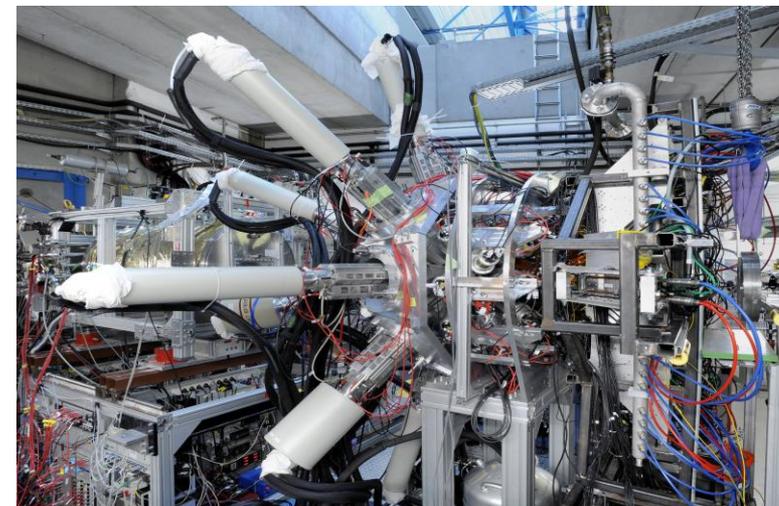
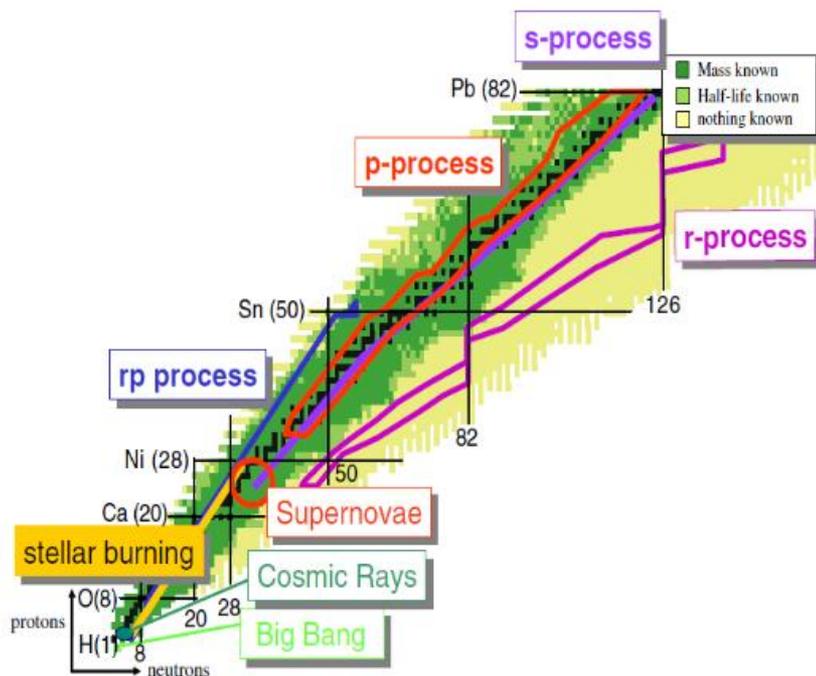




Indian Participation in NuSTAR Experiment



Samit Kr. Mandal

*Department of Physics & Astrophysics,
University of Delhi, New Delhi*

on behalf of NuStar India collaboration



Theme Meeting on FAIR - Science, Department of Physics, Panjab University, Chandigarh, 23rd - 25th April 2025

The international collaboration

FAIR 2027 : NuSTAR Experiments



Univ. Leuven



CEA Saclay
CSNSM Orsay
GANIL Caen
IPN Orsay



CLRC Daresbury
Univ. Keele
Univ. Liverpool
Univ. Manchester
Univ. Paisley
Univ. Surrey
Univ. York



FZ Juelich
FZ Rossendorf
GSI Darmstadt
HMI Berlin
LMU Muenchen
MPI Heidelberg
TU Darmstadt
Univ. Bonn
Univ. Koeln



INFN Genova
INFN Legnaro
INFN/Univ. Napoli
INFN/Univ. Padova
Univ. Camerino
Univ. Firenze
Univ. Milano



NBI Copenhagen



IFJ Krakow
IPJ Swierk
Univ. Krakow
Univ. Warszawa



University of Delhi
TIFR, BARC, Mumbai
IUAC New Delhi
VECC, SINP, CU, Kolkata
PU, AMU, KU³, BV, JU, IITR,...

