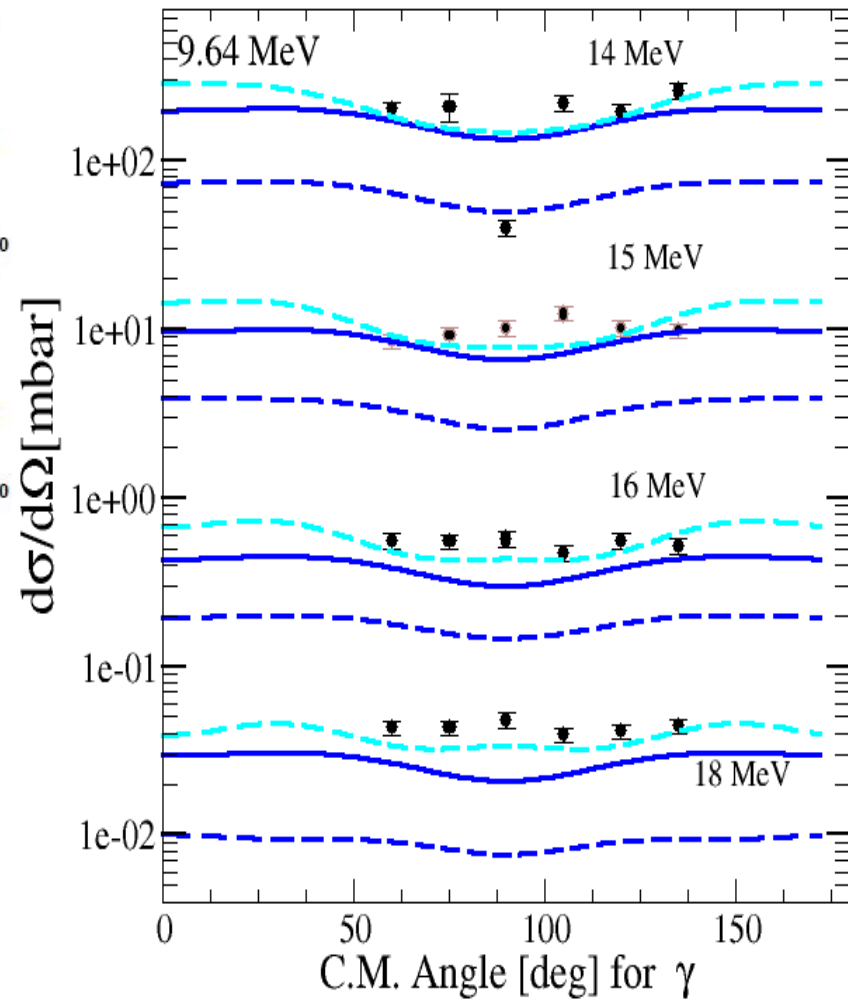
$$V(r, R) = V(r, R_0) + \frac{d}{dR_0} V(r, R_0) R_0 \sum_{\lambda, \mu} \alpha_\lambda^\mu Y_\lambda^\mu(\theta, \phi)$$



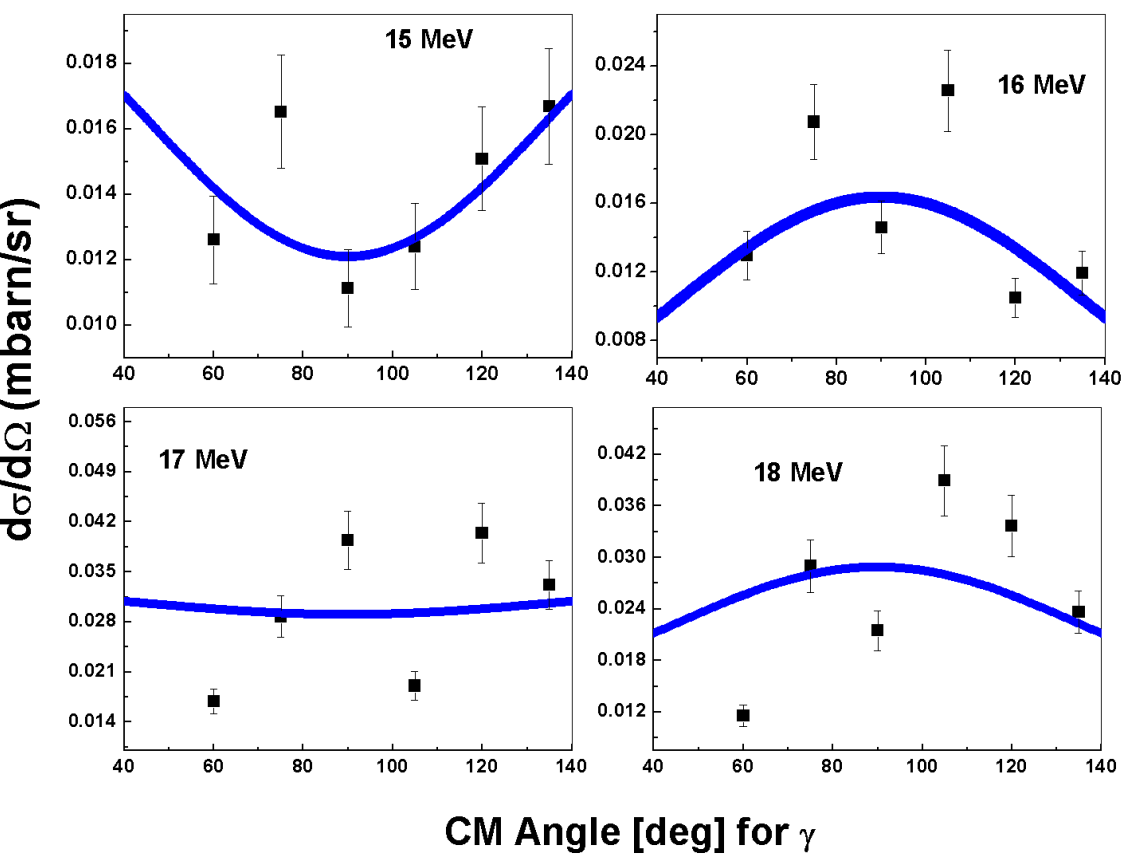
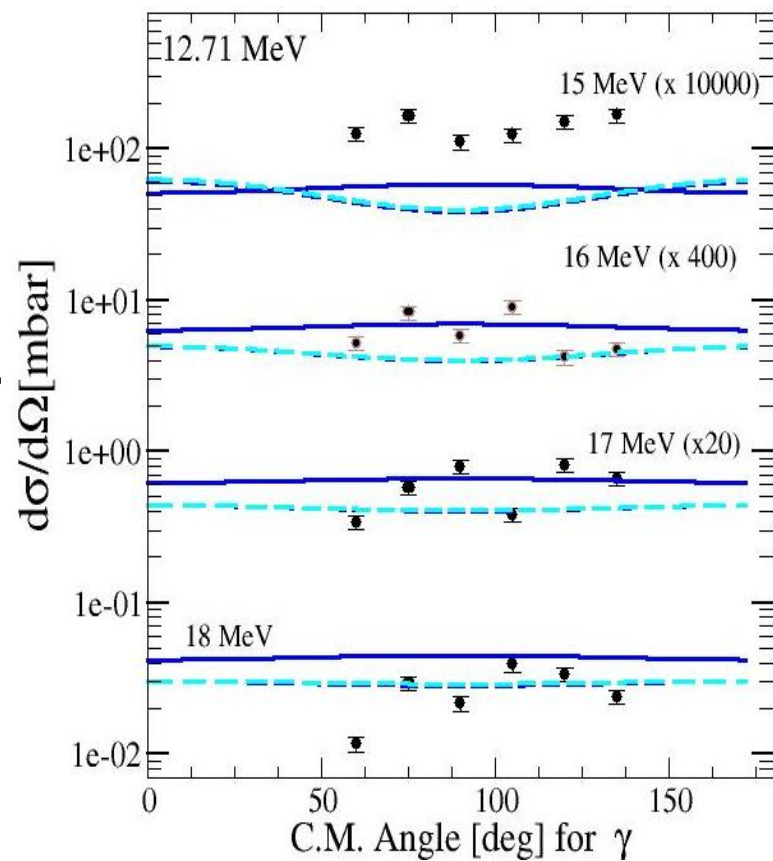


Solid blue line – Optical model without resonance
 Dashed blue line- Optical model with resonance
 Dashed light blue line- Optical model with resonances
 along with 2^+ Hoyle state resonance

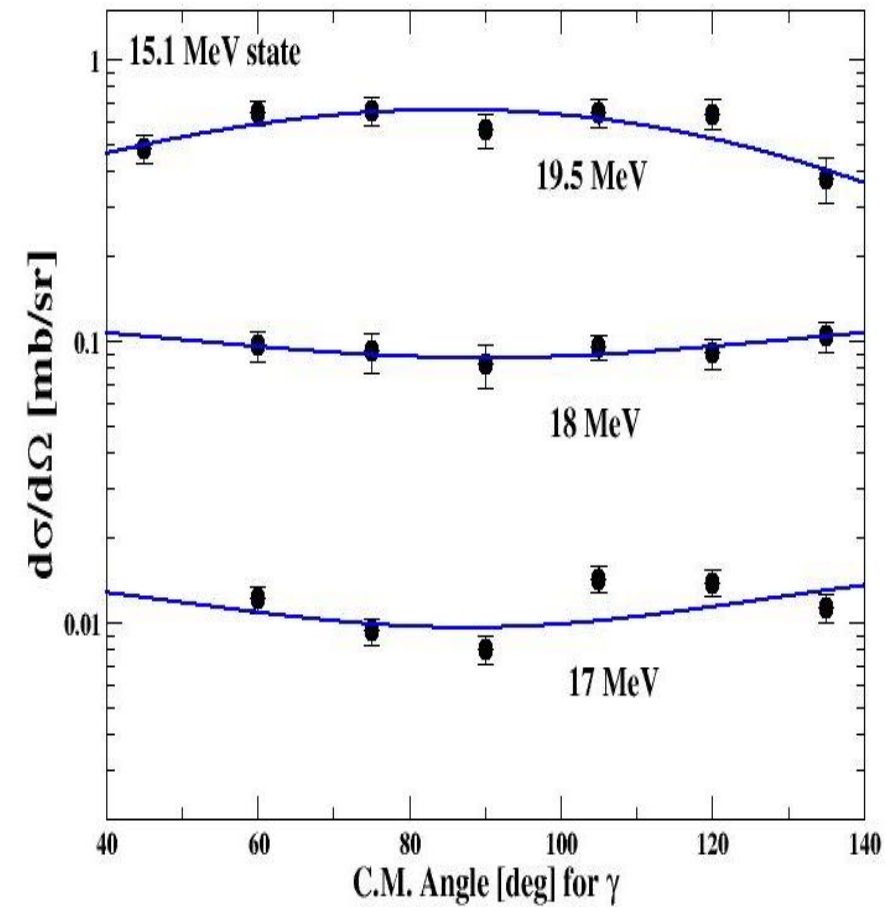
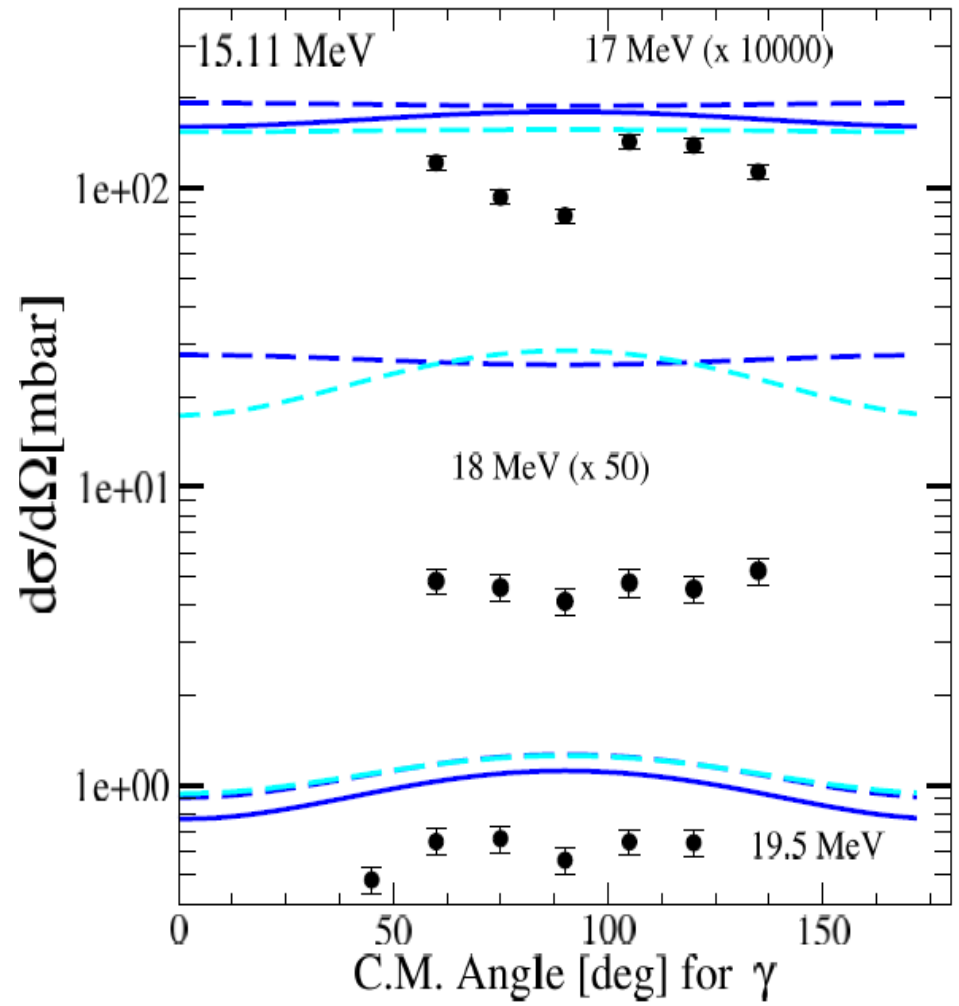
9.64 MeV State



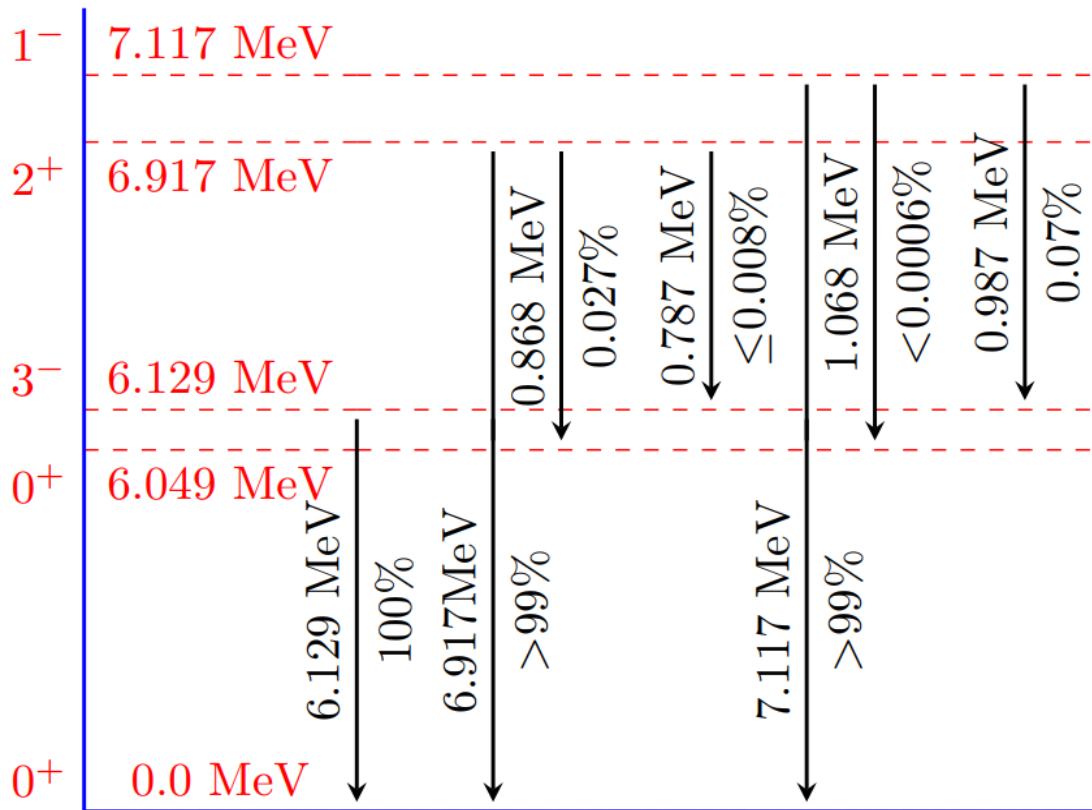
12.71 MeV State



15.1 MeV State



$^{16}\text{O}(p, p' \gamma)^{16}\text{O}$



Channels coupled	
Energy	J^π
6.13	3^-
6.92	2^+
7.12	1^-
8.87	2^-
10.35	4^+

Existing data prior to our measurements:

- 1) P Dyer et al., 1981
Absolute cross section of 6.13 MeV
- 2) M. Boromiza et al., 2020
6.13 and 7.12 MeV
Very thick target (energy averaged cross sections)
- 3) J. Kiener et al., 1998
Normalised to Dyer

Our Measurements: (With $\text{LaBr}_3:\text{Ce}$)

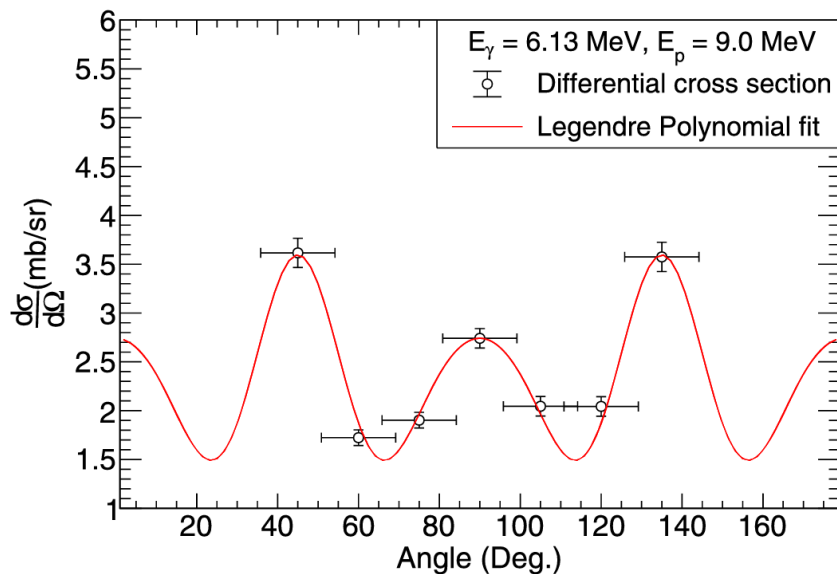
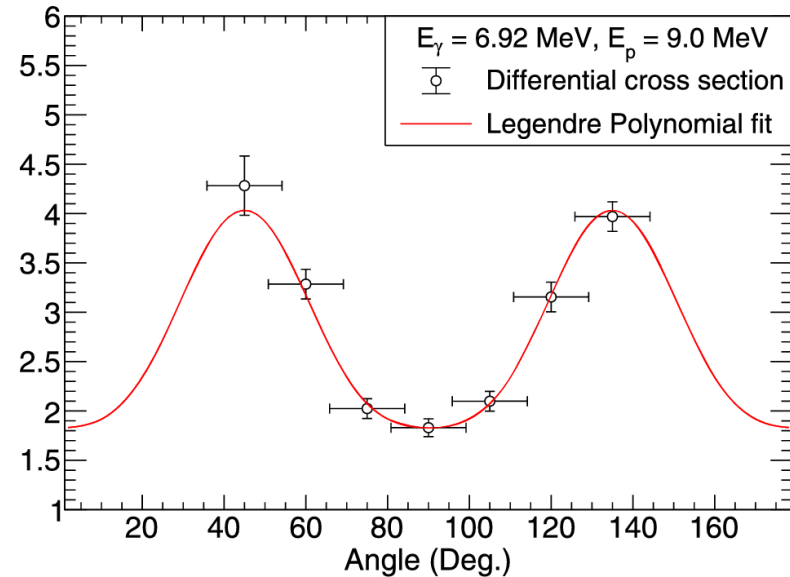
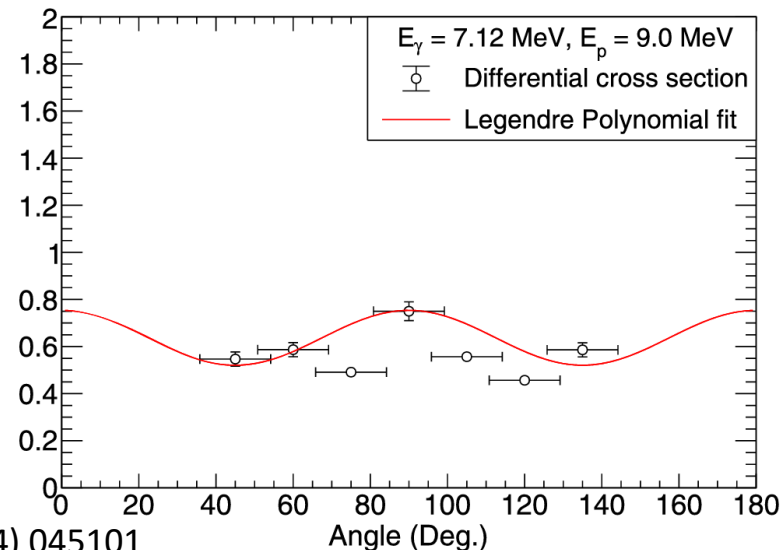
- 8 to 16 MeV
- Angular distribution at 9 MeV

