Electromagnetic radiation from the tiniest rotor ^{8}Be

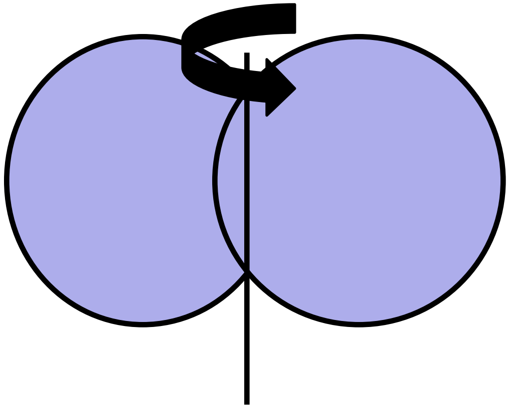
V.M. Datar

ex TIFR, BARC, Mumbai

spinning top

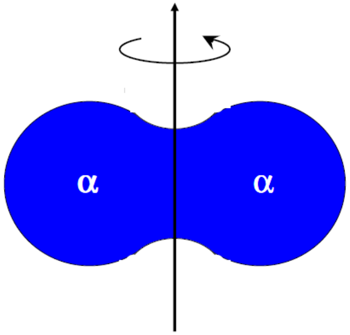
~5 cm

H_2



~ 10^{-8} cm

^{8}Be



~ 3.5×10^{-13}cm

Plan of talk

1. Introduction
2. EM transition from 4^+ to 2^+ in ^{8}Be
3. Results
4. Summary and future possibilities

1. Introduction

- Electromagnetic signals are "clean" probes of nuclei

  However, when in competition with strong process, cross sections/branching is small ($< 10^{-3}$)

- ^{8}Be is unstable in the ground state ($\tau \sim 10^{-16}$ sec)

  $\Rightarrow$ electron scattering on it not possible

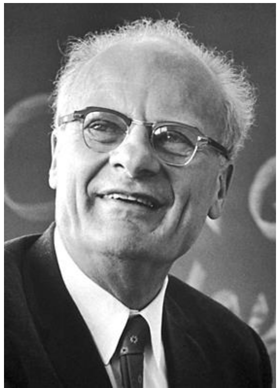
  γ-decay from excited states (resonances) possible but challenging

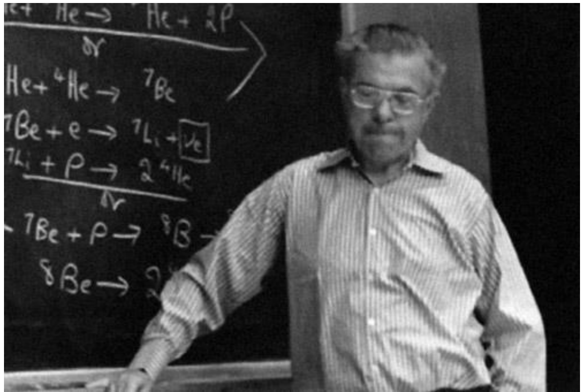
➢ **Nuclear Astrophysics**

^{8}Be important in stellar nucleo-synthesis of ^{12}C, ^{16}O,..

- ❑ 3-α reaction proposed by Bethe (1939)
- ❑ 2 step process: resonant production of ^{8}Be, then α-capture – Hoyle (1946), Opic (1952), Saltpeter (1953)
- ❑ Resonance in ^{12}C at ~7.6 MeV predicted – Hoyle (1953)

  Found by Dunbar et al (1953)



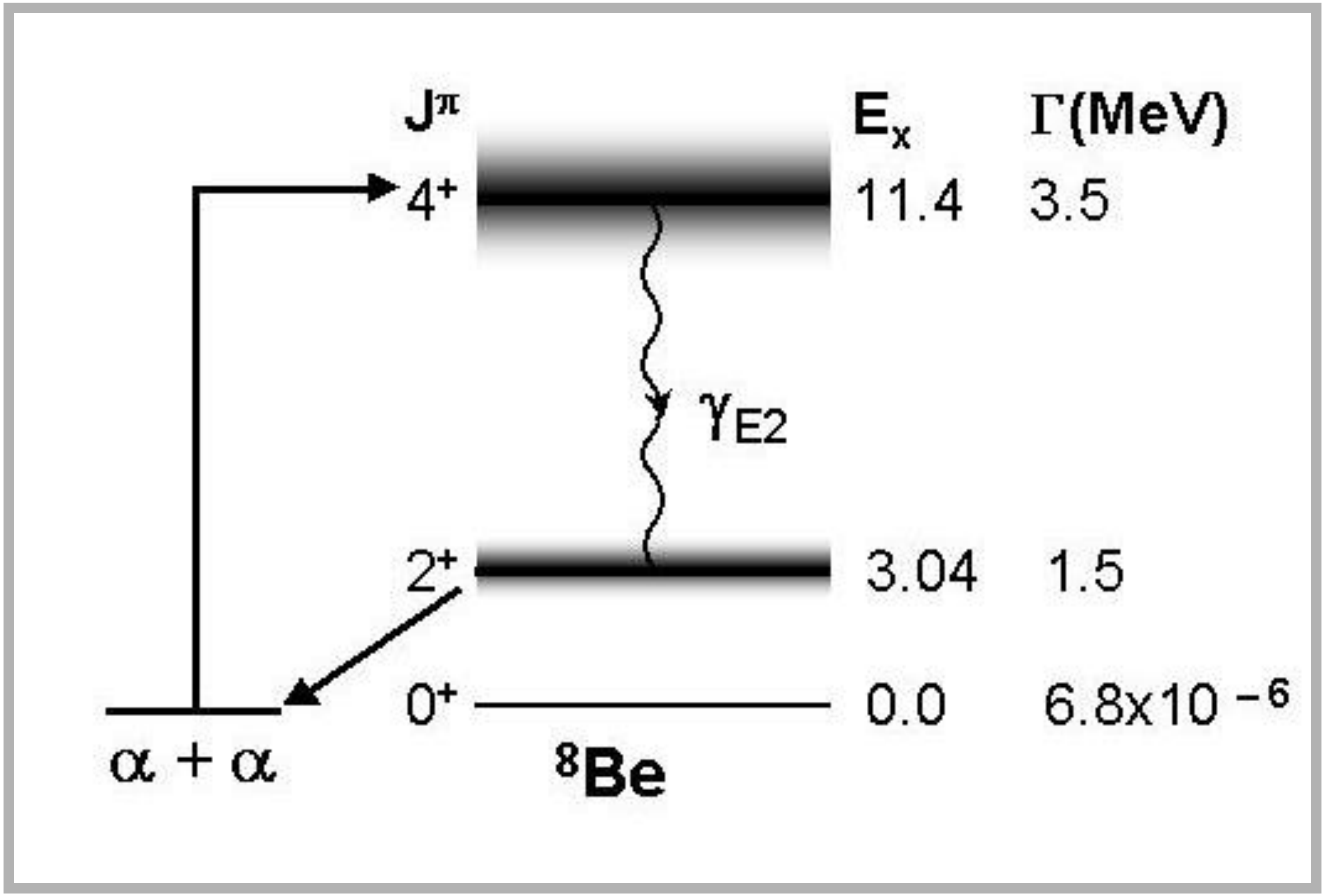


- **Clustering in nuclei** : α-clusters special

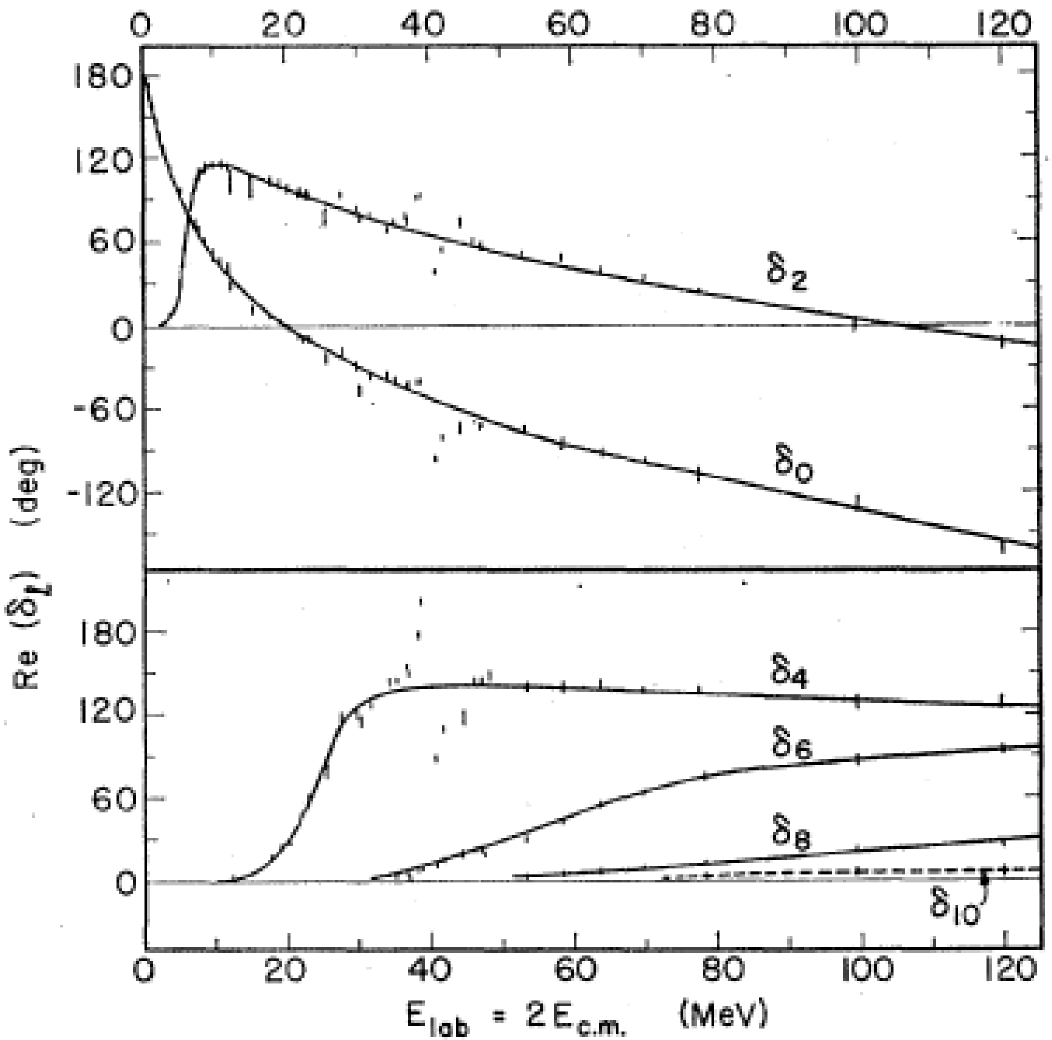
Binding Energy ~ 28 MeV, 1st exc. state @ 20 MeV

- ^{8}Be simplest α–cluster nucleus in (N=Z=2n) 4n nuclei and precursor to α–linear chain states (Ikeda)
- Energy and decay width indicative of structure (α-α) determined by **strong** interaction
- **Electromagnetic** observables provide stringent test of structure: e-scattering ($\times$), γ-ray transitions ($\surd$)