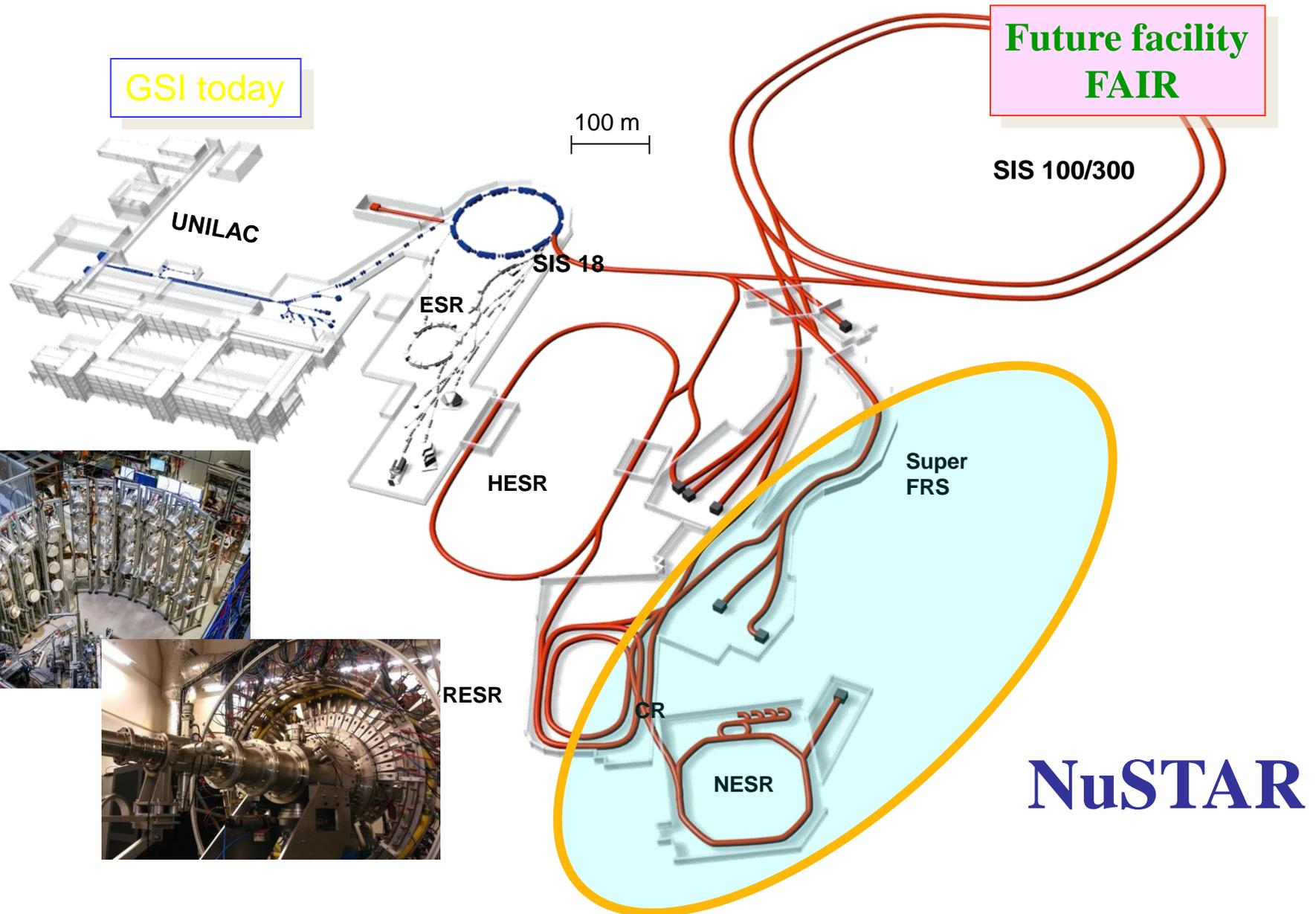


KTH Stockholm
Univ. Lund
Univ. Uppsala



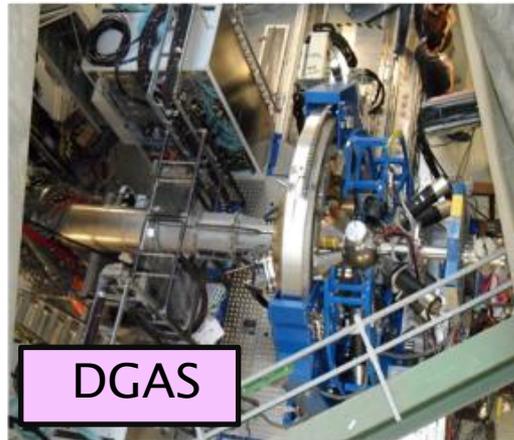
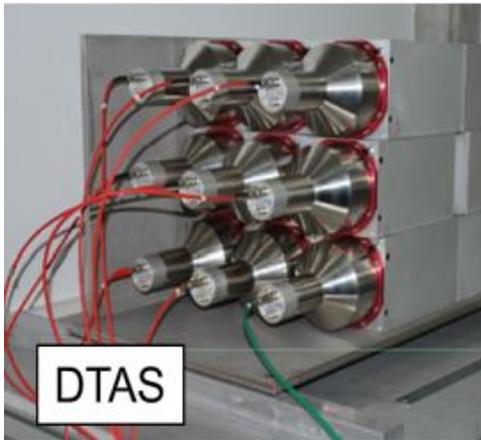
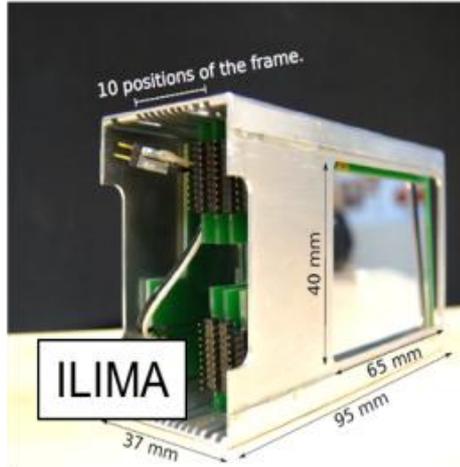
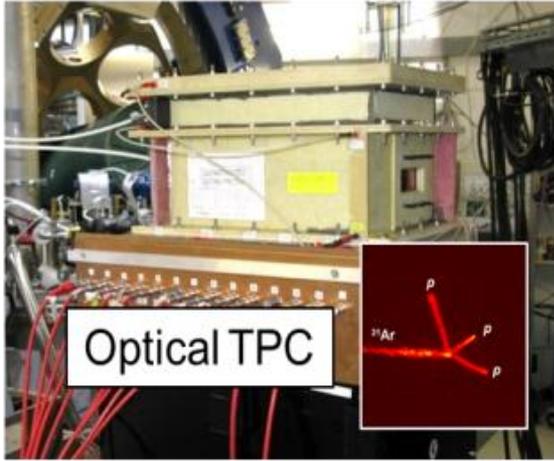
Univ. Demokritos

FAIR - Facility for Antiproton and Ion Research



POSSIBLE Detector Instrumentation : Phase-0

N
U
S
T
A
R



NUclear STructure Astrophysics and Reactions

1. Formation of Complex Nuclei from Basic Constituents

- What is the effective nucleon-nucleon interaction, and how does QCD constrain it?
- In what ways does the three-nucleon force alter our understanding of nuclear interactions?

2. Dependence of Nuclear Forces on Proton-to-Neutron Ratios

- How does the spin-orbit force depend on isospin?
- What changes occur in nuclear shell structure far from stability?
- How do nucleon-nucleon (N-N) correlations in nuclei and nuclear matter evolve with isospin?

3. Understanding Collective Phenomena from Individual Motion

- What are the different phases, relevant degrees of freedom, and symmetries in the nuclear many-body system?

4. Limits of Nuclear Existence

- Where are the proton and neutron drip lines located?
- What are the heaviest elements that can exist?

5. Nuclear Matter and Neutron-to-Proton Asymmetry

- How does the equation of state of nuclear matter vary with neutron-proton asymmetry?
- What is the magnitude and density dependence of the symmetry energy?
- What are the characteristics of neutron-rich matter?

6. Astrophysical Relevant Nuclei and Their Impact

- Which nuclei are key to astrophysical processes?
- What are their properties, and how do they influence nucleosynthesis models?

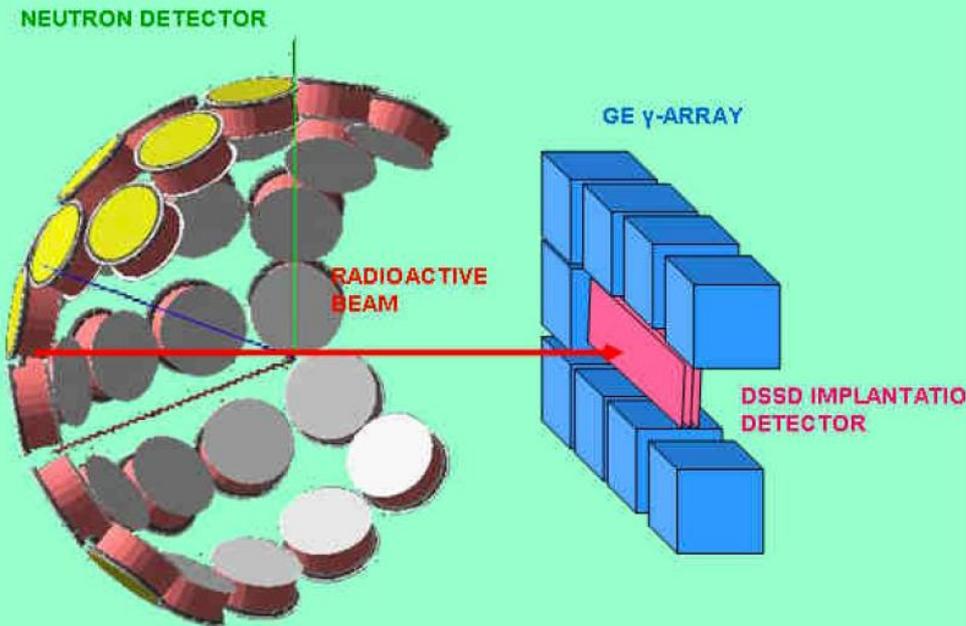
DESPEC: Identification and decay spectroscopy of Implanted Ions

„Complete“ decay spectroscopy:

- * α , β , γ -decay spectroscopy
- * conversion electrons
- * β -delayed neutrons

Highest selectivity and sensitivity due to in-flight separation and unambiguous identification in A and Z

→ Decay studies with few events/hour



Requirements from DeSpec:

Very cleanly separated stopped beams best for high-energy primary beams

- Minimum fragment rate: $10^{-4} - 10^{-5} \text{ s}^{-1}$
- Maximum total rate: $10^{+3} - 10^{+4} \text{ s}^{-1}$ to perform ion-decay correlation
- Limited focal plane size from 8×8 to $8 \times 24 \text{ cm}^2$

India is contributing to DEGAS, MONSTER and MATS

In search of the building blocks of the Universe...

