Existing and upcoming particle accelerators in India

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INDC(IND)-0050

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Bhabha Atomic Research Centre

- BARC-TIFR14 UD Pelletron Accelerator with LINAC
- Folded Tandem Ion Accelerator(FOTIA)
- 14/2.45 MeV neutron generator (5 x 10^{10} n/sec), **ADSS benchmarking, radiography, TOF, APT, Padova Univ**
- 10 MeV electron RF LINAC **photo-fission, nuclear data**
- 3 MeV electron DC Accelerator **food processing, industrial applications**
- 6 MeV electron RF LINAC **Cargo Scanning**
- 16.5 Medical cyclotron **Isotope Production and PET**

Variable Energy Cyclotron Centre

224 cm Variable energy cyclotron (K-130)

Raja Ramanna Centre for Advanced Technology

Synchrotron Radiation Source INDUS-I & II

450 MeV & 2.5 GeV

1.7-3 MV Tandetron Accelerators

Guru Ghasidas Vishwavidyalaya, Bilaspur, Indian Institute of Technology, Kanpur, Indira Gandhi Centre for Atomic Research, Kalapakkam, Institute of Physics, Bhuvaneshwar, National Centre for Compositional Characterisation of Materials (CCCM), Hyderabad

15 UD Pelletron Accelerator with LINAC

Inter University Accelerator Centre

Microtron Accelerator (8 MeV) photo-fission, neutron source Mangalore University

Low energy cyclotron (2-3 MeV proton)

Panjab University, Chandigarh

14 MeV Neutron Generator **IPR, Gandhinagar, Pune University**

6.5 MeV Race-Track Microtron ^{9}**Be(γ, n)** **Pune University**

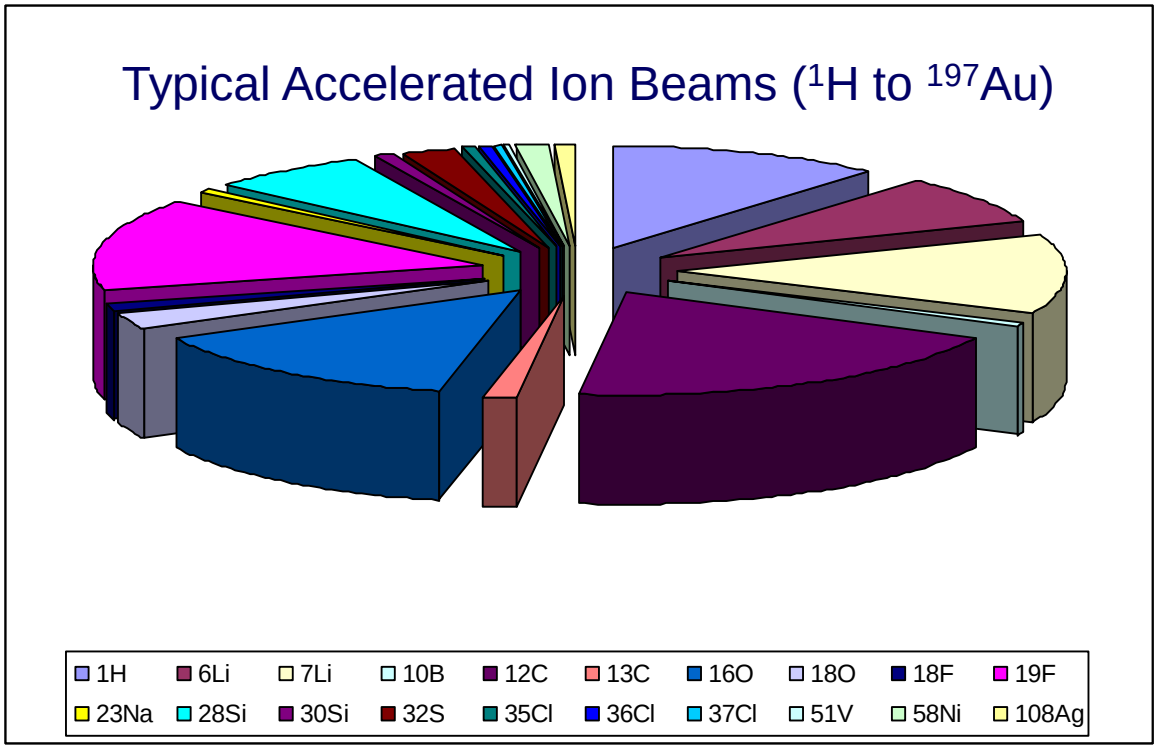
: 6 M irradiation set up for neutron physics experiments

BARC-TIFR 14 UD Pelletron-LINAC Facility (PLF) Mumbai

Beam Species	Max. Energy	Max. current/Intensity
^{6,7}Li, ^{10,11}B, ^{12,13}C, ^{14}N, ^{16,18}O, ^{19}F, ^{24}Mg, ^{27}Al, ^{28,30}Si, ^{31}P, ^{32,34}S, ^{35,37}Cl	Upto 8-10 MeV/A	1-5 pnA
Proton	Upto 24 MeV	200 nA
Neutron	Using ^{7}Li(p,n) and ^{9}Be(p,n)	10^{7}-10^{8} n/sec/cm^{2}