Partial level scheme of ^{8}Be



α–α (real) phase shifts from elastic scattering



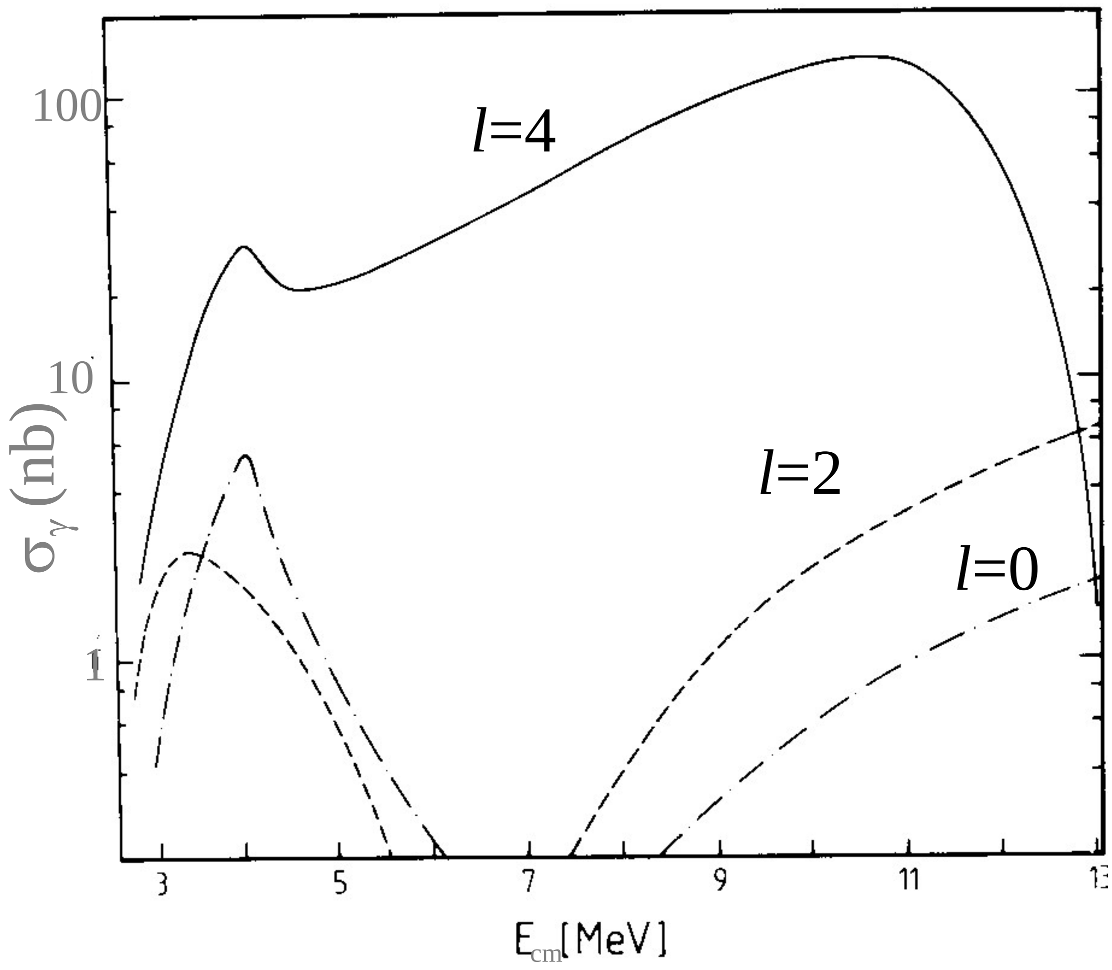
3.8-12 MeV : Tombrello (1963)

53-120 MeV: Darriulat (1965)

~10-50 MeV: Berztiss (p.c.)

Bohr and Mottelson,
Nuclear Structure Vol II

Capture cross-sections from initial α+α partial waves



σ_γ (10.8 MeV) ≈ 134 nb

⇒ $B(E2;4^+\rightarrow2^+) \sim 20$ W.u.

$B(E2;2^+\rightarrow0^+) \sim 75$ W.u.

Very large for A=8 system!

$B(E2) \propto Q_2^{\,2} \propto Z^2A^{4/3}$

	$B(E2)/Z^2A^{4/3}$
^{160}A (superdef)	0.11
^{8}Be	0.08 (0.30)

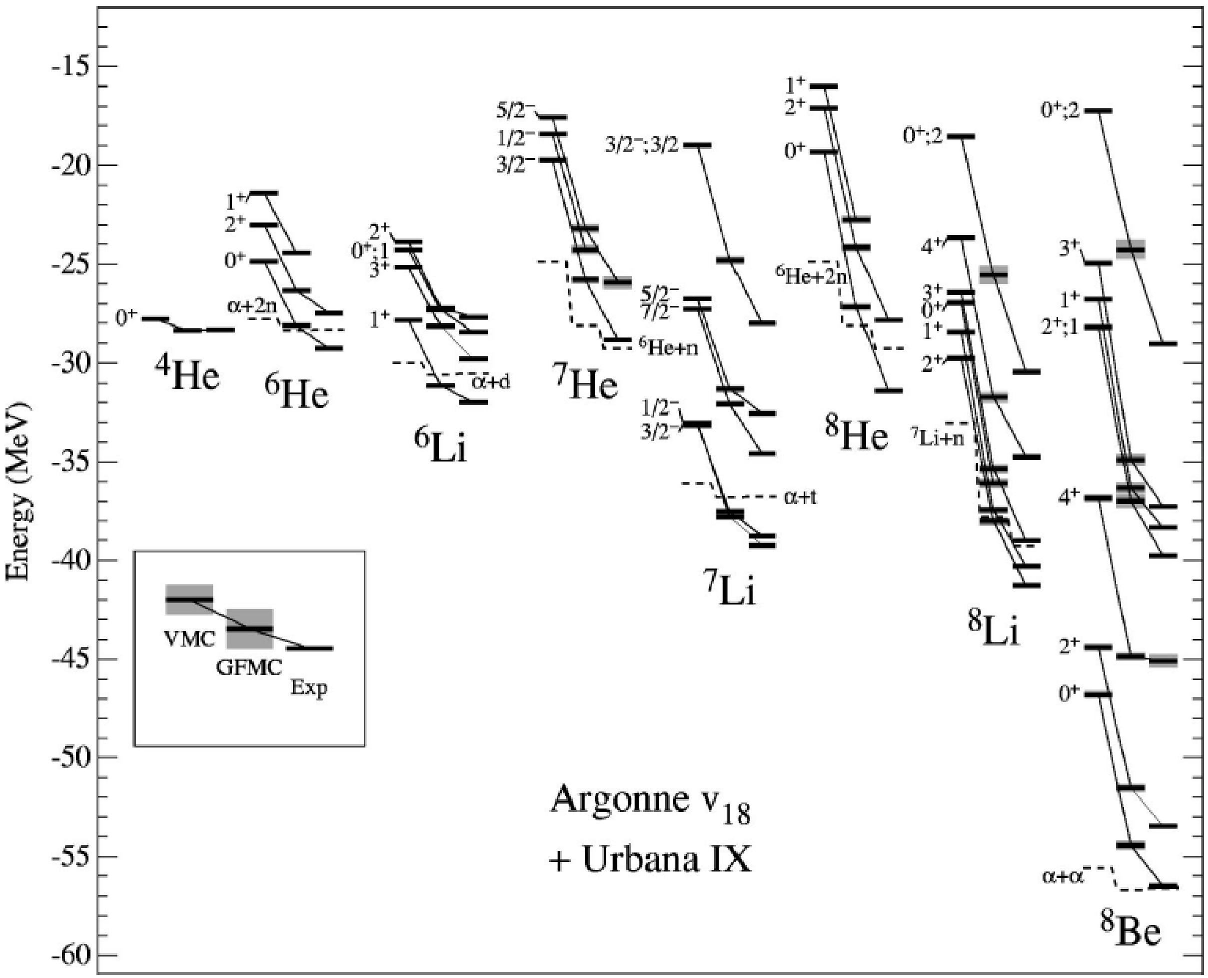
However, γ-branch ~ 10^{-7}

K. Langanke, C.Rolfs, Z.Phys. ***A324****, 307 (1986)*

K. Langanke, C.Rolfs, Phys. Rev. C ***33****, 790 (1986)*

Ab initio calculations by Argonne group

2-body potential: v_{18}, 3-body potential: Urbana IX

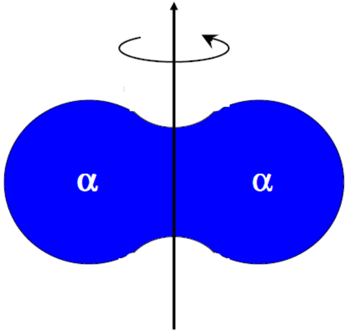


Variational Monte Carlo (VMC) + Green's Function Monte Carlo (GFMC)

Reduced transition probability for ^{8}Be $B(E2;4^+ \rightarrow 2^+) = 18.2 \pm 0.6\ e^2 fm^4$

Wiringa, Pieper, Carlson, Pandharipande, Phys. Rev. C **62**, 14001 (2000)

2. EM transition from 4^+-to-2^+ in ^{8}Be



- EM decay of 4^+ to 2^+ resonance in ^{8}Be observed for first time (~35% precision) *PRL **94**, 122502 (2005)*

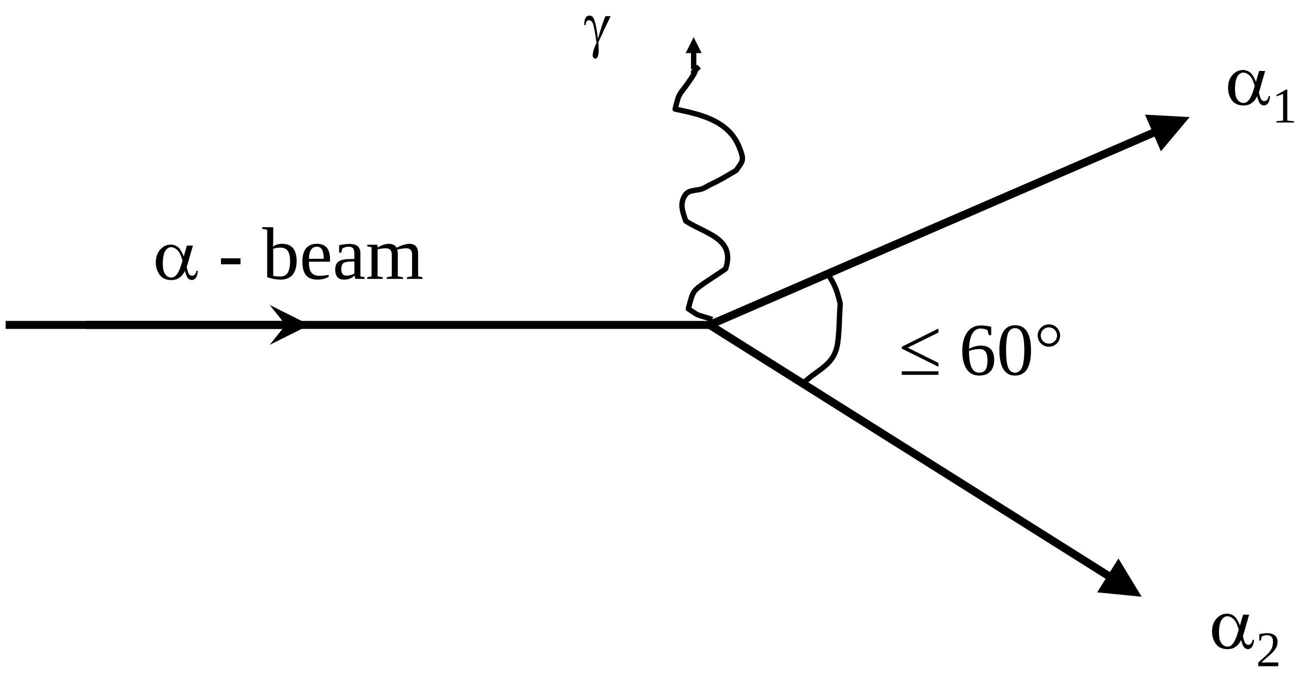
- α-cluster model and *ab initio* calculations of B(E2) differ by ~20% . An accurate measurement needed!