Angular distributions

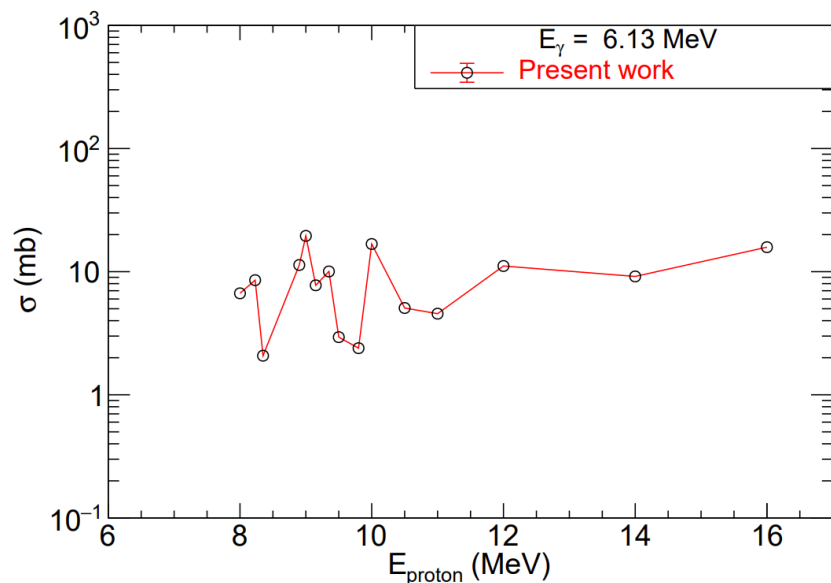
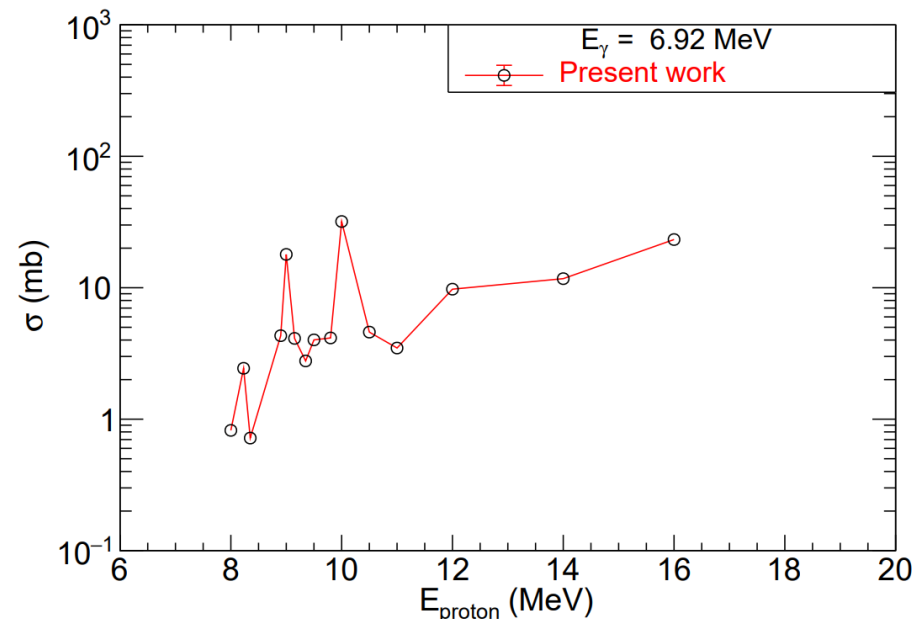
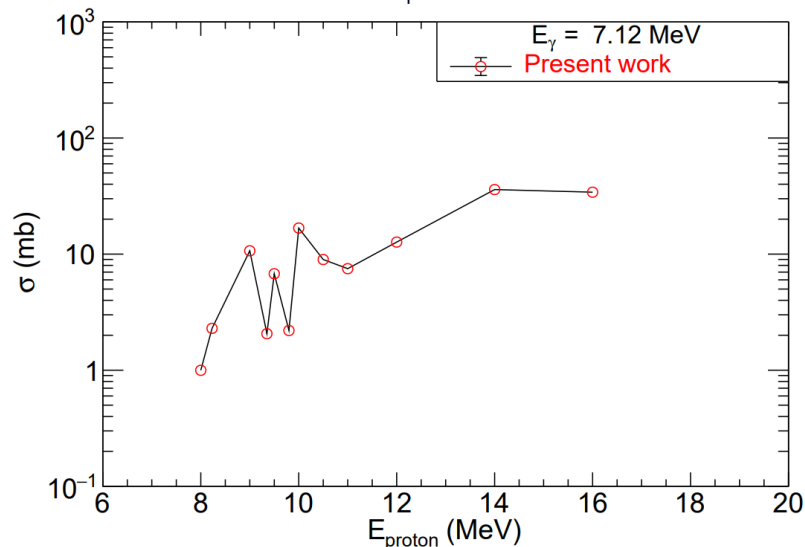
- Angular distribution measured for 7 angles at 9 MeV
- Angular distributions were fitted with a series of Legendre polynomials

$$W(\theta) = \sum_{l=0}^{l=l_{max}} a_l P_l(\cos \theta) (l = \text{even})$$

$$\sigma = 4\pi a_0$$



Our Measurements of Cross-section



- First measurements of absolute cross-section of 6.92 and 7.12 MeV transition
- A lot of structure is there at the lower proton energies
- **Reproducing the structure is the challenge**

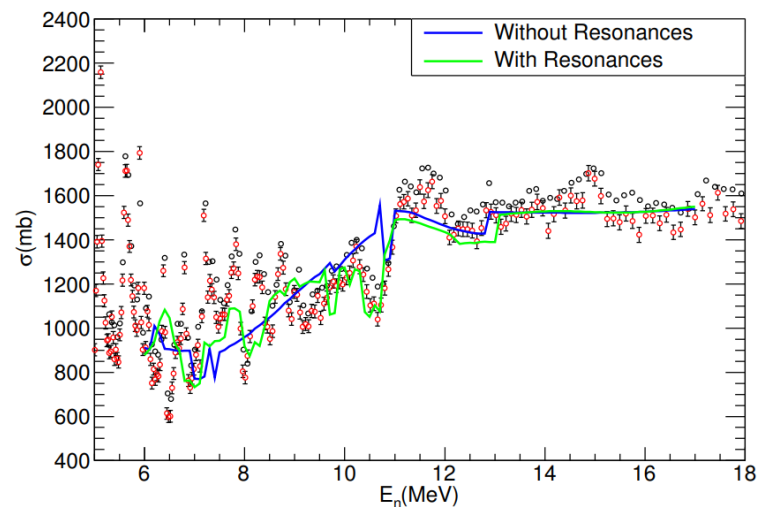
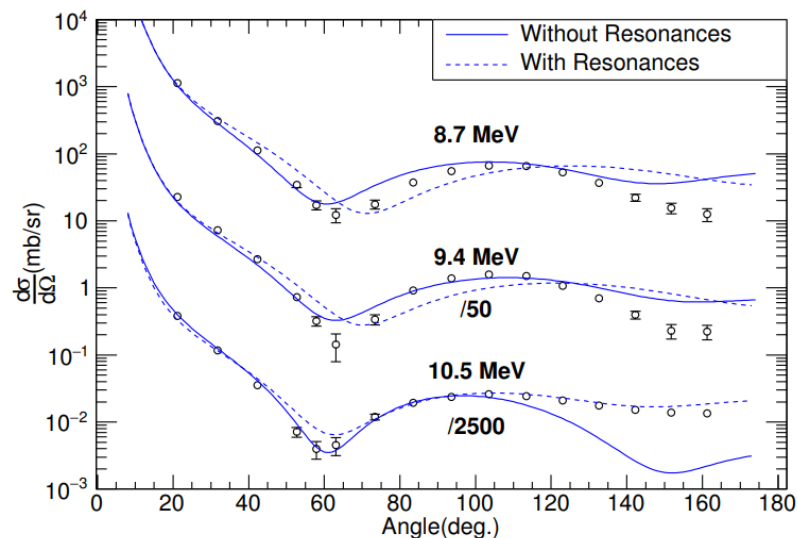
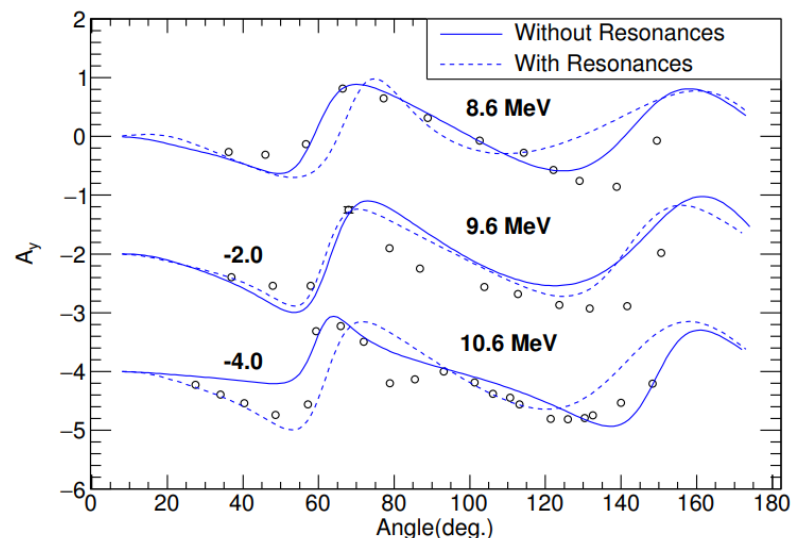
Ranga, Mazumdar *et al.*,
Journal of Physics G: Nucl. Part. Phys. 51 (2024) 045101

Theoretical analysis of $^{16}\text{O}(p,p')^{16}\text{O}$ data

STEP 1:

All elastic scattering data from 5-20 MeV for

- $^{16}\text{O}(p, p), ^{16}\text{O}(n, n)$
- 1000 different data points were used in fitting
- Data taken from EXFOR



Theoretical analysis of $^{16}\text{O}(p,p'\gamma)^{16}\text{O}$ data

STEP 3: Inclusion of Resonances

Resonances included	
Energy(MeV)	Width
5.67	0.32
6.99	0.21
7.81	0.20
8.24	0.20
9.84	0.30
10.55	0.20
12.44	0.20

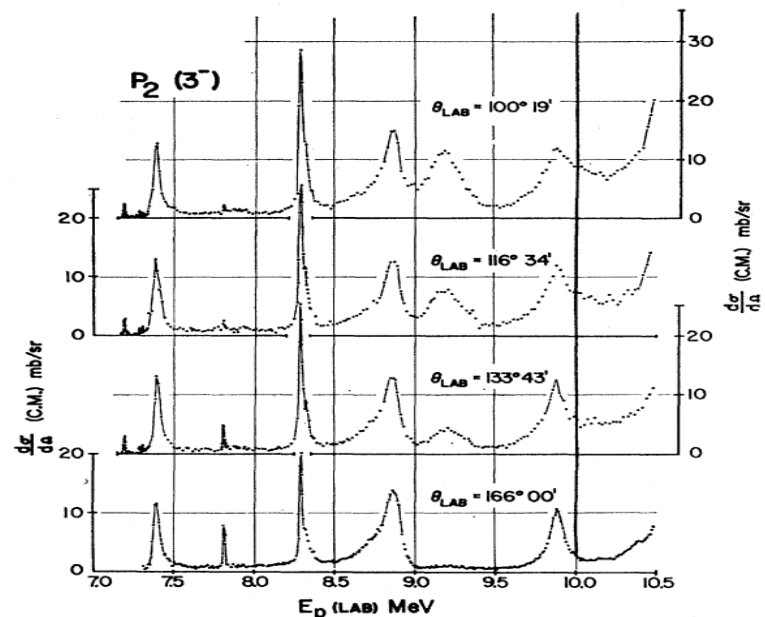
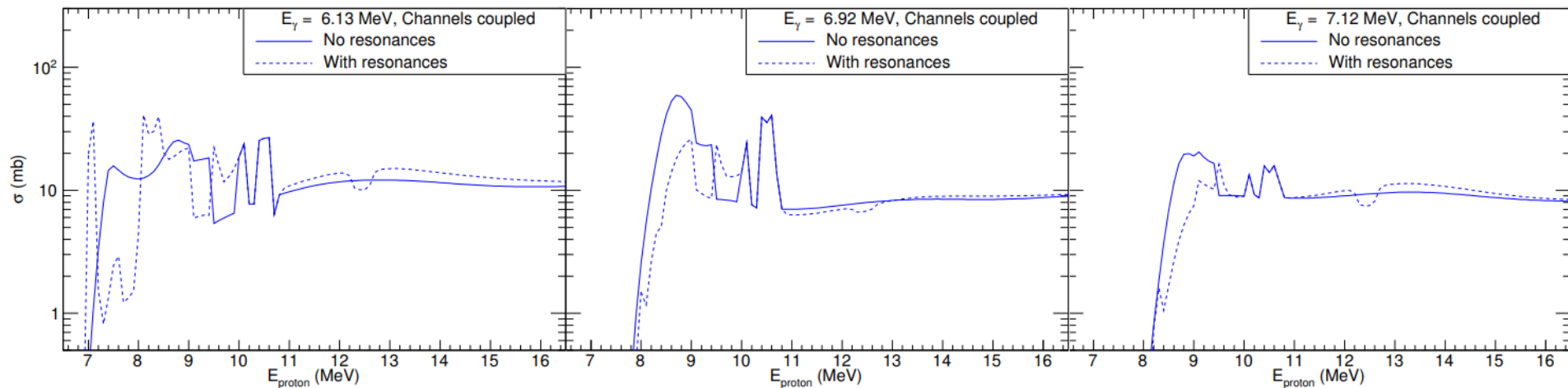


FIG. 3. Excitation curves for protons leaving O^{16} in its second excited state.



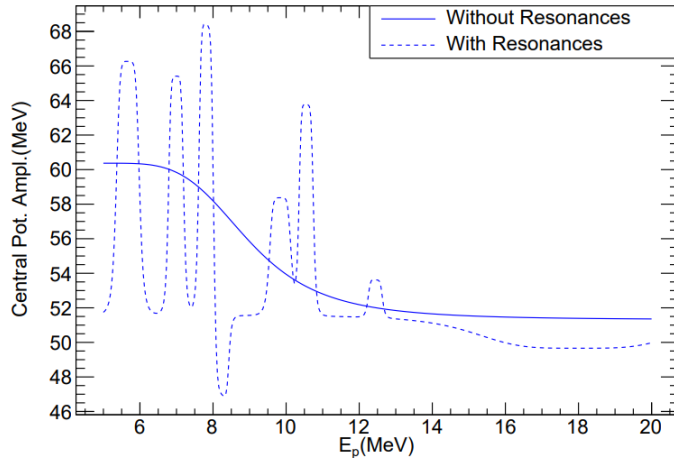
Inclusion of resonances

$$V_0 = -111.533 - \frac{1.9125(E - 18.000)^4}{(E - 18.000)^4 + 3.000^4} + \sum_i^{res.} \frac{\mathcal{A}_{0i}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i}$$

$$W_0 = -0.416 + \frac{0.2965(E - 18.934)^4}{(E - 18.934)^4 + 3.1487^4}$$

$$V_s = 6.4697 - \frac{4.6311(E - 8.4178)^4}{(E - 8.4178)^4 + 4.1768^4}$$

$$W_s = 2.3981 - \frac{5.8619(E - 22.00)^4}{(E - 22.00)^4 + 10.3884^4} + \sum_i^{res.} \frac{\mathcal{A}_{si}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i}$$



$$r_0 = 0.6748 - \frac{0.055231(E - 17.7335)^4}{(E - 17.7335)^4 + 3.6787^4} + \sum_i^{res.} \frac{\mathcal{R}_{0i}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i}$$

$$a_0 = 0.5431 + \frac{0.196843(E - 5.000)^4}{(E - 5.000)^4 + 16.1121^4}$$

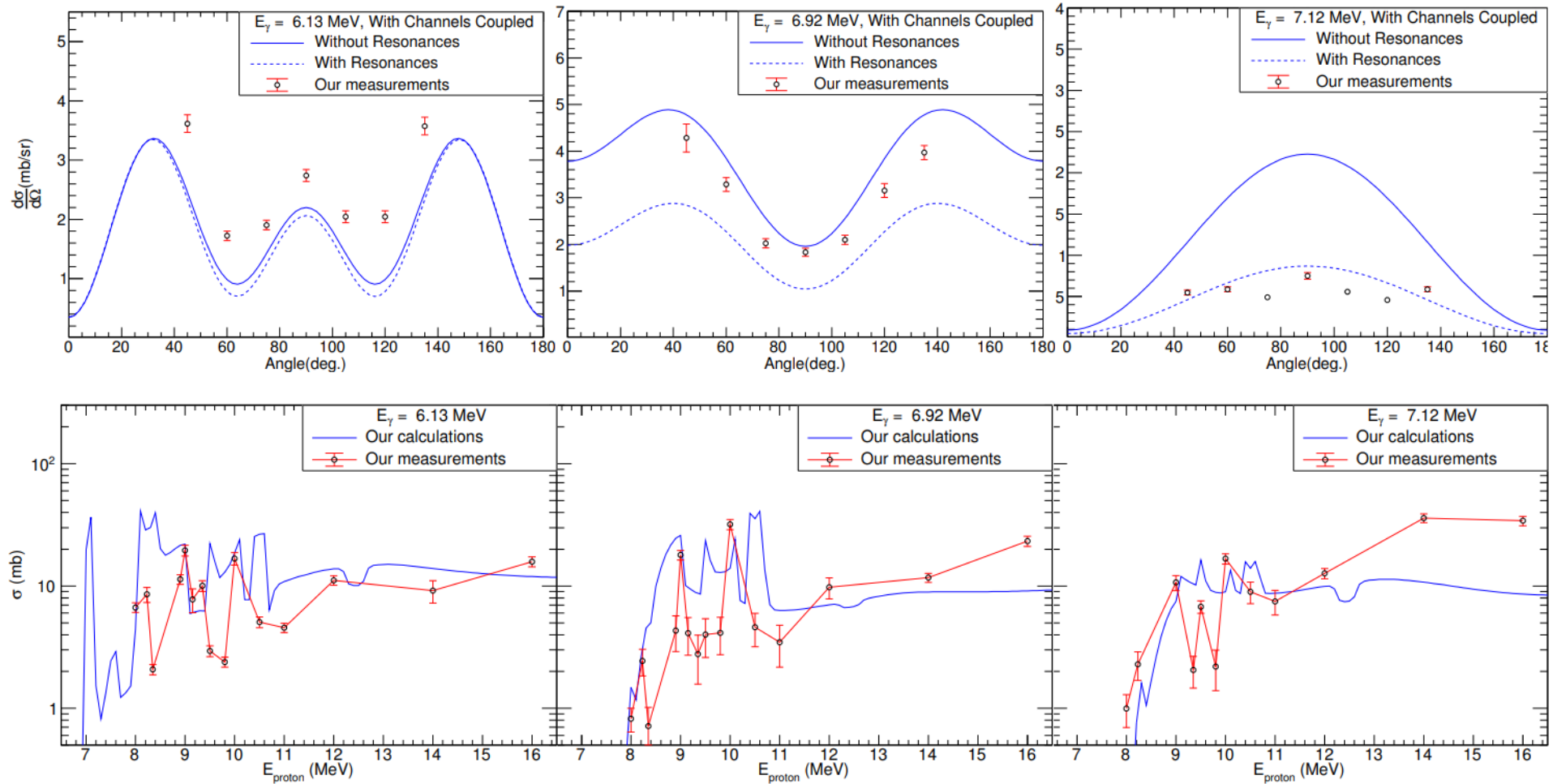
$$r_s = 1.7125 - \frac{0.083141(E - 16.17)^4}{(E - 16.17)^4 + 3.000^4} + \sum_i^{res.} \frac{\mathcal{R}_{si}(E - E_i)^6}{(E - E_i)^6 + \mathcal{W}_i}$$

$$a_s = 0.38018 - \frac{0.04292(E - 21.692)^4}{(E - 21.692)^4 + 3.038^4}$$

The seven resonances used with their term dependent amplitudes.