What are we made of?



So how, where and when have the elements been made?

Indian philosophers: 5 building blocks

Pr̥thvī (Earth) - solidity, support



Vāyu (Air) - movement, dynamism

Āpas (Water) - liquidity, cohesion

Tejas (Fire) - transformation, energy

Ākāśa (Space/Ether) - emptiness, vibration, containment

1896 Mendeleev

92 building blocks (chemical elements)

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun								
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

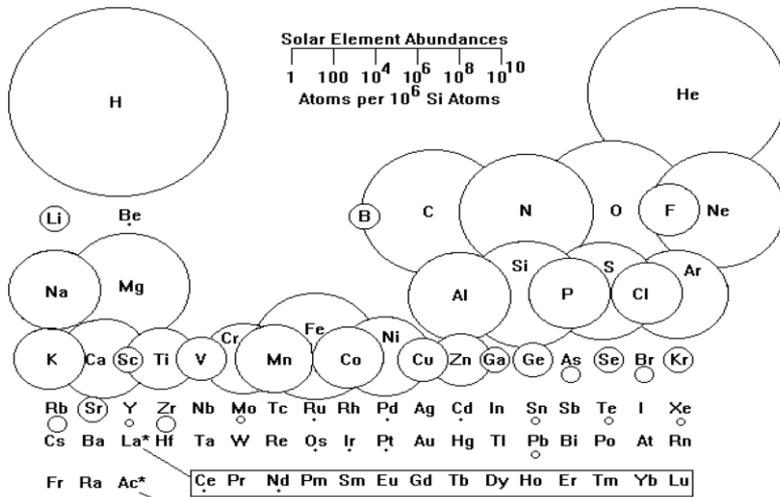
Why are some elements much more abundant than others?



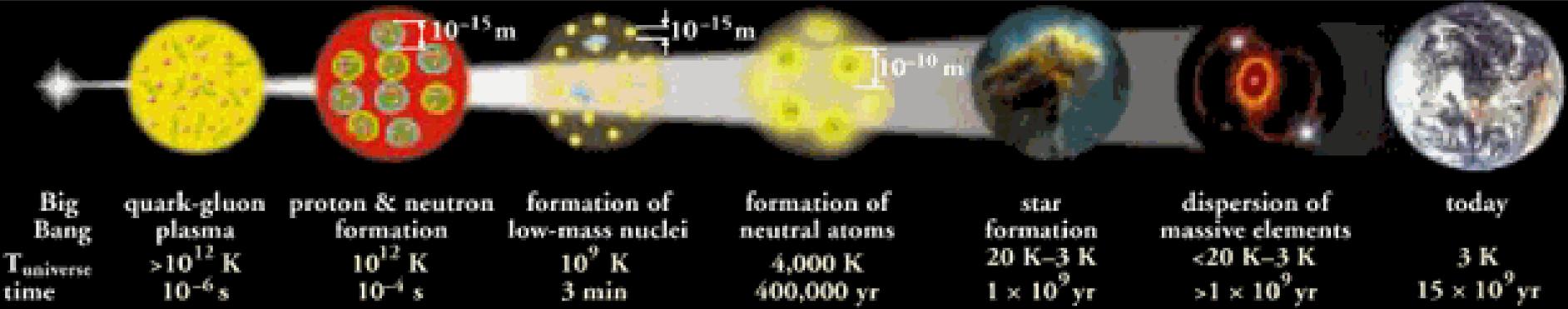
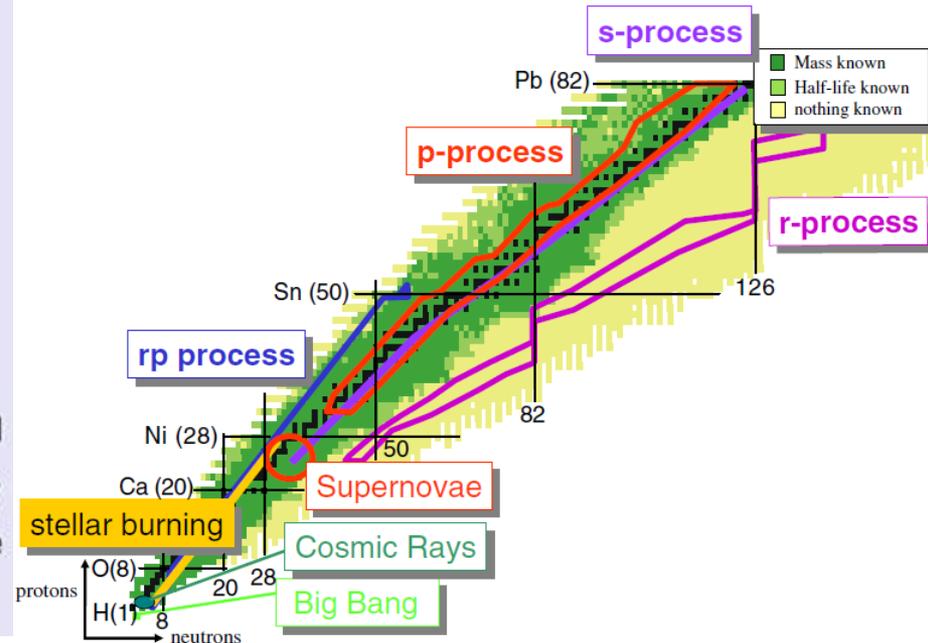
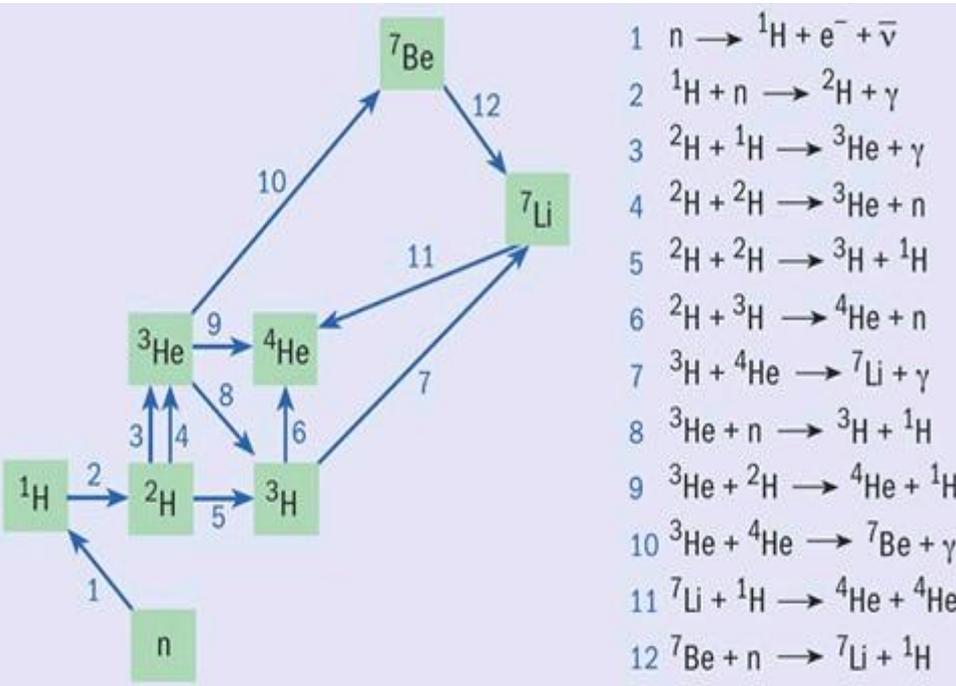
Iron extracted at 2.5 billion tonnes/yr