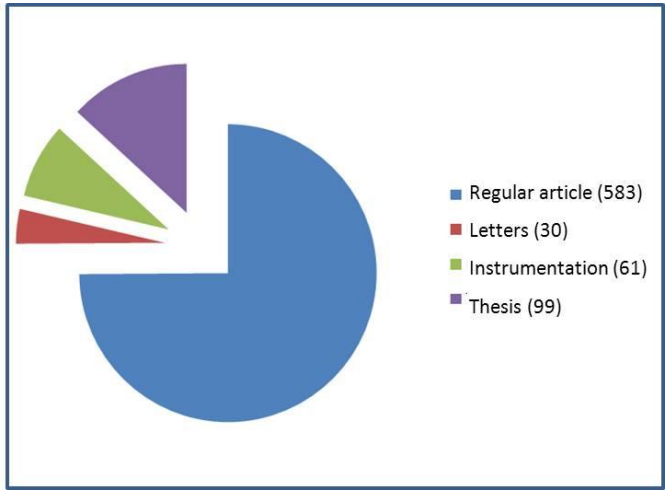
BARC-TIFR Pelletron-LINAC Facility

- **Experimental Facilities for**
  - ❖ Nuclear physics
  - ❖ Atomic physics
  - ❖ Condensed matter physics and material science
  - ❖ Radioisotopes production
  - ❖ Production of track-etch membranes
  - ❖ Low flux Protons irradiation damage studies
  - ❖ Secondary neutron production
  - ❖ Accelerator Mass Spectrometry



- **Users**
  - ❖ BARC
  - ❖ TIFR
  - ❖ SINP & VECC, DRDO, ISRO and other research & educational institutions.

Publications



Hall 1

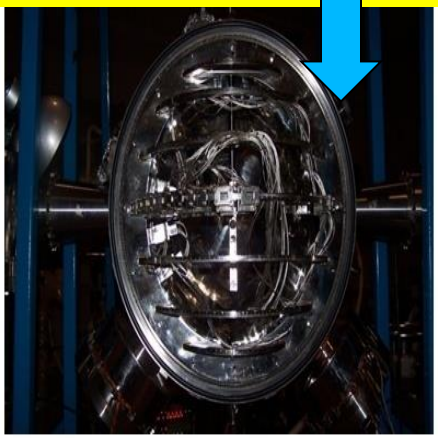
EXPERIMENTAL FACILITIES AT BARC-TIFR PLF

General purpose scattering chamber

Neutron array

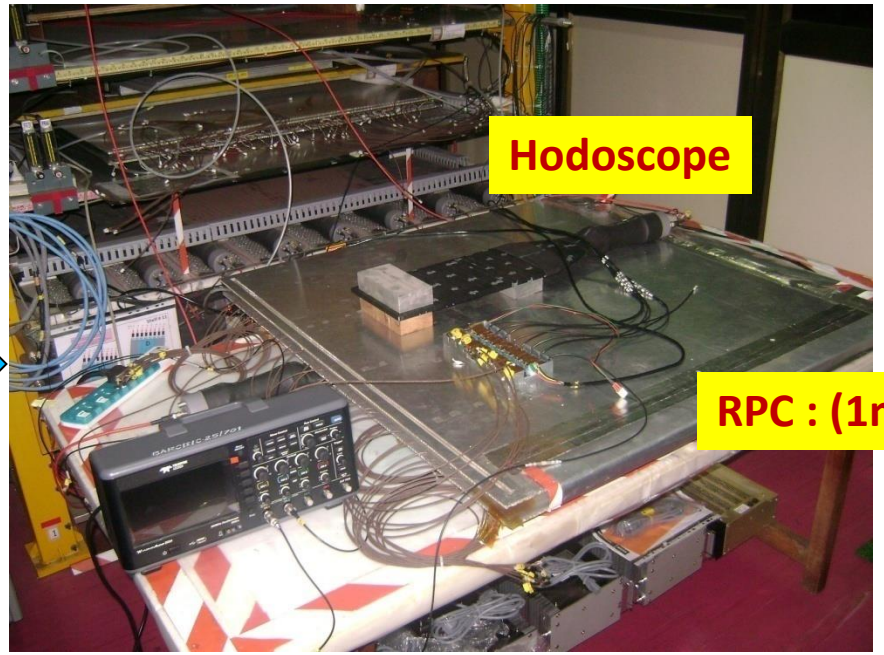
Charged Particle Array setup at PLF, Mumbai

(a) View of the CPDA setup in the LINAC beam hall at TIFR



(b) Experiment using 10 nos of detector telescopes mounted inside the vacuum chamber.

One of the six, RPCs (1m x 1m) under cosmic test, to be put in the hodoscope for muon tomography



Stack of 4x4matrix of Plastic Scintillators(10cmx 10 cm x 100 cm : 160 kg) wrapped with Gd foils and coupled to a digital DAQ

