Nuclear Physics with polarized beams and targets

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TIFR-Mumbai

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SINP
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Plan of the talk

- **Low energy Nuclear Physics with polarized beams**

  » *Reasons for polarized beam/target facility*
  » *Existing facilities*
  » *Few experiments*
  » *Possible Indian Initiative(s)*

- **The 4π sum-spin spectrometer at TIFR**

  » *Need for such an array*
  » *Existing arrays*
  » *The 4π array at TIFR*

FRENA [previous talks by Oosterhout & Banerjee]

- **3 MV Tandem**
- **Can go down to 200 keV**
- **Proton 500 μ amp**
- **HI (^{12}C, ^{16}O) ~ 50 μ amp**
- **Pulsed beam for H, D, He**

A polarized beam/target facility

Why polarized beam/target?

- **To study the spin dependence of nuclear scattering and reactions in fuller details**

- **To study reactions in light systems important for nuclear astrophysics**

- **To initiate a viable experimental program in few-body physics**

- whether the properties of bound nuclei having more than 2, especially 3,4 nucleons can be explained using the best information available about the underlying pair-wise n-n interaction

- to study three-body force (3NF) in light nuclei.

3 and 4-body systems both bound and scattering sector

Two ways to do polarized beam experiments.

Double scattering method:

Many experiments in the past (mainly with protons)

Polarized p beam produced by scattering an unpolarized beam (say on He or C target)

The partially polarized scattered beam hits a second target under investigation

Some typical numbers are like,

10^8 protons with 35% polarization after first scattering — *Friche et al. Phys.Rev. 156 (1967)*

10^7 protons with 100% polarizattin — *Baugh et al. Nucl. Phys. 83 (1966)*

Very large intensity on the first target required

Reactions with high cross sections

(elastic or inelastic to low-lying strongly excited rotational or vibrational states)

Wolfenstein, Ann Rev. Nucl. Sci. 6 (1956)
Haeberli, Ann. Rev. Nucl. Sci 17 (1967)
Barschall, Am. Jour. Phys. (1966)

- *Ninth international workshop on polarized sources and targets:*
  Ed: V.P. Derenchuk, B.P. Przewoski

- *Spin 2000, Osaka:*
  Ed: Hatanaka, Nakano, Imai, Ejiri

- *Compilation and reviews by T.B. Clegg*

- *Private communications (KVI)*

Operational sources:
three basic types

Oldest of these facilities are ~30 years old.

Few new systems added in last 7-8 years

Important centres

TUNL
IUCF
COSY
RCNP
BNL
Munich
Groningen?
Bonn
Cologne
RIKEN
JINR

PSI, Viligen
Kyushu

TRIUMF
Wisconsin

Kyoto

T.B. Clegg, Polarized sources & targets, 2002

- ***Lamb- Shift Polarized Ion Sources:***
- ***Optically pumped polarized Ion sources:***
- ***Atomic Beam Polarized Ion Sources:***

Individual designs vary even among same types

<u>Features</u> are driven by 1) experimental program 2) requirements of accelerator

Ion species, H^+ H^- D^+ D^-
Current
DC or Pulsed
Polarization

Lamb Shift Polarized Ion Sources:

Donnaly & Sawyer, PRL. 15, 439 (1965)

Advantages: Relatively Simple
Inexpensive
Reliable
DC beams ideally suited for tandem accelerators

Major Disadvantage: Very small output intensity (< 0.5 μA)

Laboratory	Intensity (mA) H-	Intensity (mA) D-	Polarization %	
Cologne	0.0005	0.0005	0.7 – 0.8	NIM A150 (1978)
Kyushu	0.0003	0.0003	70(p), 65(d)	1986
Tsukuba	0.0003	0.0003	80(p), 75(d)	NIM A149 (1979)

Optically Pumped Polarized Ion Sources (OPPIS)

Two such sources:

DC source at TRIUMF *(Levy, Cologne Workshop proc. 1995)*

Pulsed source at BNL/RHIC *(Mori et al. Rev Sci. Instr. 71, (2000))*

Laboratory	Max Intensity (mA)	Polarization (%)	Type
TRIUMF	1.2	< 75	DC

A.N. Zelenski,
SPIN 2000, Osaka

Atomic Beam Polarized Ion Sources (ABPIS):

T.B. Clegg,
Cologne Proc. 1995
World Scientific

Most Common Sources
~ 15 operational facilities

(Abragam & Winter, PRL 1, 374 (1958))

Laboratory	Intensity (mA) H-	H+	D-	D+	Polarization	Type
TUNL	.0008	.05	.008	.07	75(P) 80(d)	DC
IUCF	1.5		1.5		80	
Groningen		0.5		0.4	70(p) 60(d)	DC
Munich		.01		.009	65(p) 70(d)	DC

- PRC 65, 034002 (2002)
- PRC 63, 044013 (2001)
- NPA 684, 549C (2001)
- PLB 428, 13 (1998)

3N Problem (p-d scattering)

- PRC 74, 034001 (2006)

4N Problem

- NPA 631, 627C
- PRC 70, 064601
- PRC 56, 2565 (1999)

Polarized radiative Capture studies

Experiments at TUNL

•10 MV FN tandem + ion sources
•Most intense pol sources of dc H^+, D^+
•Energies between 40 to 680 keV

•TUNL+Ohio+Pisa groups

3NF essential to describe light nuclei

Modern phenomenological N-N potentials fail to reproduce BE of ^3He, ^3H

underestimate by ~0.5 to 1.0 MeV

So, 3NF is introduced based upon 2π exchange involving a delta excitation

TM (1979), BR (1983), UR (1995)