Schematic of method

α-beam on ^{4}He gas target

Measure γ-ray transition and alphas from 2^+ decay.

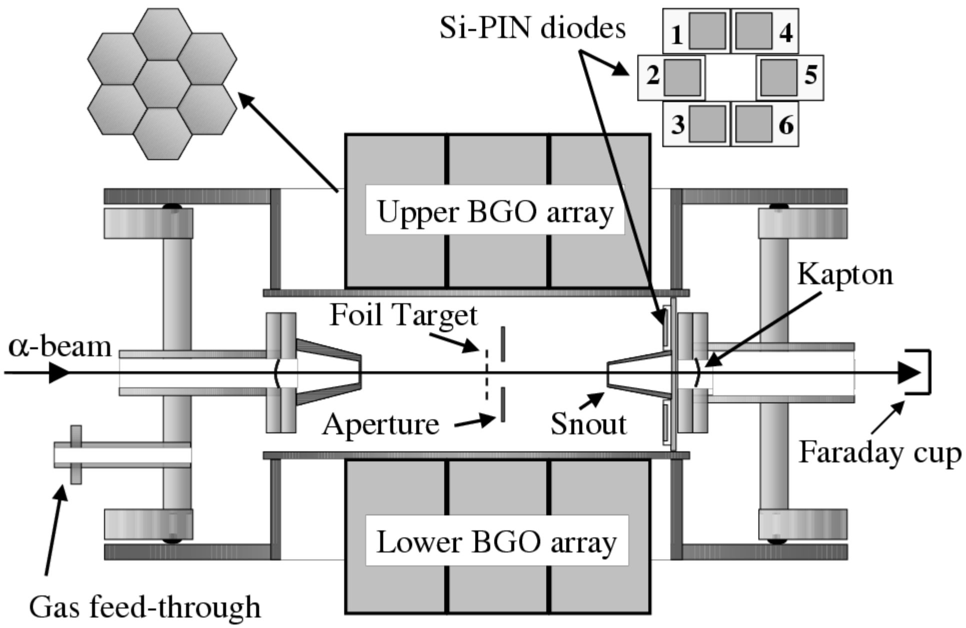
$\theta_{\alpha\alpha}$ smaller than about 60° compared to $\theta_{\alpha\alpha}$ (elastic) = 90°

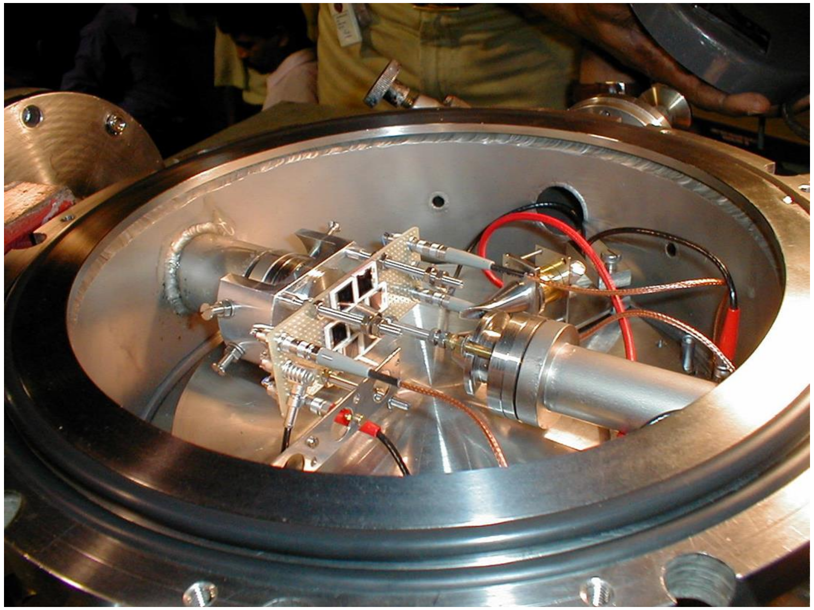


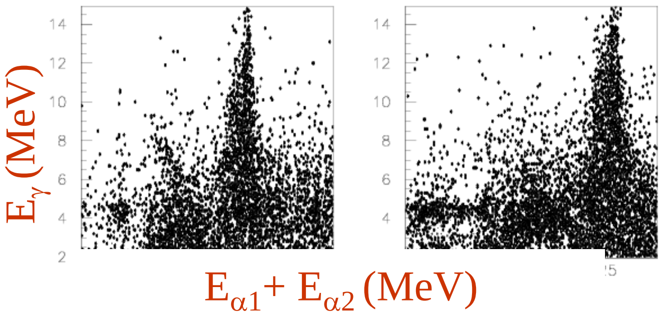
Pelletron LINAC Facility @ TIFR, Mumbai

14 MV Tandem (1988), SC Linac booster (2002/2007: 3/7 modules)

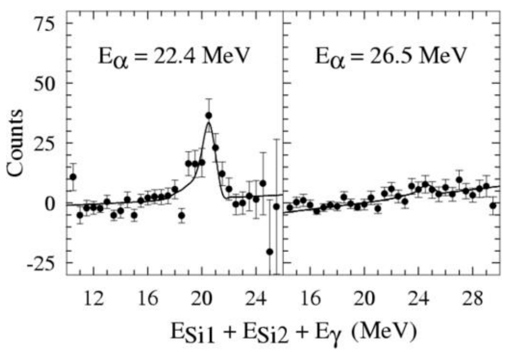
First measurement reported in 2005







2D spectra On, Off resonance



E_{sum} spectra On, Off resonance

	Expt	Cluster model	QMC
σ_γ (22.4 MeV)	165 ± 54	134 nb	
σ_γ (26.5 MeV)	39 ± 26	12 nb	
Γ_γ (eV)	0.53 ± 0.17	0.45	
B(E2) e^2fm^4	25 ± 8	21.9	18.2 ± 0.4 (*Wiringa 2000*)
			26.0 ± 0.6 (*Wiringa , p.c. 2004*)

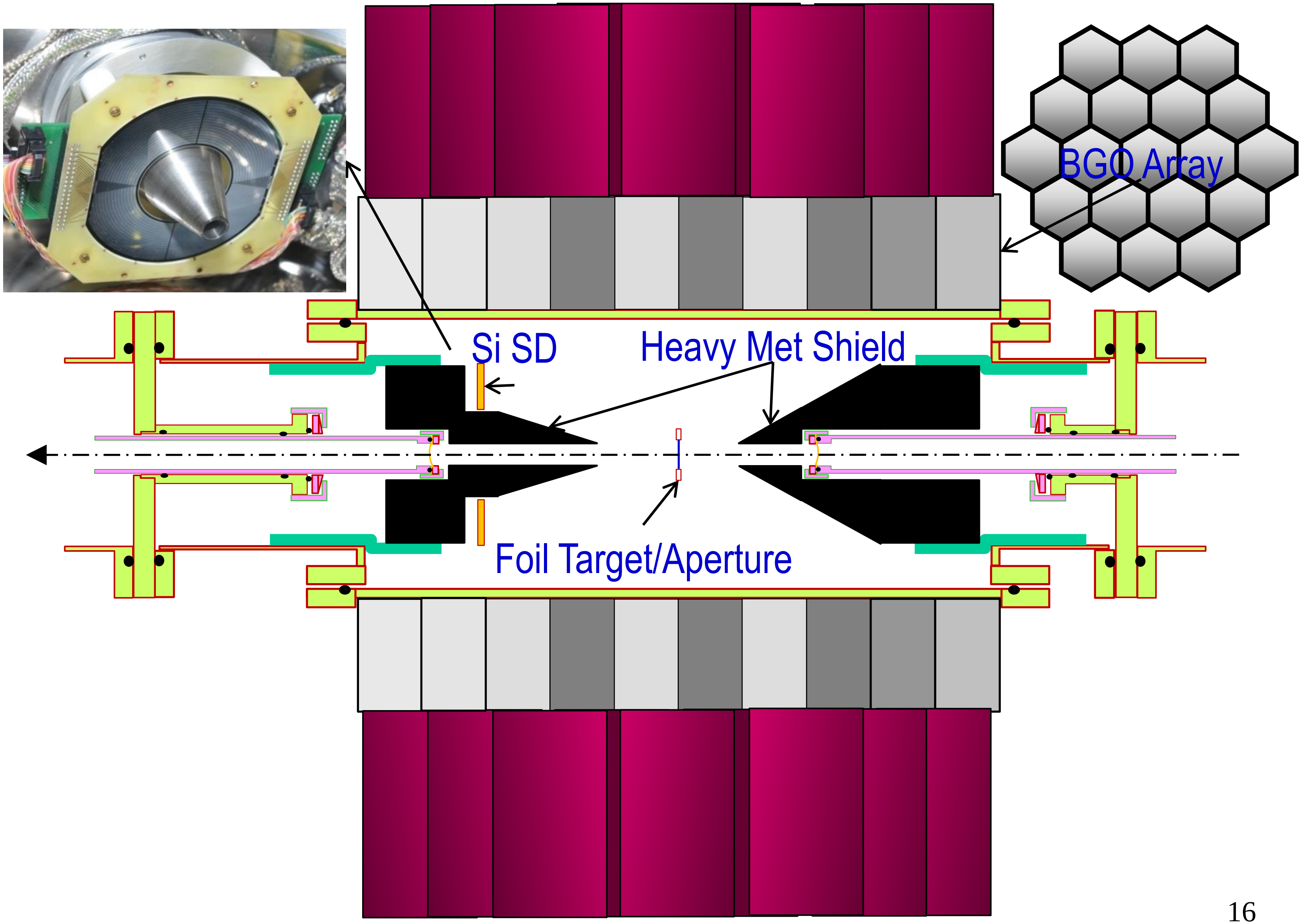
V.M. Datar, Suresh Kumar, D.R. Chakrabarty, V. Nanal, E.T. Mirgule, A. Mitra and H.H. Oza, Phys.Rev.Lett. ***94****, 122502 (2005)*

A first observation but *large errors (33% on resonance)*

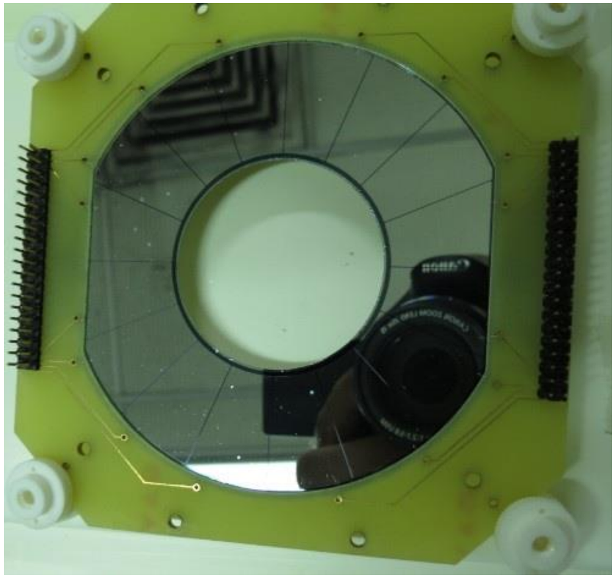
Details of improved experiment

- Expt at Pelletron Linac Facility, TIFR, Mumbai
- **^{4}He beams at 4 energies across 4^+ resonance**
- ^{4}He gas target (isolated by 1 mg/cm^2 Kapton)
- **α-particles detected in annular Si strip detector** (16 θ L/R, 16 ϕ) 500 μm thick, 48 mm ID, 96 mm OD
- γ-rays in **2×19** hex. Bismuth Germanate (BGO) dets.
- **Heavymet shield** around Kapton windows
- Limiting aperture of 24 mm dia to shield scattered beam