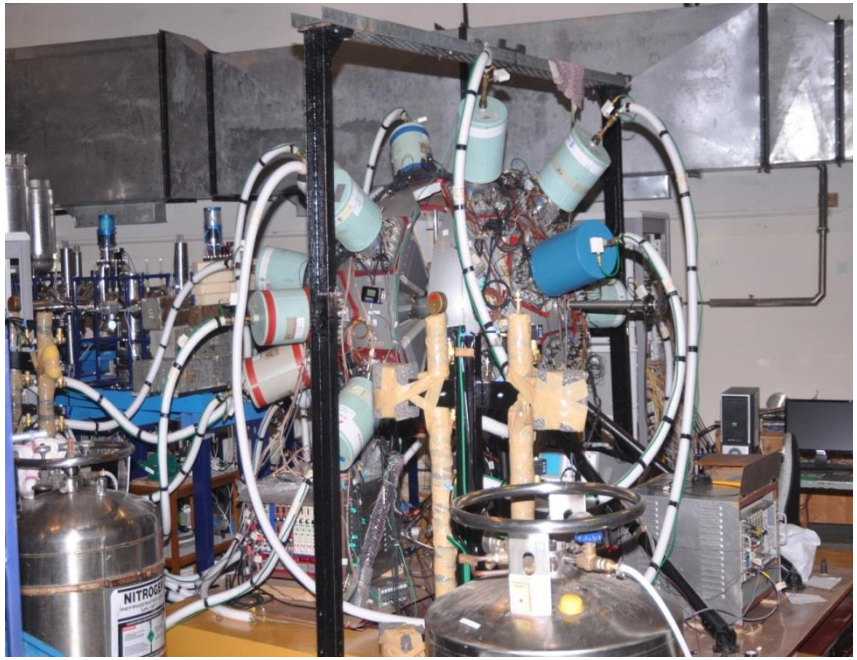
Lowest x-sec ~ 20 nb

Novel sensitive γ spectroscopy Technique using KX- γ coincidence at PLF

Typical Research Activities

- Fusion dynamics
  - Fusion around Coulomb barrier with stable. weakly bound and exotic projectile **Phys. Lett. B, 755, 332 (2016).**
- Fission dynamics (neutron and charged particles emission, fragment angular, mass and total kinetic energy distributions)
  - Dynamical hindrance, Nuclear level density ***Phys. Rev. Lett. 110, 062501 (2013)***
  - Studies in super heavy mass region , **Phys. Rev. C 94 (2016) 044618**
- Fission fragment spectroscopy using reactors and accelerators, INGA experiments, **Phys. Rev. C 96, 014315 (2017)**
- Elastic, inelastic scattering, breakup, multi-nucleon transfer, threshold anomaly studies, cluster states - electromagnetic transitions, **Phys. Rev. C 94 061602(R) (2016)**
- Nuclear Data with direct and surrogate method, **Phys. Rev. C 93, 021602(R) (2016)** Nuclear Data Physics Centre of India **(About 350 entries to EXFOR database), N_TOF studies at CERN**
- Development of Monte Carlo nucleon transport codes, **GEANTV, MONC**
- Theoretical studies of geometrical phases of anti-neutrino propagation ***Phys. Lett. B754, 135 (2016)*, INO**
- Nuclear Collisions at high energy, **Phys. Lett. B770, 357 (2017).**

INGA campaign



Physics Highlights

Search and characterization of novel excitation

Magnetic and Anti-Magnetic Rotation

Degenerate dipole bands and chirality

Wobbling Excitation

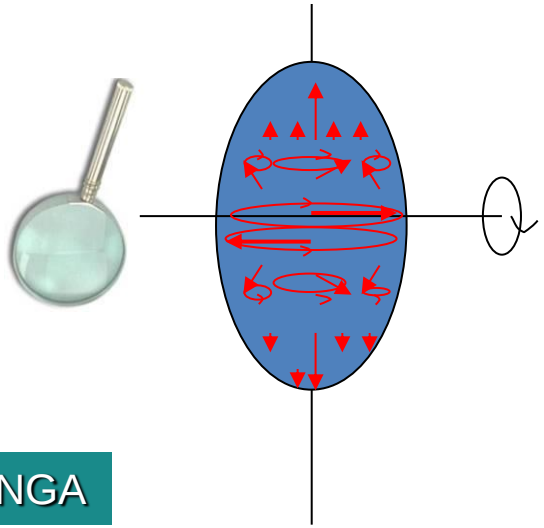
Shell model excitation and emergence of collectivity

Isomers and its application

Fission fragment spectroscopy

Reaction dynamics study

BARC, IUAC, IUC-KC, SINP, TIFR, VECC, IITs, Univ



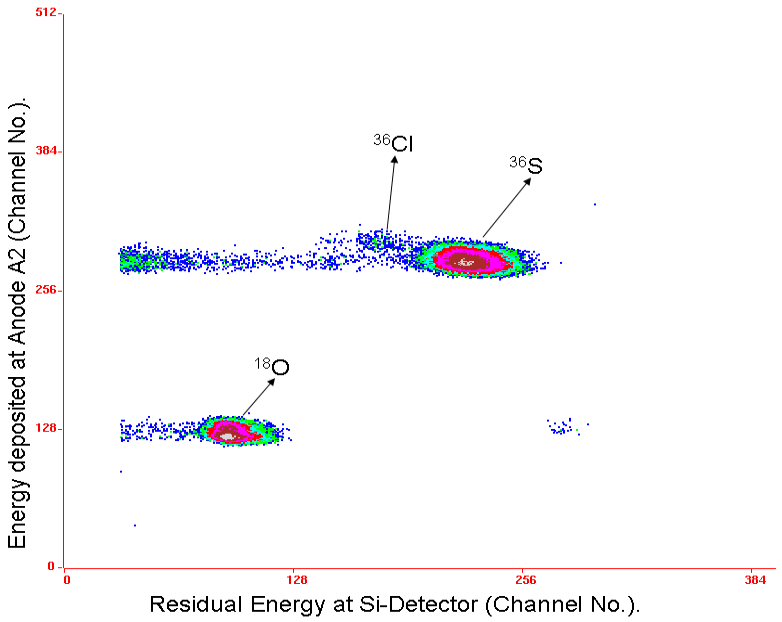
Investing in the polarization measurements of gamma rays and "wide-range timing spectroscopy" proved to be a successful approach for creating our specific "niche" and complement research at large scale facilities.

DSP based DAQ has Increased the data throughput by 10 times for INGA

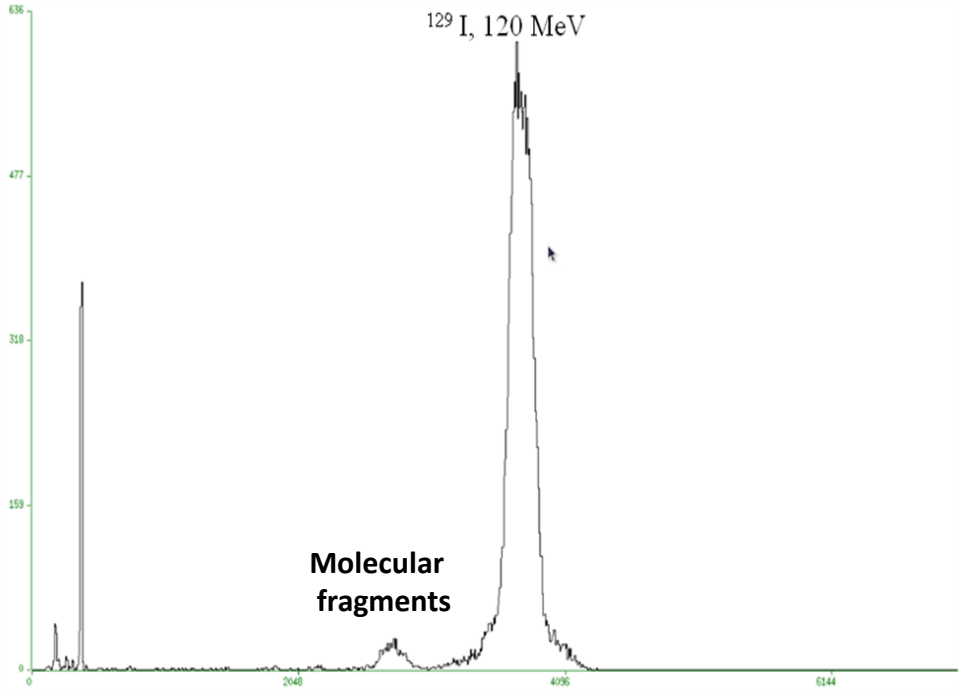
R. Palit et al. NIMA 680, 90 (2012)