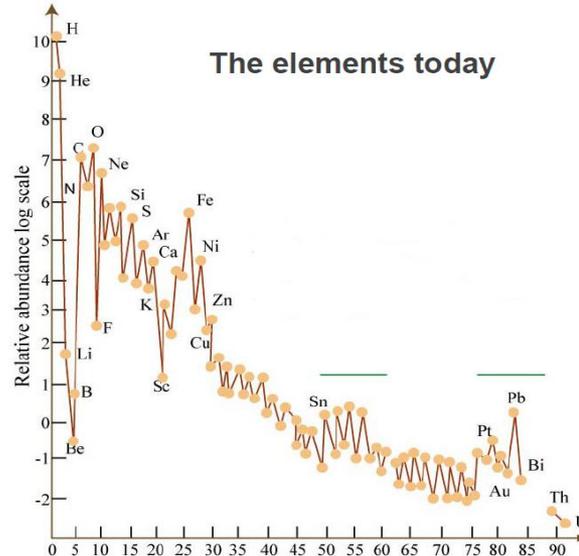
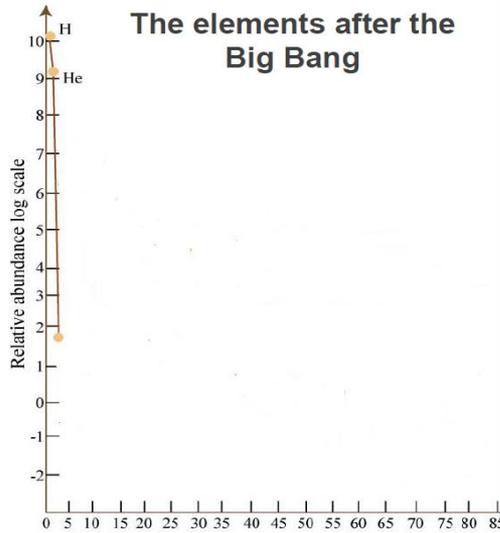
Gold extracted at 3000 tonnes/yr



Stellar Life and the Cosmic Origins of Elements



WHAT THE STARS HAVE GIVEN US



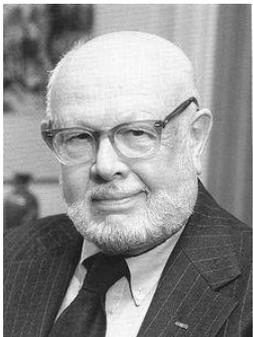
Solar Abundance

Assumption of a N=82 shell quenching leads to a considerable improvement in the global abundance fit in r-process calculations

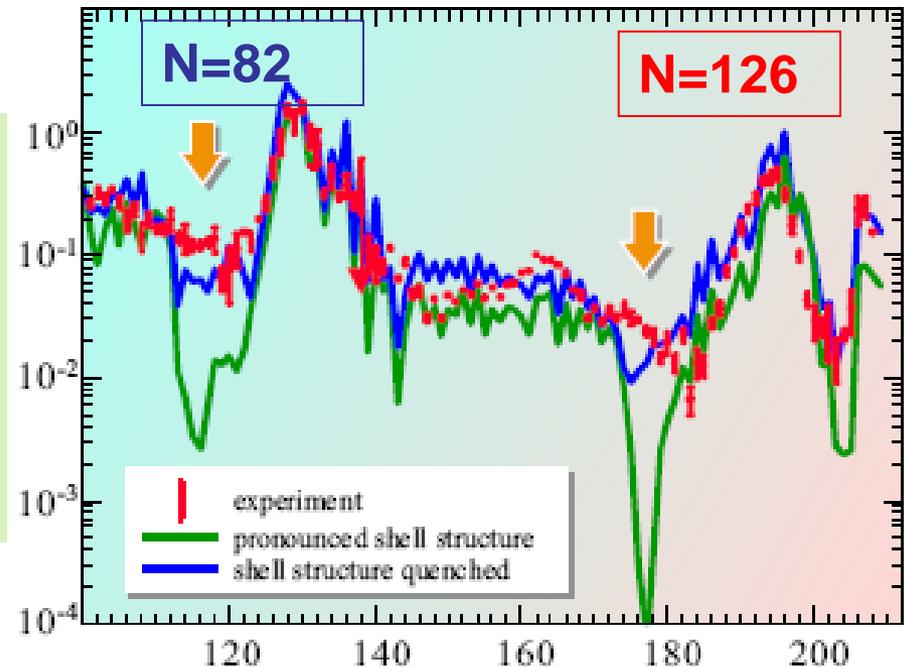
Foundation of modern theory of nuclear astrophysics:

- Burbidge, Burbidge, Fowler and Hoyle (1957)
- Cameron (1957)

Nobel prize to Willy Fowler (1983)

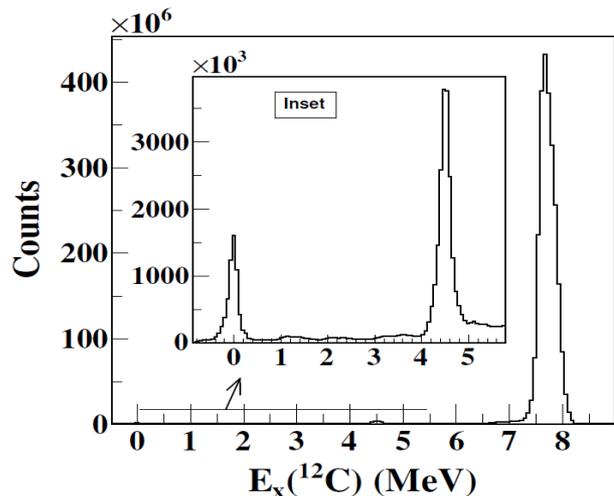


Willy Fowler (1911-95)



Study of Hoyle state in ^{12}C

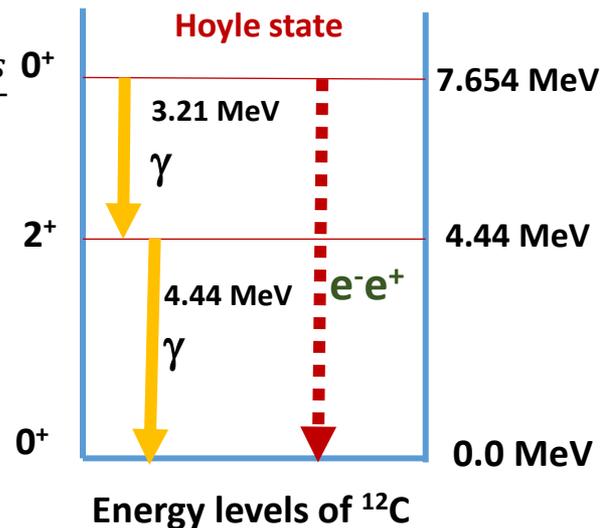
Using $^{12}\text{C}(p,p'\gamma)^{12}\text{C}$ reaction at 10.6 MeV of proton energy, the Hoyle state can be observed as a triple coincidence events between an outgoing proton (~ 1.5 MeV), 3.21 MeV γ -ray and 4.44 MeV γ -ray



$$\frac{\Gamma_{\text{rad}}}{\Gamma} = \frac{p\gamma\gamma \text{ coincidence events}}{p \text{ singles events}}$$

$$\frac{\Gamma_{\text{rad}}}{\Gamma} = 4.01 (30) \times 10^{-4}$$

Our finding do not align with a recently reported 34% increase in the $\frac{\Gamma_{\text{rad}}}{\Gamma}$ but is consistent with the currently accepted value.



Excitation energy spectra of ^{12}C . Inset is the expanded view of the lower excitation portion.