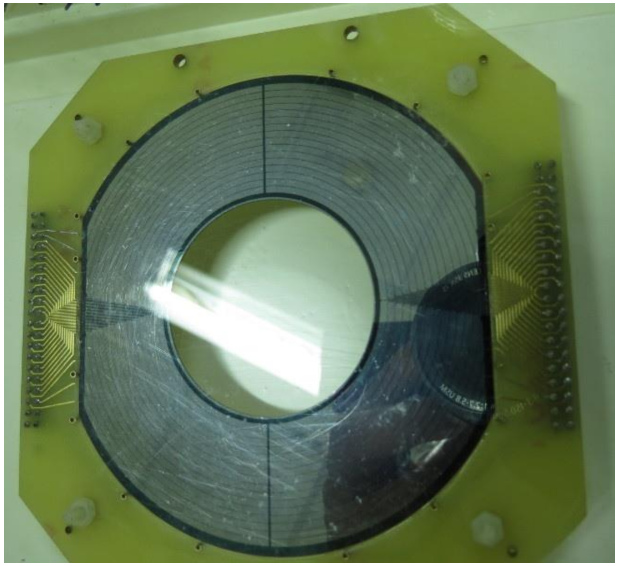
Schematic of experimental setup



Detectors: BGO array (γ), Si-strip detector (α_1, α_2)

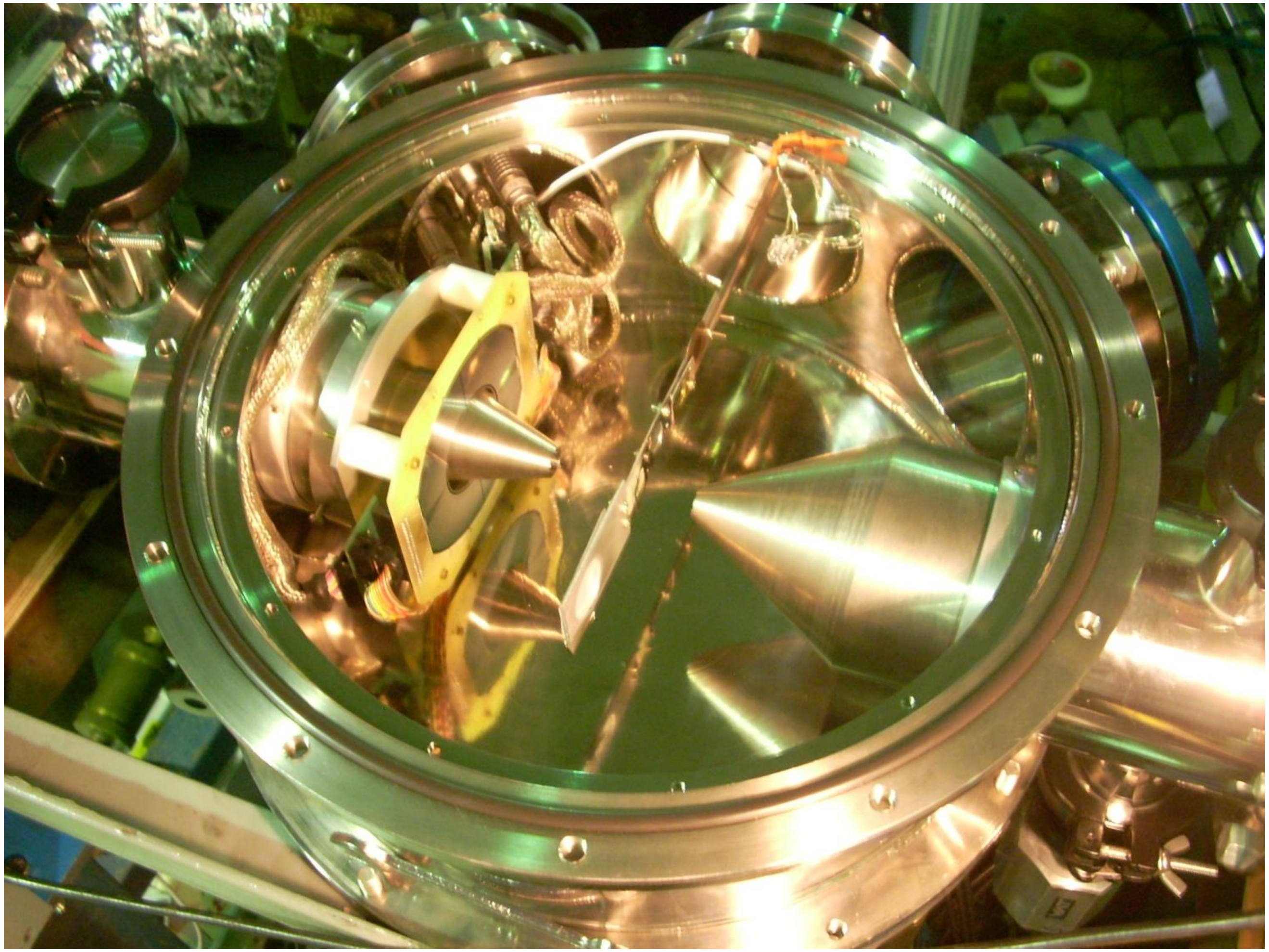


16 φ sectors



2×16 θ rings (2L + 2R quadrants)

Gas target chamber with SiSD and heavymet shield

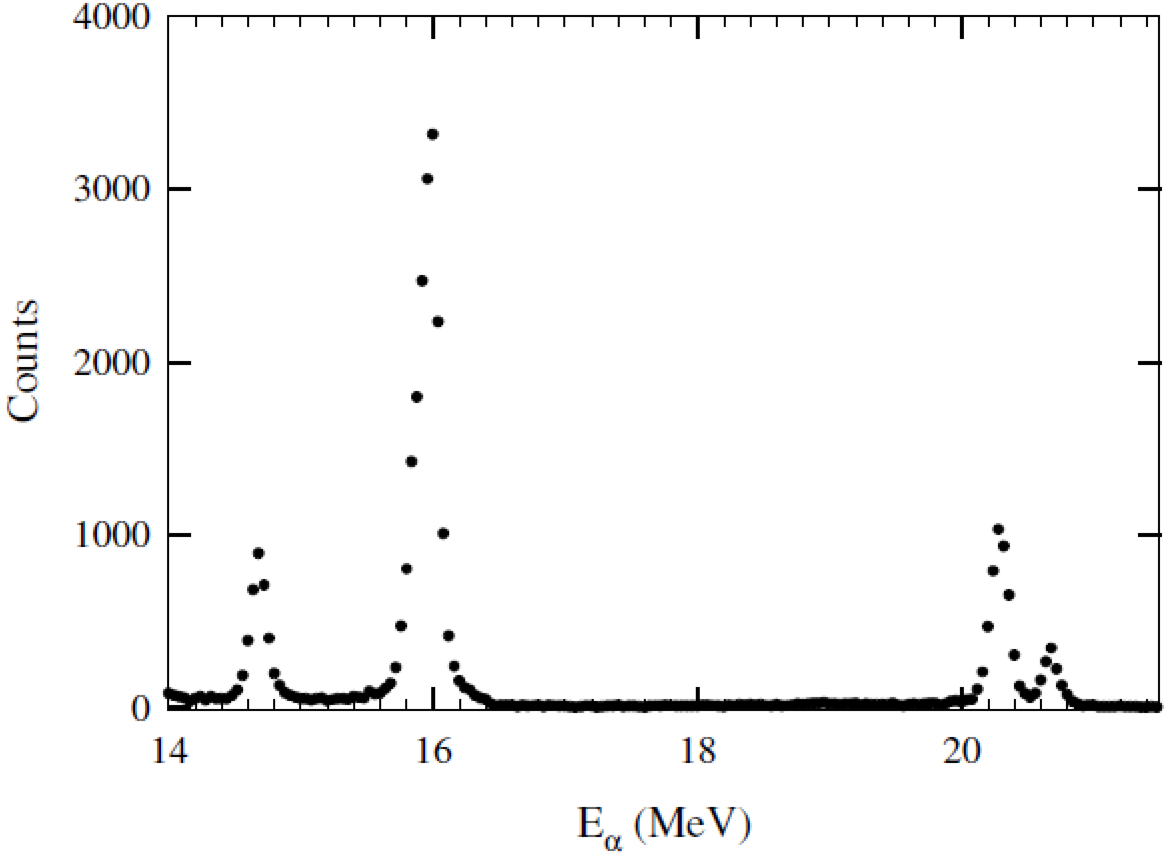


3. Results

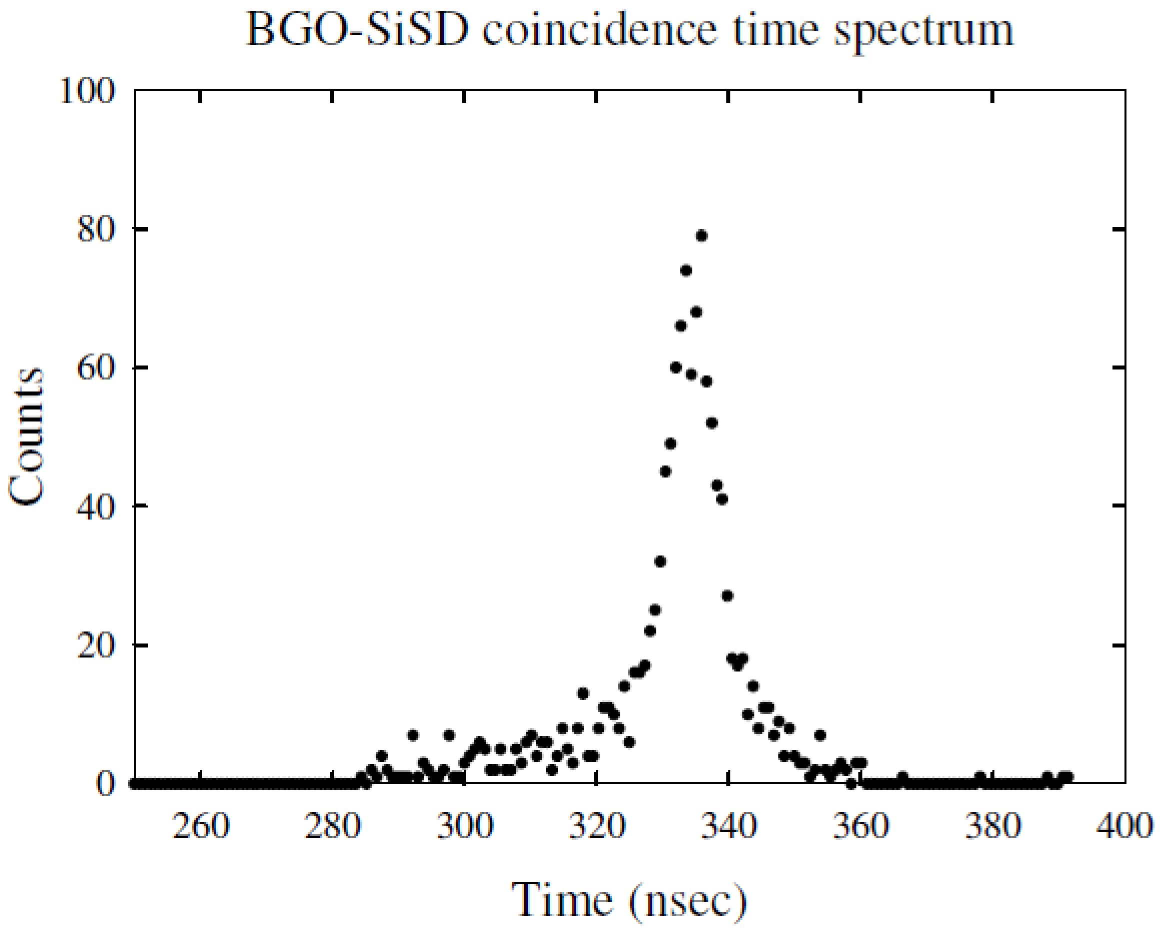
Some spectra…α calibration spectra in DSSD