Accelerator Mass Spectrometry Programme at Pelletron

- Accelerator Mass Spectrometry (AMS): ultra-sensitive means of counting individual atoms of long half life.
- This technique is already established for ^{36}Cl (10^5 yrs) for waste disposal site identification.
- The measurements further extended to ^{129}I (10^7 yrs) for environmental studies .



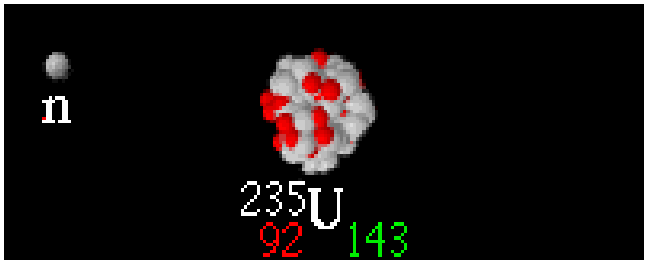
Anode A2 vs. Silicon detector for a standard sample



^{129} I spectra for standard sample

Fission Fragment Spectroscopy Studies using thermal neutrons:

(1) Understanding of Nuclear Fission Process
(2) Nuclear data required for decay heat calculations and future advanced reactor/RIB design
(3) Nuclear applications from Prompt Gamma Neutron Activation Analysis (PGNA)



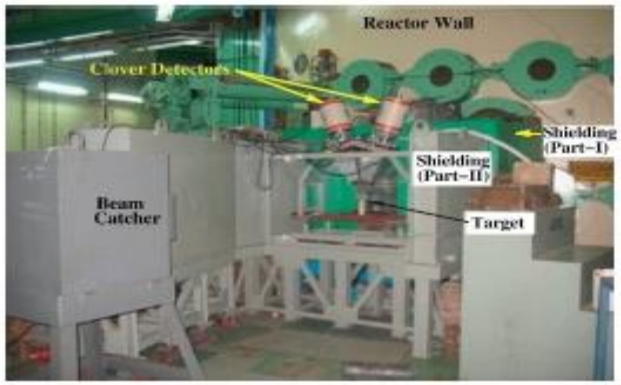
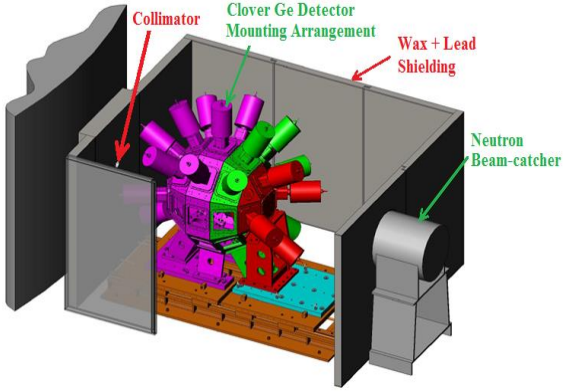


Fig. 1. Experimental setup at the CIRUS reactor facility for studying prompt γ–γ coincidence spectroscopy.

Neutron flux : 10^7 cm^{-2} sec^{-1} (at target position)

Detection system : 2 Clover Germanium detectors were used for gamma ray measurements



Upcoming facility at Dhruva reactor beam-line R-3001

Experiment at CIRUS reactor: ^{235}U(n, *f*)

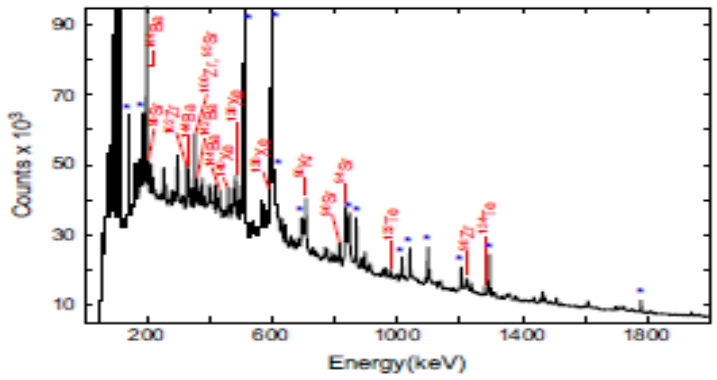
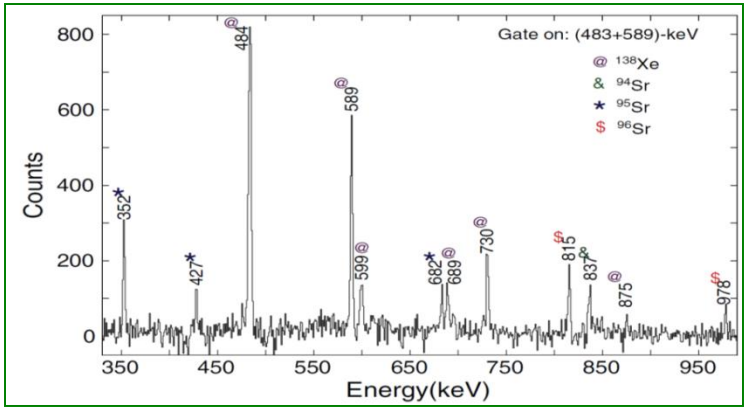


Fig. 5. Total projection spectrum from the γ–γ matrix in ^{235}U(n_{th}, f) reaction. The transitions from the isotopes with higher yields are labeled and the γ-rays marked with the * are from unidentified fragments or background contamination.