These are adjusted to reproduce BE for A=3,4

- *Heavier systems (A=5-8) persistent underbinding*

  More complicated structure for 3NF required

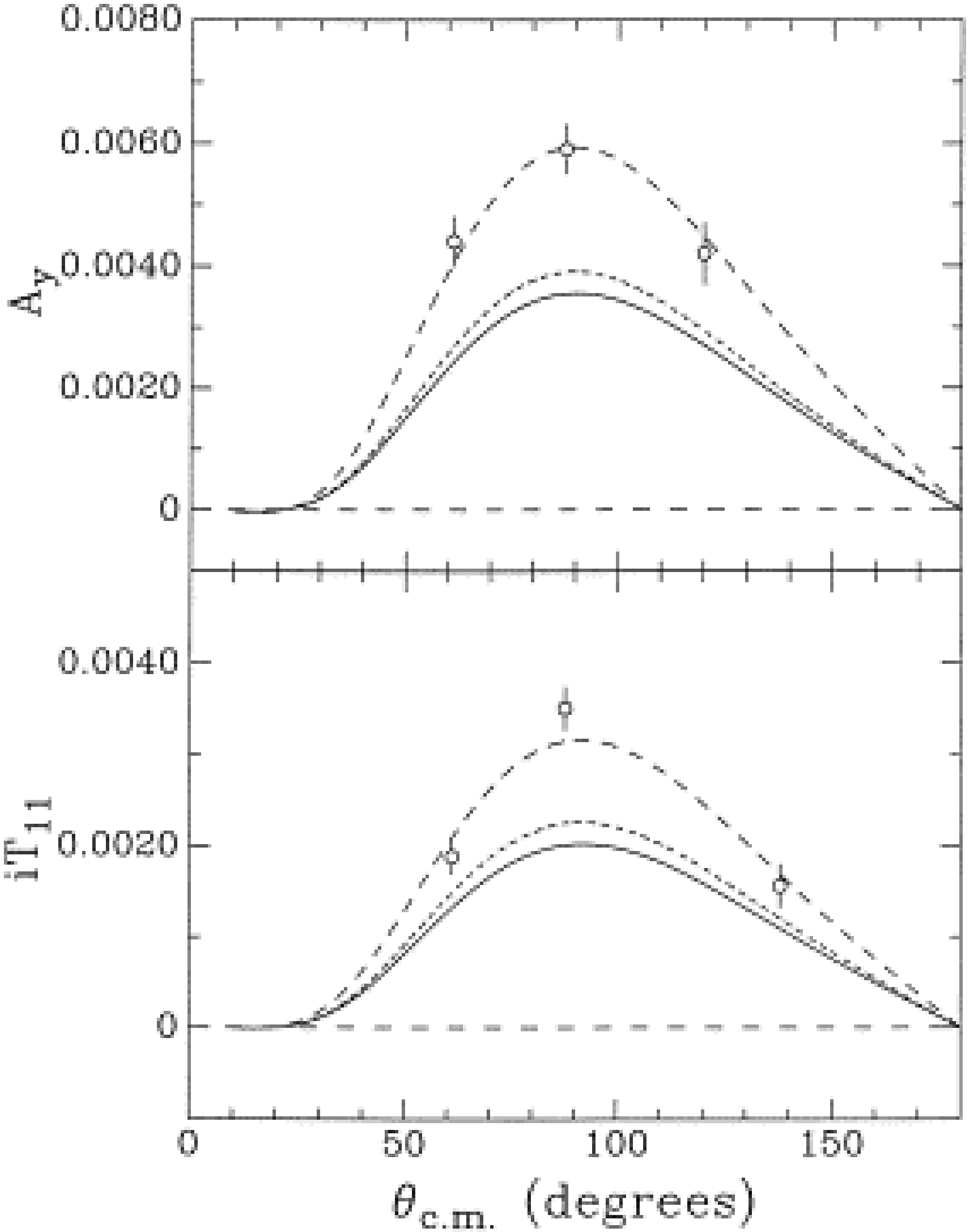
- *Large discrepancy between Theory & Expt. In vector analyzing power for n-d system*

  Same "Puzzle" observed in p-d system as well where Coulomb is involved

Very precise measurements by TUNL group at { *667 keV PRC 65, 034002 (2002)*; *432 keV PLB 428, 13 (1998)* }

Excellent agreement with theory including 3NF for p-d elastic cross section

~40% discrepancy for VAP Ay at the max of angular distribution



C.R. Brune et al.,
Phys. Lett. B 428, 13 (1998)

p-d scattering @ 432 keV

The puzzle is reported even at intermediate energy p-d elastic scattering:

Kalantar-Nayestanaki et al. NPA 684 (2001)

KVI Group:

Looking for cross section and analyzing power for p-d system between 60 – 190 MeV

Resolving the puzzle by invoking 2N force based on EFT
Epelbaum et al., PRL 86, 4787 (2001)

A More rfecent study by Entern, Macleidt, Witala negates this claim

Their conclusion:

"no quantitative 2N force, phenomenological, meson theory, EFT will ever solve n-d A_y puzzle."

4N System

- *Many reactions, like, $^2H(d,p)^3H$, $^2H(d,n)^3He$, or $p+{}^3He \rightarrow {}^4He + \nu_e + e^+$ are of Extreme Astrophysical interest. Play important roles in solar models or BB nucleosynthesis.*

- *4N are testing ground for models of nuclear force and few-body techniques.*

- *A=4 is still a challenging problem for nuclear few-body theory.*
  - *study of α-particle bound state has reached satisfactory level of accuracy*
  - *4N scattering state is still less satisfactorily developed*
  - *Disagreements exist between theoretical groups and approaches*
    - *(n-^{3}H total cross section in the peak region (E_{CM} = 3 MeV)*
    - *R.Larauskas et al. PRC71, 034004 (2005)*
    - *Faddeev-Yakubovsky & Kohn's variational approach*

- *About 40% discrepancy between expt. & theory for proton analyzing power in p-^{3}He Elastic scattering.* *M. Viviani et al. PRL 86, 3739 (2001)*

- *Existing 4N data are of lesser quality compared to N-N and 3N (N-d) systems*

p-^{3}He studied in great detail by Fisher et al. PRC74, 034001 (2001)

The experiment:

At TUNL with both polarized and unpolarized beams.

- ***Accurate $\sigma(\theta)$ and proton analyzing power A_y for elastic scattering at***

  $\sigma(\theta)$ @ E_p= 0.99, 1.59, 2.24, 3.11 and 4.02 MeV
  Angular distribution of A_y @ E_p = 1.6, 2.25, 3.11 and 4.05 MeV

- ***4-Body variational calculations done by including realistic 2N and 3N***

Result:

For unpolarized beam good agreement with theory with 3N force.
For polarized beam 50% discrepancy even with 3N force.