$Res.$	$E_i[MeV]$	$\mathcal{W}_i[MeV]$	$\mathcal{A}_{0i}[MeV]$	$\mathcal{A}_{si}[MeV]$	$\mathcal{A}_{soi}[MeV\ fm^2]$	$\mathcal{R}_{0i}[fm]$	$\mathcal{R}_{si}[fm]$	$\mathcal{R}_{soi}[fm]$
1	5.67	0.32	14.694	1.533	-2.735	0.0368	-0.0869	0.0309
2	6.99	0.21	13.838	2.015	-1.049	0.106	-0.0625	-0.0690
3	7.81	0.20	16.870	-0.735	0.413	0.184	-0.0514	0.0566
4	8.24	0.20	-4.747	1.384	0.451	-0.0735	0.0112	0.181
5	9.84	0.30	6.825	0.522	0.977	0.104	-0.0457	0.0397
6	10.55	0.20	12.20	0.880	0.840	0.140	0.00620	-0.0400
7	12.44	0.20	2.191	-1.452	-0.264	0.0142	-0.0448	-0.0771

Comparison with Our Theoretical Calculations



- Overall agreement between our measured data and our theoretical calculations
- Differences in finer structure can be attributed to intricate interplay among channel coupling, resonances and deformation.
- Ranga, Mazumdar *et al.*, Journal of Physics G: Nucl. Part. Phys. 51 (2024) 045101
- Mazumdar, Weppner, Ranga, Few Body Systems 66 (2025)
- Ranga, Mazumdar et al., Act. Phys. Pol B (2023)

$^{10,11}\text{B} (p, p' \gamma) ^{10,11}\text{B}$ Reactions

Isotopically enriched ^{10}B with 97.5% and ^{11}B with 95% enrichments were used

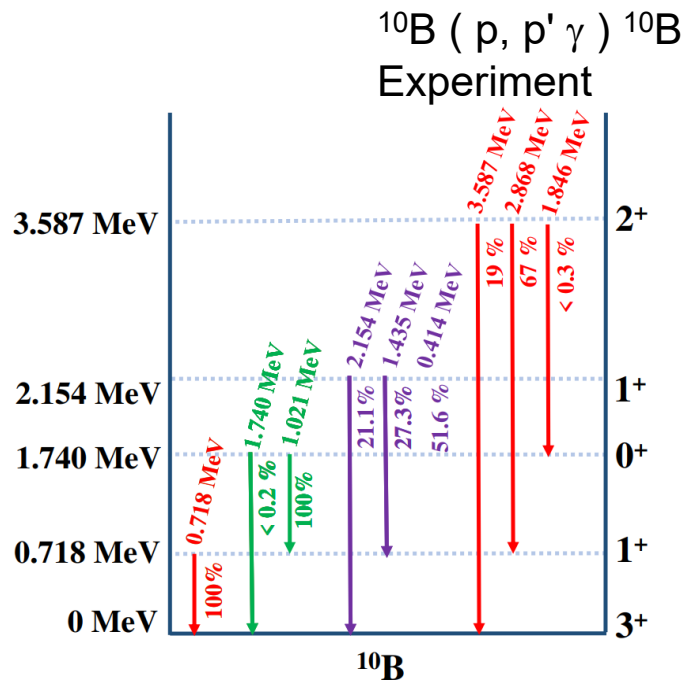
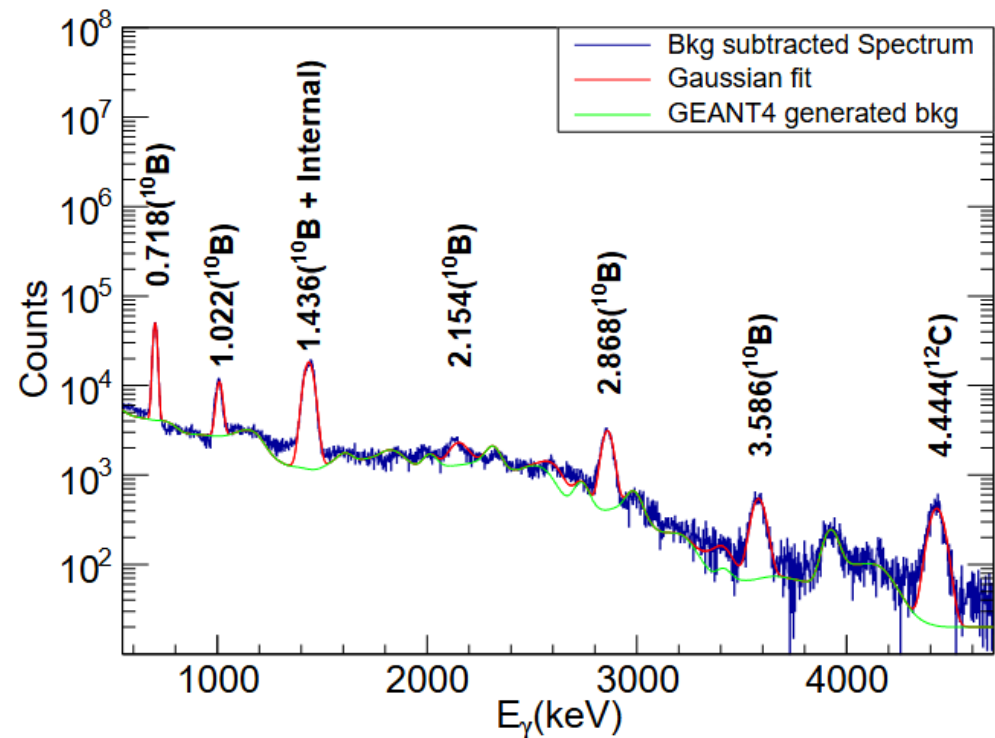
Detectors used:

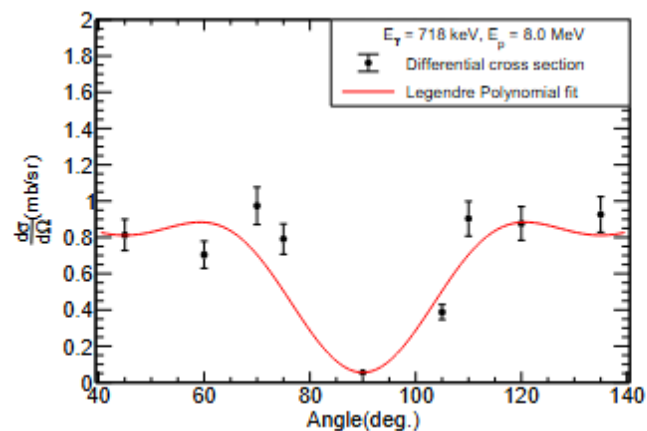
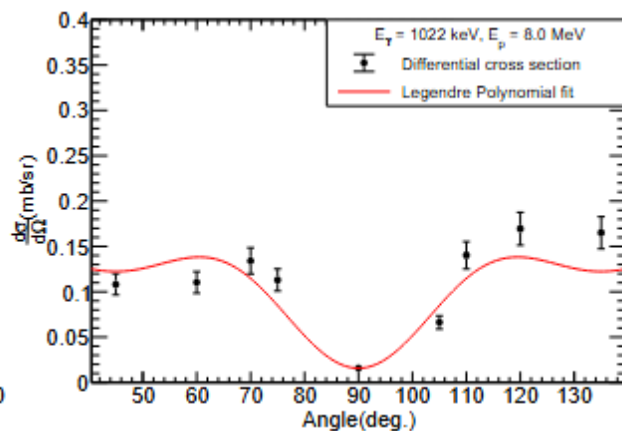
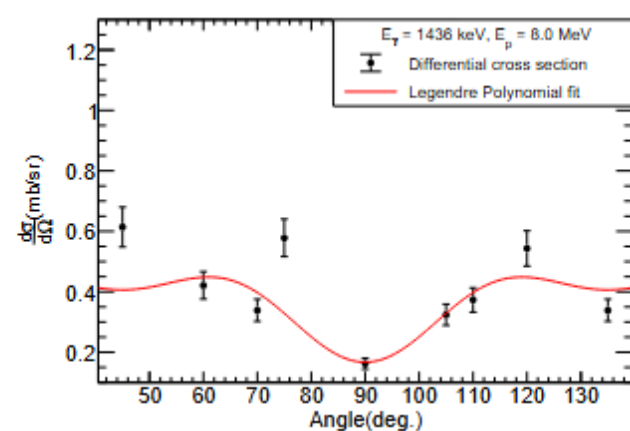
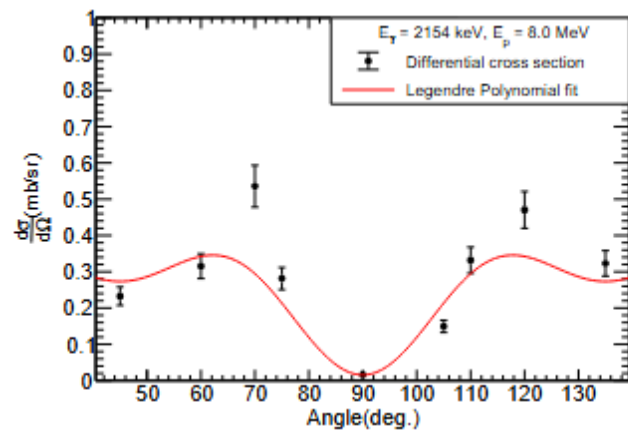
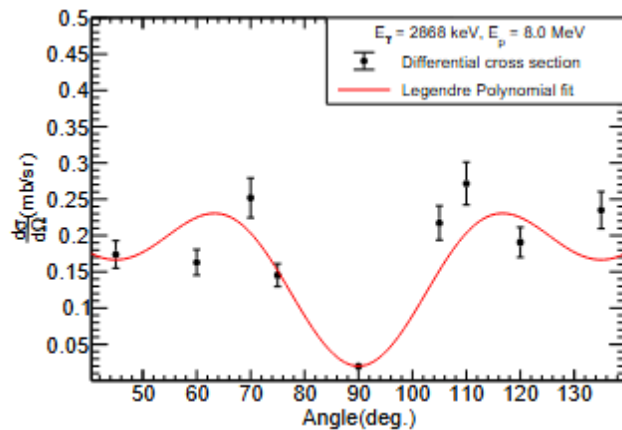
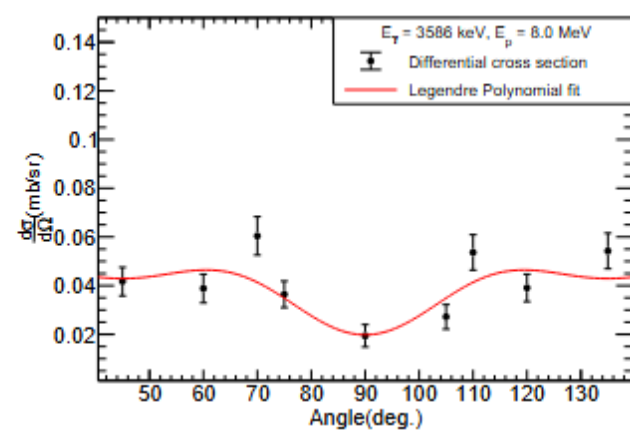
- Three 3.5"×6" LaBr₃:Ce and three 4"×4" NaI(Tl) No data available for $^{11}\text{B}(p, p' \gamma)^{11}\text{B}$

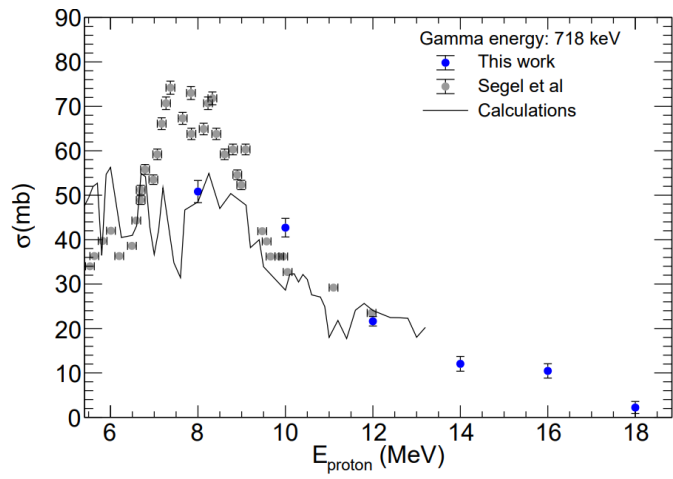
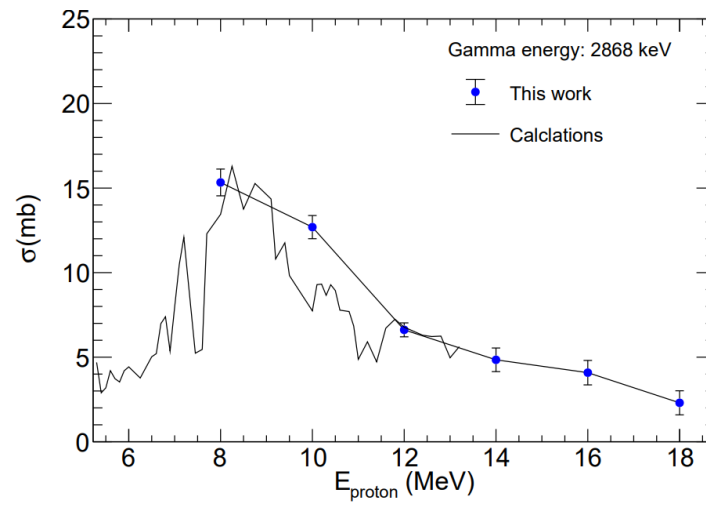
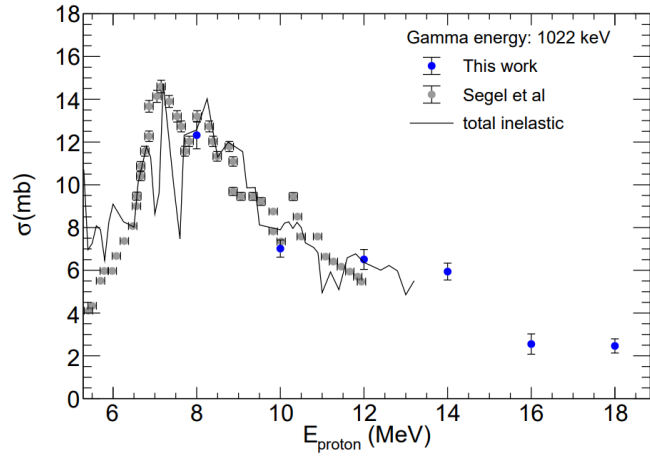
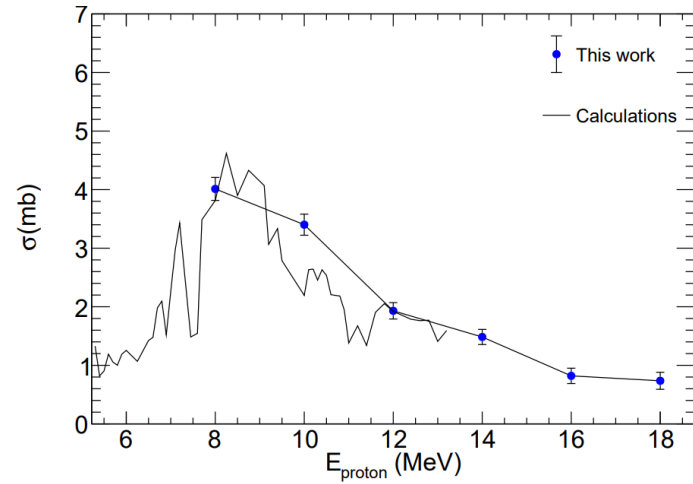
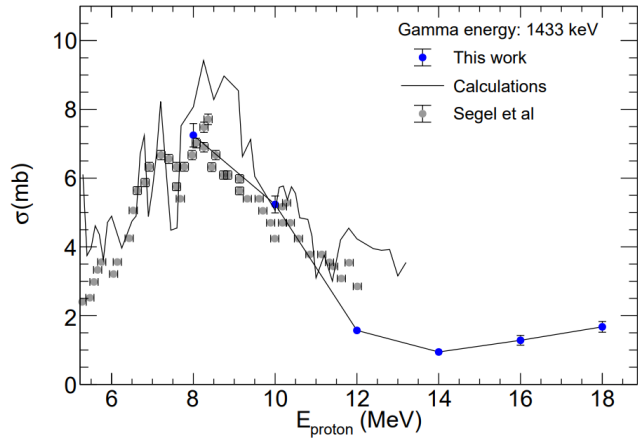
Prominent γ -rays for ^{10}B :

0.72, 1.02, 1.43, 2.15, 2.86, 3.58 MeV

Only one set of data for $^{10}\text{B}(p, p' \gamma)^{10}\text{B}$ up to 12 MeV

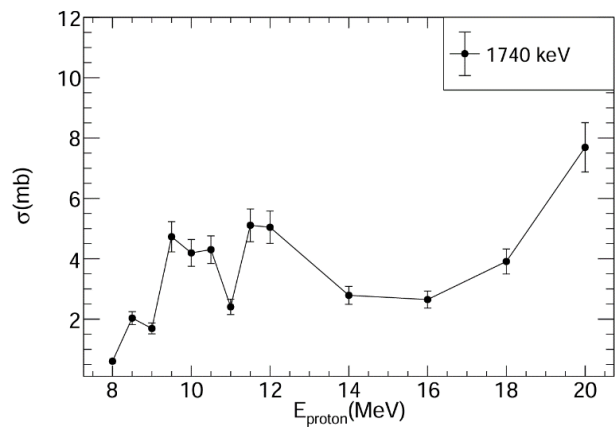
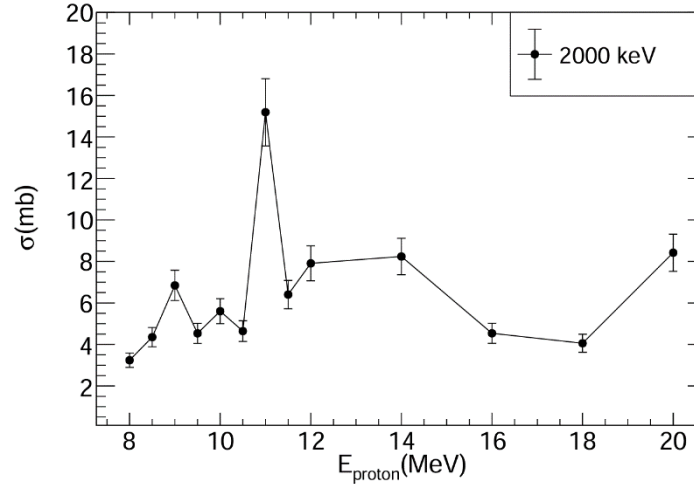
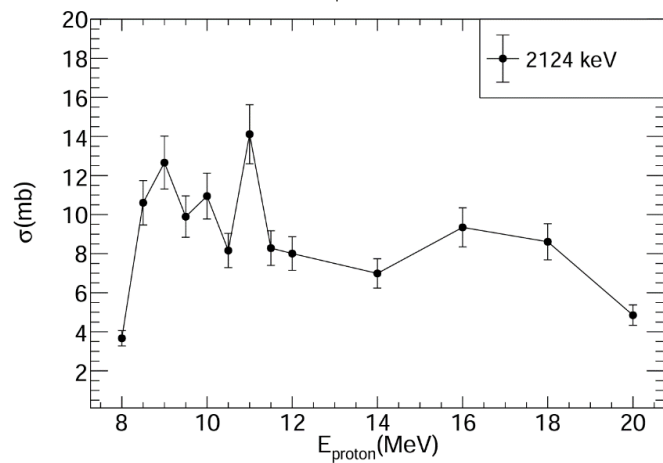
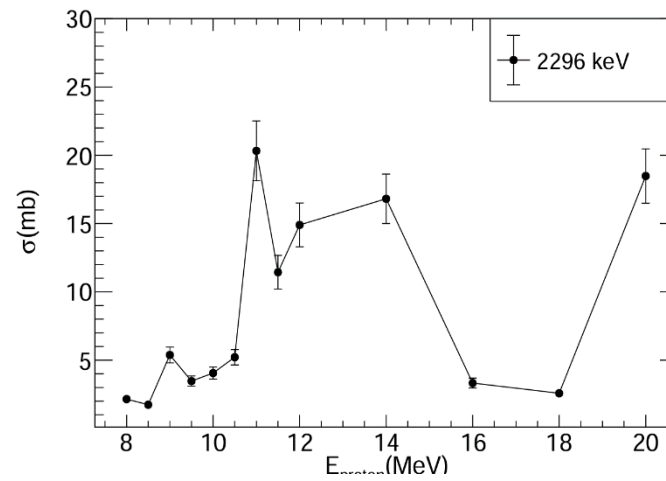
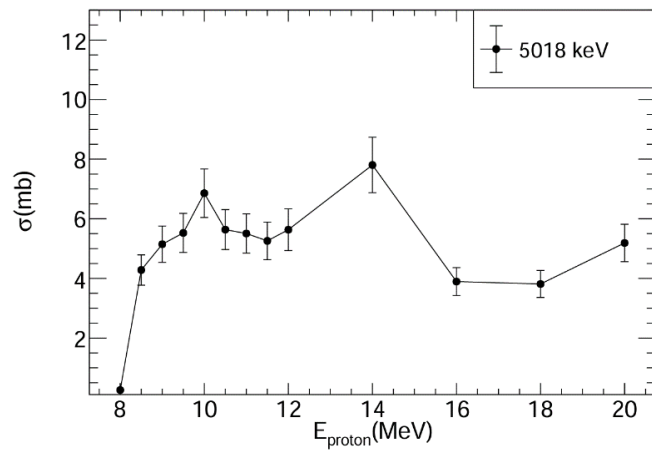
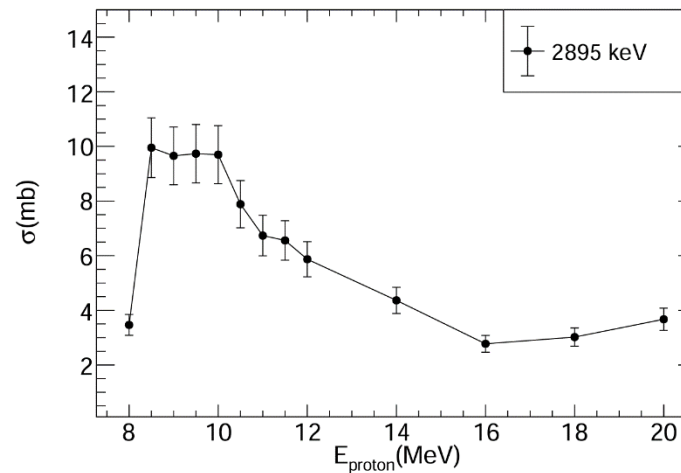