D.C. Biswas et al., Nucl. Inst. and Meth A 703 *(2013) 163,* S. Mukhopadhyay et al., Phys. Rev C85, 064321 (2012)

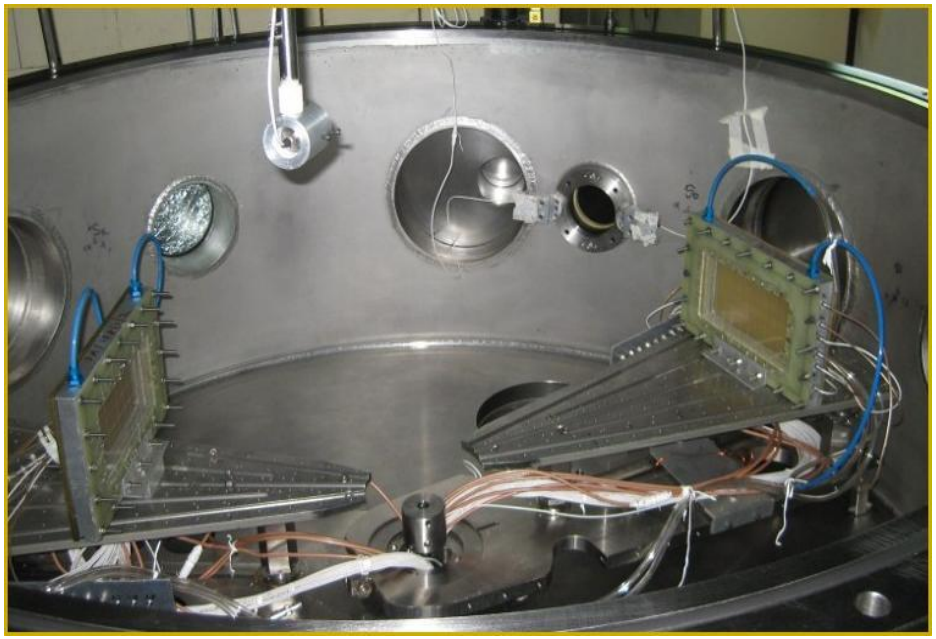
15 UD Pelletron with superconducting LINAC booster

The facility has never been used as neutron source for neutron physics experiments

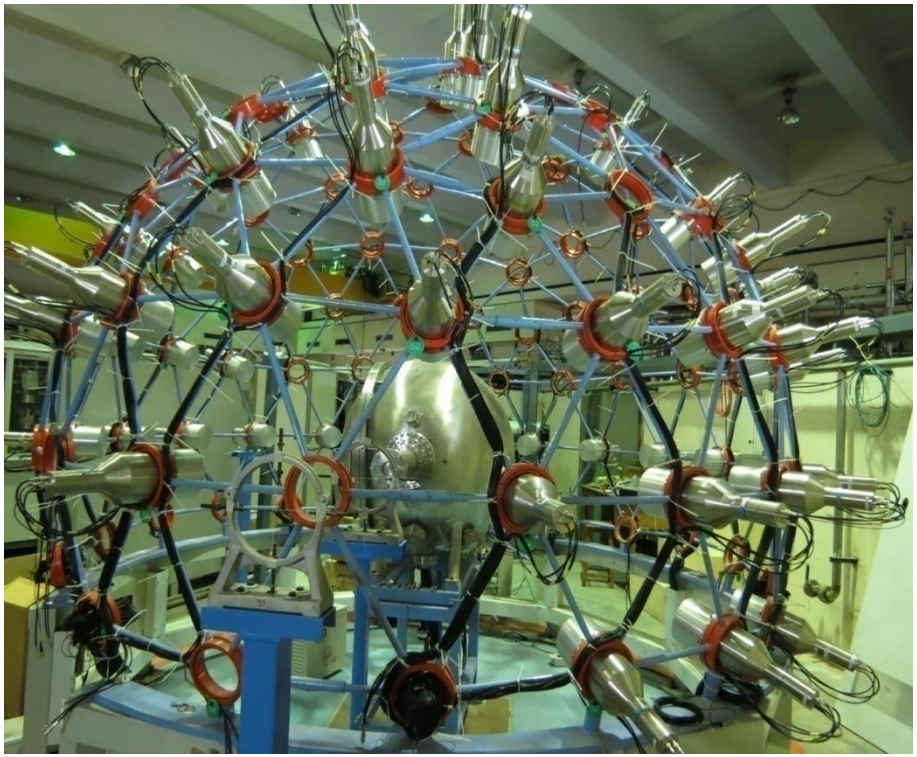
Indian National gamma Array (INGA): 24 Clover Detector array with a total photo-peak detection efficiency of ~5%

Gamma Detector Array (GDA): 12 Compton suppressed HPGe detectors setup
Heavy Ion Reaction Analyzer (HIRA): One of few recoil mass spectrometers (RMS) in the world and first of its kind in Asia dedicated to the study of heavy ion induced nuclear reaction dynamics.
Hybrid Recoil mass Analyzer (HYRA)
General Purpose Scattering Chamber (GPSC): A1.5 m diameter scattering chamber equipped with
rotating arms and in-vacuum target transfer system.
National Array of Neutron Detectors (NAND): About100 organic liquid scintillators of 5" diameter and
5" thickness for fission fragment in coincidence with neutrons studies.
Accelerator Mass Spectrometry (AMS):