This is analogous to A_y puzzle in n-d system

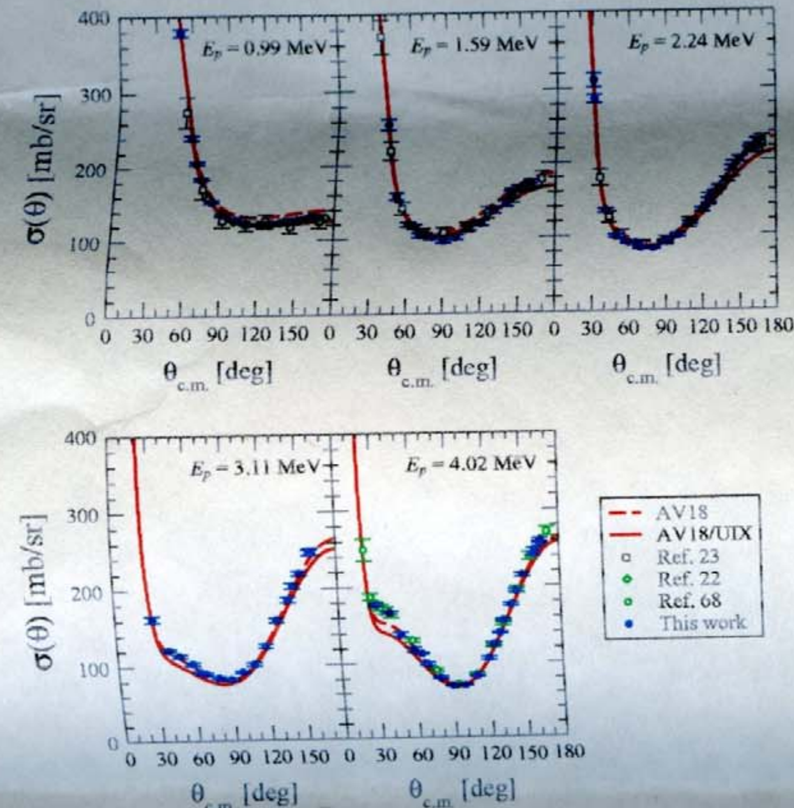


FIG. 4. (Color online) Measured p-^{3}He elastic differential cross sections (solid circles) at five different energies are compared with the data reported in Ref. [23] (open squares), Ref. [22] (open diamonds), and Ref. [68] (open circles). Curves show the results of the theoretical calculations for the AV18 (dashed lines) and AV18/UIX (solid lines) potential models.

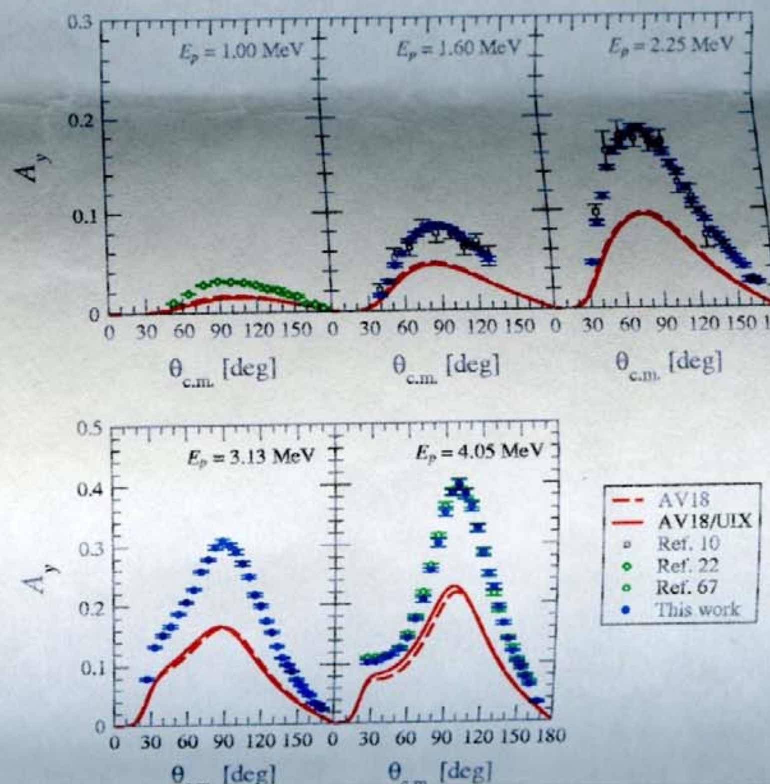


FIG. 5. (Color online) Measured p-^{3}He proton analyzing power A_y (solid circles) at five different energies are compared with the data of Ref. [10] (open squares), Ref. [22] (open diamonds), and Ref. [67] (open circles). Curves show the results of theoretical calculations for the AV18 (dashed lines) and AV18/UIX (solid lines) potential models.

Reactions of interest in astrophysics often proceed by resonant and direct reaction mechanism

To decouple these processes we need as much reaction observables as possible.
Polarization observables are particularly important in this context.

Reaction: ***$^{3}He(d, p))^{4}He$***

W.H. Geist et al. PRC 60, 054003, 1999 (TUNL Few-Body Group)

B. Braizinha et al. PRC 69, 024608 (2004) (TUNL+Ohio)

The experiment: *Angular distribution of cross sections and analyzing powers measured at 60, 99, 199, 424, 641 keV*

Importance of this study:

- *Very useful for the analysis of ^{5}Li system (many broad levels).*
- *Plays important role in primordial nucleosynthesis of light elements*
- *Important case for experimentally studying nuclear screening effect.*

enhancement factor $f(E) = \sigma_{exp}(E)/\sigma_{BN}(E)$

The 4π sum-spin spectrometer at TIFR

Mazumdar et al. (in preparation)

Why do we need them?

Multiplicity Filter

Discrete Spectroscopy

Angular Momentum Gating

Spin dependence on structural evolution and reaction dynamics

- ***High energy continuum spectroscopy***
  GDR Decay studies
- ***Reaction dynamics:***
  Entrance channel effects
- ***Nuclear Level Density***
- ***Angular momentum gated charged particle, neutron spectroscopy***
- ***Fission hindrance and dissipative mechanism***

Total sum energy measurements

Valuable information to tell us the E* at the entry state

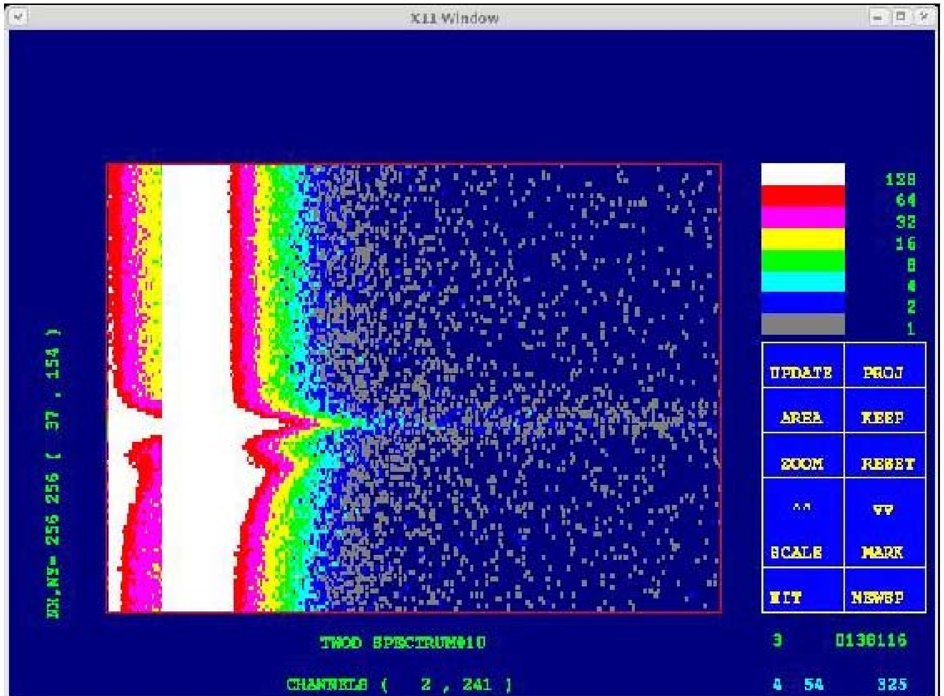
Some of the 4π Gamma multiplicity arrays