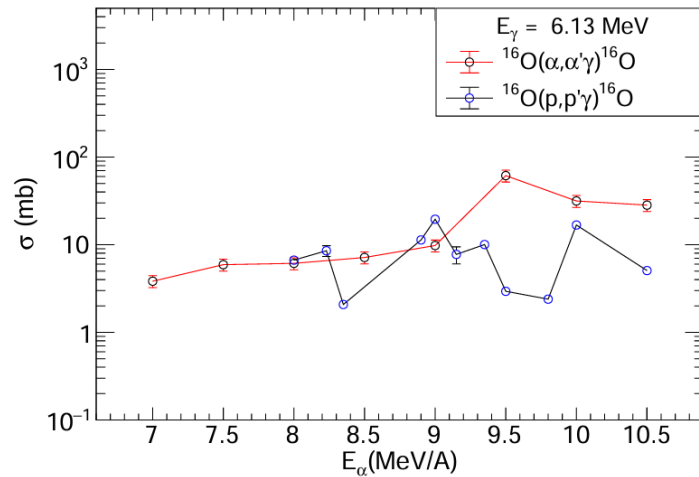
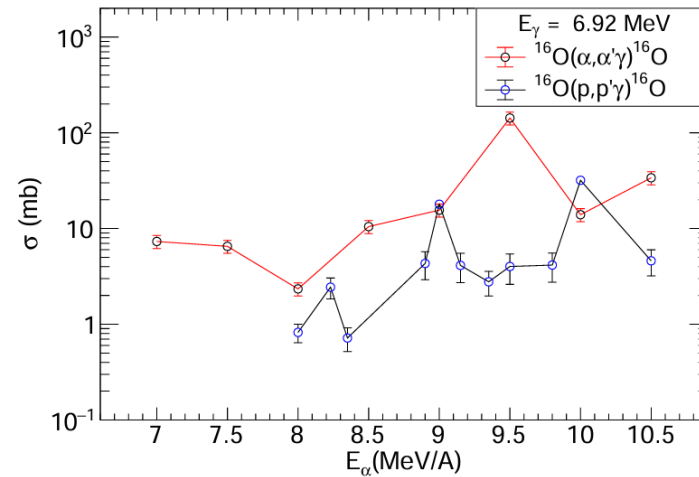
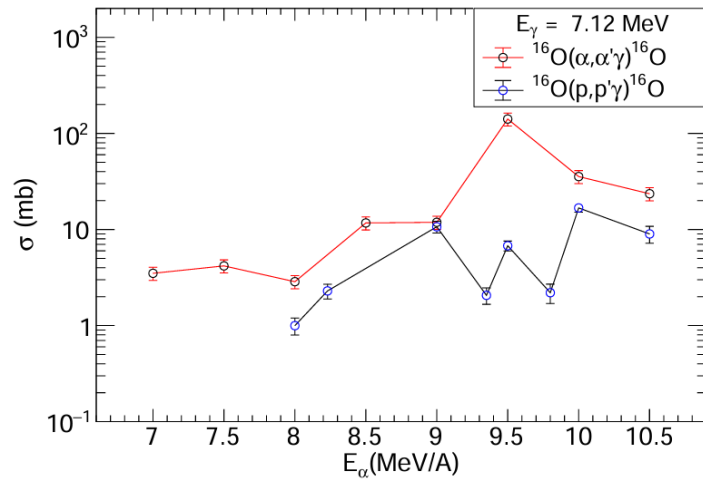
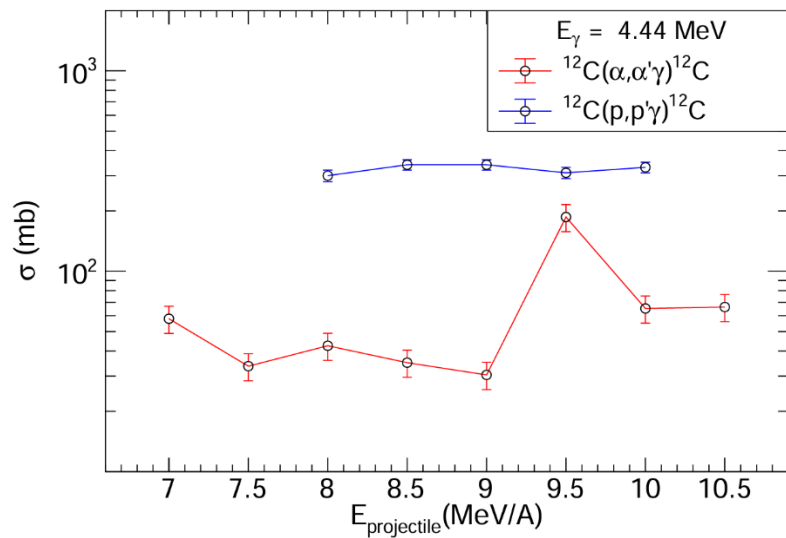


V. Ranga, I. Mazumdr et al., In preparation

$^{11}\text{B} (p, p' \gamma) ^{11}\text{B}$ Reaction



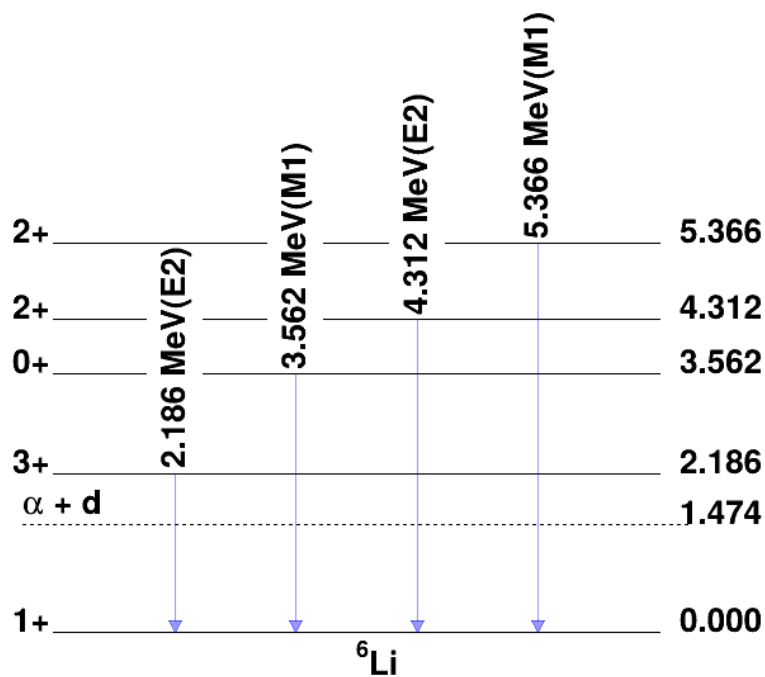
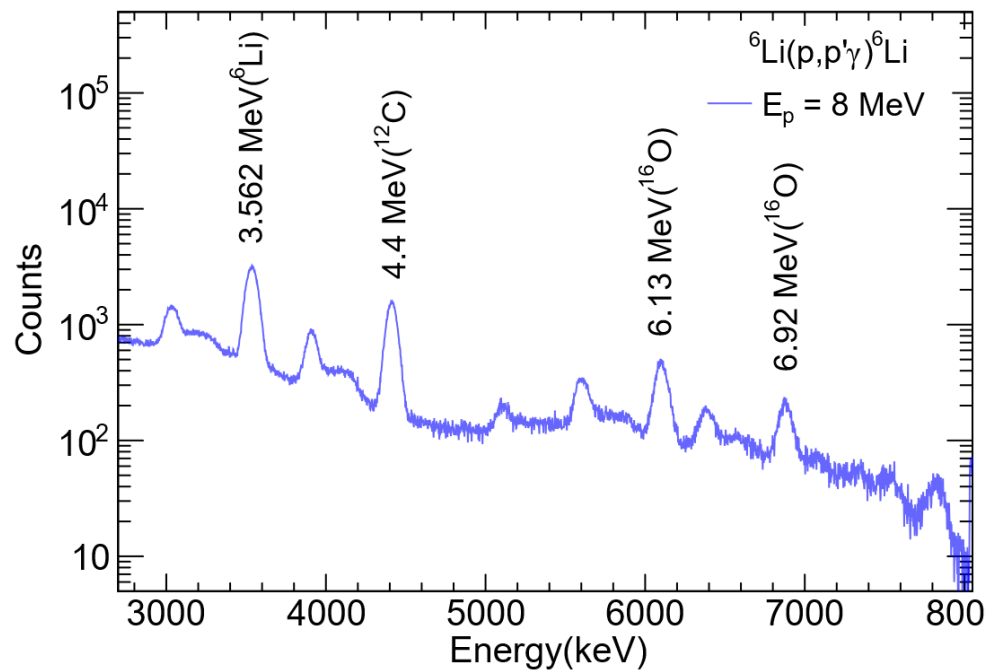
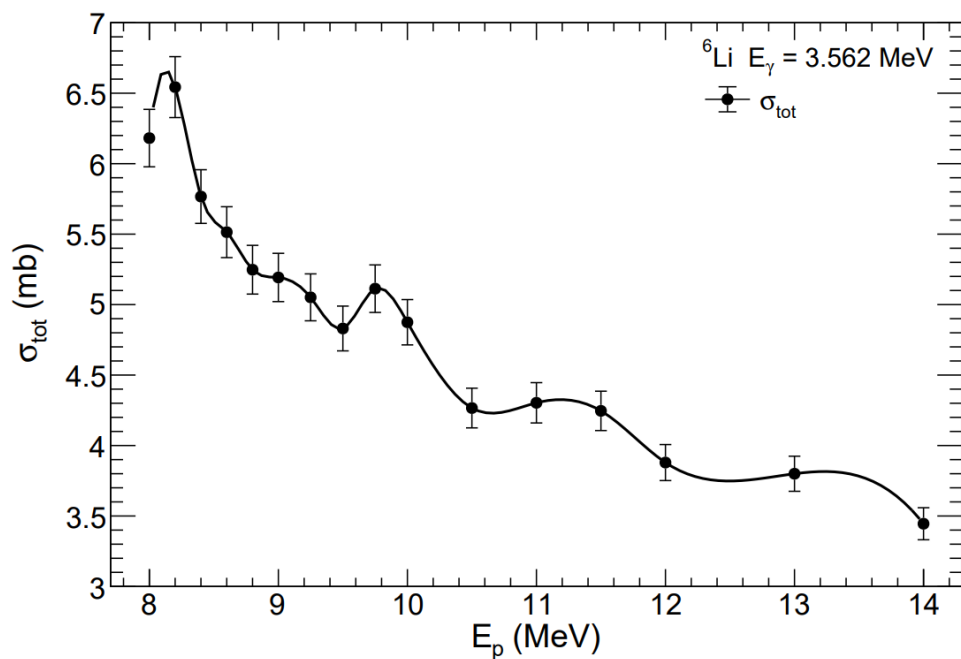
Comparison of proton and alpha induced reaction cross sections The VECC Campaign

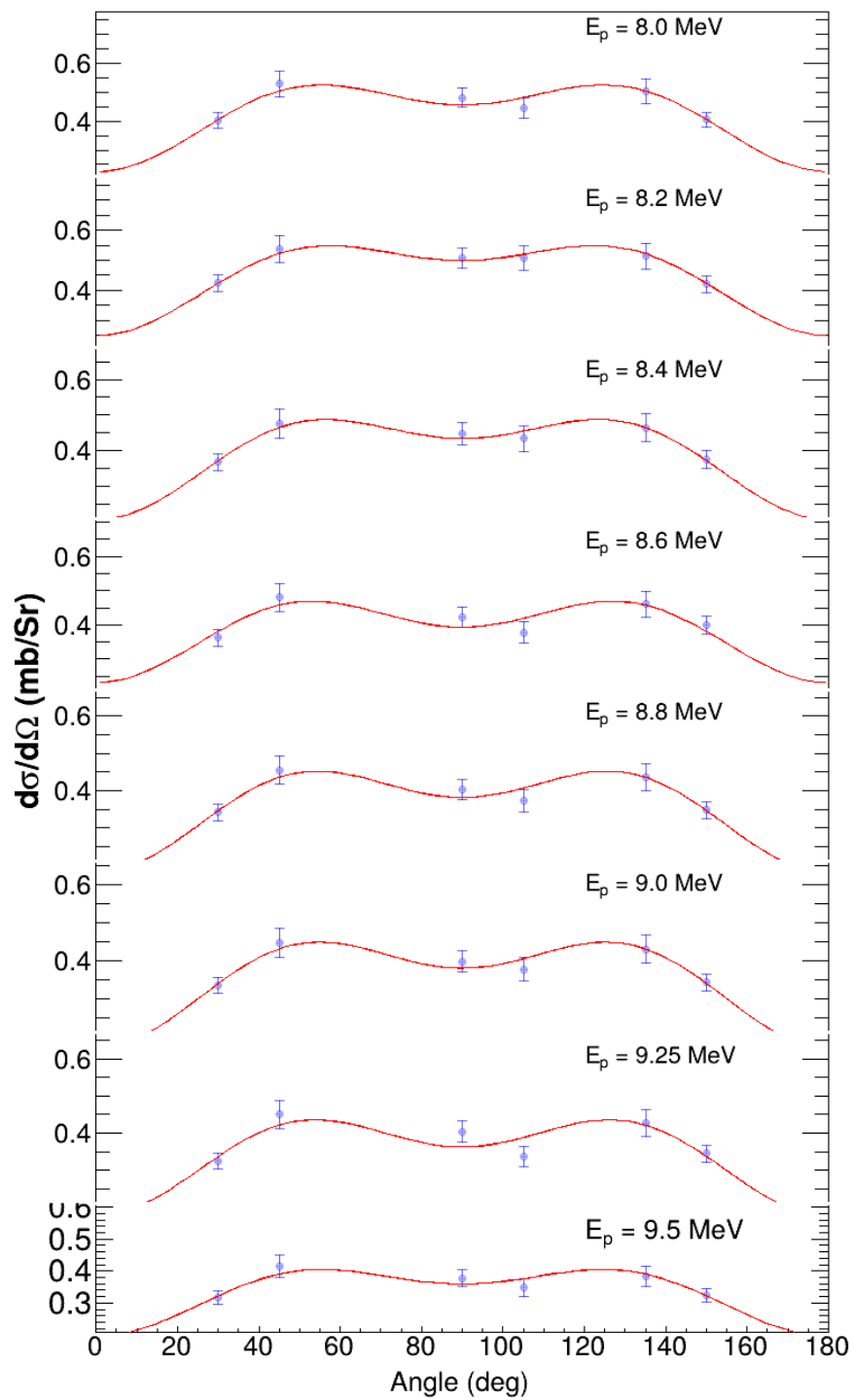
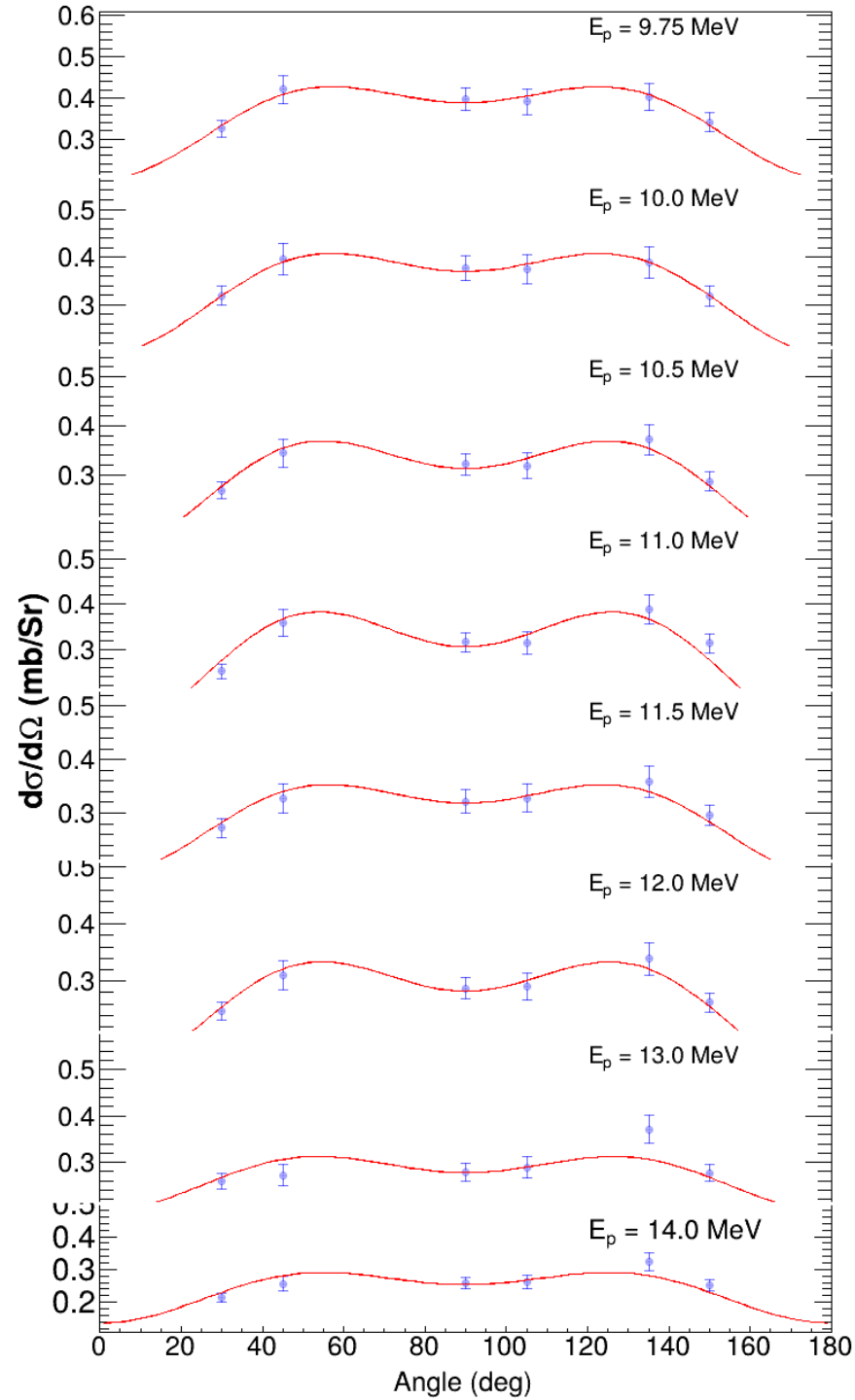


- Alpha induced gamma-ray cross sections are consistently higher than that of proton induced for ^{16}O

${}^6\text{Li}(p, p'\gamma){}^6\text{Li}$ reaction

Moving from compact to cluster structures





Part IV

Proton Capture Reactions for Nucleosynthesis

Nuclear Astrophysics

The Goals:

- *Understanding Birth & Death of stars*
 - *The energy production mechanism*
 - *Formation of Elements*
- *D.D. Clayton (1968)*
 - *C. Rolfs & W. Rodney (1988)*
 - *C. Iliadis (2007)*
 - *Thompson & Nunes (2009)*
 - *B2FH, Rev. of Mod. Physics, 15 (1957)*

The overarching role of Nuclear Physics:

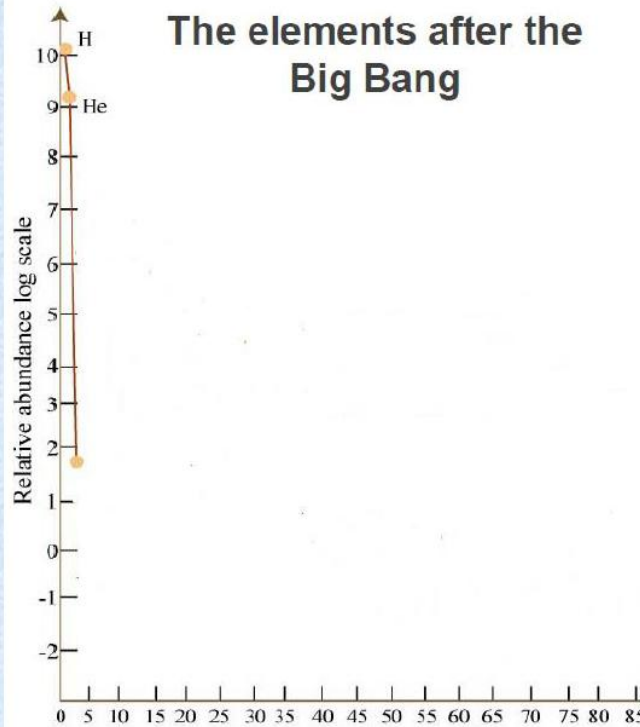
Structure: Mass, Life Time, Decays (α , β , γ , fission)
Nuclear levels, resonances, strength functions, Nuclear Level Density

Reaction: Capture cross sections, reaction rates, inelastic scattering

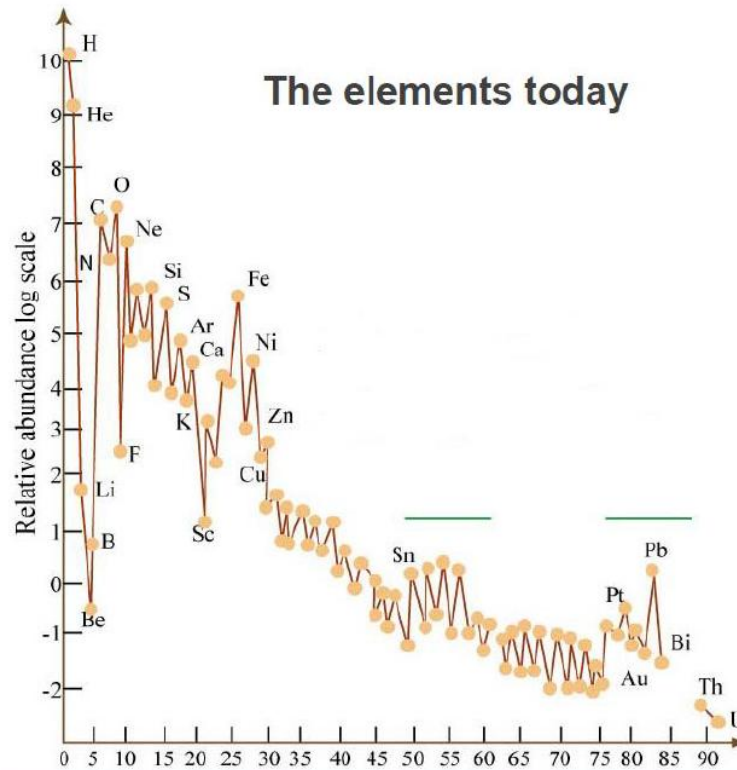
N-N interaction, N- ν interaction

Elements relative abundances

The elements after the Big Bang



The elements today



Atomic number

Dark Energy	73.4%
H, He	4.1%
Heavy Elements	0.07%
Neutrinos	0.7%

A confluence of :