Physics Letters B
Volume 859, December 2024, 139083

ELSEVIER

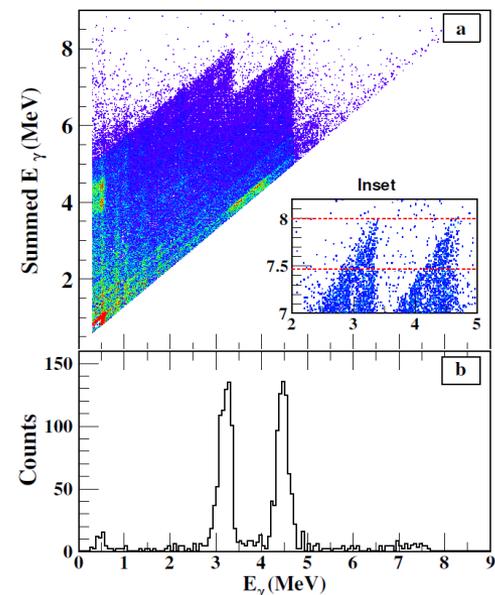
Letter

New measurement of the Hoyle state radiative transition width

T.K. Rana ^{a,b}, Deepak Pandit ^{a,b}, S. Manna ^{a,b}, Samir Kundu ^{a,b}, K. Banerjee ^{a,b}, A. Sen ^{a,b}, R. Pandey ^a, G. Mukherjee ^{a,b}, T.K. Ghosh ^{a,b}, S.S. Nayak ^{a,b}, R. Shil ^c, P. Karmakar ^{a,b}, K. Atreya ^{a,b}, K. Rani ^c, D. Paul ^{a,b}, R. Santra ^a, A. Sultana ^{a,b}, S. Basu ^{a,b}, S. Pal ^{a,b}, S. Sadhukhan ^{a,b}, Debasish Mondal ^{a,b}, S. Mukhopadhyay ^{a,b}, Srijit Bhattacharya ^d, Surajit Pal ^a, P. Pant ^a, Pratap Roy ^{a,b}, Sk M. Ali ^{a1}, S. Mondal ^a, A. De ^f, Balaram Dey ^e, R. Datta ^g, S. Bhattacharya ^{a,2}, C. Bhattacharya ^{a,2}

^a Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata - 700 064, India
^b Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai - 400094, India

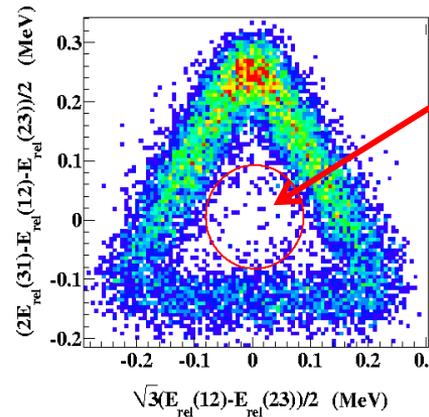
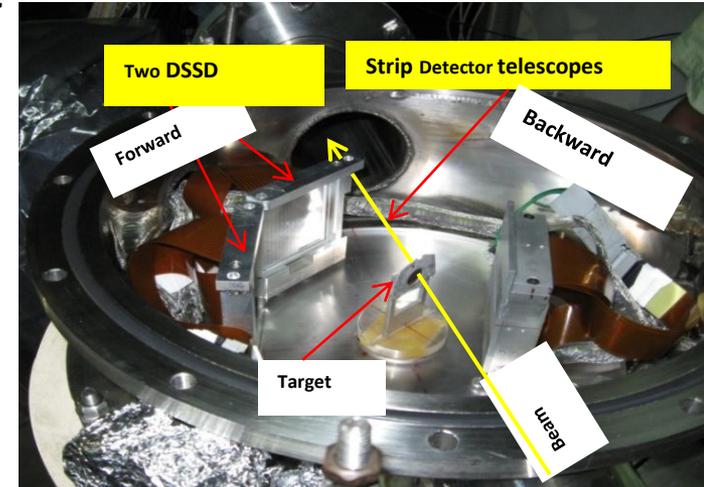
(a) Singles vs sum of coincidence γ -energies. Inset is the expanded view around Hoyle state. (b) Projected spectra of the gated portion.



Structure of Hoyle state

- ❖ Electron scattering data indicate rms radius of the Hoyle state is 1.5 times the ground state value *PRL 98, 032501 (2007)*
- ❖ Ab-initio lattice calculation: gr. St. and first 2+ state -> compact triangular configuration of alpha-cluster
Hoyle state as -> bent arm like structure *PRL 109, 252501 (2012)*

Studied by VECC group from decay of Hoyle state



Direct Decay

Result in nutshell

Decay through sequential emission of α - particle
 α - cluster structure of Hoyle state

Total Direct decay $\leq 0.02\%$

T. K. Rana et al. Phys Letts B 793, 130 (2019)

INDIAN Involvement in DESPEC/HISPEC Experiment at NUSTAR/FAIR

- ❖ **Shared Physics Interests** between the Indian nuclear physics community and GSI.
- ❖ **Early Involvement** in FAIR project development, beginning with the CDR phase in 2001.
- ❖ **Initiated Funding Requests** for Indian participation in NUSTAR/FAIR starting in 2006.
- ❖ **Technical Contributions** to TDRs of key experiments such as DEGAS, MONSTER, and MATS.
- ❖ **Active Role in R&D** for the development of advanced detectors.
- ❖ **Organized NUSTAR Meetings and Workshops** within India to foster engagement.
- ❖ **Expanded Collaborative Scope** with NUSTAR to enhance scientific cooperation.

Groups involved from India:

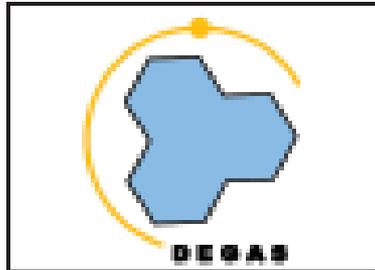
TIFR, DU, VECC, IUAC, PU, IIT Ropar, IIT Roorkee,