Facilities for fusion-fission study at IUAC



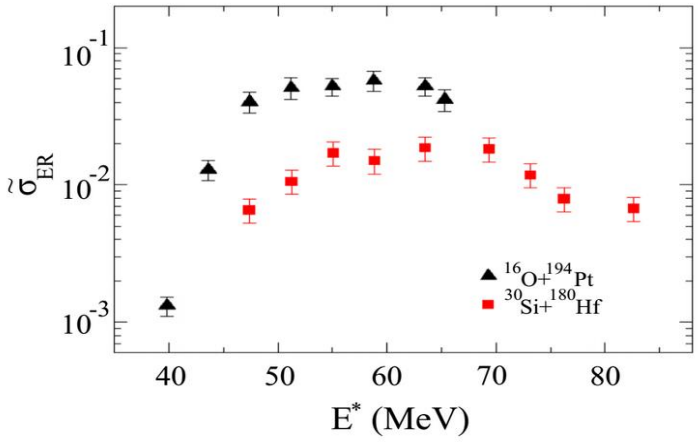
Fission fragment mass distribution measurement using MWPC time of flight set-up inside scattering chamber



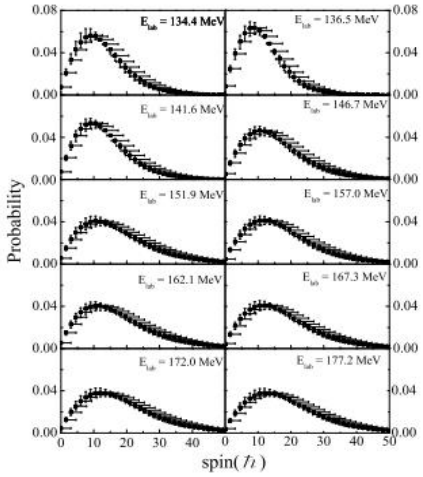
Neutron detector array for measuring neutron multiplicity in coincidence with fission fragments

HYbrid Recoil mass Analyzer (HYRA) at IUAC, New Delhi

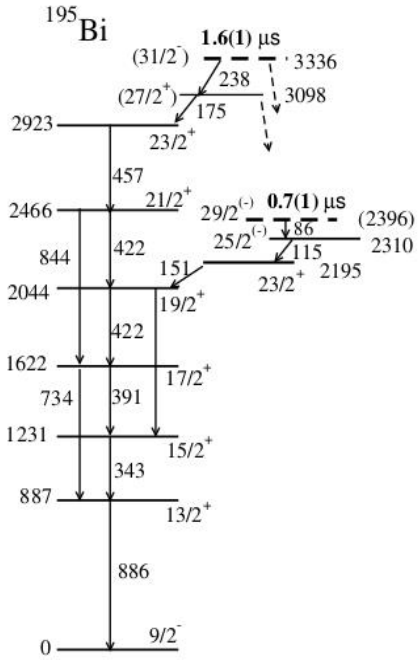
Fusion reactions around Coulomb barrier
Evaporation Residue (ER) spin distribution measurements
ER-gated high spin spectroscopy
Microsecond isomer search
Clustering Vs Pairing in nuclei



ER excitation function for $^{16}O + ^{194}Pt$ and $^{30}Si + ^{180}Hf$ both leading to same Compound Nucleus $^{210}Po^*$



ER spin distributions for $^{31}P + ^{170}Er$ leading to Compound Nucleus $^{201}Bi^*$



New isomer of 1.6 ms lifetime observed in ^{195}Bi nucleus

Variable Energy Cyclotron Centre (VECC), Kolkata, India
K=130

Beam details: : Extracted and Delivered to the users for experiments. Presently available maximum energies are given in the parenthesis.

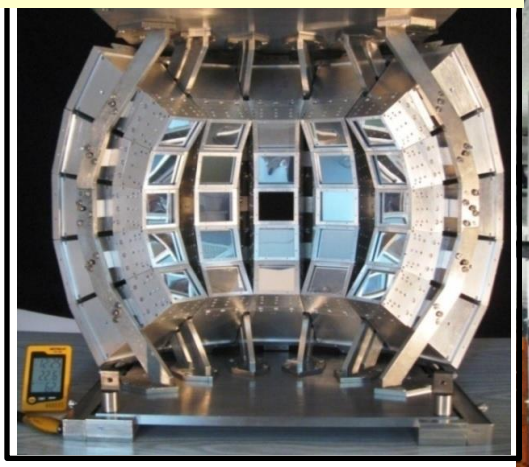
Beam Species	Max. Energy (MeV)	Max. current/Intensity (nA)
Proton	7-20 (15)	10000 (Ch 1)
Alpha	26 – 80 (60)	4000 – 5000 (Ch 1), upto 20 (ch 2/ch 3)
Nitrogen	122	135 (extracted)
Oxygen	180	410 (extracted)
Neon	200	310 (extracted)
Argon	350	150 (extracted)

facility has not been used as a neutron source for neutron scattering or as a neutron generator

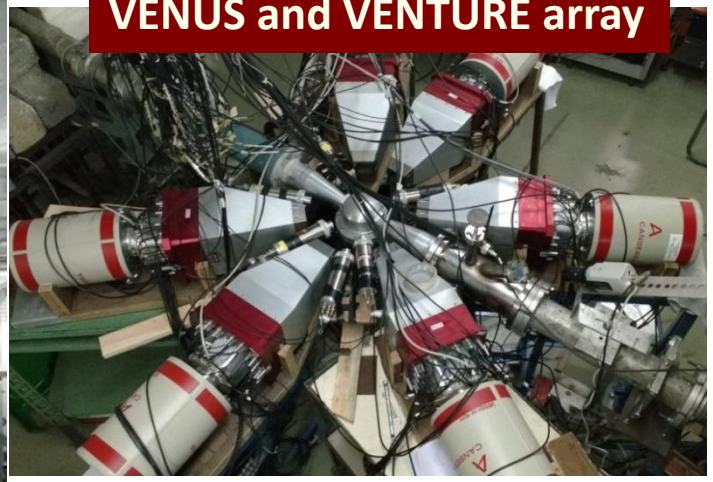
^{14}O (71 sec), ^{42}K (12.4 hrs), ^{43}K (22.2 hrs) and^{41}Ar (1.8 hrs) have been successfully produced , using a novel gas-jet recoil transport coupled Electron Cyclotron Resonance (ECR) ion- source