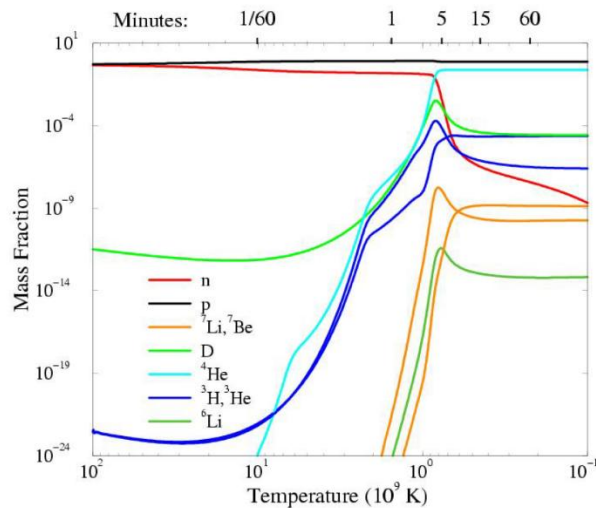
Atomic Physics, Nuclear Physics,
Particle Physics, Plasma Physics,
Cosmology, Gravitation

Different Stages & Sites of Element Formations

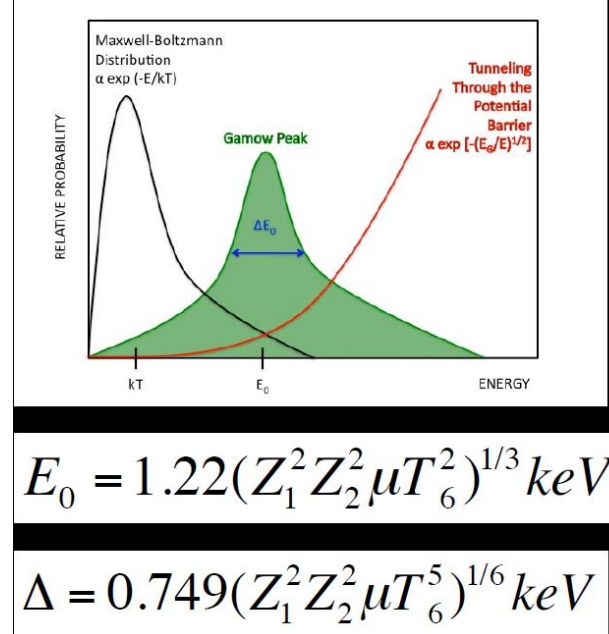
Big Bang Nucleosynthesis (mostly H, He, Li)

Stellar Nucleosynthesis Slowly (Quiescent) $\sim 10^9$ years [The Sun, $H \rightarrow He$]
Langanke & Barnes, Adv. Nucl. Phys. 22 (1996)

Fast (Explosive) $\sim$ a few seconds
 [Iron $\rightarrow$ Heavy elements]



Burles, Nollett, Turner, ApJ



Formation of Heavy Elements

- Beyond Fe Coulomb Barrier is too high.
- Nucleosynthesis is dominated by
 1. Sequence of slow n-capture & β decays (S-process) *Fowler, rev. Mod. Phys. 56 (1984)*

Source of Neutrons:

	$^{13}\text{C}(\alpha, n)^{16}\text{O}$	;	$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$	reactions
Q value	2.216 MeV		-0.480 MeV	

2. Accretion-Driven Explosions: p & rp processes

32 Stable, proton-rich nuclei between ^{74}Se and ^{196}Hg “ p-nuclei formed during these processes. [Nova or X-ray bursts] *Parikh & Sala (2014)*

3. *Rapid neutron capture (r – process)* *R. Surman et al. 2008*

Possible sites SN, neutron star mergers, exotic neutron-rich nuclei are produced.

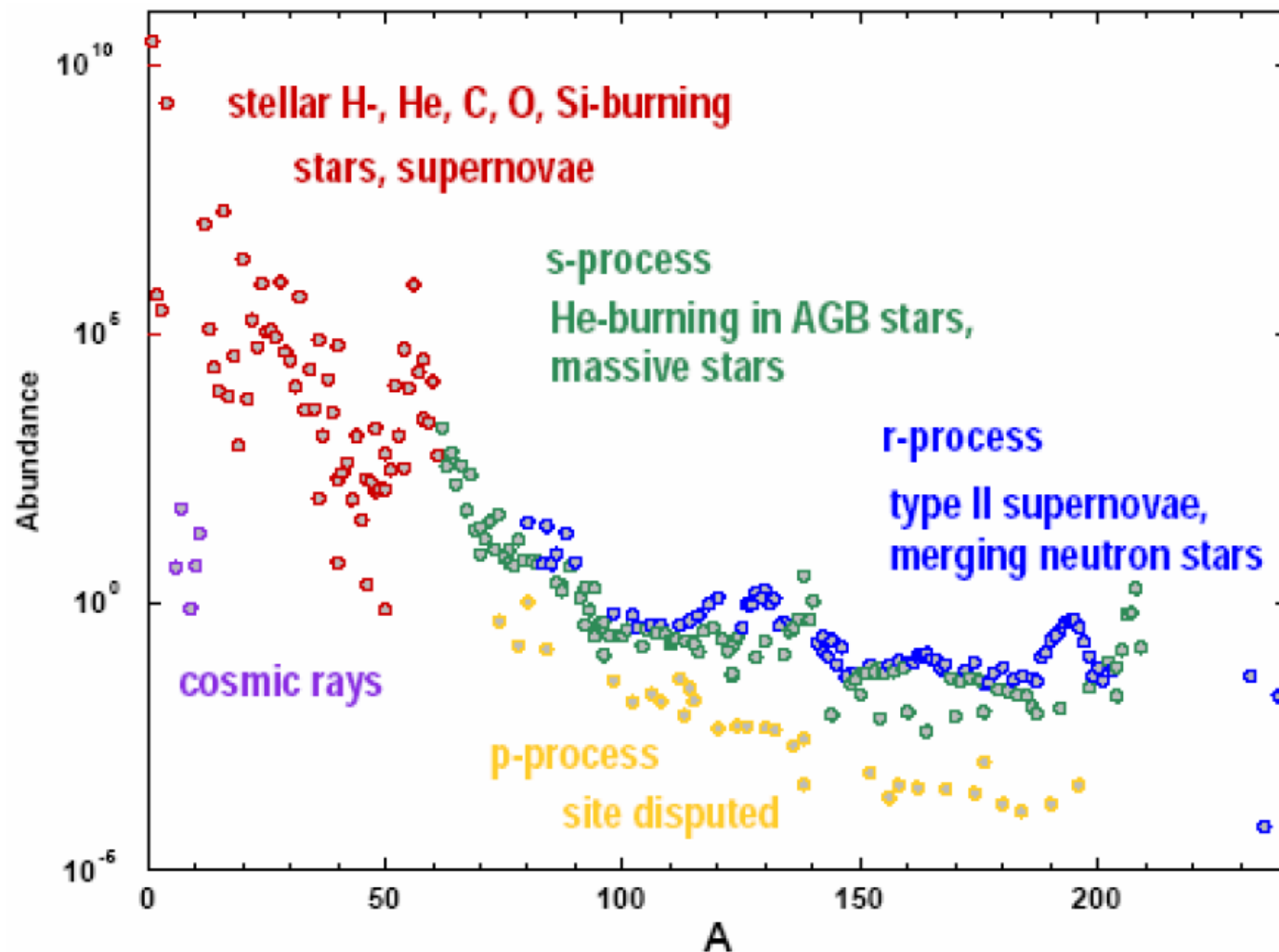
s process: 3×10^8 neutrons /cm³

r process: 10^{20} neutrons /cm³

properties of the nuclei, like mass, life-time etc. on the r-path are unknown
Highly neutron-rich exotic nuclei

The Synthesis of the Elements in Stars

Burbidge, Burbidge, Fowler & Hoyle (B²FH): Rev. Mod. Phys. 29 (1957) 547



from: M. Wiescher, JINA lectures on Nuclear Astrophysics

Nuclear Astrophysics: *The Experimental Challenges*

- Extremely Small Cross Sections

Need for high current low energy accelerators

Need for indirect (break-up) reactions

- Reduction of Background

Demands underground measurements

- Reactions demanding unstable nuclei

Need for RIB facilities

- High purity targets / Gas targets

- High Efficiency Detectors / Array of Detectors

p Capture reaction

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

Proton-proton chain reaction diagram:

- Two protons (^1H) fuse to form deuterium (^2H) and a positron (e^+).
- Deuterium (^2H) and a proton (^1H) fuse to form helium-3 (^3He) and a gamma ray (γ).
- Two helium-3 (^3He) nuclei fuse to form helium-4 (^4He) and two protons (^1H).
- Helium-4 (^4He) and beryllium-7 (^7Be) fuse to form lithium-7 (^7Li) and a neutron (n).
- Lithium-7 (^7Li) and a proton (p) fuse to form beryllium-7 (^7Be) and a helium-4 (^4He).

Legend:

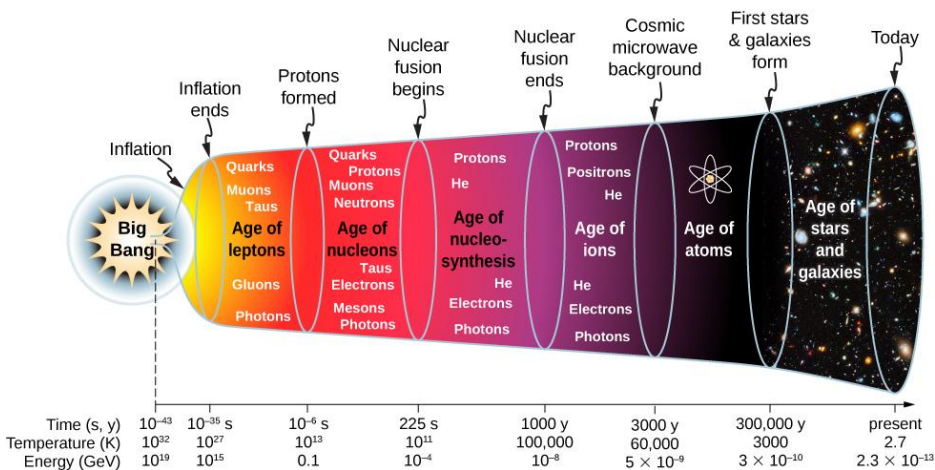
- Red sphere: Proton
- Grey sphere: Neutron
- Small grey sphere: Positron

depends upon the exact nature of the problem

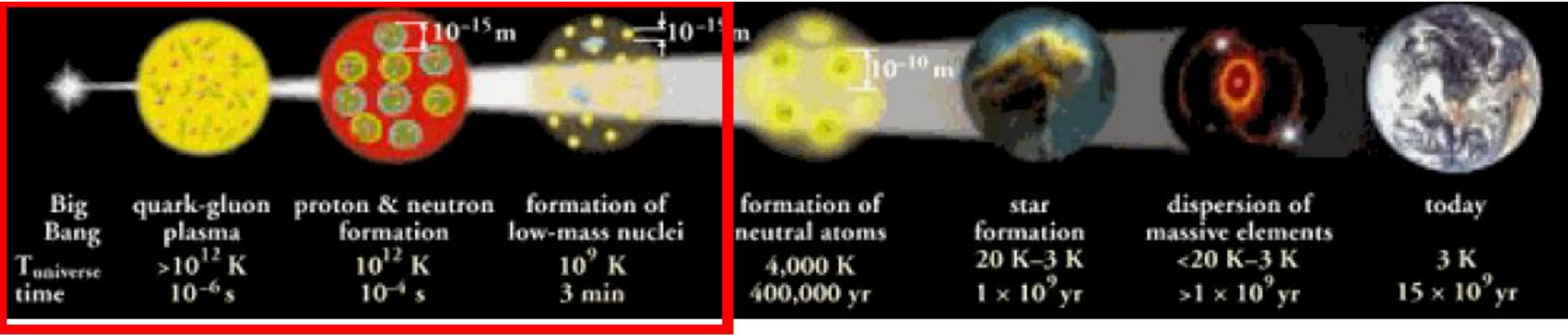
Few-body systems, N-N interactions (Need for polarized beam/target)

- ✓ **Big bang nucleosynthesis** C. Casella *et al.* (LUNA expt.)
- ✓ **Stellar nucleosynthesis** Nucl. Phys. A 706 (2002)
- ✓ **Formation inside proto stars** 22 To 2.5 keV

D/H ratio governed by the reaction rates.



- 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).



Big bang Nucleosynthesis(BBN)



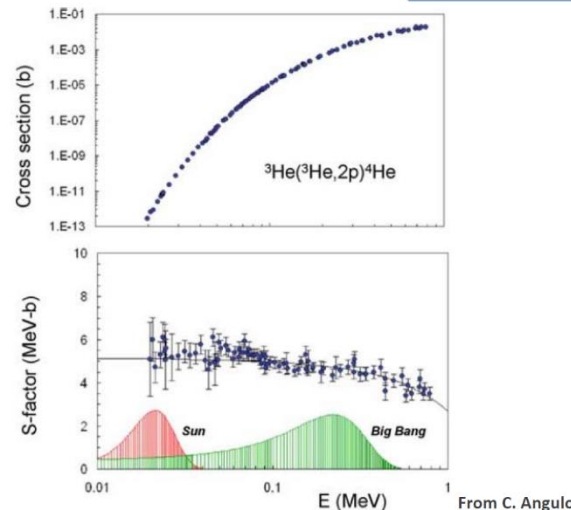
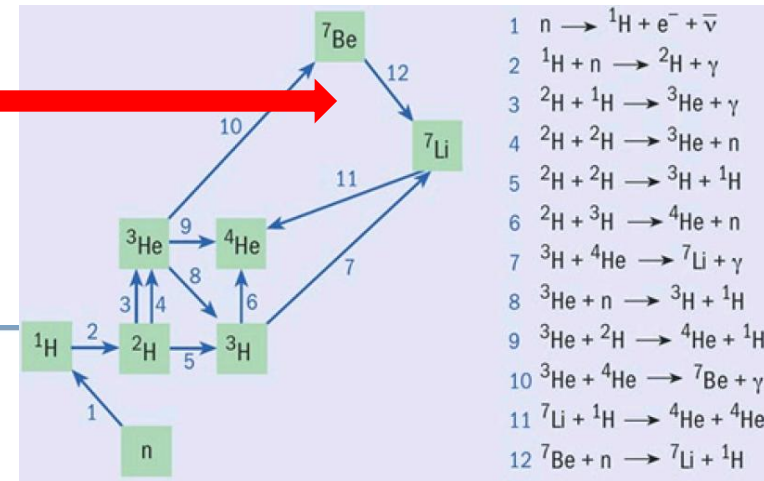
$T \sim 10^9 \text{ K}$, $\Delta t \sim 3 \text{ min}$



Very limited data in the BBN region

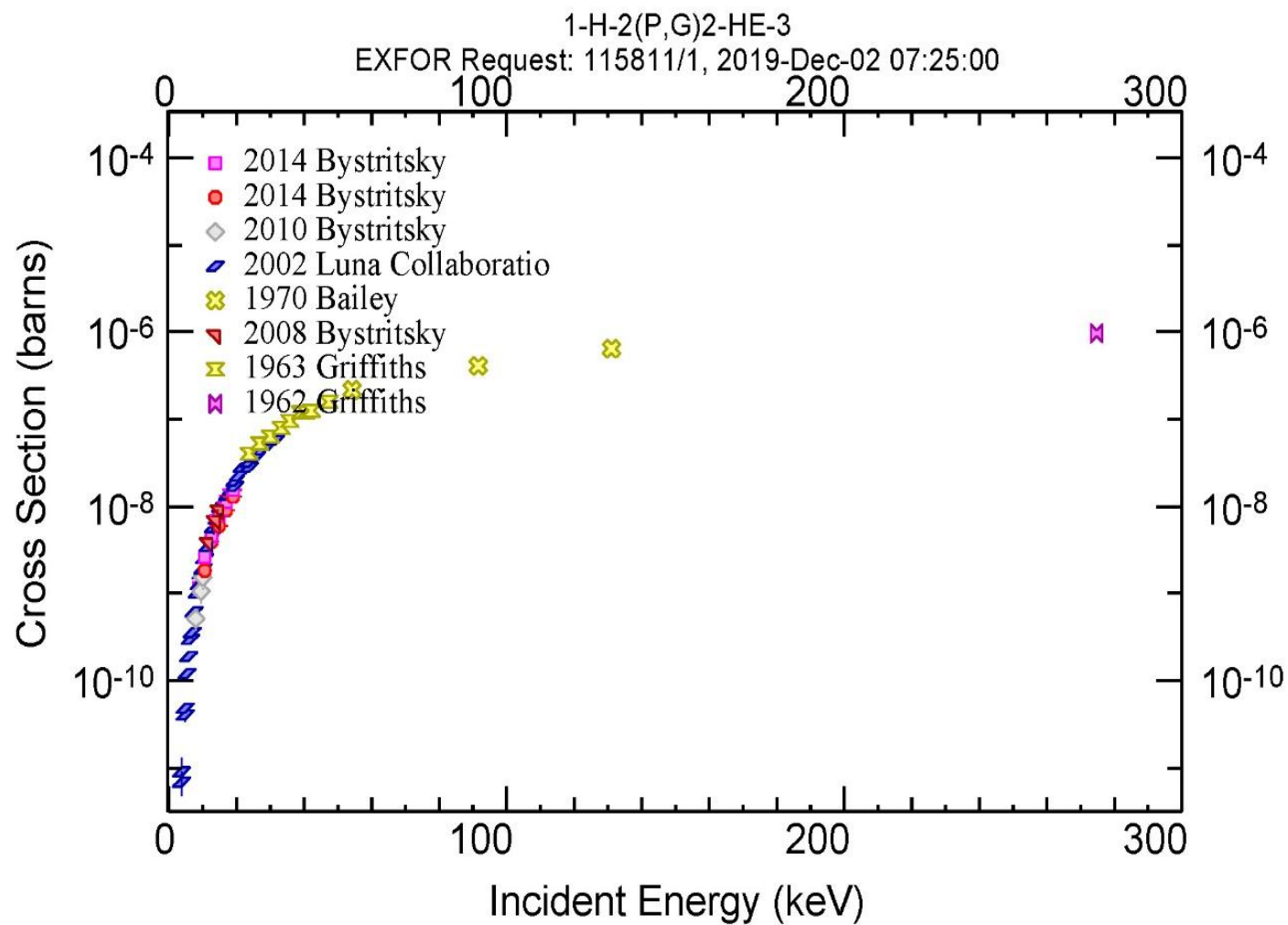
Suitable beam energy.
Accessible using existing facilities in India

Calculations by Marcucci et al. PRL (2016)



Elements formed in BBN

${}^1\text{H}$ (0.75), ${}^2\text{H}$ (2.5×10^{-5})
 ${}^3\text{He}$ (4×10^{-5}), ${}^4\text{He}$ (0.23)
 ${}^7\text{Li}$ (5×10^{-9})



Cross section measurement of $d(p,\gamma)^3\text{He}$ at low energies

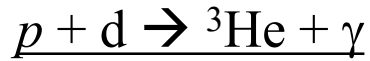
Experimental Details



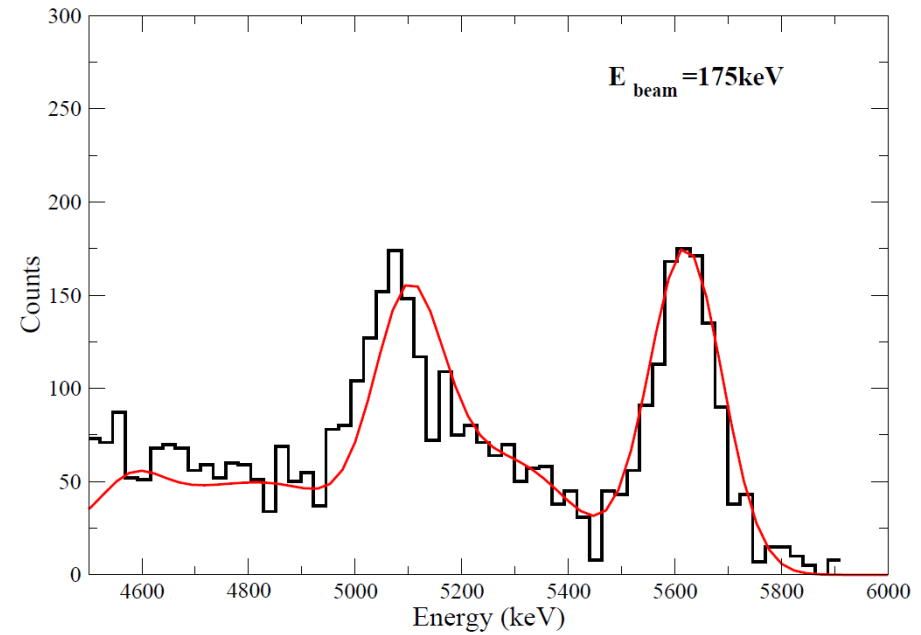
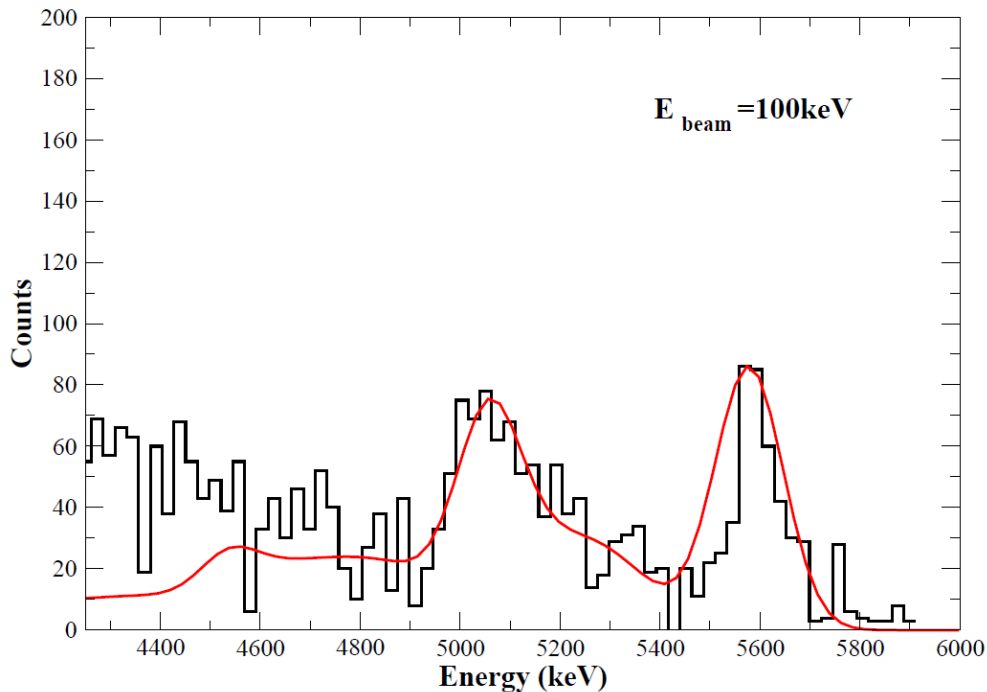
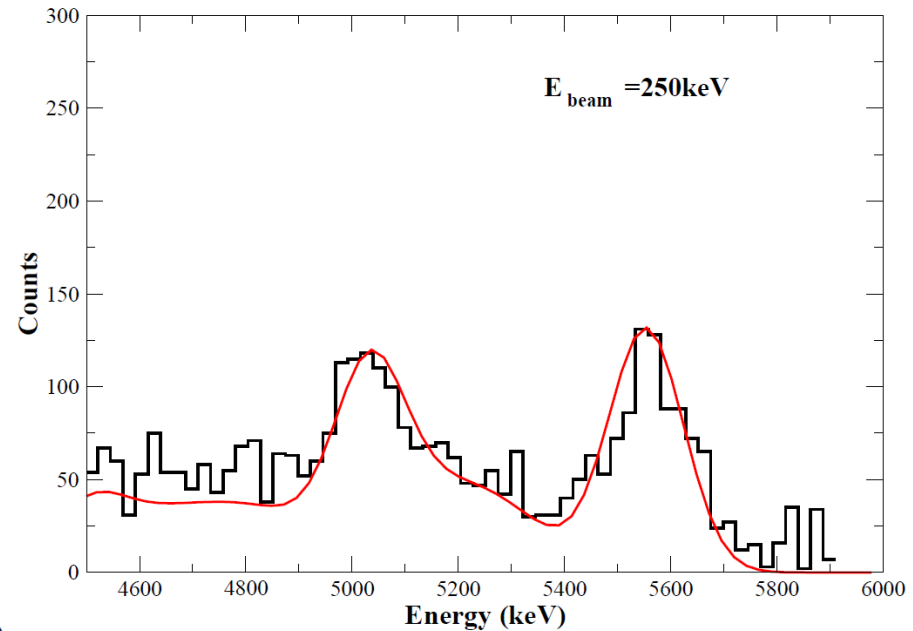
Top view