α + mylar (^{12}C, ^{16}O) at E_α = 22.5 MeV

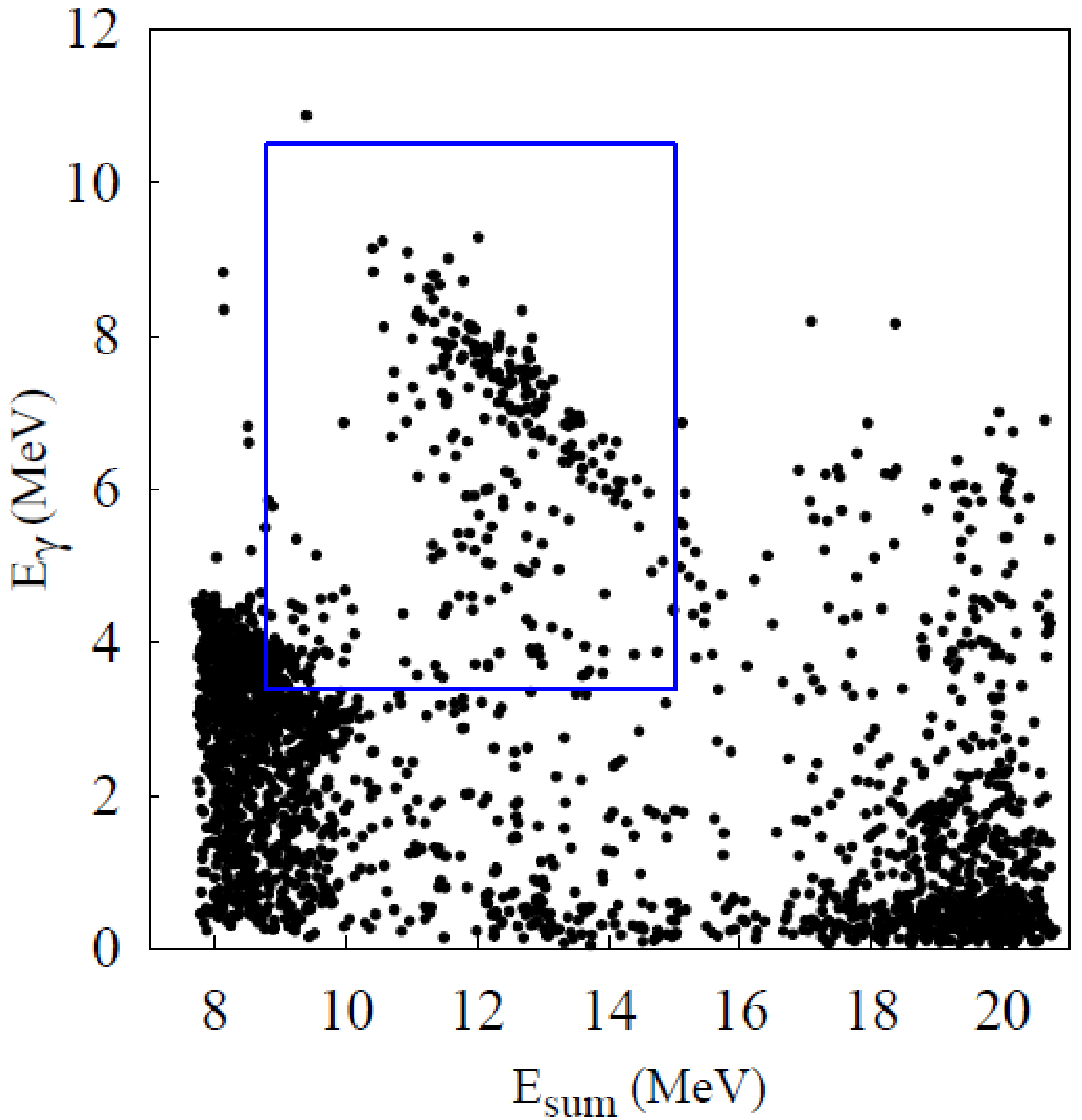
Left θ ring#6



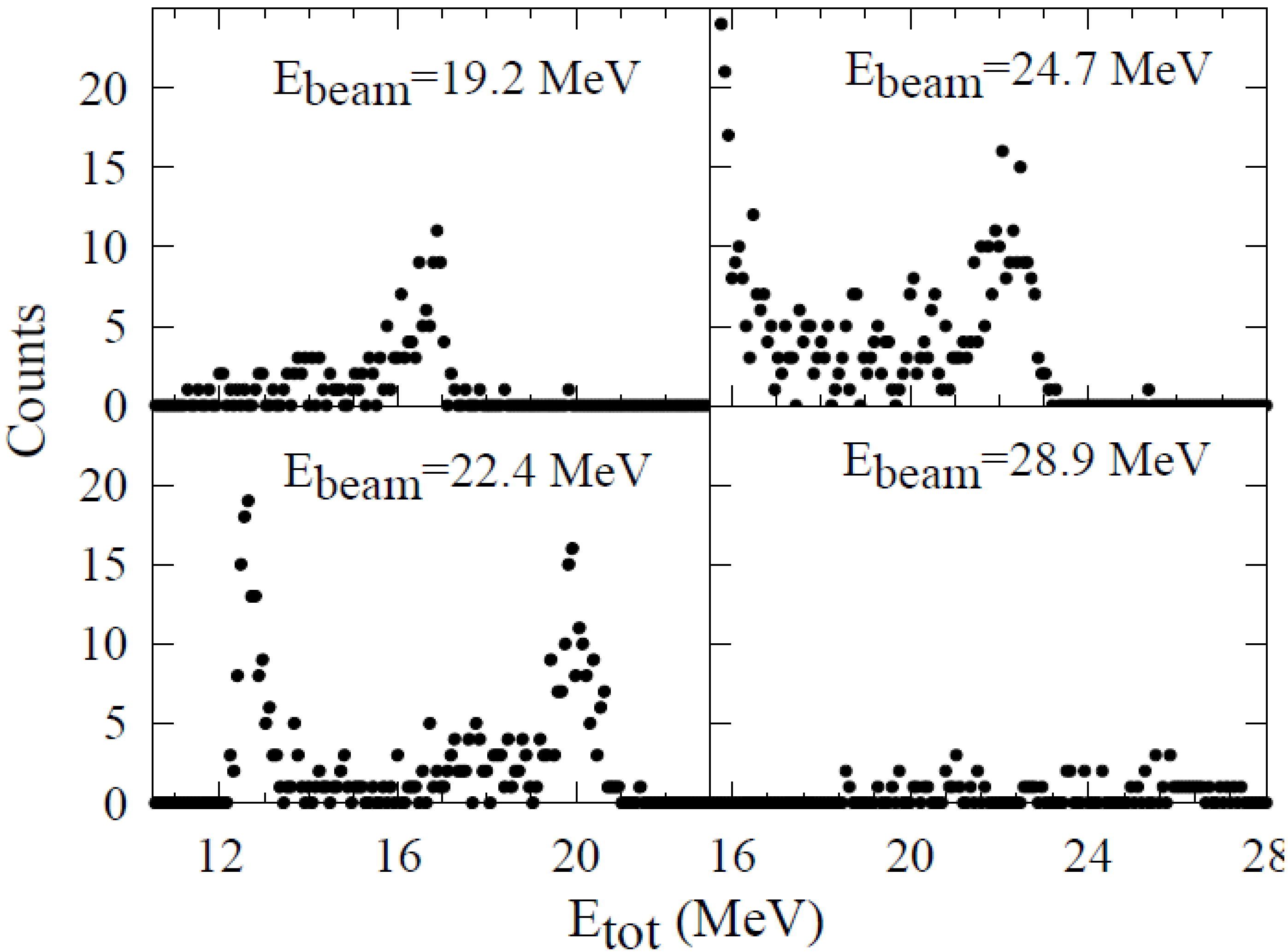
Prompt time spectra between DSSD and BGO