Experimental facilities and Nuclear Physics Research Activities at VECC

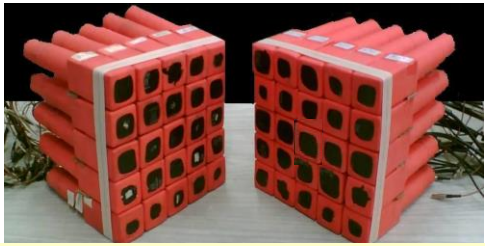
Charge particle detector array



VENUS and VENTURE array

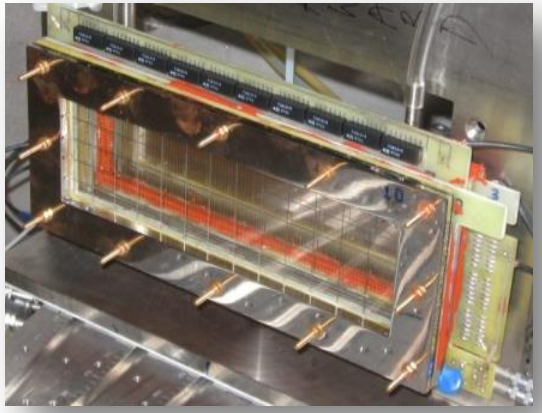


Neutron Detectors

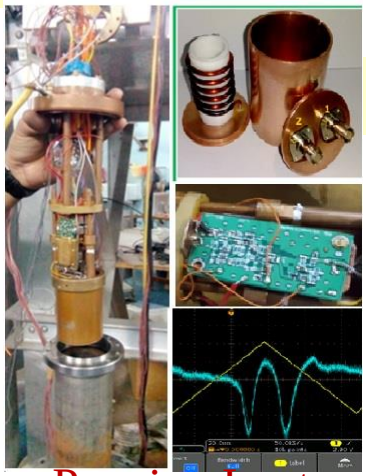


Gamma Multiplicity Filter

Segmented Clover



MWPC



Penning Ion trap

LAMBDA Detector array

Folded Tandem Ion Accelerator (FOTIA)

Beam Species	Max. Energy	Max. current/Intensity
^{7}Li, ^{12}C, ^{16}O and ^{19}F and other heavy ion beams upto A=40	66 MeV	< 100 nA
Proton	Upto 6 MeV	200 nA
Neutron	Below 5 MeV using $^{7}Li(p,n)$ and $^{9}Be(p,n)$	10^{6}-10^{7} n/sec/cm^{2}

Multipurpose scattering chamber
Scintillator detectors for neutrons (NE213)
Charged particle detectors
PIXE (Particle Induced X-ray Emission)
RBS (Rutherford Back Scattering)
PIGE (Particle Induced Gamma Emission)

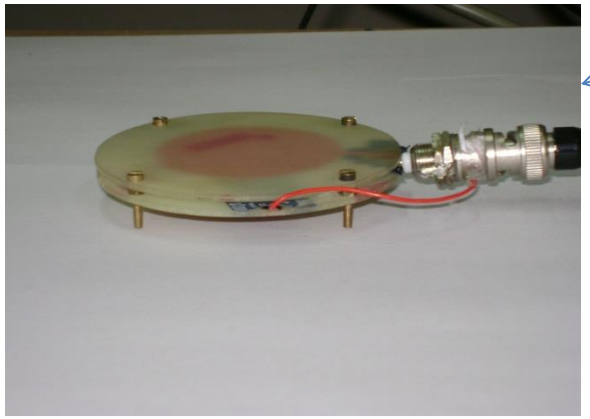
25 degree Hill-Side Beam Line being developed for inverse Kinematics ^{7}Li beam on proton