- 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- $\text{CD}_2 \sim 10^{17}$ atoms/cm²
- Detector facility- 3.5 "× 6" cylindrical LaBr_3 and array(2x2) of LaBr_3
- Q of reaction = 5.493 MeV

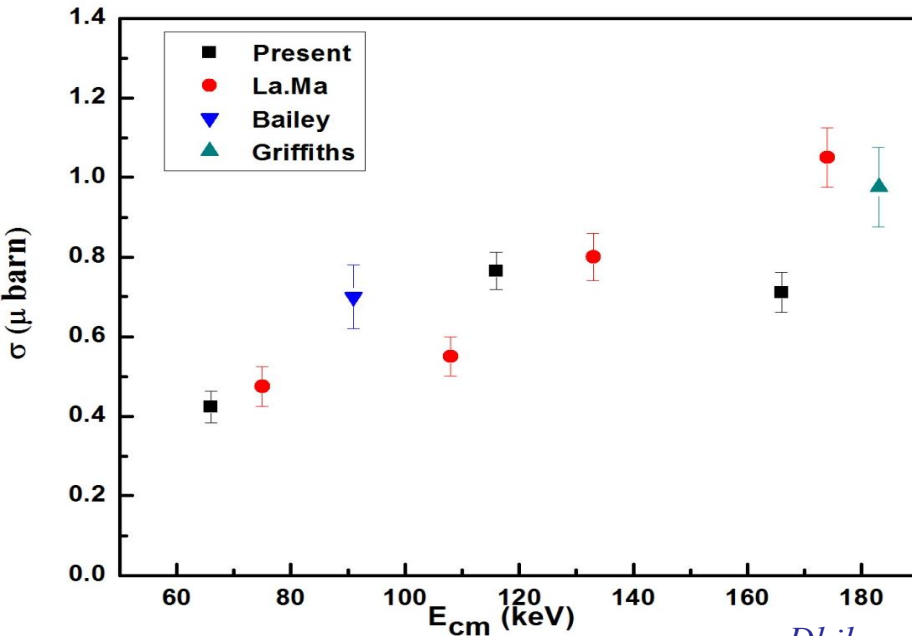
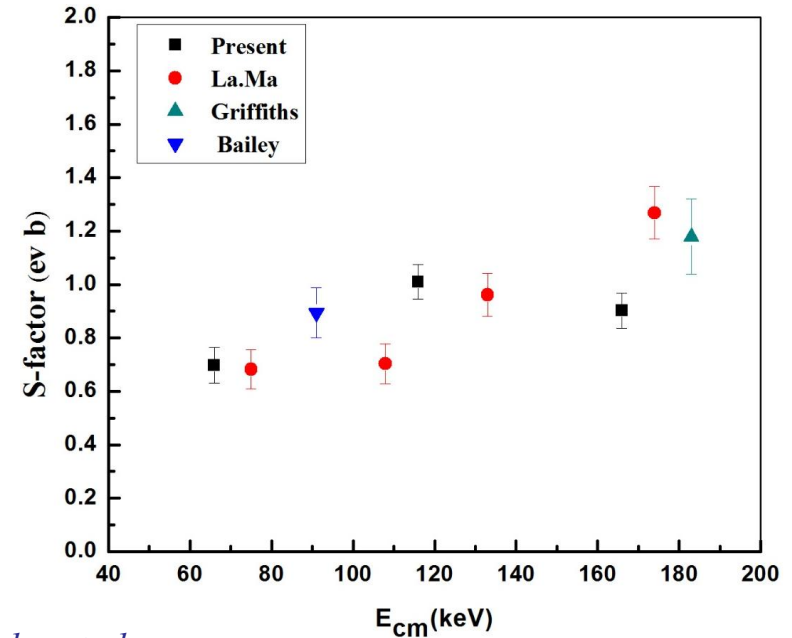
- Accelerator facility- ECR ion source facility at TIFR (Upto 400 keV proton energy)
- Proton Beam Energy used: $E_p = 250, 175, 100$ keV
- Current ~ 200 nA
- Target- $\text{CD}_2 \sim 10^{17}$ atoms/cm²
- Detector facility- 3.5 "× 6" cylindrical LaBr_3 and array(2x2) of LaBr_3
- Q of reaction = 5.493 MeV



$V_{\text{coul}} = 600$ keV
Gamow Window $\sim 8 - 24$ keV



Cross section and S-factor



Dhibar, Mazumdar et al,

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

- Mazumdar *et al.* Act. Phys. Pol B,(2019)
- Mazumdar, Asro Particle Physics (2020)
- Griffiths *et al.*, Can. J. Phys. 41 ,724 (1963).
- Bailey *et al.*, Can. J. Phys. 48 , 3059 (1963).
- Ma *et al.*, Phys. Rev. C 55, 2 (1997).
- V. Mossa et al, Nature 587 (2020)
- S. Turkat et al. PRC 103, 045805 (2021)
- L. Stockel, PRC 110, L032801 (2024)

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

L. E. Marcucci,^{1,2} G. Mangano,³ A. Kievsky,² and M. Viviani²

PRL 116, 102501 (2016)

PHYSICAL REVIEW LETTERS

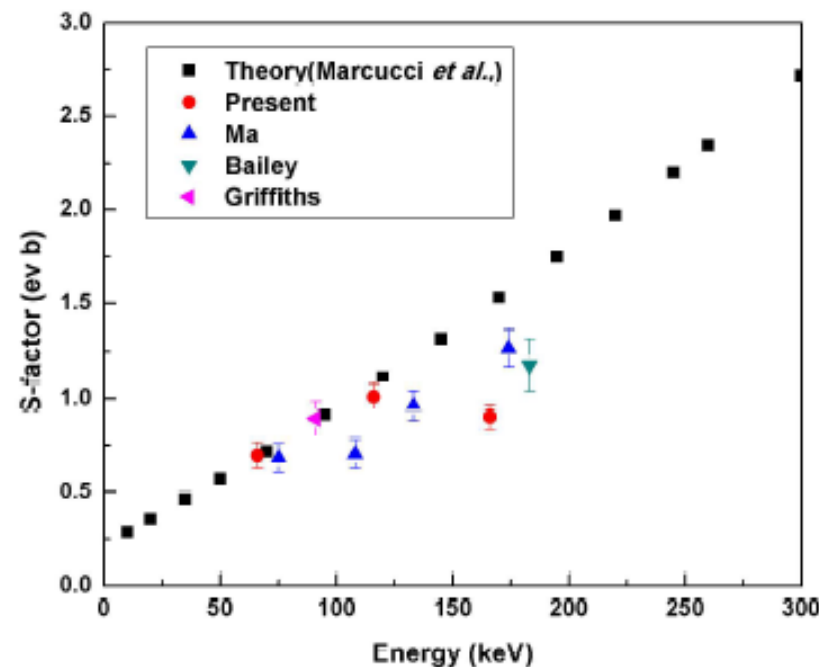
week ending
11 MARCH 2016

way is to increase the value of the $d(p,\gamma)^3\text{He}$ 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 $d(p,\gamma)^3\text{He}$ 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, $E \approx 30\text{--}300$ keV, would be very important.

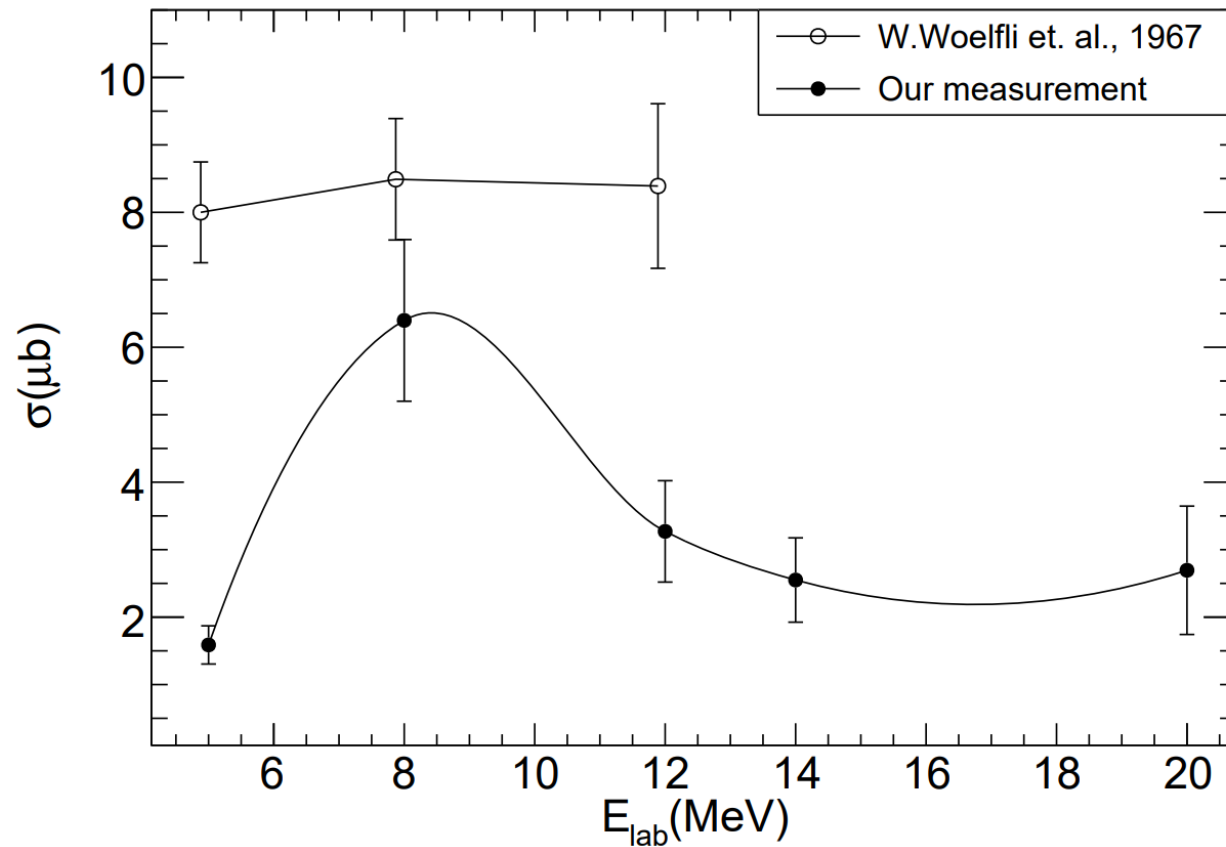
The astrophysical S factor at low energy, around the solar Gamow peak $E_G \approx 9$ keV, is well known, thanks to the results of the LUNA experiment [10]. However, for the BBN relevant energy range, the experimental situation is rather unclear, since the only available experimental data [11] are quite in disagreement with the polynomial best fit of $S(E)$ for $E \approx 0\text{--}2$ 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 $d(p,\gamma)^3\text{He}$ 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 $d(p,\gamma)^3\text{He}$ 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 $d(n,\gamma)^3\text{H}$ 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 $d(p,\gamma)^3\text{He}$ 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 ^4He primordial mass fraction Y_p , since it is insensitive to this reaction rate. For example, a change of the $d(p,\gamma)^3\text{He}$ 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



Capture cross-sections at Higher Energies: *Relevant for N-N Interaction studies*



Mazumdar et al
In preparation

Breakup threshold of deuteron: 2.225 MeV

- Loosely bound nucleus is capturing at much higher energy than breakup-threshold
- Extended the experimental data above 12 MeV up to 20 MeV.
- Few-body calculations are in progress.

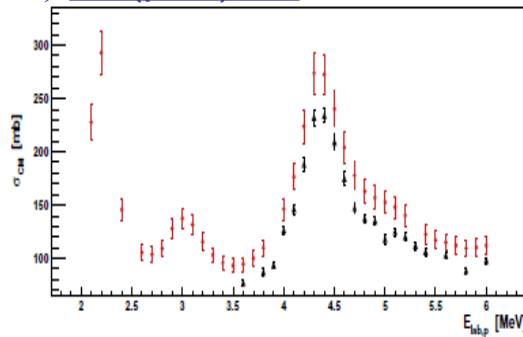
p Capture & (p, n) reactions
The Story of the L nuclei

Proton capture of $^{10}\text{B} \rightarrow ^{11}\text{B}$

- ❖ Very little data for the $^{10}\text{B}(p,\gamma)^{11}\text{C}$ reaction
- ❖ Only one data set in the energy region of 8 to 16 MeV
- ❖ Astrophysical Relevance of $^{11}\text{B}/^{10}\text{B}$ ratio
- ❖ Production of Mass 11 Nucleus

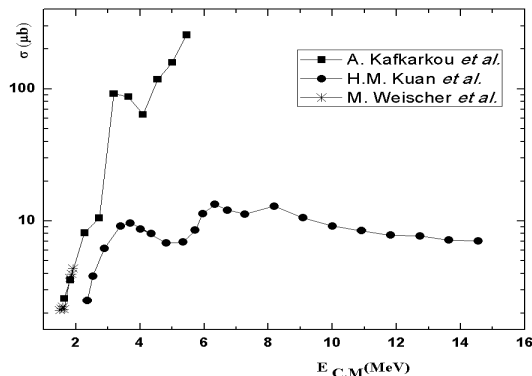
Two Different Decay Channels

A) $^{10}\text{B}(p, \alpha)^7\text{Be}$

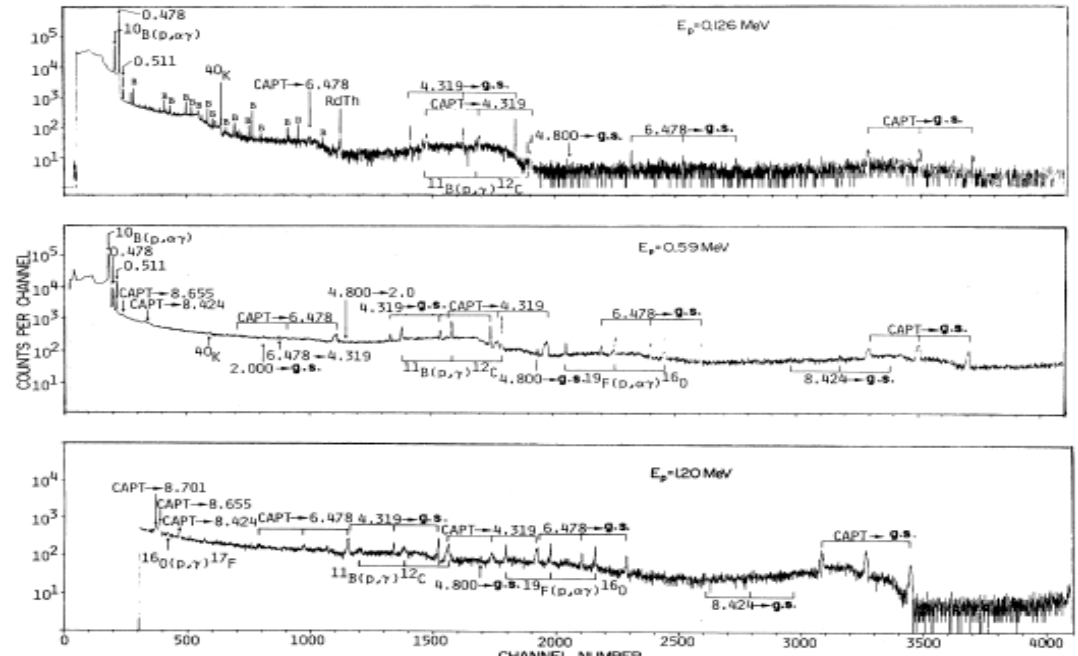
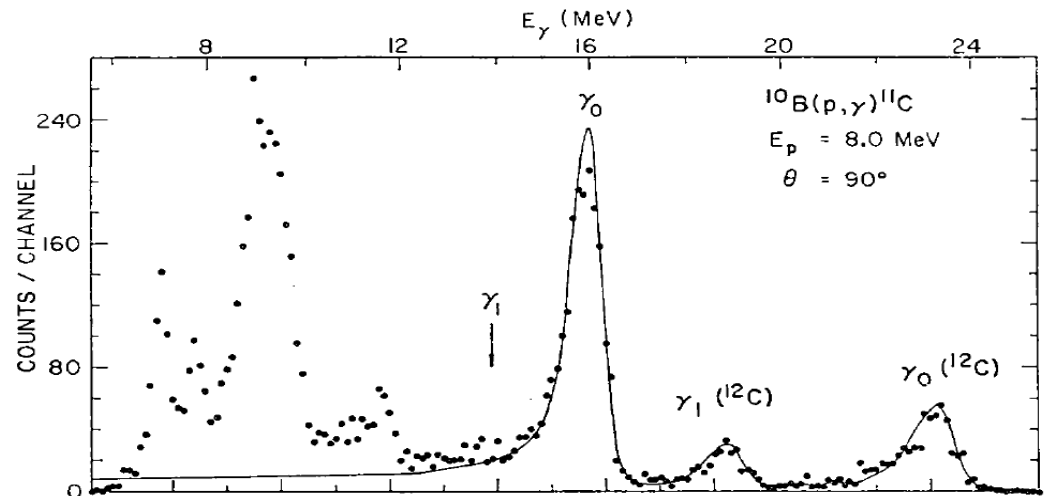


Kafkarkou *et al.* NIM-B 316 (48)

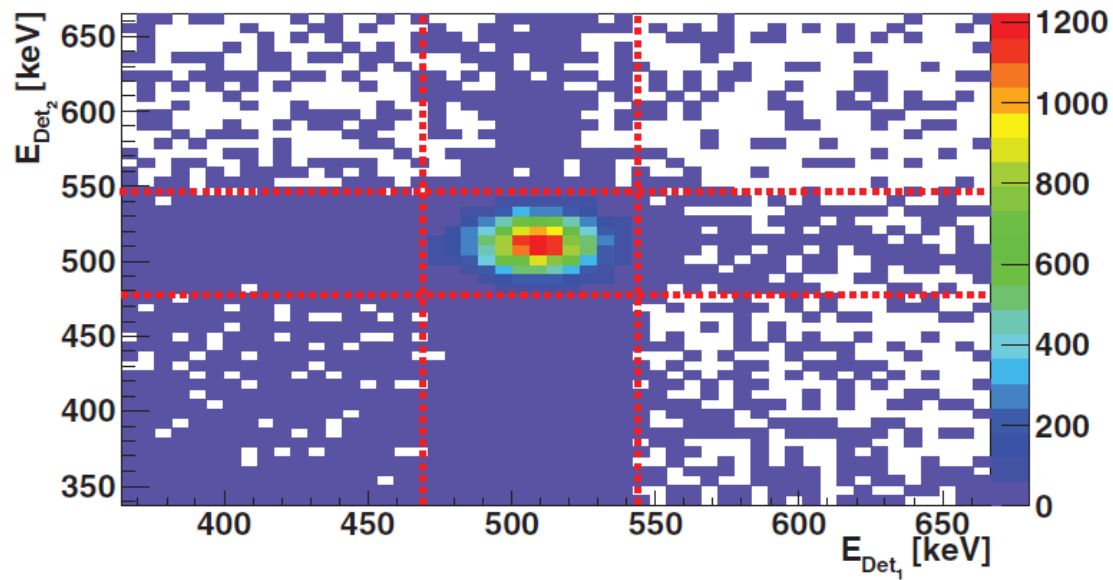
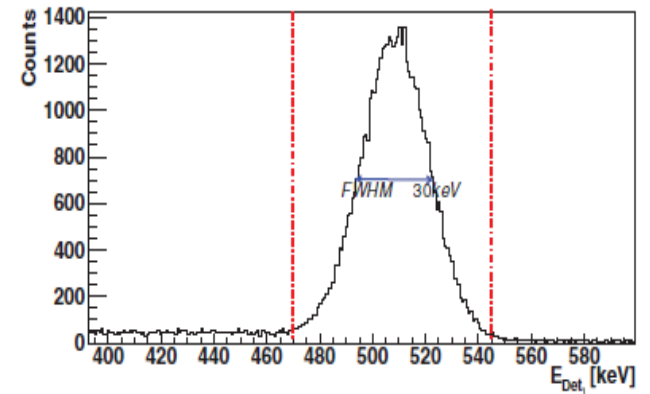
B) $^{10}\text{B}(p, ^{11}\text{C})\gamma$



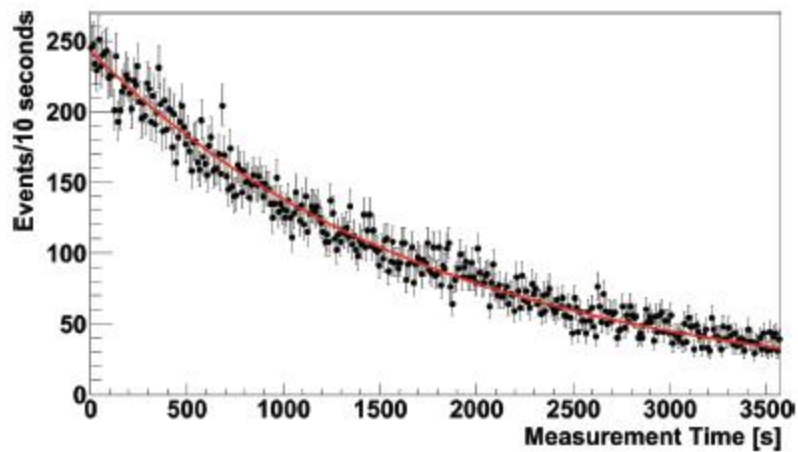
Kafkarkou *et al* Phys Rev C 89, 014601



H.M. Kuan *et al.*, Nucl Phys. A (1970)



2-D plot of energy signals from the two detectors at $E_p = 4.0$ MeV.