Array	Material	Detectors	Ref.
Spin Spectrometer Oak Ridge	NaI	72	Jaaskelainen et al 1983
Crystal Ball	NaI	162	Metag et al 1982
4π Gamma Array	BaF_2	42	Wisshak et al. 1990

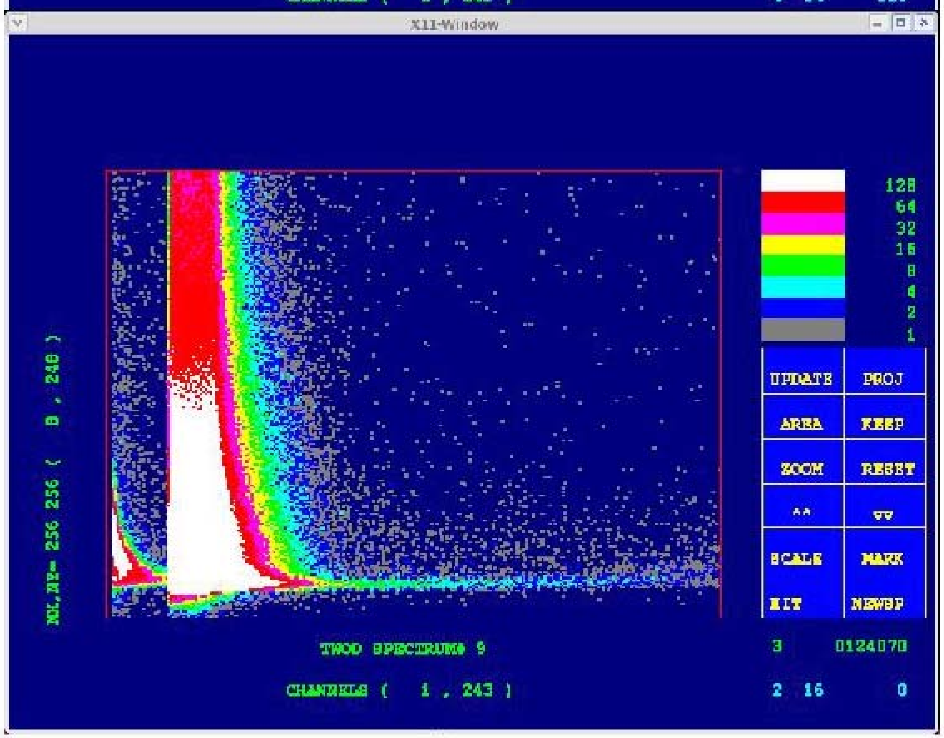
"to investigate the origin of heavy elements in slow neutron capture prcess"

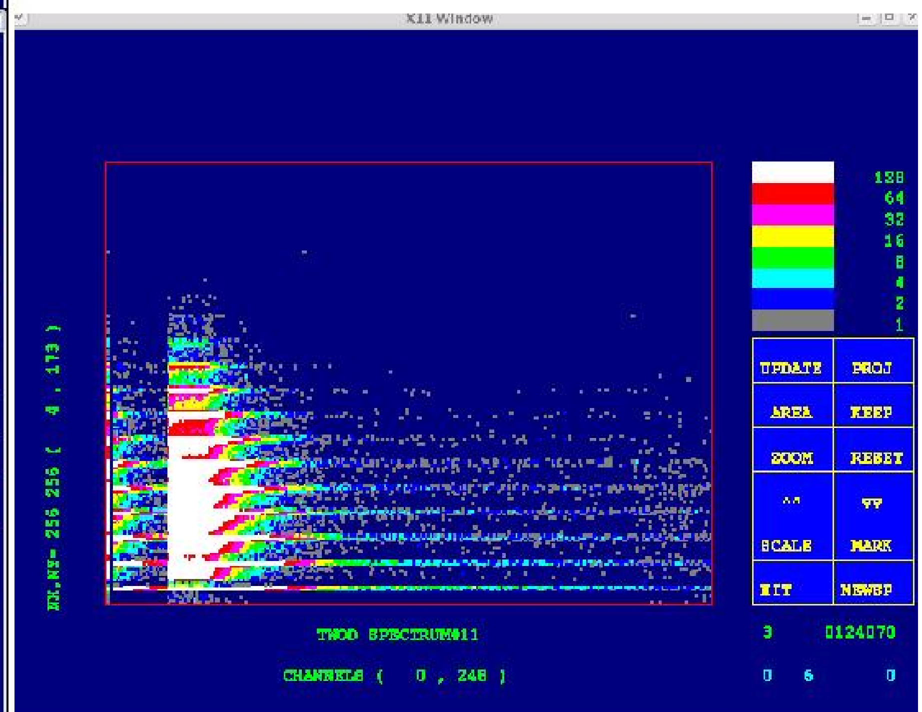
Arrays in Castle Geometry

GASP Array	*BGO*	*80*	
Hector-Helena	*BaF_2*	*38*	*1994*
NSC Array	*BGO*	*14*	
TIFR Array	*NaI*	*14 (2)*	
BARC Array	*BGO*		
VECC Array	*BaF_2*	*50*	*2008*