Gated 2D spectrum at E_{beam}= 22.4 MeV

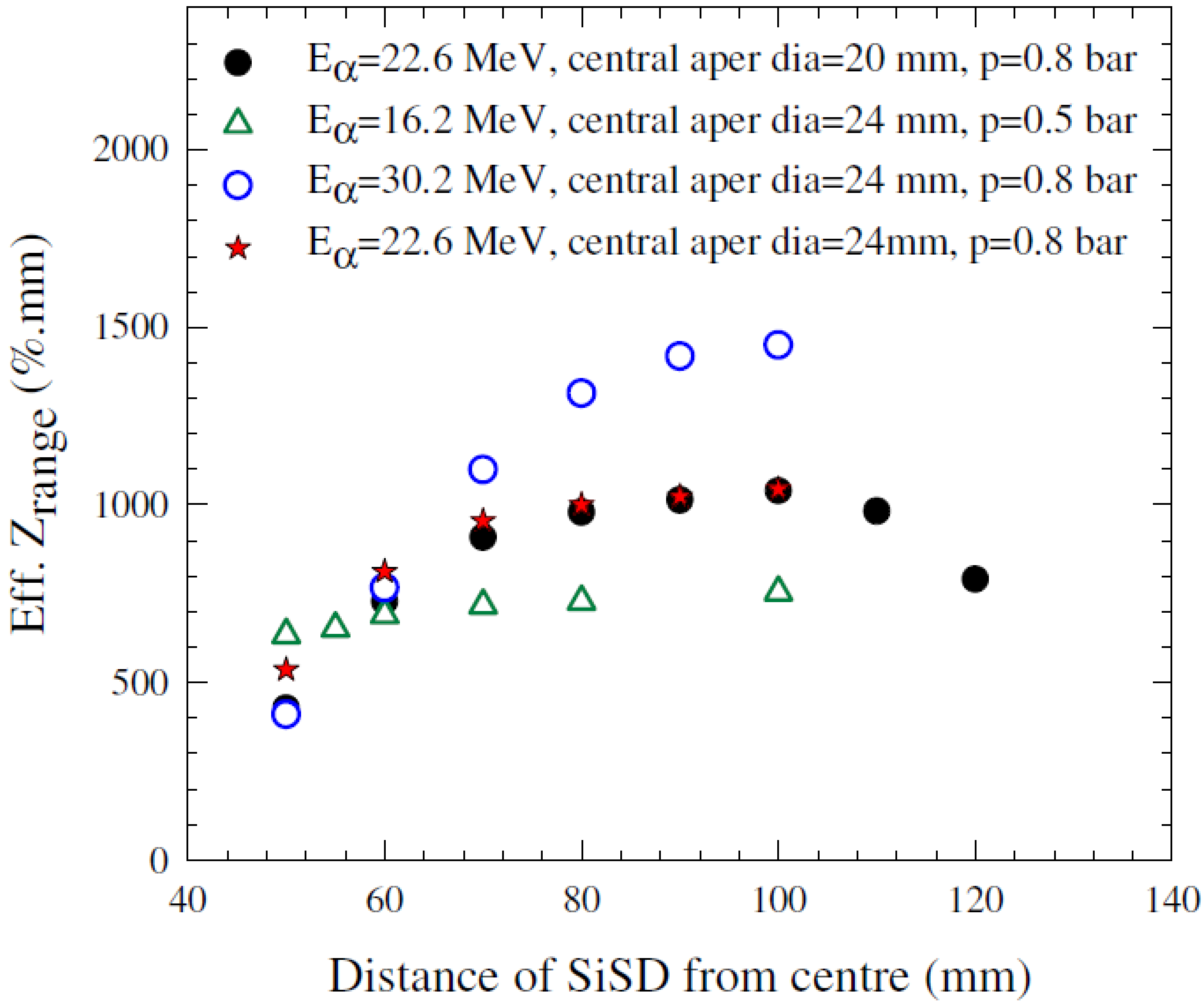


$E_{\alpha 1}+E_{\alpha 2} + E_{\gamma}$ sum energy plots at 4 beam energies



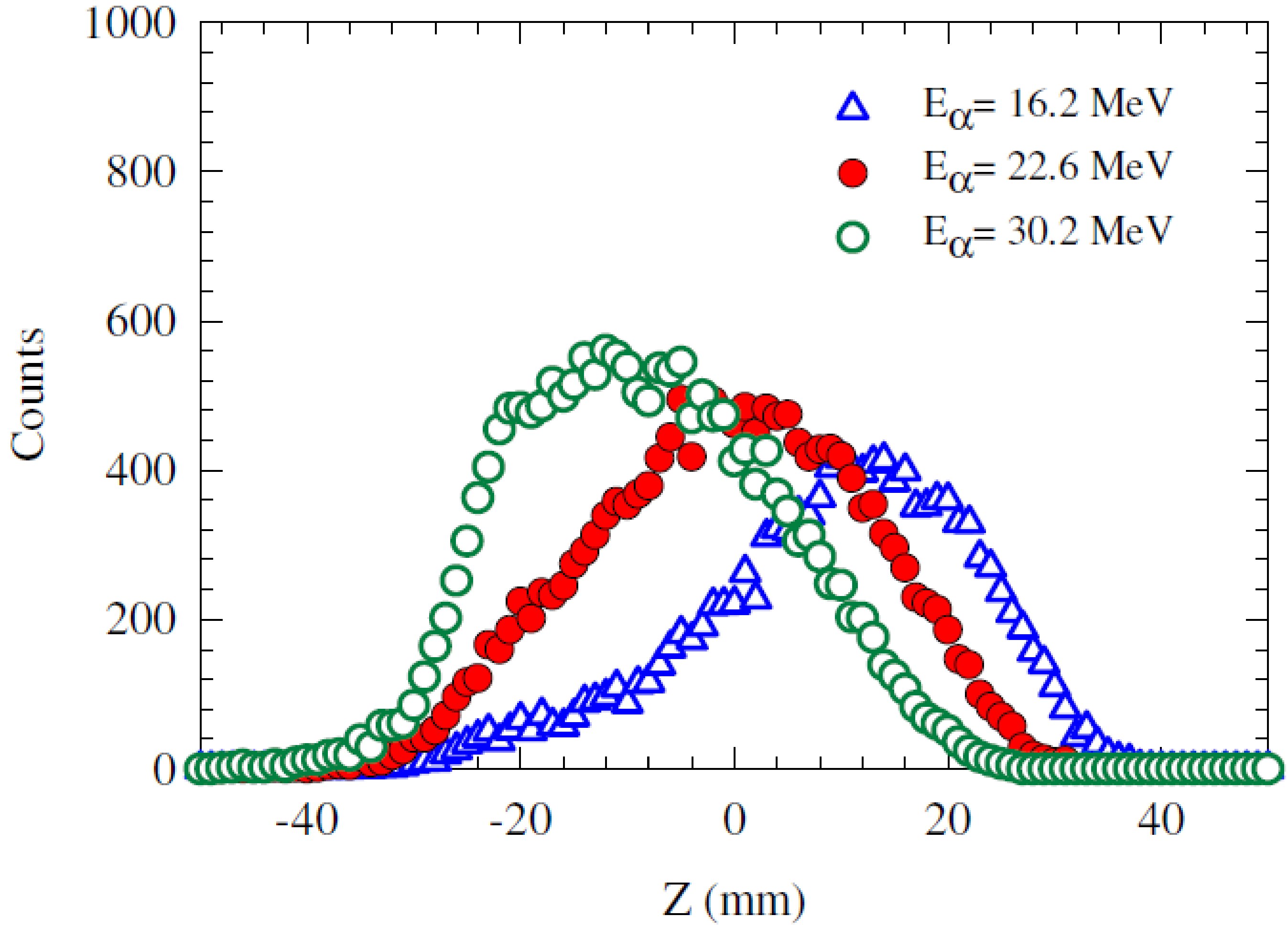
Monte Carlo simulation & data reduction

- Monte Carlo simulation of setup including
- extended gas target, aperture
- energy loss of beam and decay αs
- angular distribution of 4^+ to 2^+ γ-rays, decay αs
- γ-ray response in BGO array (GEANT 3.1)
- Identical gates on simulated and actual data for arriving at radiative capture cross sections at 4 beam energies

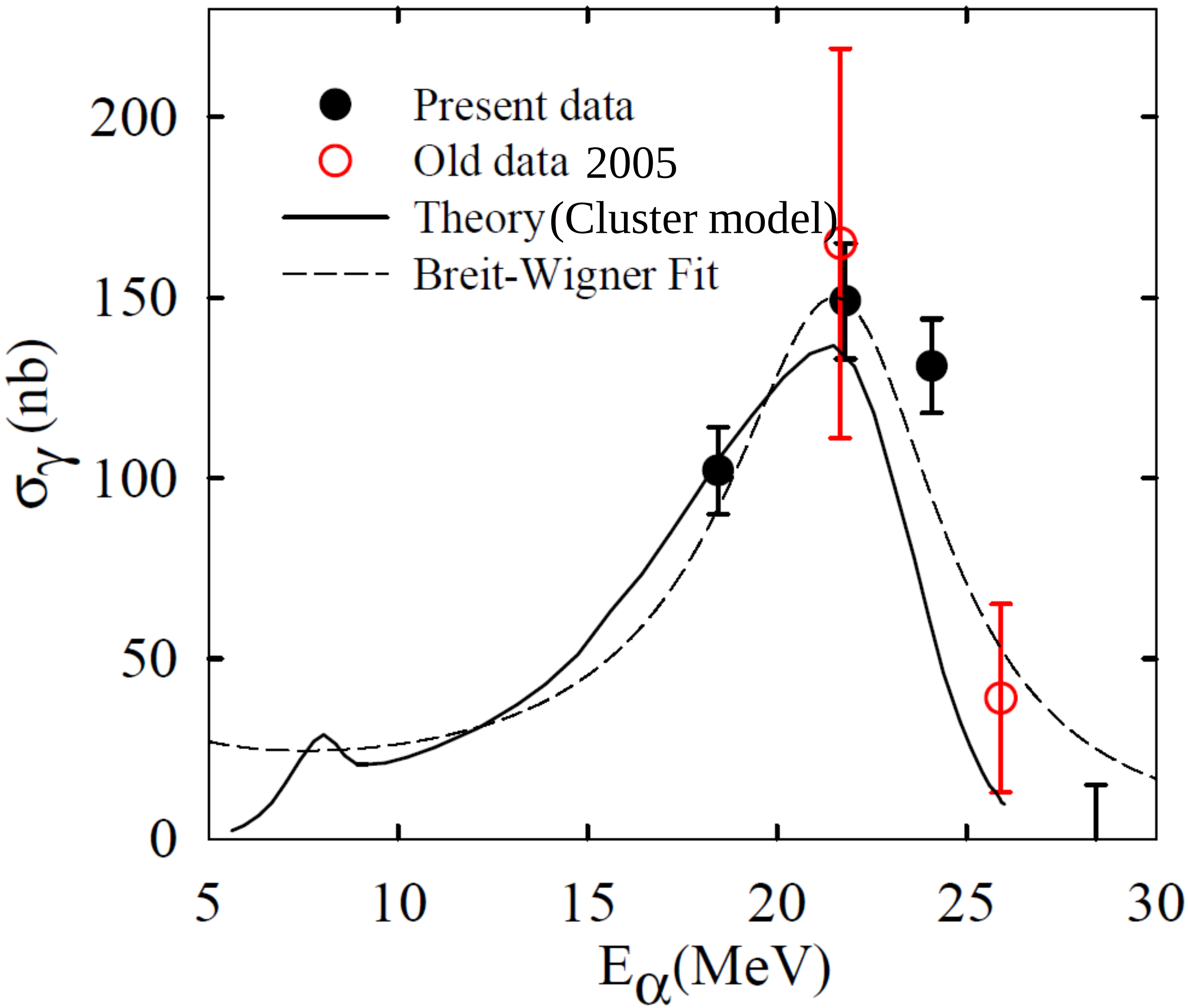


Eα=22.6 MeV, central aper dia=20 mm, p=0.8 bar
Eα=16.2 MeV, central aper dia=24 mm, p=0.5 bar
Eα=30.2 MeV, central aper dia=24 mm, p=0.8 bar
Eα=22.6 MeV, central aper dia=24mm, p=0.8 bar
Eff. Zrange (%.mm)
Distance of SiSD from centre (mm)
0
500
1000
1500
2000
40
60
80
100
120
140