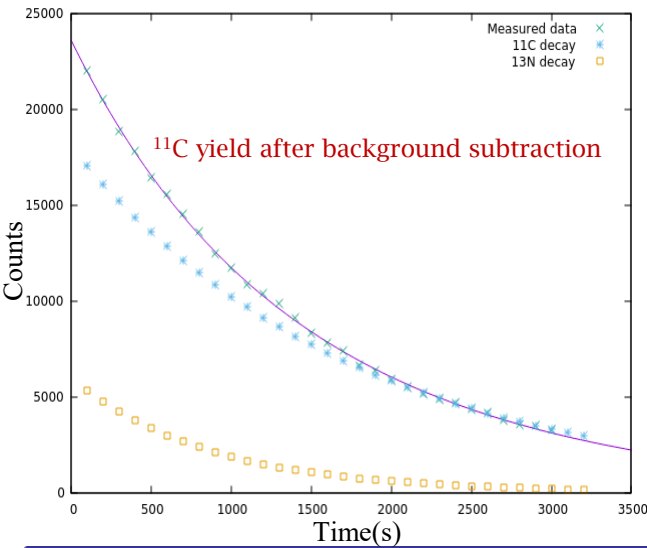
^{11}C decay curve for 4.0 MeV incident proton.
Data points are 511 keV coincidence counts per 10 s bin.

$^{10}\text{B}(\text{p}, \gamma)^{11}\text{C}$ reaction

Depletion of ^{10}B and creation of ^{11}B

Measured from 8 to 16 MeV

Important Reaction in ISM



^{11}C production cross section is described by

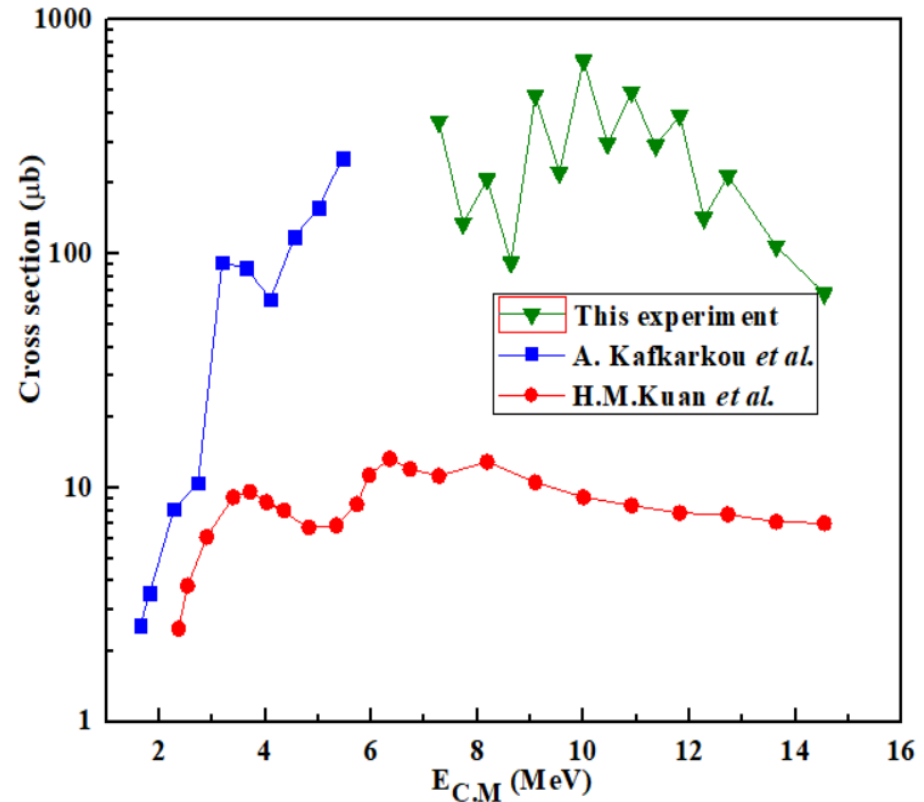
$$\frac{d(N_C(t))}{dt} = \sigma N_t \frac{dQ(t)}{dt} \Theta(t_i - t) - \lambda N_C(t)$$

Final cross section:

$$\sigma = \frac{\frac{N^d [\exp(\lambda(t_i + \Delta t)) - 1]}{1 - \exp(-\lambda t_m)}}{\chi_\varepsilon [Q(t_i) \exp(\lambda t_i) - \lambda \int_0^{t_i} Q(t) \exp(\lambda t) dt]}$$

$$\chi_\varepsilon = N_t \cdot \varepsilon$$

Measurements by Irradiation Technique



A. Kafkarkou et al NIM-B (2013)

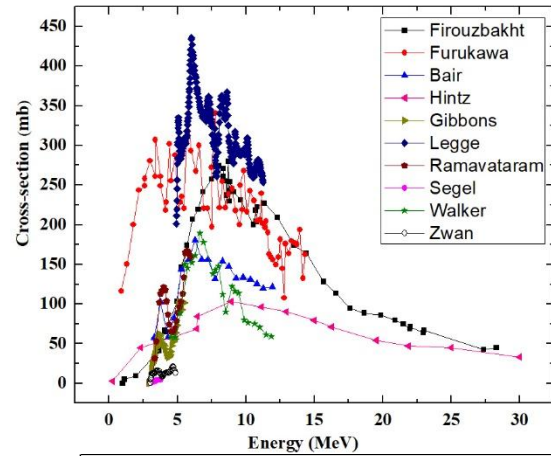
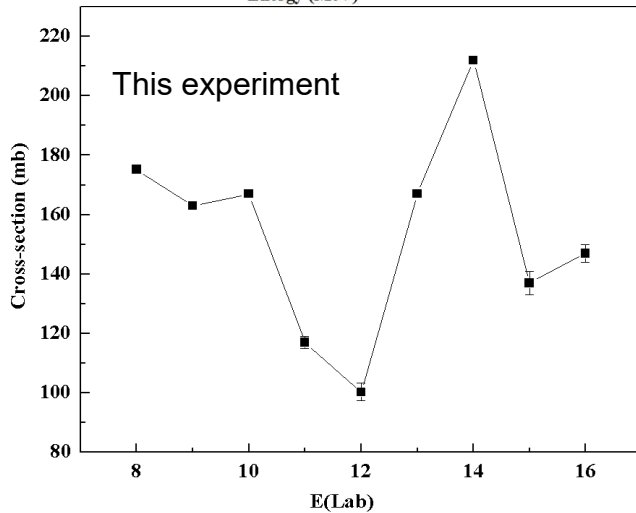
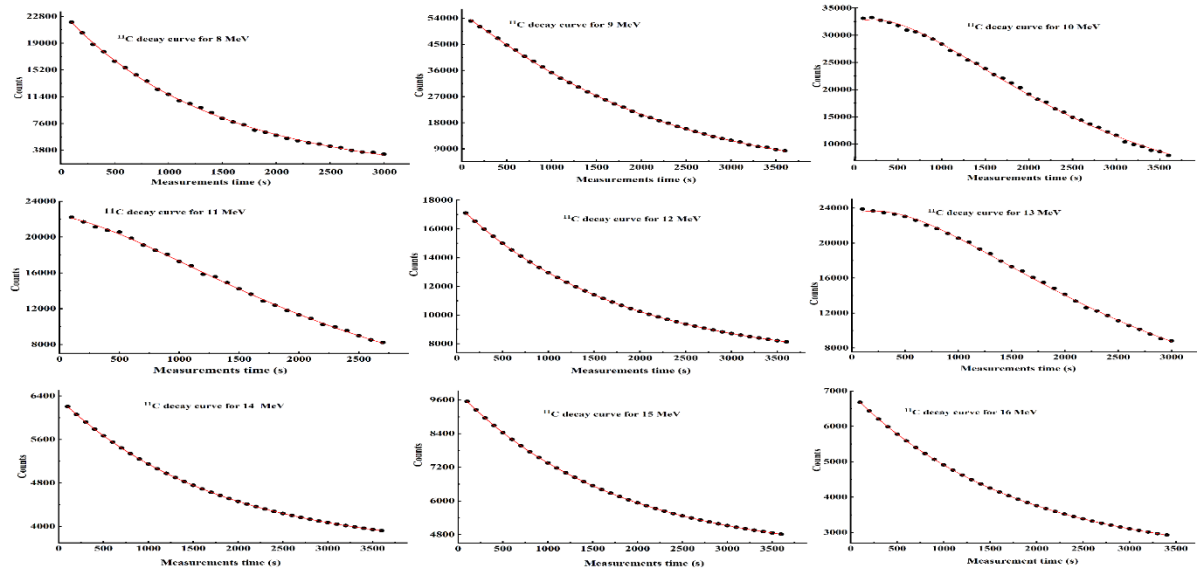
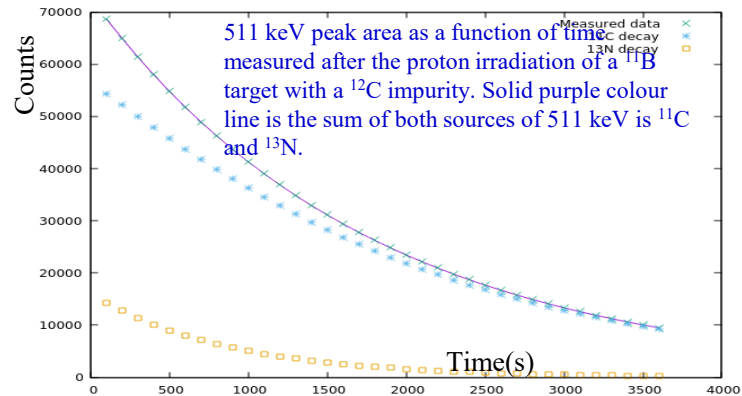
A. Kafkarkou et al., Phys. Rev C (2013)

- N^d is the number of ^{11}C nuclei
- t_m time of measurement
- Δt is the time gap between the end of irradiation and start of measurement
- n remanent from previous
- ε is total detection efficiency and N_t is target thickness

$^{11}\text{B}(\text{p},\text{n})^{11}\text{C}$ reaction

Reaction of Considerable Significance for Multiple Reasons

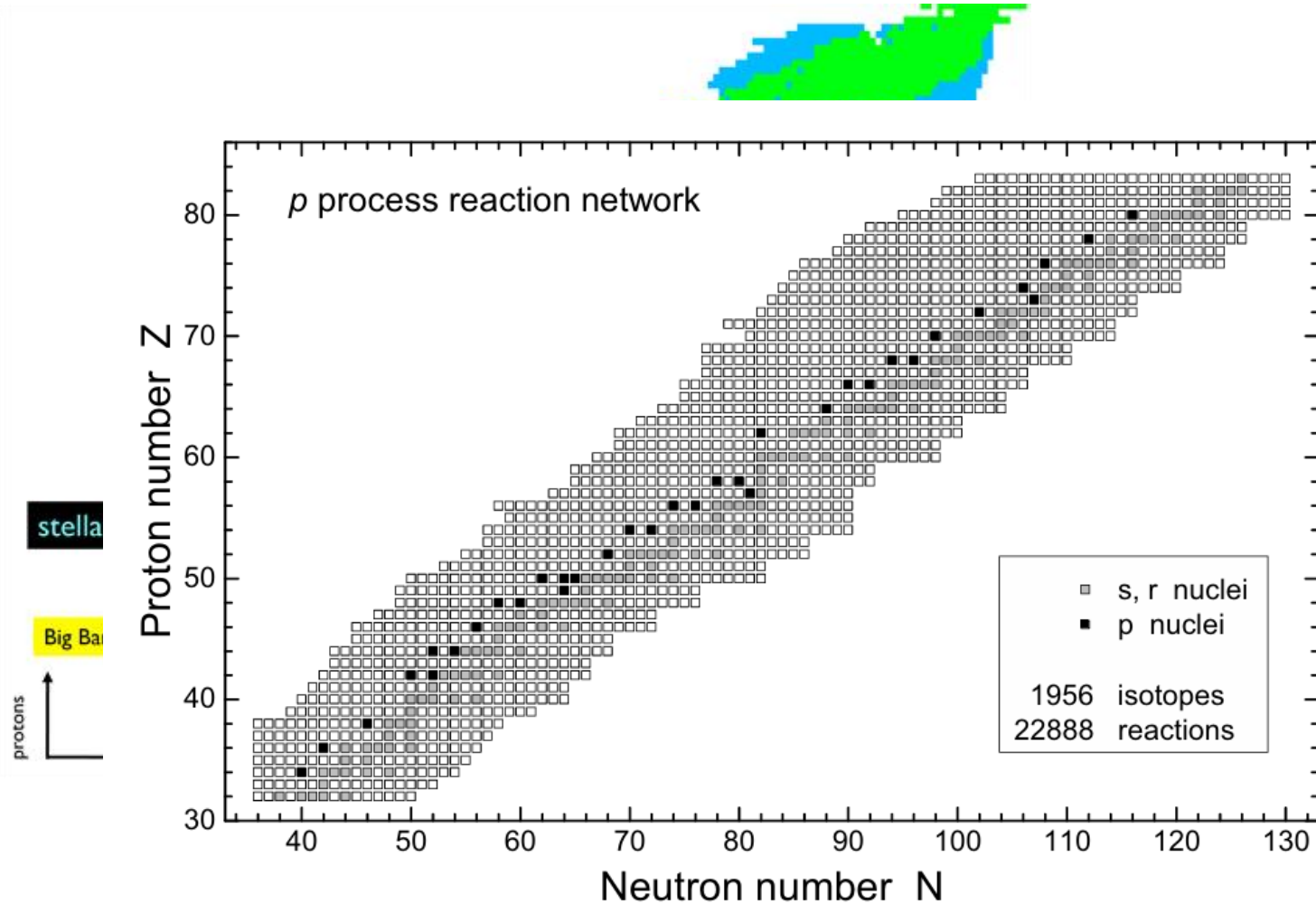
Measured from 8 to 16 MeV



Panwar, Mazumdar et al (Under review)

p Capture reactions Continues
The production of the p -nuclei

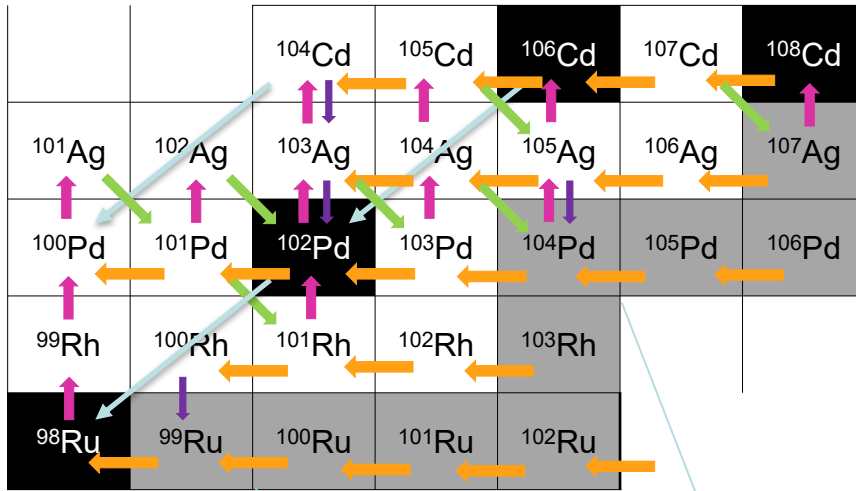
Different processes happening within the stellar environment