In Collaboration with GSI/FAIR

Technical Report for the Design, Construction and Commissioning of the

DESPEC Germanium Array Spectrometer - DEGAS

DEGAS Collaboration



2014

GSI Darmstadt, Germany
J. Gerl, M. Gorska, I. Kojouharov,
H. Schaffner

IFIN-HH Bucharest, Romania
N. Marginean

ISZU Istanbul, Turkey
N. Erduran

JYFL, Jyväskylä, Finland
C. Scholey

KTH Stockholm, Sweden
B. Cederwall, M. Doncel

STFC Daresbury, UK
P. Aden, I. Burrows, A. Grant, M.
Labiche, J. Simpson

TIFR, Mumbai, India
R. Palit

TU Darmstadt, Germany
C. Louchard, N. Pietralla

Univ. Brighton, UK
A. M. Bruce

Univ. Delhi, India
S. Mandal

Univ. Liverpool, UK
A. J. Boston, P. J. Nolan, R. D. Page

Univ. Madrid, Spain
A. Jungclaus

Univ. Salamanca, Spain
B. Quintana, S. Martin

Univ. Surrey, UK
Zs. Podolyak

Univ. Valencia, Spain
A. Algora, C. Domingo, A. Gadea,
B. Rubio, J. Tain

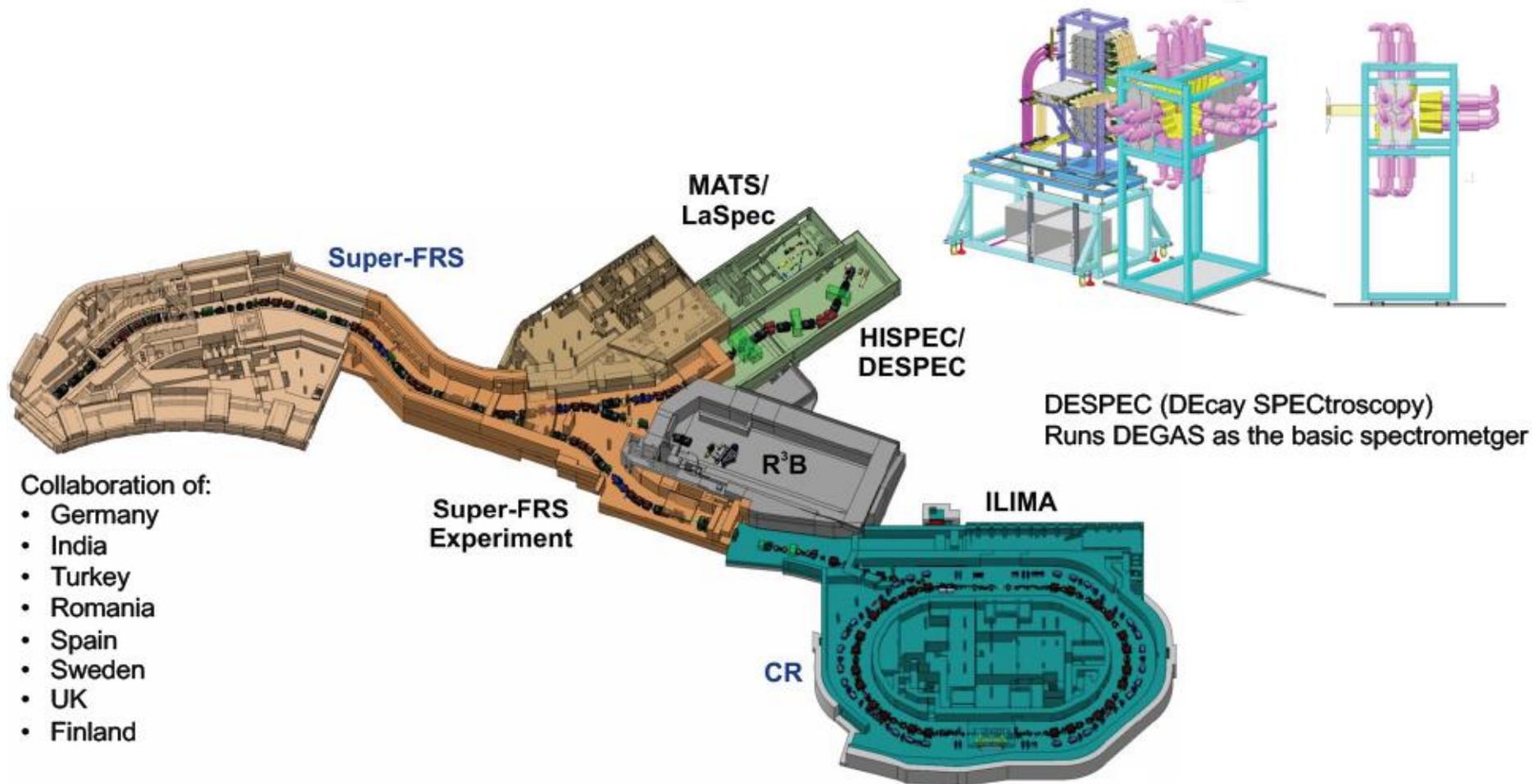
YTU Istanbul, Turkey
T. Yetkin

DEGAS – the HPGe array spectrometer for NUSTAR



(DESPEC Germanium Array Spectrometer)

1. HISPEC/DESPEC at NuSTAR



Collaboration of:

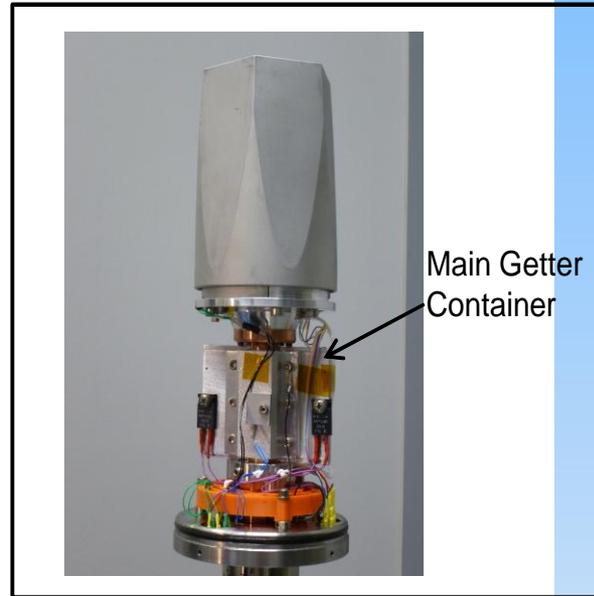
- Germany
- India
- Turkey
- Romania
- Spain
- Sweden
- UK
- Finland

DEGAS TDR (2016)

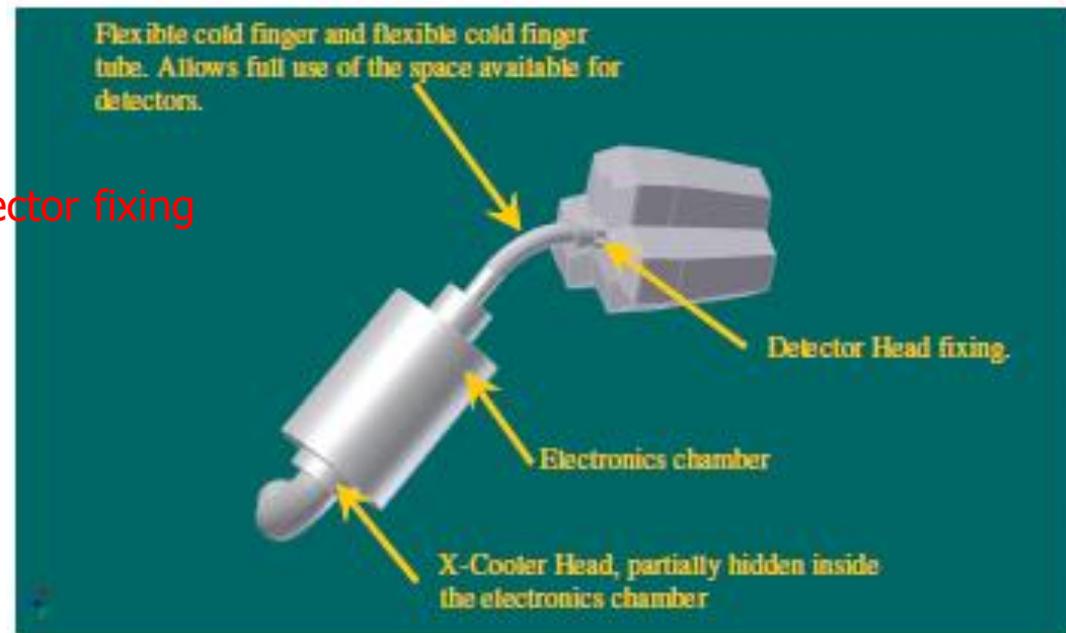
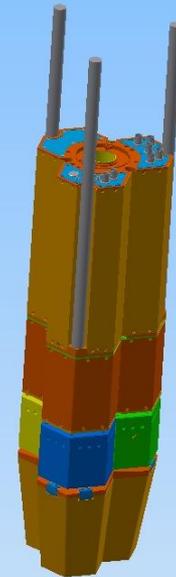
DEGAS Detector