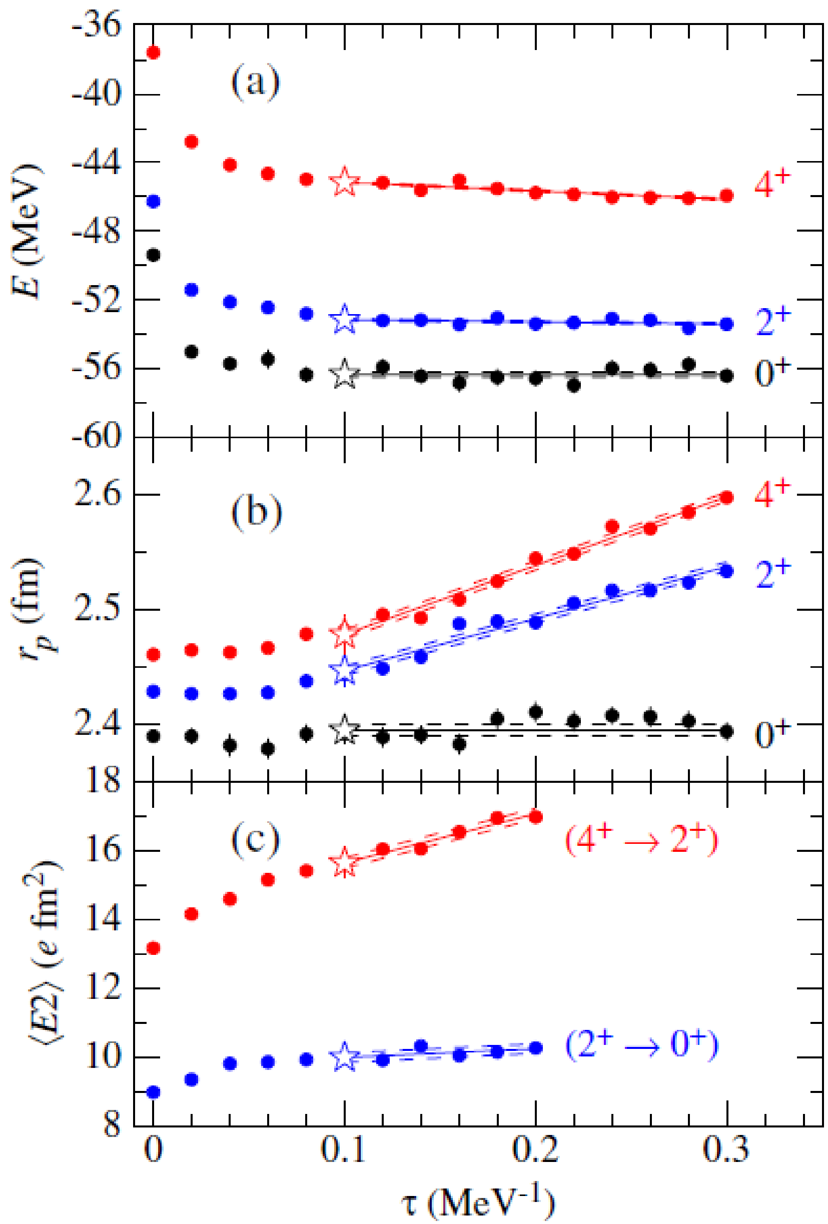
Effective target zone at 3 beam energies



Radiative capture cross section at four α-energies



Greens Function Monte Carlo calculations



Pastore (USC), Wiringa (ANL)

NN:Argonne v_{18} potential

3N: Illinois 7 potential

VMC trial w.f. → GFMC in imaginary time

Mean values at τ=0.1 MeV

Error: MC + variation from values between τ = (0.08 -0.12) MeV^{-1}

$B(E2;\, 4^+ \rightarrow 2^+)\ e^2fm^4$

Cluster model	21.6
Ab initio (GFMC)	27.2 ± 1.5
Expt. *	21.0 ± 2.3

*Assuming Breit Wigner $E_R = 10.9$ MeV, $\Gamma = 3.5$ MeV,

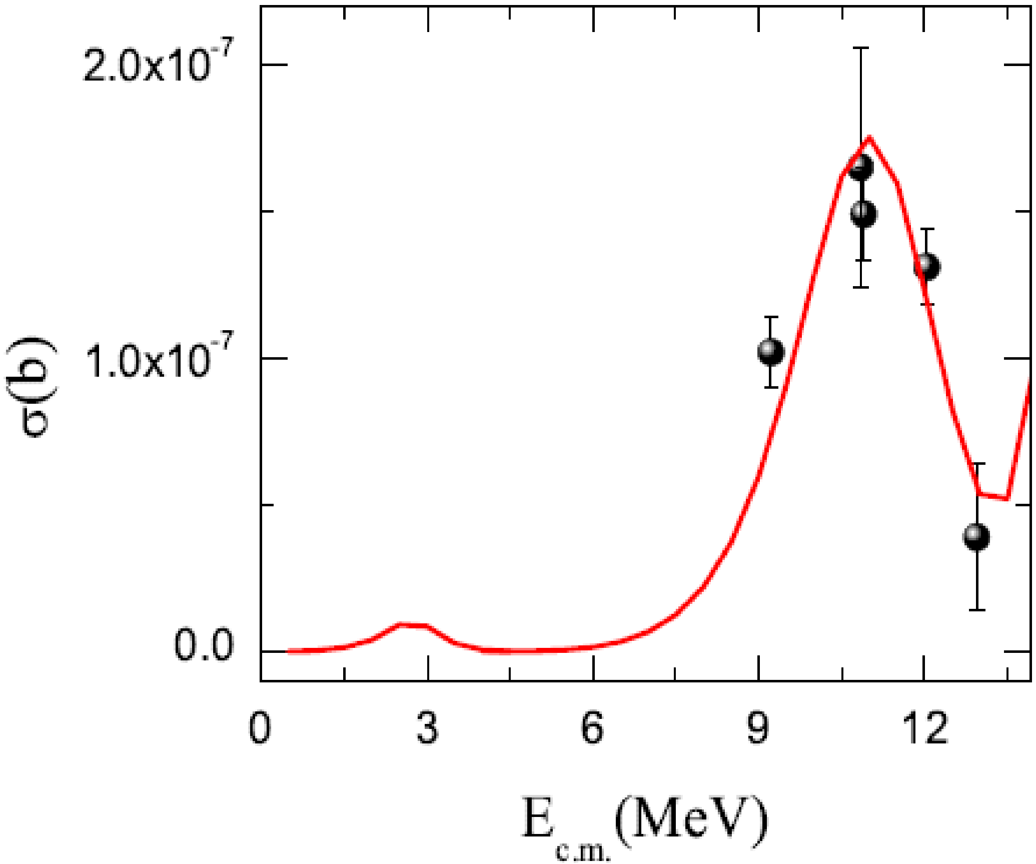
$E(2^+) = 3.04$ MeV, extracted $\Gamma_\gamma = 0.48 \pm 0.05$ eV.

However for $2^+ \rightarrow 0^+$ cluster model gives large B(E2)

of 40 e^2fm^4 compared to *ab initio*'s $20.0 \pm 0.8\ e^2fm^4$

*V. M. Datar et al, Phys. Rev. Lett . **111**, 062502 (2013)*

R matrix analysis of $\alpha(\alpha, \gamma)\ ^8Be$ capture cross section

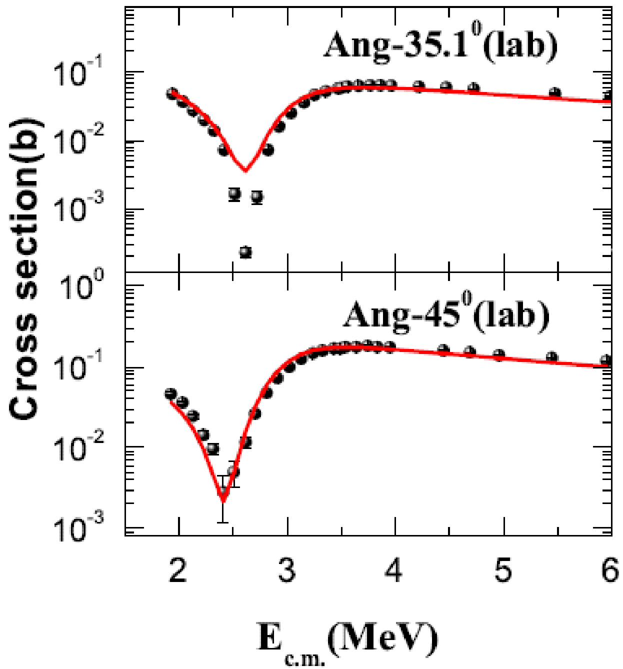


Data: PRL **111,** 062502 (2013)

R matrix analysis: Suprita Chakraborty, Subinit Roy et al. (SINP) M/S in preparation

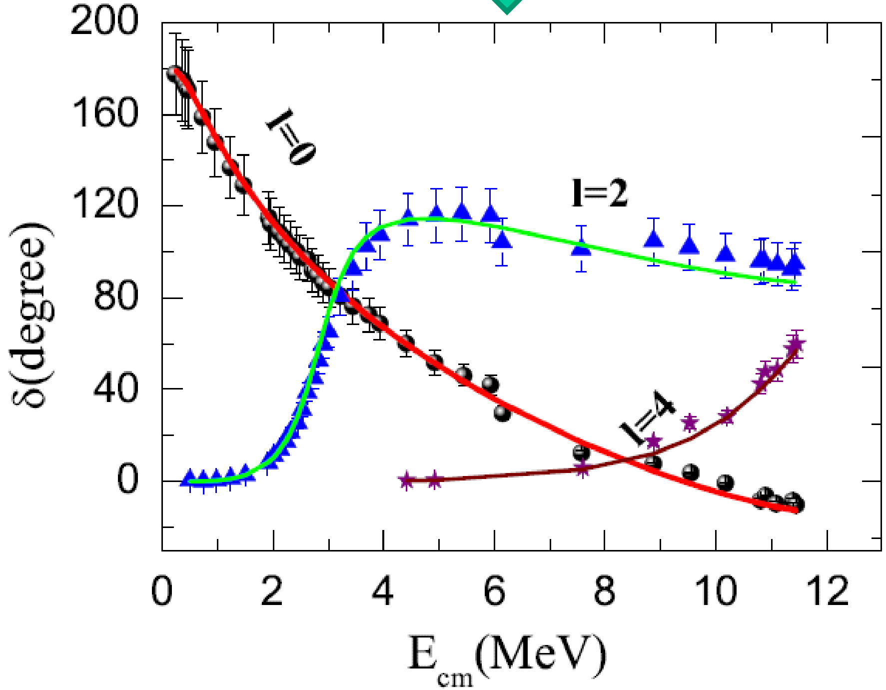
R matrix code AZURE2: R. Azuma et al. Phys. Rev. C **81**, 045805 (2010)

Simultaneous R matrix Fits to α + α elastic scattering data



Elastic Scattering Excitation Function

Phase Shift δ (E)



Data from
T.A. Trombello *et al*. PR **129**, 2252 (1963)
N.P. Heydenburg & G.M.Temmer, PR **104**, 123 (1956)
R. Nilson, *et al*. PR **104**, 1673 (1956)

Resonance parameters from R matrix fits

E_x (MeV)	J^π	$\Gamma_{particle}$ (MeV)	$\Gamma_{\gamma 0}$ (eV)	$\Gamma_{\gamma 2}$ (eV)
0.00	0^+	5.57 eV		
3.02	2^+	1.68	0.009	
11.4	4^+	4.02		0.68
18	0^+	6.5		4.83
18	2^+	6.51		1.73
18	4^+	6.6		23.03

$\Rightarrow$ B(E2) $\approx$ **28.4 ± 3.1** e^2fm^4
Agrees with *ab initio* calculations giving **27.2 ± 1.5** e^2fm^4

Suprita Chakraborty, et al., DAE-BRNS Symp. On Nucl. Phys. (2018)

4. Summary and future possibilities

- Results of more accurate measurement of 4^+-to-2^+ γ-decay in dumbbell shaped nucleus ^{8}Be

- **A better theory combining *ab initio* structure calculations with reaction models needed** (as in *n*-^{4}He)

- A measurement of more challenging 2^+ to 0^+ radiative transition in ^{8}Be needed (~ 4 or 2×10^{-9}) Cluster model vs ***ab initio*** B(E2): 40 vs **(20 ± 0.8)** e^2fm^4

- **Possible reactions for 2^+ to 0^+ EM transition:**

$^4He + ^4He$ (gas jet tgt) $\rightarrow 2\alpha + \gamma$ ($E_\alpha = 3 - 9$ MeV) cleaner!

or $^{11}B(p,\alpha_1)$ to populate 2^+ at E_R=163 keV IS on 200 kV deck

Need highly segmented fast detectors, diamond array/over-biased Si strip detectors for αs, $LaBr_3$(Ce)/INGA (24 HPGe clover detectors) for γ-ray

Gas Target: $\theta_{\alpha\alpha} \approx 20°$ (on resonance)

Background: Random coinc. 2 or 3 α-γ (tail of 4.44 MeV)

- Intra-state E2 transition (diagonal E2 moment)?