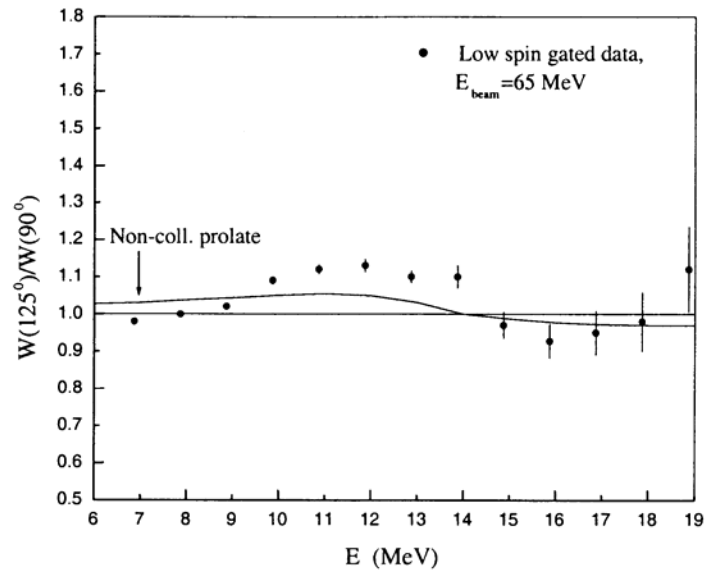


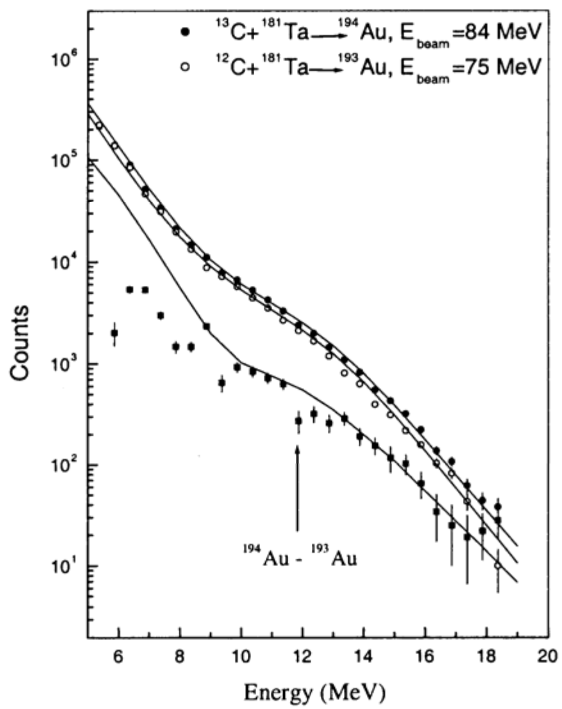
Two dimensional plots of
E_γ vs TOF, E_γ vs Pileup,
E_γ vs multiplicity