Cluster Detector fixing



DEGAS fixing

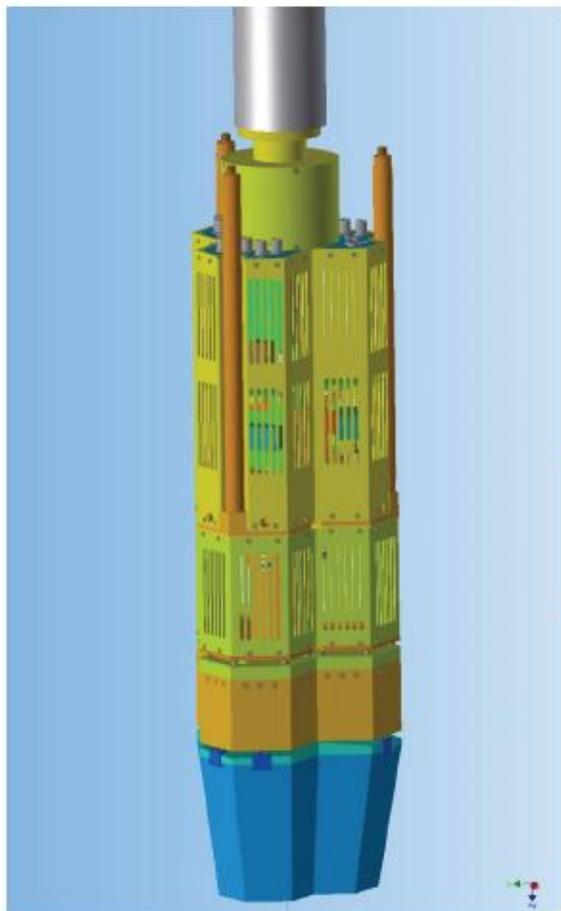




Detector at FAIR for the study of formation of heavy elements in the Universe

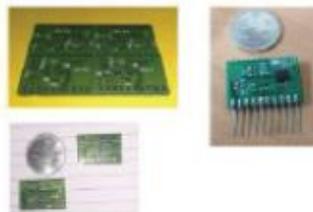
A complex device

- Encapsulated HPGe crystals in the cryostat with electrical cooling.
- 38 producible components (some of them several pieces per cryostat)- Cu, stainless steel, Al.
- High vacuum.
- Signal processing electronics.
- Imaging capability



**Fabrication,
First mechanics test, TIFR, Mumbai,
India, February 2016**

DDH PCB



Waiting for the approved funding from India-FAIR project.!!!
In-kind contract finalized.

- Various components of DEGAS
- HPGe detector with Imaging
- BGO catcher with SiPM

Design and fabrication of of preamplifier at TIFR

Major Contributions From India towards DEGAS

Production and Quality Control of DEGAS mechanics
at Central workshop TIFR

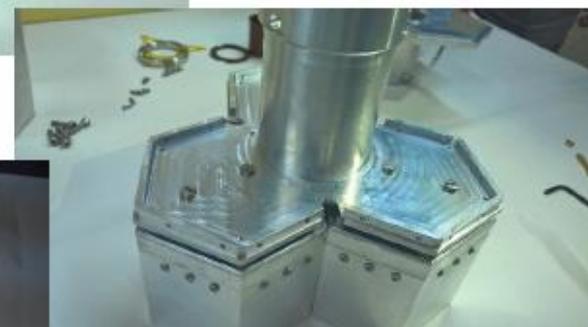


- Prototype of DEGAS mechanics made in India has been approved
- DEGAS mechanics fabricated in India are used in Experiment
- An Implant High Purity Germanium Double Sided Strip Detector was used in test experiment at GSI/FAIR for low energy γ -ray detection
- Geant4 Simulation for DEGAS
- Several Ph.D students are being trained in R&D related to DEGAS
- Active contribution in experiments of DESPEC Collaboration
- Fabrication of TEGIC for beam tracking