  $E_x(4^+) + \Gamma/2 \rightarrow E_x(4^+) - \Gamma/2$

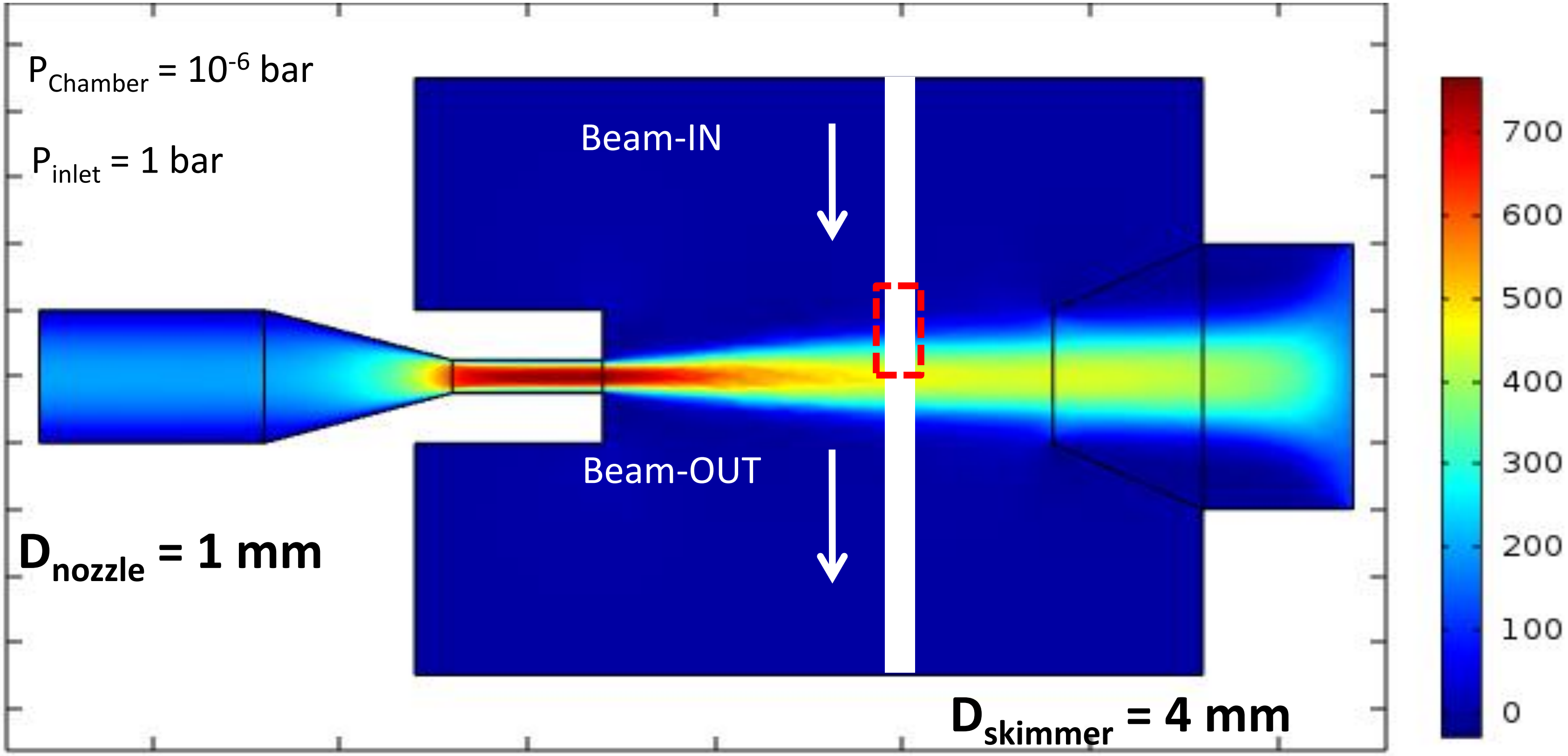
  Expected branching ratio ~ $10^{-2} \times 10^{-7} =$ $\mathbf{10^{-9}}$

While the same setup as in the measurement of the 4^+ to 2^+ EM branch could be used, a gas jet target could be a cleaner option.

- **As far as I know no observation of an intra-resonance EM transition in atomic or hadronic system.** For example, Δ-resonance ($E_R \approx 1232$ MeV, $\Gamma \approx 117$ MeV) decay to N seen with $\Gamma_\gamma/\Gamma \sim 6\times10^{-3}$. Intra-resonance branch could be ~ 4×10^{-4}.

- Possibilities for EM decay of unbound states in ^{5}Li/^{6}Be?

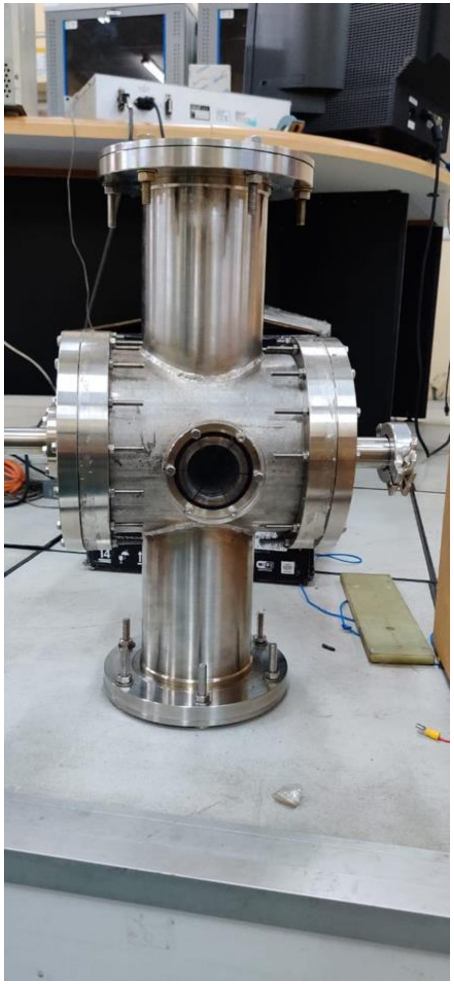
Schematic of gas jet target



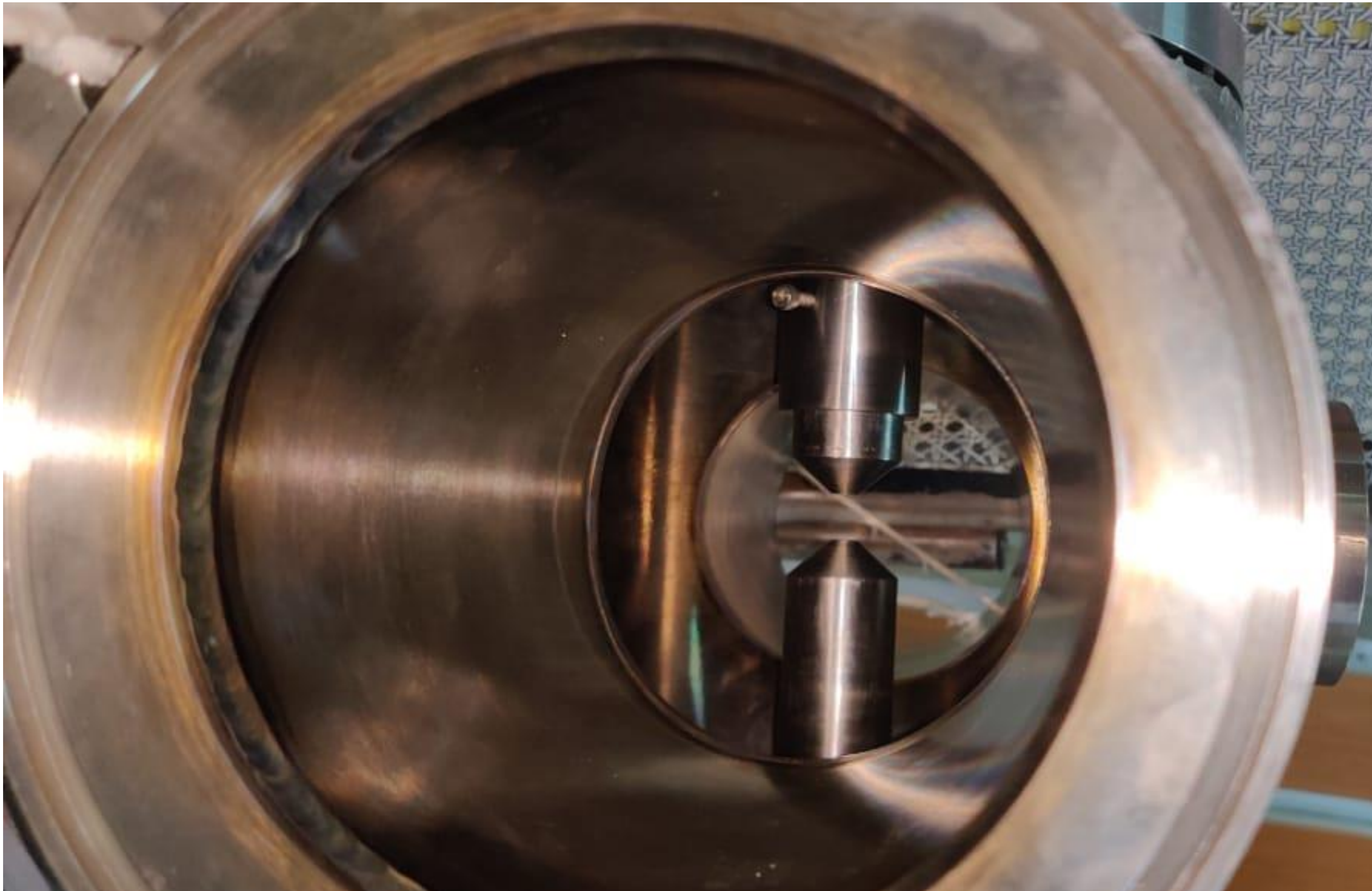
The number of He gas at 10 mm distance from the nozzle expected to be ~ $10^{17}/cm^3$ assuming a 1 mm beam diameter

B. Dey (Bankura Univ.), D. Pandit (VECC), P.Y. Nabhiraj (VECC), Subinit Roy (SINP)

Prototype Gas Jet Target Components Fabricated @ Workshop, VECC Kolkata



Nozzle-skimmer arrangement inside the chamber



Acknowledgement

D.R. Chakrabarty, Suresh Kumar, S.P. Behera, A. Chatterjee, E.T. Mirgule, A. Mitra, K. Ramachandran, P.C. Rout, A. Shrivastava (BARC), V. Nanal, R.G. Pillay (TIFR), P. Sugathan (IUAC), S. Pastore, R.B. Wiringa, C.J. Lister (ANL,US) D. Jenkins, O. Roberts (York, UK); Subinit Roy, Suprita Chakraborty (SINP)

Special thanks to staff of Pelletron Linac Facility.

Thank you!

Lesser flamingoes @ mangroves near BARC, Mumbai

Green woodpecker @Corbett National Park