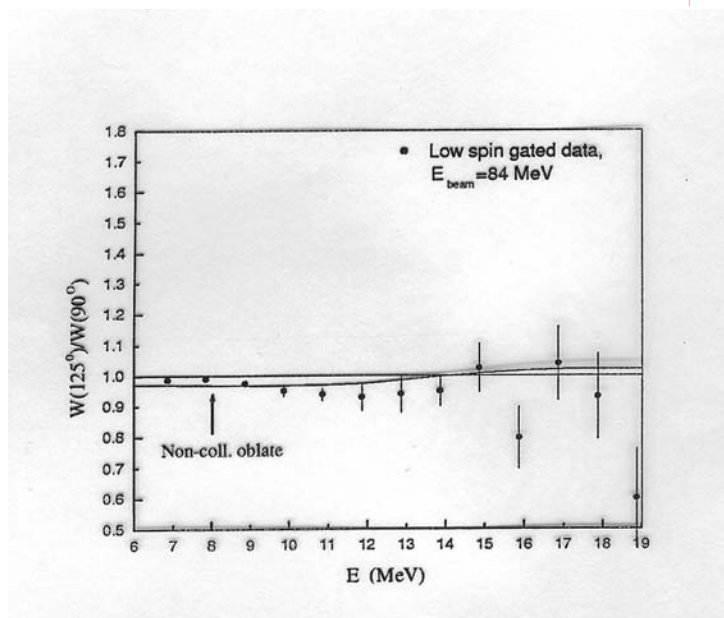




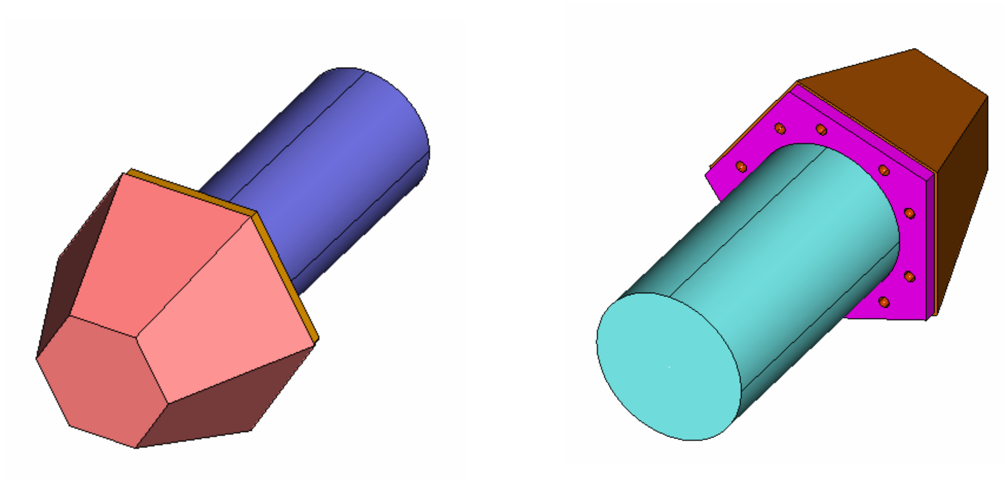
GDR decay from ^{194}Au



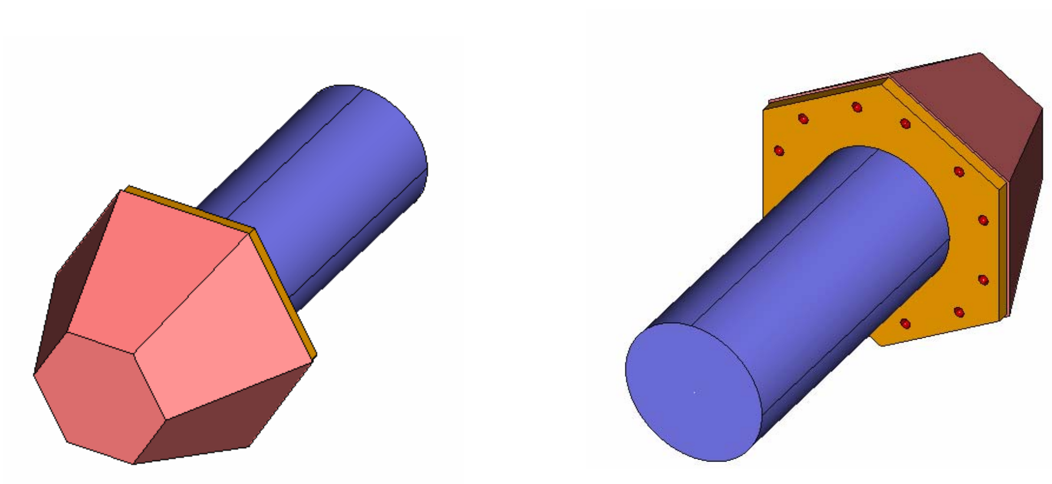




I. Mazumdar et al.Nucl. Phys. 731A 146 (2004)



Pentagon



Hexagon

Specifications

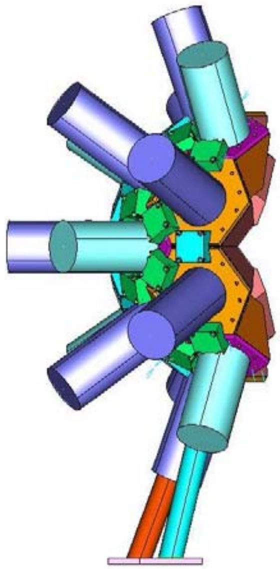
Length 96 mm
Sides 44 mm
88 mm

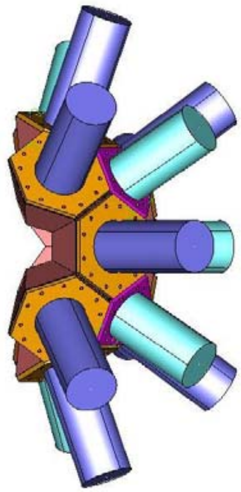
PMT 3" dia XP3332/PB

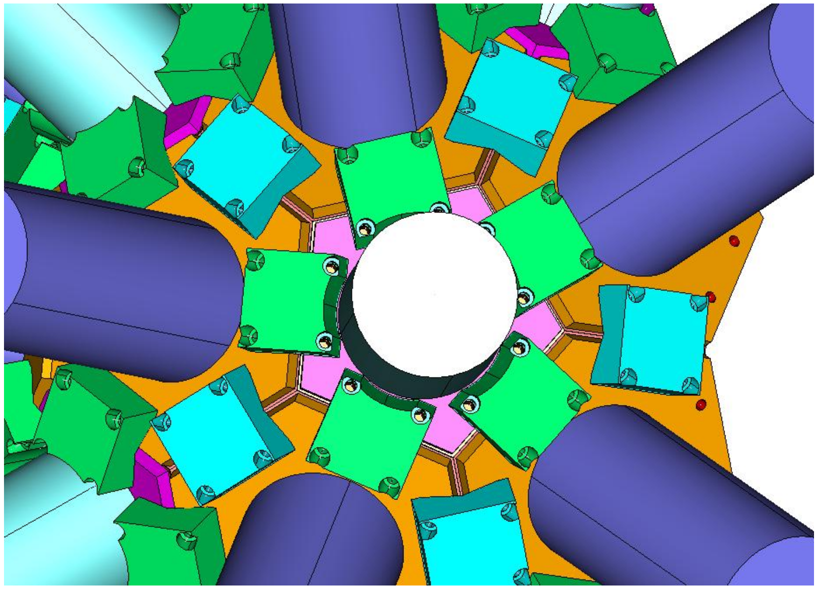
Energy
Resolution ~6.5% @ 661 keV

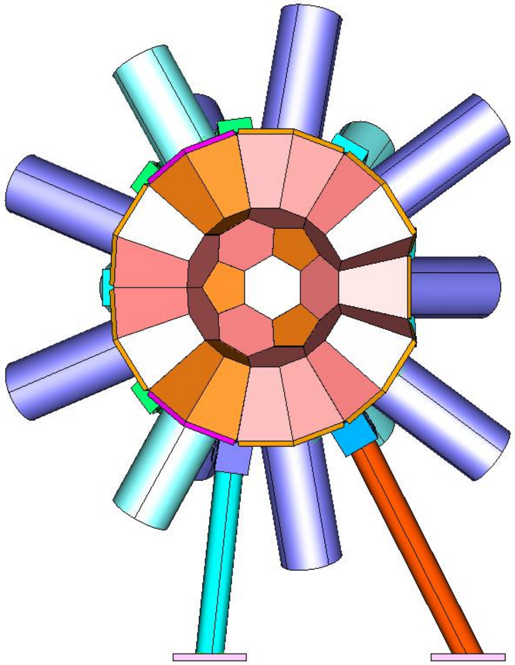
Bias +800 V

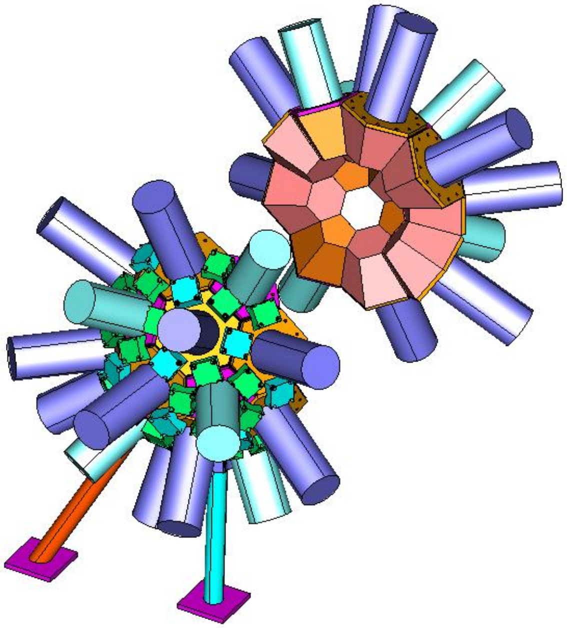
The TIFR 4π sum-spin spectrometer