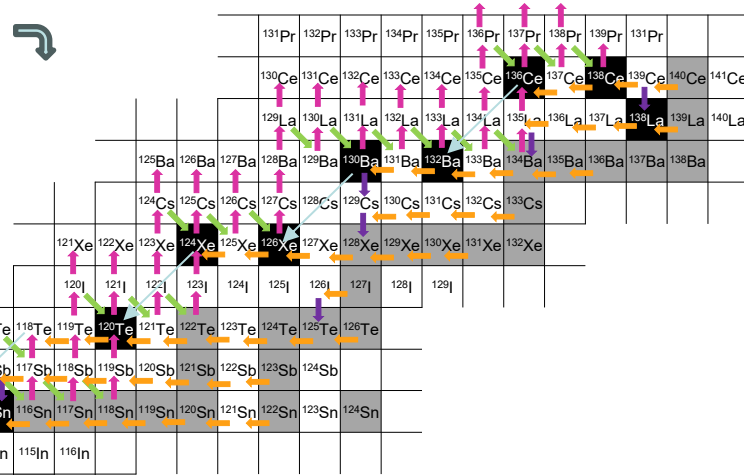
Harissopulos, EPJ, 2018

<https://goo.gl/images/UnXSUY>

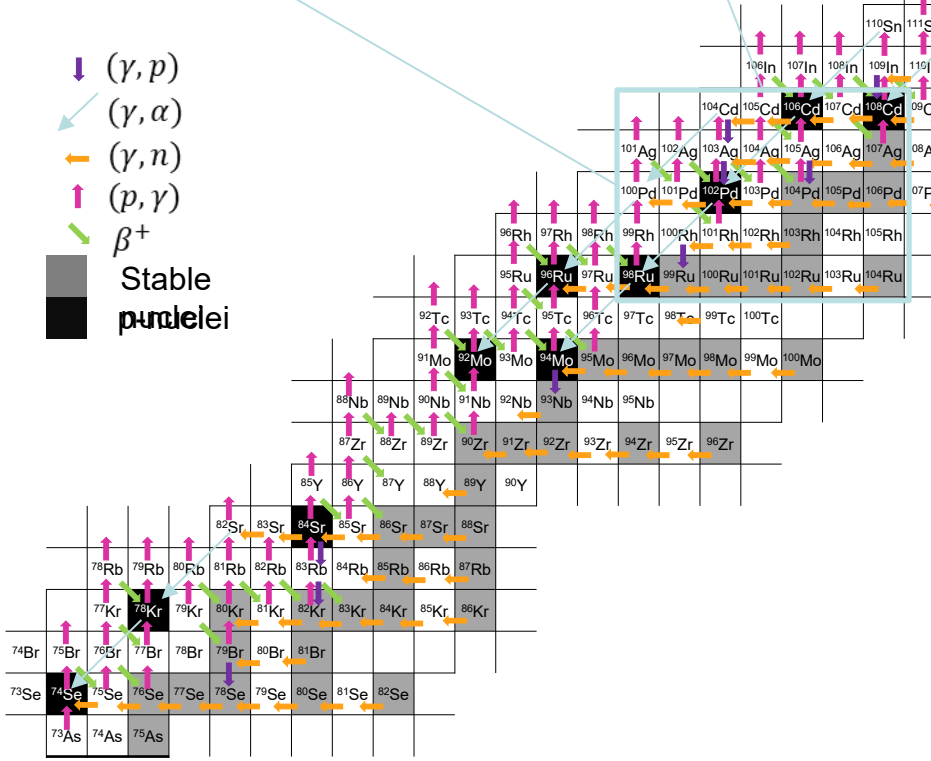
p-process path



Part of the Segre chart including 2/3 no of p-nuclei



- ↓ (γ, p)
- ↙ (γ, α)
- (γ, n)
- ↑ (p, γ)
- ↘ β^+
- Stable nuclei



- Key reactions
- Experimental scope

Summary of our very recent measurements

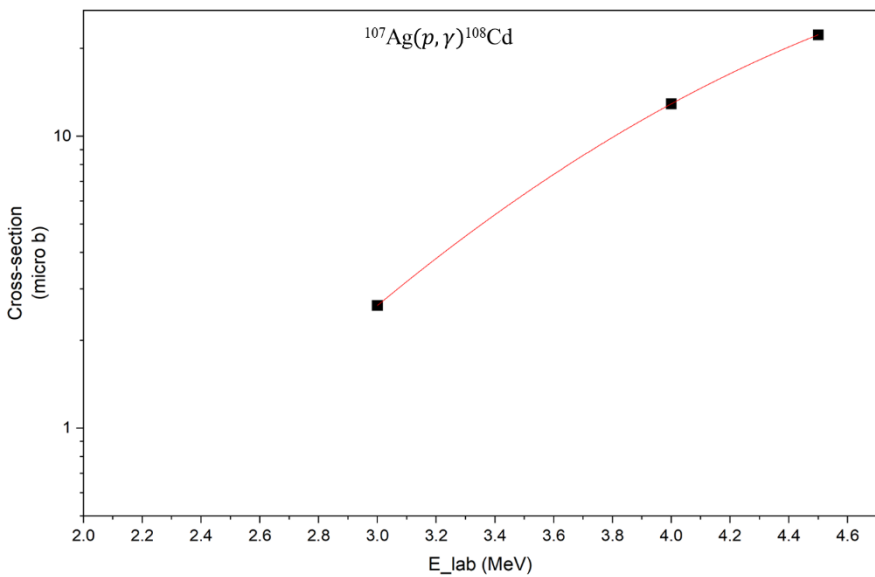
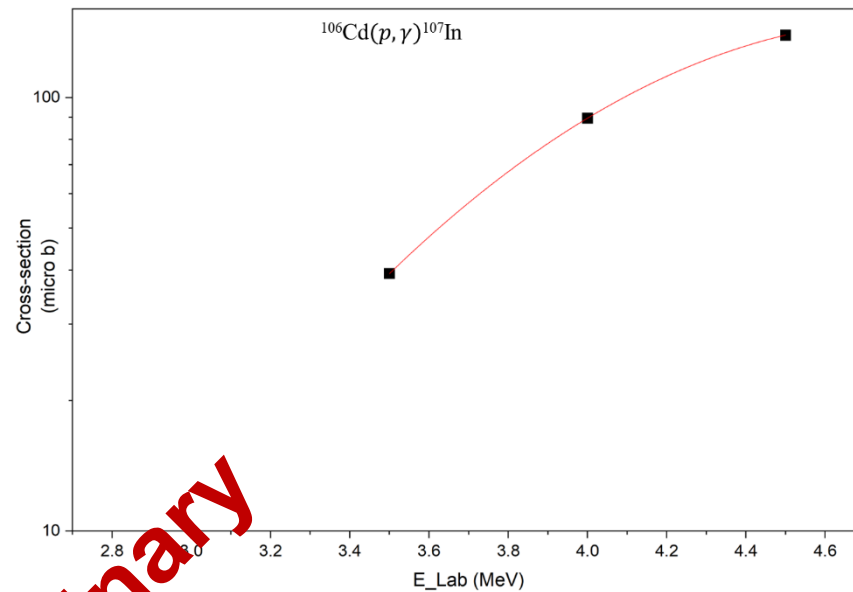
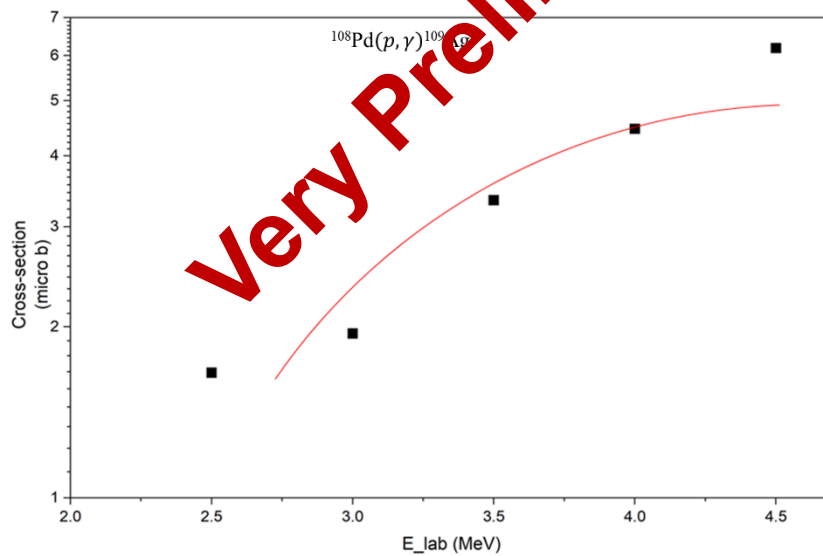
Reaction	Coulomb barrier (MeV)	Gamow window (MeV)
$p + {}^{107}\text{Ag}$	9.813	1.60 – 4.70
$p + {}^{106}\text{Cd}$	10.048	1.63 – 4.77
$p + {}^{108}\text{Pd}$	9.580	1.58 – 4.65

All the three measurements are carried out at the BARC-FOTIA Accelerator Facility.

Highly enriched isotopic targets used (> 96% or more)

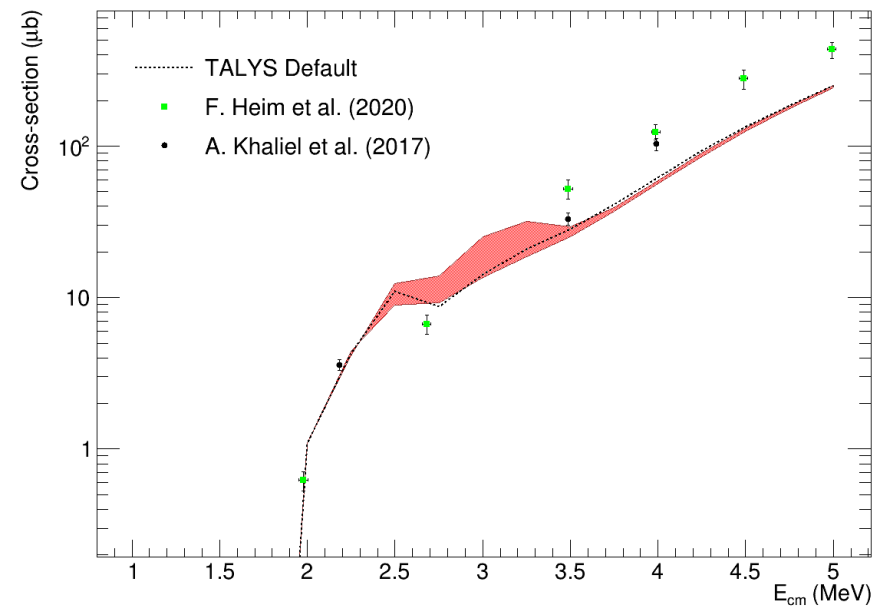
HPGe detector for γ -ray detection

Large volume Lanthanum Bromide for direct decay to ground state

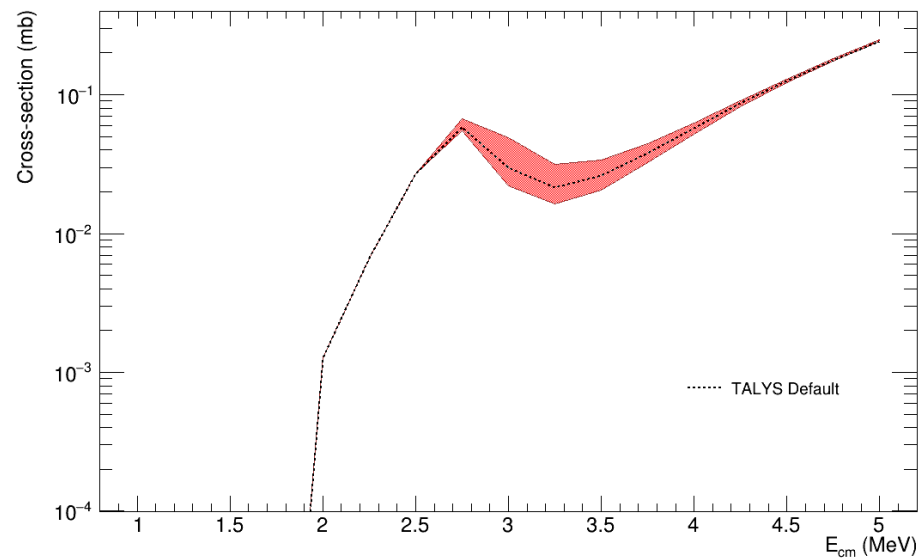


Very Preliminary

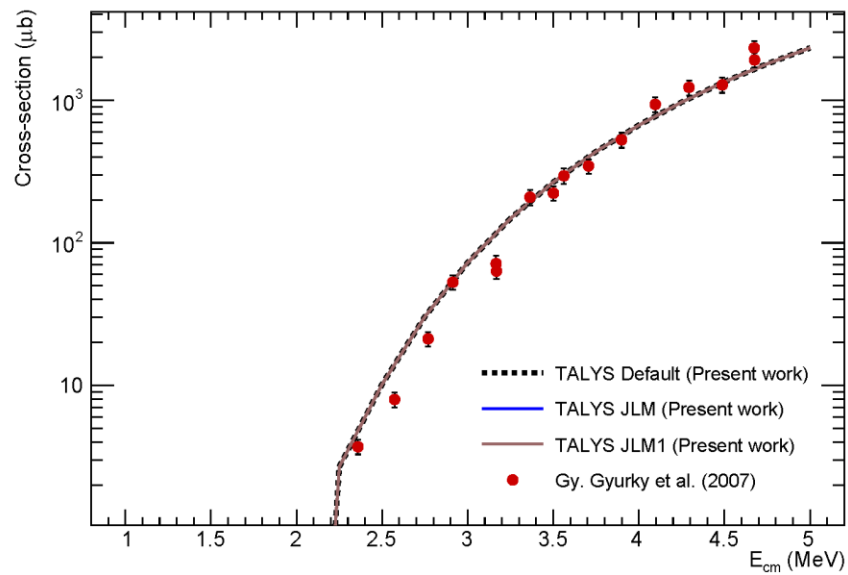
$^{107}\text{Ag}(p, \gamma)^{108}\text{Cd}$



$^{108}\text{Pd}(p, \gamma)^{109}\text{Ag}$



$^{106}\text{Cd}(p, \gamma)^{107}\text{In}$



Very Preliminary

Summary:

A composite program being pursued to study,

1) nuclear structure & reaction 2) elemental abundance in ISM, 3) nucleosynthesis

A large body of new data on absolute cross sections of $(p, p' \gamma)$ reactions are generated

Cross sections are compared for both proton and alpha projectiles with same energies

A semi-microscopic formalism is developed:

Roles of channel couplings, resonances and deformations studied.

Capture cross sections for $d(p, {}^3\text{He} \gamma)$ measured at three BBN energies

Proton capture cross section of ${}^{10}\text{B}(p, \gamma){}^{11}\text{B}$ reaction measured

(p, n) reaction cross section of ${}^{11}\text{B}(p, n){}^{11}\text{C}$ reaction measured

Efforts on to study reaction mechanisms for highly clustered nuclei

Absolute Proton capture cross sections on the p-nuclei path are measured

The Road Ahead:

Need of more measurements with weakly bound & nuclei with cluster structure

Need for exclusive particle gamma coincidence measurements

Reduction of parameter space for OM analysis, moving toward semi-microscopic approach

Systematic measurements of proton & neutron capture reactions to study p-nuclei formation
More measurements of BBN reactions

A definite need for reviving low and medium energy nuclear spin physics,
Polarised beam/target facilities

Global collaborations of experimental and theoretical groups

Acknowledgement

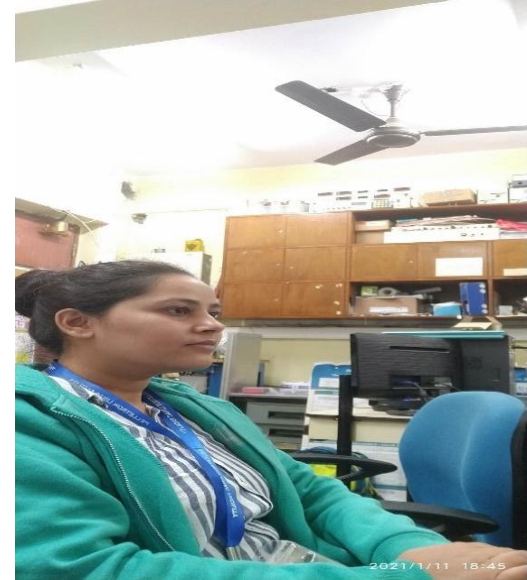
M. Dhibar
S. Panwar
V. Ranga
P. Saha
A.K.Gourishetty
L.C. Tribedi

S. P. Weppner

Florida & Ohio

S M Patel TIFR
P B Chavan TIFR

TIFR Pelletron Facility
TIFR ECR Facility
VECC NP Group
BARC FOTIA Facility
Duke TUNL Facility



N-N interaction Studies with Light Ion Probes:

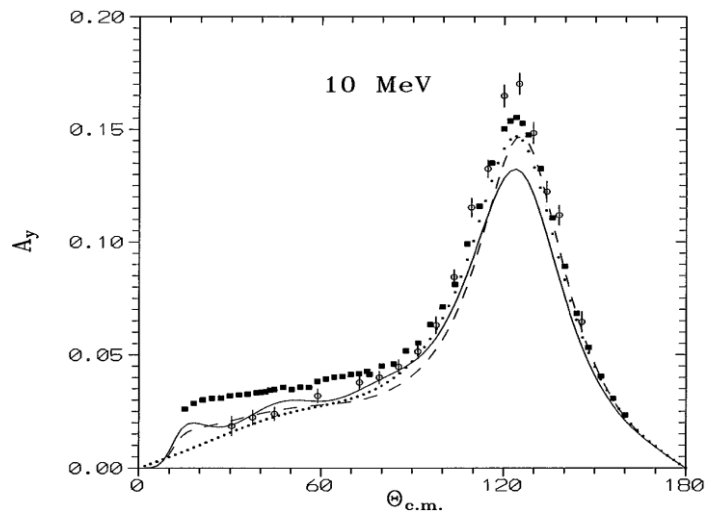
Measurements with polarized beam and targets:

cross sections, angular distributions, analyzing powers

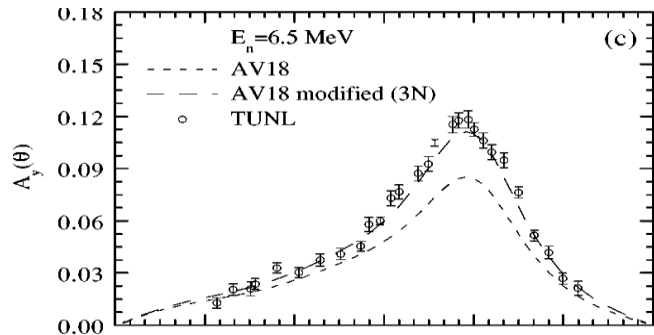
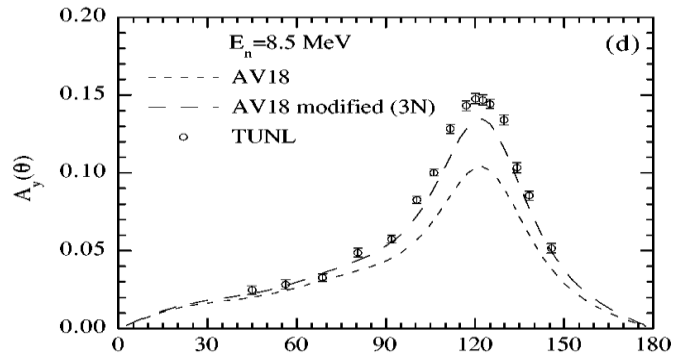
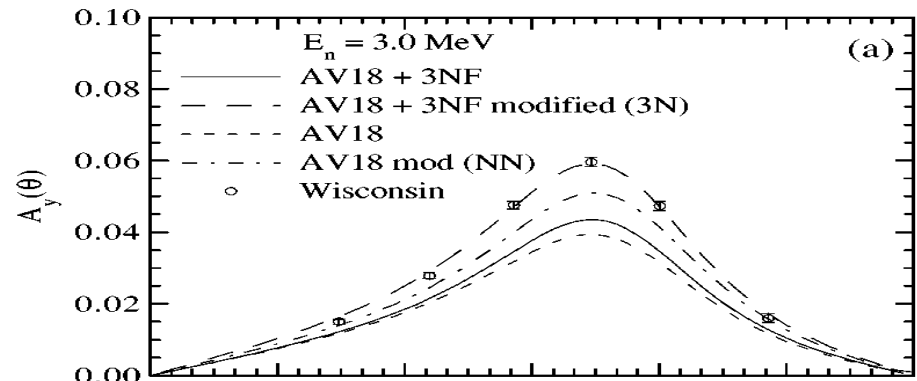
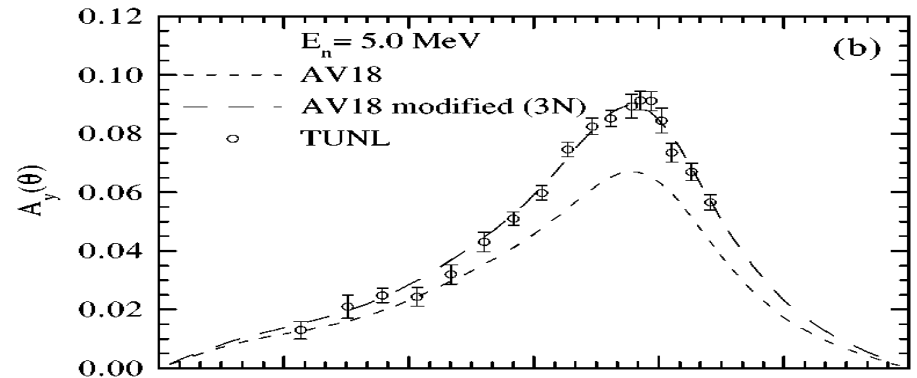
elastic and inelastic scattering experiments, breakup reactions

To understand 1) N-N interactions, 2) Search for 3-body force

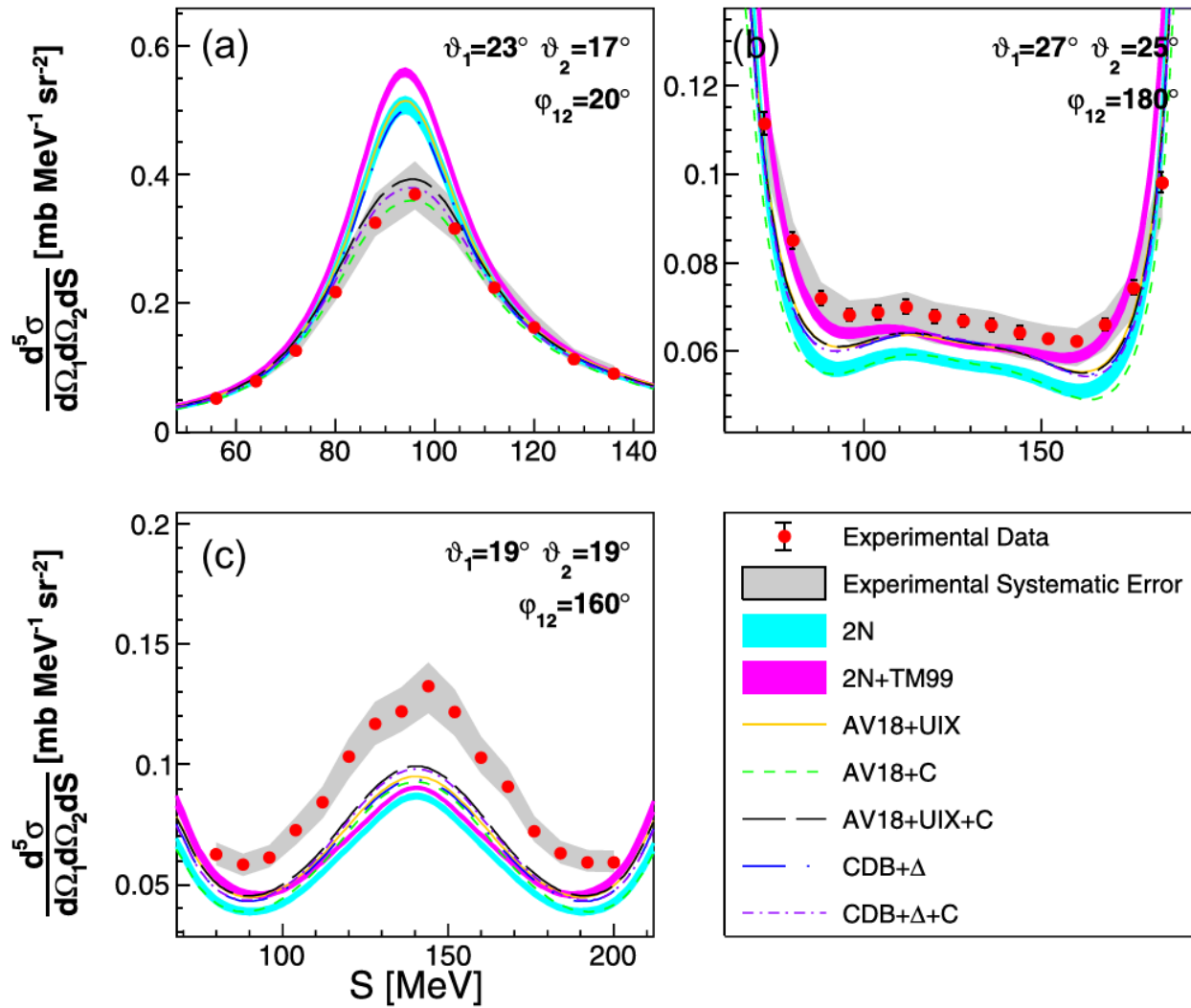
3) outstanding unsolved problems like A_y puzzle



p + d Analysing Power



n + d Analysing power



W. Parol et al., Phys Rev C 102 (2020)
p-d breakup at 160MeV

Thank You