Scattering Chamber

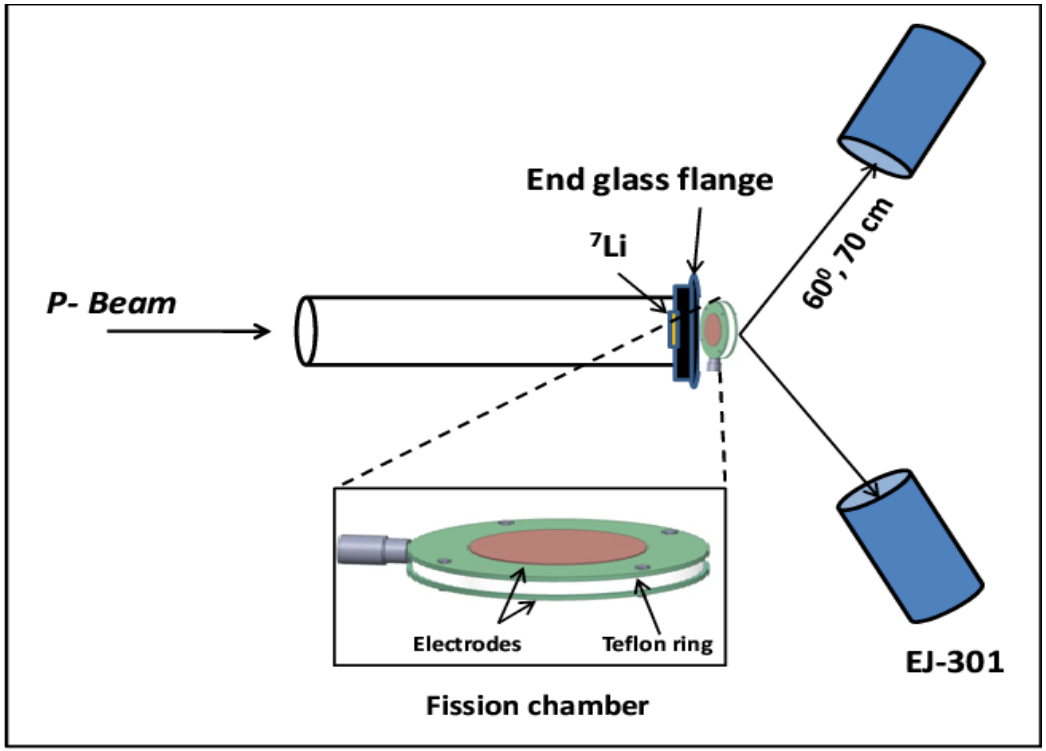
FOTIA BEAM HALL

EXPERIMENTAL DETAILS FOR PFNS STUDIES

- Natural ^{7}Li metallic target of thickness of 4.0 mg/cm2 (1.0 × 1.0 cm^2 area)



Fission fragments were detected in 2π geometry



12.7 cm in diameter and 5.0 cm thick

Photograph of Fission chamber and neutron detector used in the experiment.

Schematic of the experimental setup.

14 MeV Neutron Generator, Pune University, BARC

14 MeV neutrons with flux ~ 10^8 n/cm2-sec

(n, g), (n, p), (n, a), (n, 2n)

Deutron induced cross-section measurements for light elements important for astrophysics.

Future Plans/ Upcoming facilities

- ECR Injector for the SC Linac (Delhi)(in progress)
- ECR Injector based HI accelerator(Mumbai)(Design and Development)
- Low Energy High Intensity Proton Accelerator(LEHIPA) – 20 MeV Proton Accelerator-(Mumbai)(in progress)
- FRENA – 3 MV Accelerator for Astrophysics (installation in progress Kolkatta)
- SC K=500 cyclotron- (Beam trials) (Kolkata)
- ANURIB–National RIB (Design and Development) (Kolkatta)

30 MeV (500 μA) Medical Cyclotron

Studies in Nuclear Astrophysics at SINP: experimental and theoretical efforts

Experimental

•. Indirect methods in Nuclear Astrophysics-

- *•Cluster transfer, breakup and ANC technique.*
- *•Coulomb breakup*

Theoretical

- *•Nuclear reaction modelling- Continuum Discretized Coupled Channel (CDCC) and Asymptotic Normalisation Constant method*
- *R-matrix theory analysis of capture reaction*
- *Shell model studies of neutron – rich exotic nuclei on the r-process path: new shell closure predicted*

- **Facility for experimental Nuclear Astrophysics (FRENA) : 3MV Tandetron**

Civil work for installation of the machine in full swing

Developmental work for utilization of FRENA

- *•Detector testing: background suppression*
- *• Implanted Target preparation, development and characterization*
- *•Gas detector development*
- *•Offline gamma array installation – digital data acquisition testing*

Roadmap for Accelerator Development for ADS

LEHIPA

High current injector 20 MeV, 30 mA

Proton IS 50 keV

RFQ 3 MeV

DTL 20 MeV

Phase 1

Normal Conducting

DTL/ CCDTL

Phase II

Super-conducting

Phase III

200 MeV

SC Linac

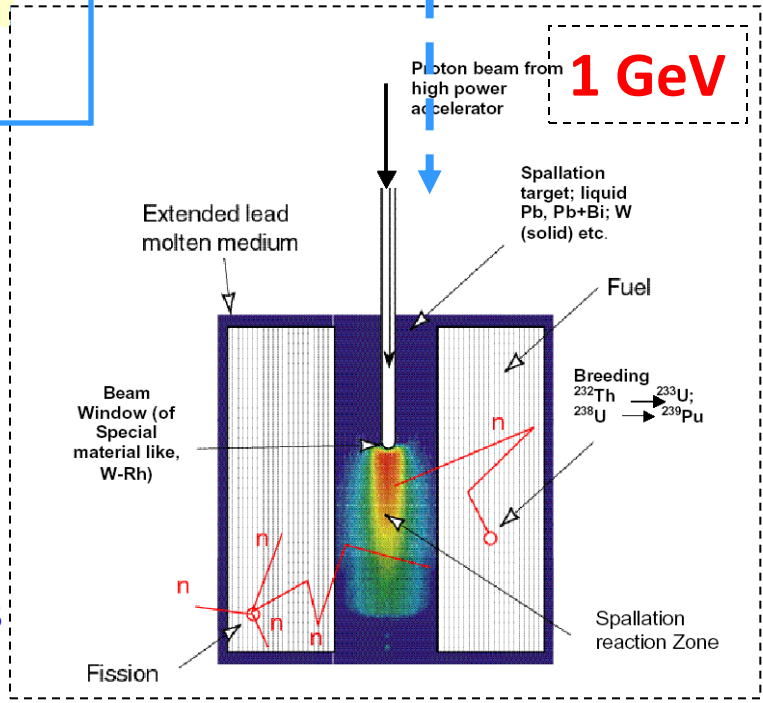
1 GeV

Super-conducting

Latest road map

Superconducting structures after RFQ

Spoke resonators/
Half Wave Resonators



Ongoing Projects/Activities in DAE & IUAC

Design and development work for proton accelerator and support technologies viz superconducting cavities, cryogenics, RF power, magnets is going on at RRCAT, BARC, VECC, IUAC

- LEHIPA (BARC)
- R&D Activities of high energy Proton Linac for SNS (RRCAT)
- SCRF Cavities, Test stands, RF Power and Control Instrumentation (RRCAT, BARC, VECC, IUAC)

International Collaborations

- Fermilab (Project X)
- CERN (Linac 4)