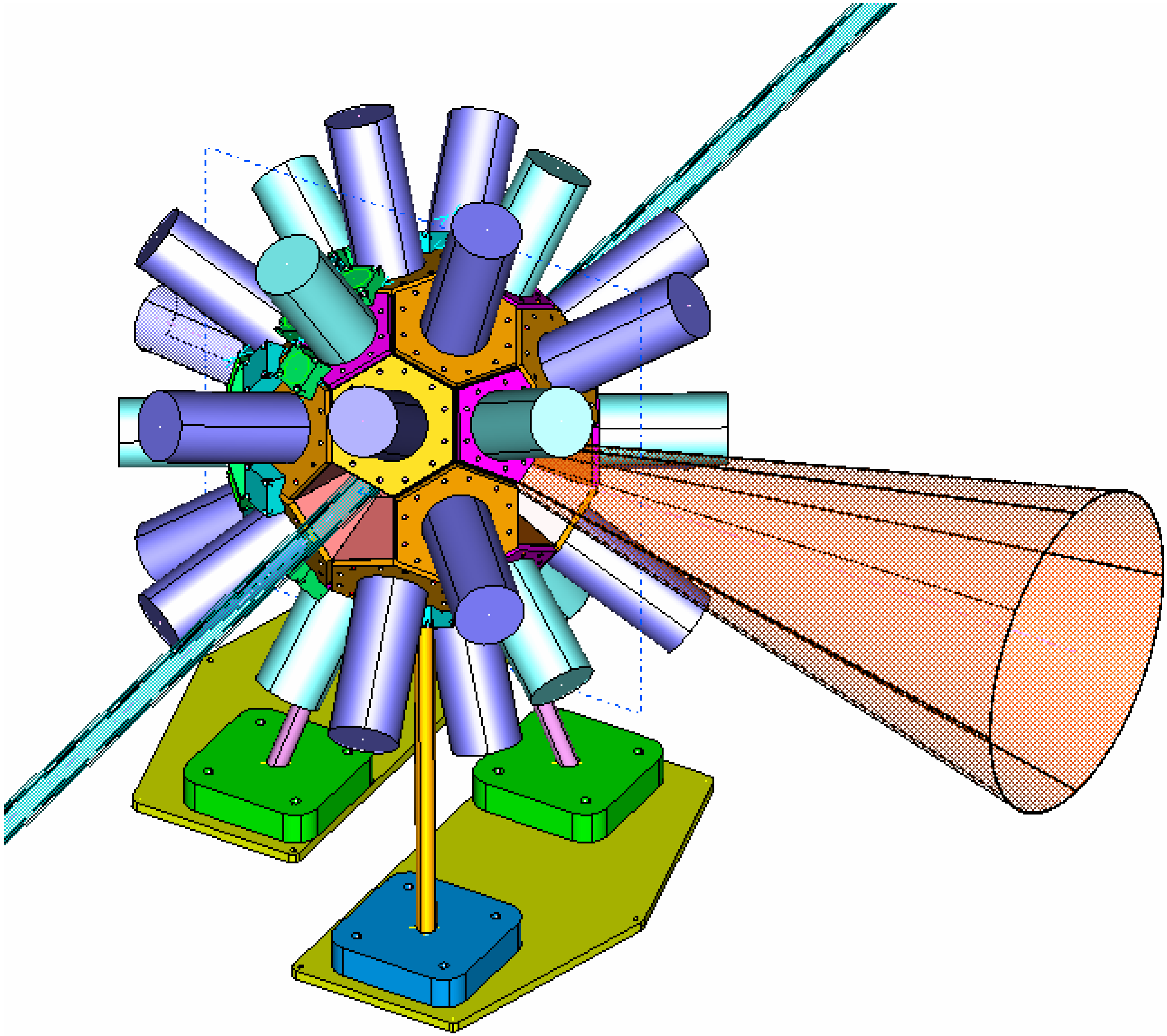


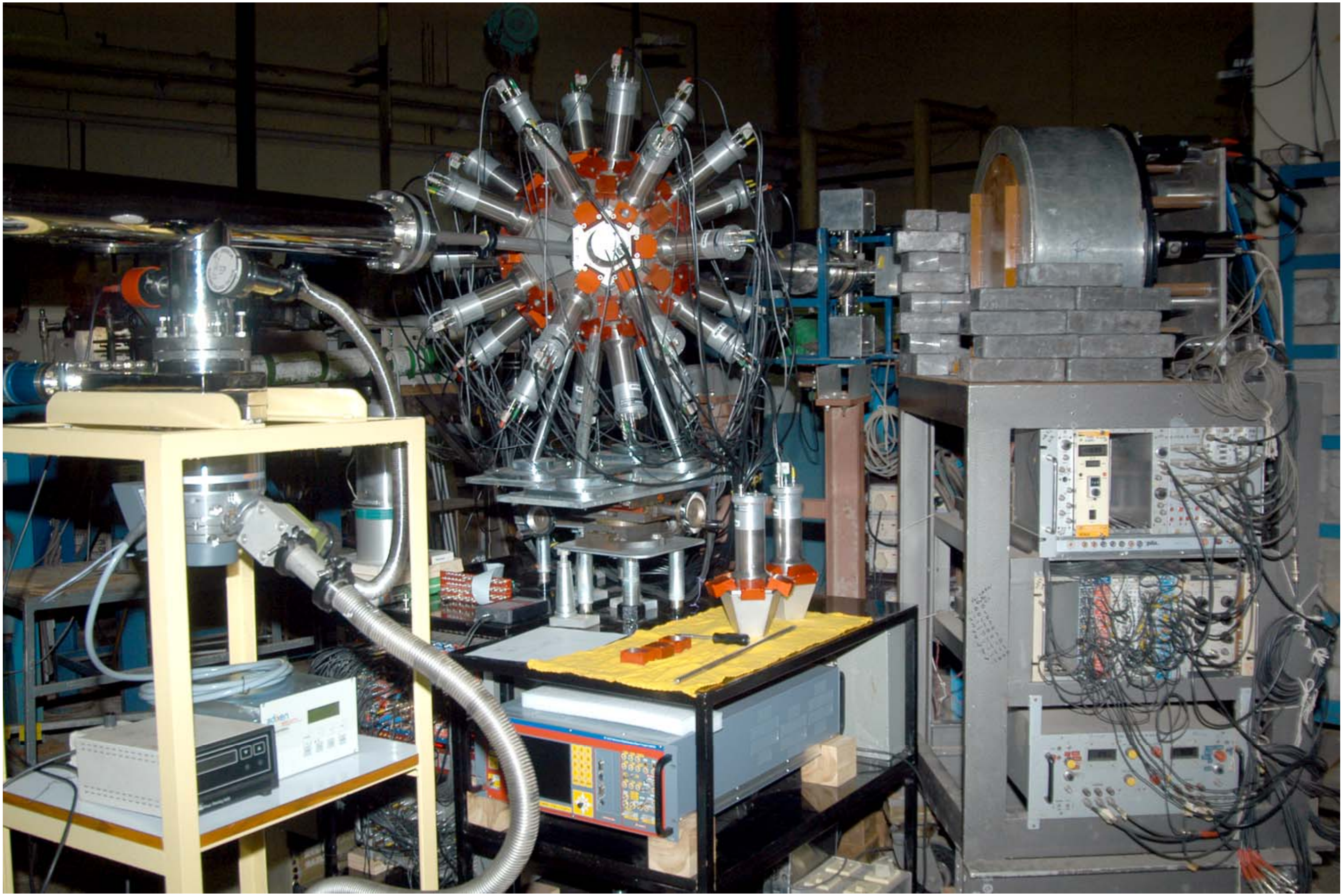


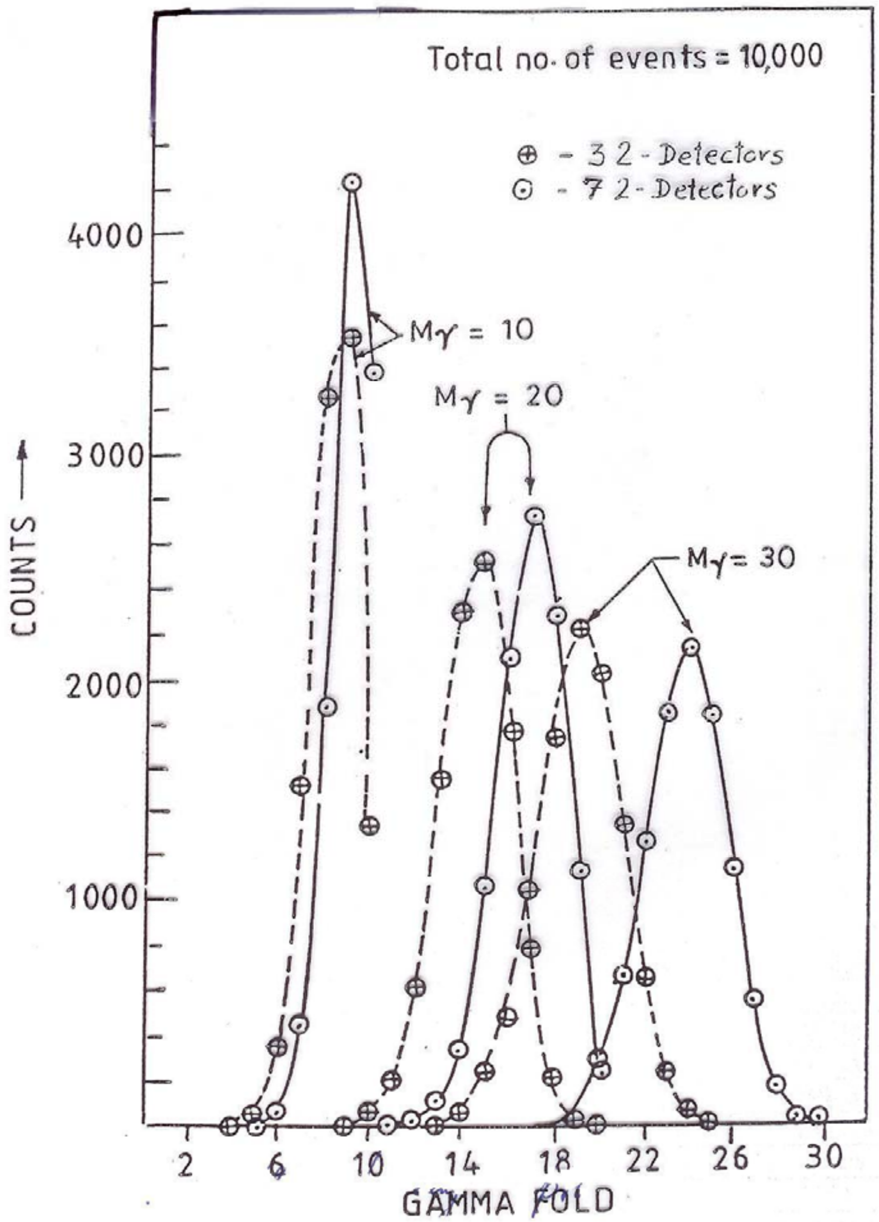


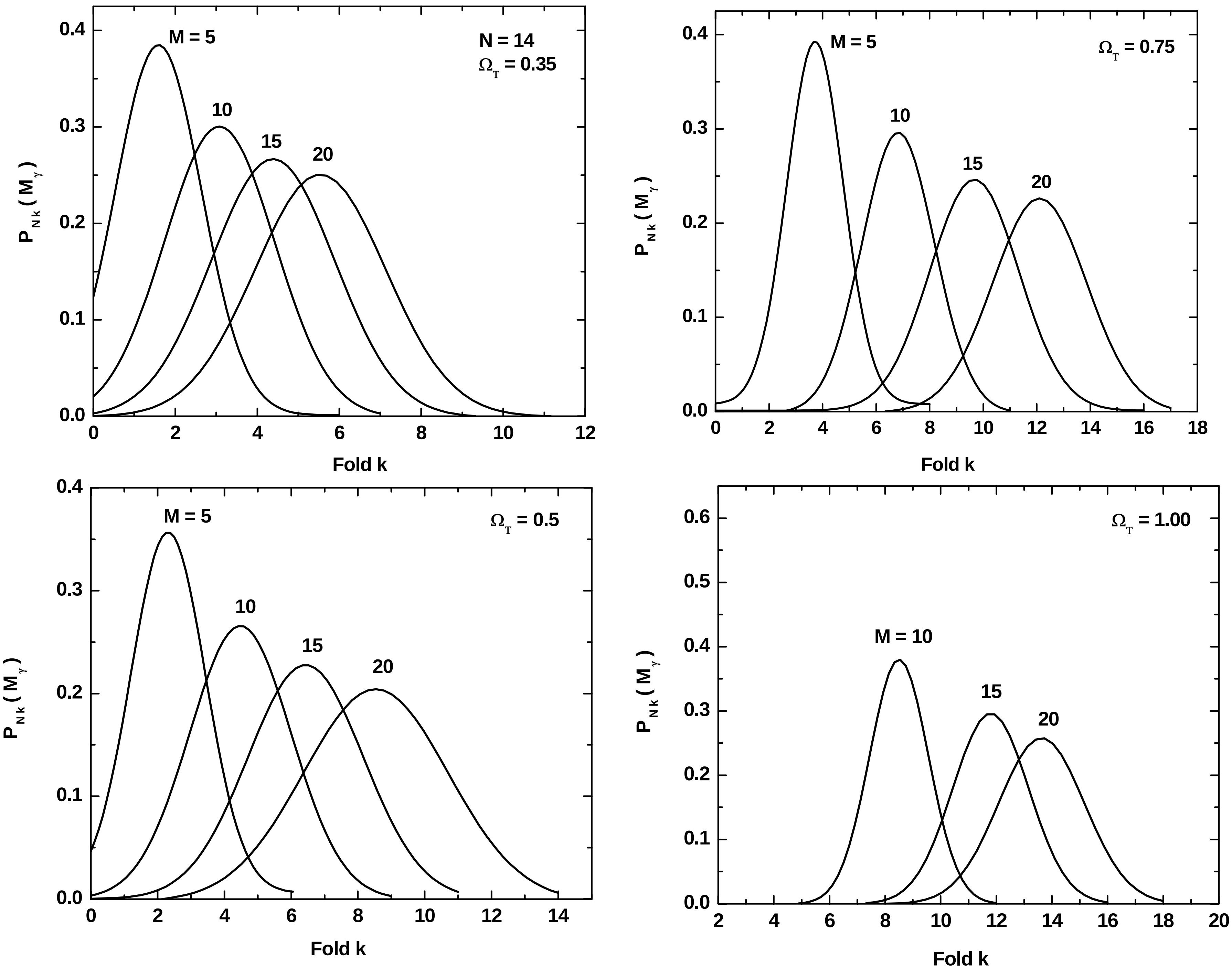









Total no. of events = 10,000
⊕ - 32 - Detectors
⊙ - 72 - Detectors
Mγ = 10
Mγ = 20
Mγ = 30
COUNTS
4000
3000
2000
1000
2
6
10
14
18
22
26
30
GAMMA FOLD



N = 14
Ω_T = 0.35
M = 5
10
15
20
$P_{Nk}(M_\gamma)$
Fold k
Ω_T = 0.75
M = 5
10
15
20
$P_{Nk}(M_\gamma)$
Fold k
Ω_T = 0.5
M = 5
10
15
20
$P_{Nk}(M_\gamma)$
Fold k
Ω_T = 1.00
M = 10
15
20
$P_{Nk}(M_\gamma)$
Fold k

First full scale experiment in jan-feb 2008

$^{12}C + ^{180}Hf \rightarrow ^{192}Pt^*$
65 MeV, 85 MeV, angular distribution

Offline analysis with calibrated sources

Geant simulation

Fold to multiplicity calculations

Experiments of Nuclear Astrophysics interest:

Capture Reactions

Future experiments:

In-beam:
GDR decay stdies
Multiplicity gated CPD, neutrons
Fission hindrance, NLD etc.

With Radioactive Sorces:

Summary:

- ***To work towards a possible polarized beam facility at FRENA***

    to work out the exact program (experiments), source specifications, theoretical support, team

- ***Explore possible experiments with an existing 4π array***

THANK YOU