DEGAS – the HPGe array spectrometer for NUSTAR

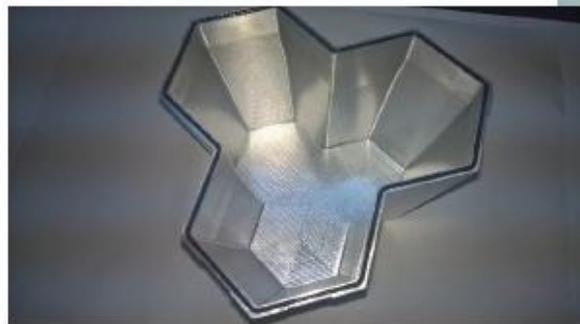


Vacuum 5.10^{-7}



First mechanics test, TIFR, Mumbai, India, February 2016

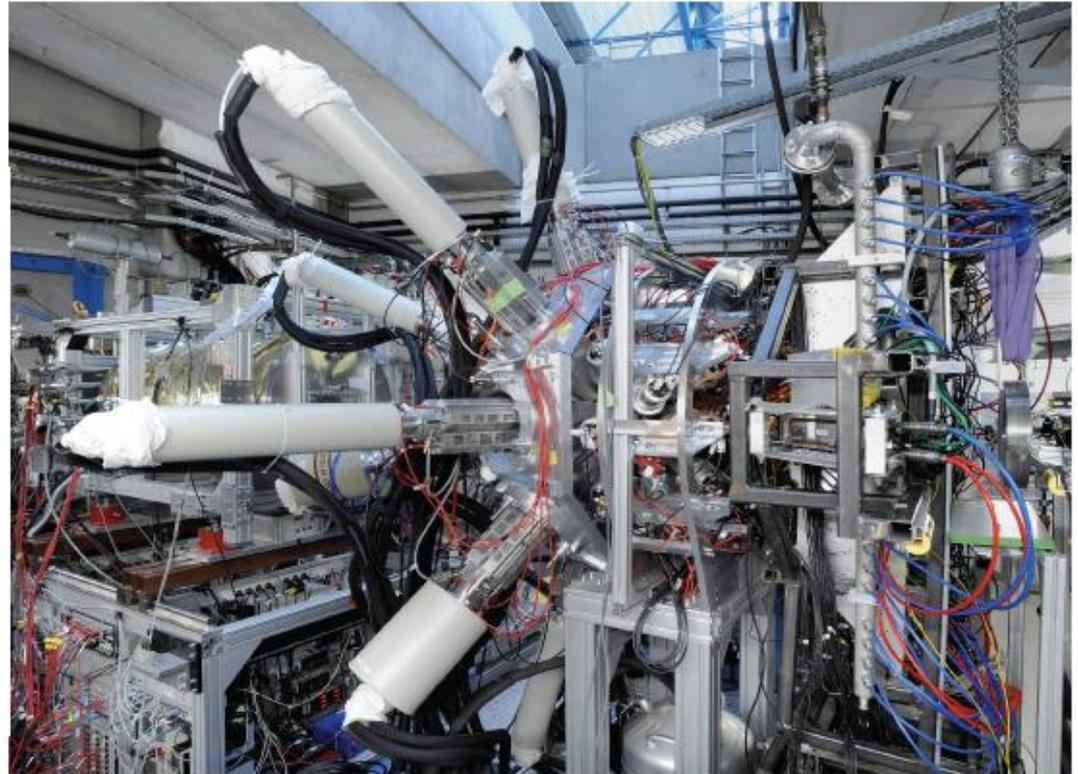
First test and characterization – 2016



DEGAS Array



Different mechanical parts of DEGAS cryostat and BGO back-catchers



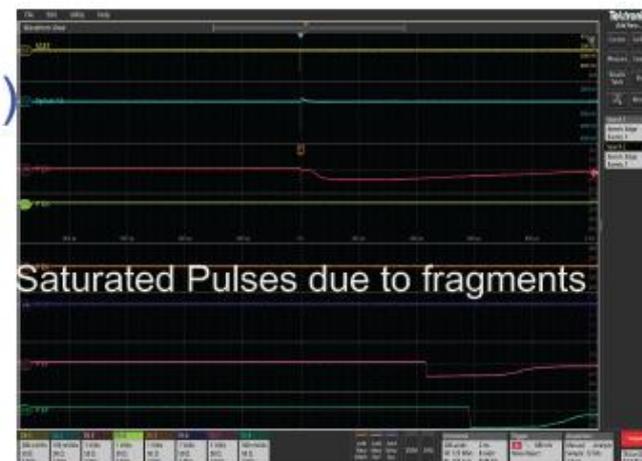
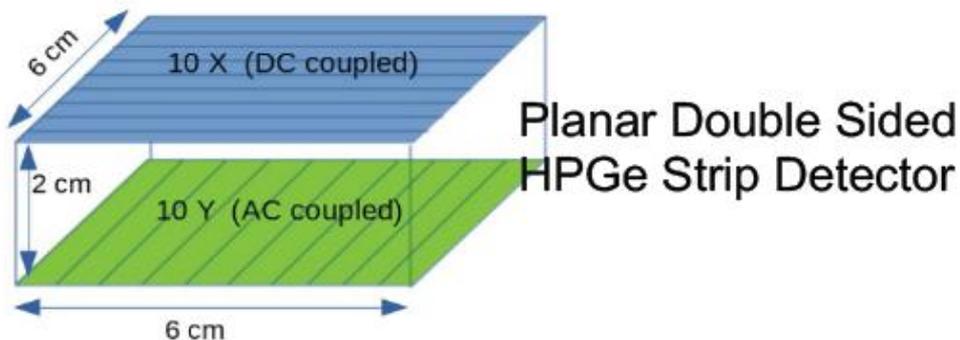
From workshop to beamline

Planar HPGe detector as implant detector along with DEGAS

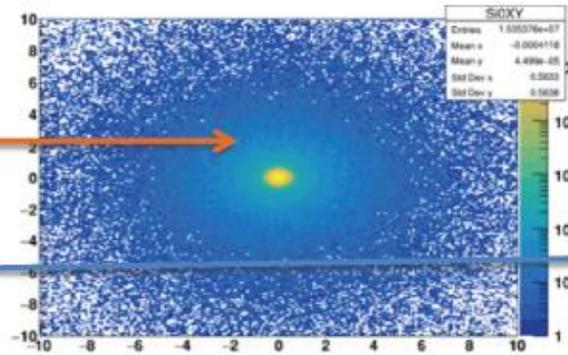
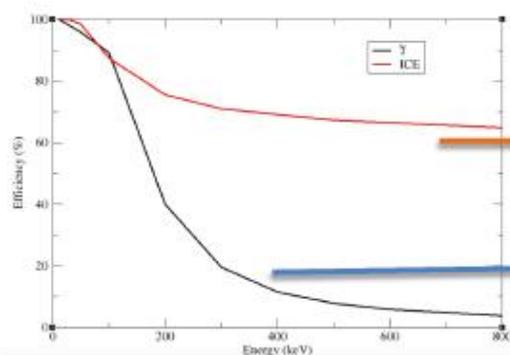


- Measure low energy γ -rays from isomeric decay.
- Sensitive to the Internal conversion electrons (ICE)

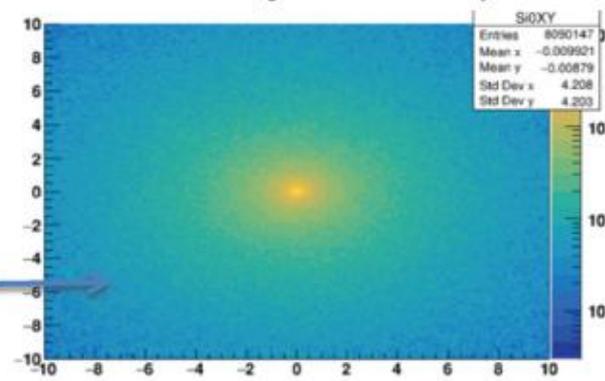
First test @ GSI (2022) with 30 GeV ^{184}Pt



1 MeV electron



1 MeV gamma-ray





Pulse Shape Analysis, Tracking & Imaging

Tracking: Reconstruct the path of the γ to get better P/T and background reduction

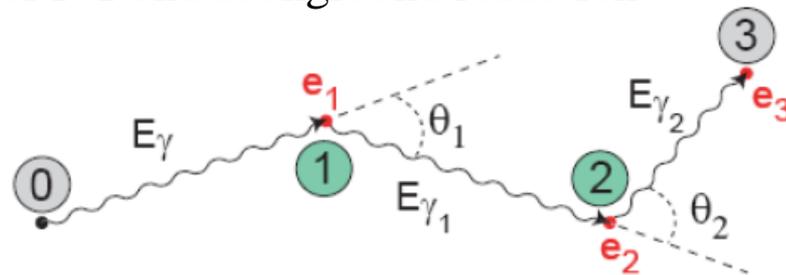
Requirements:

- Good Energy & Position resolution
- High granularity

$$E_{\gamma} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2} (1 - \cos \theta)}$$

$$\cos \theta = \frac{\vec{01} \cdot \vec{12}}{|\vec{01}| \cdot |\vec{12}|}$$

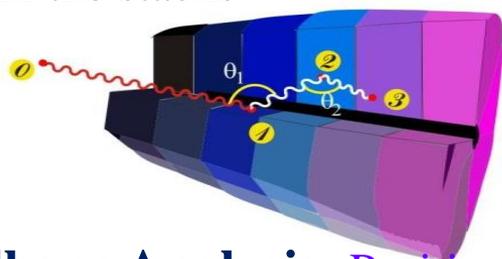
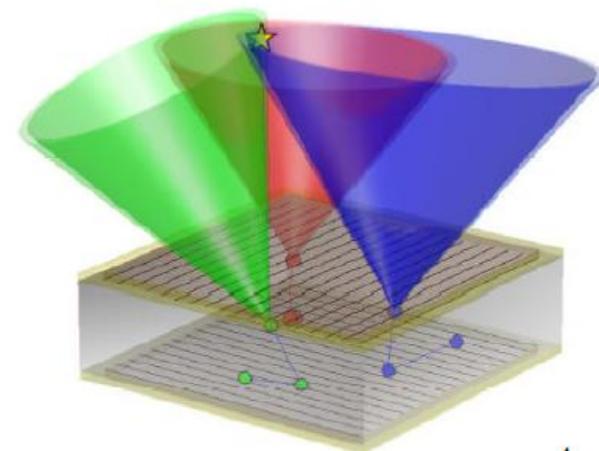
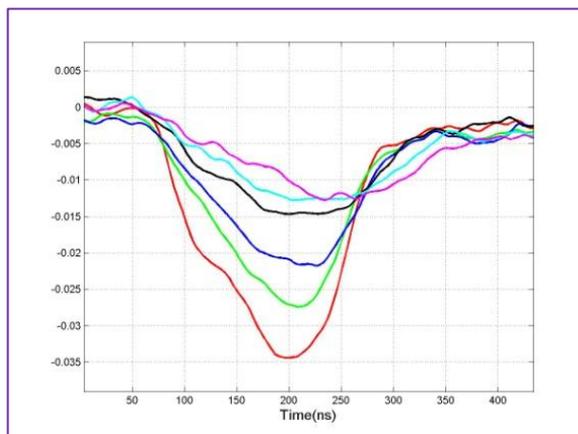
$$E_{\gamma} = E_1 + E_2 + E_{\text{photo}}$$



Imaging: Reconstruct the origin of the γ in the implantation plane for the isomeric decay

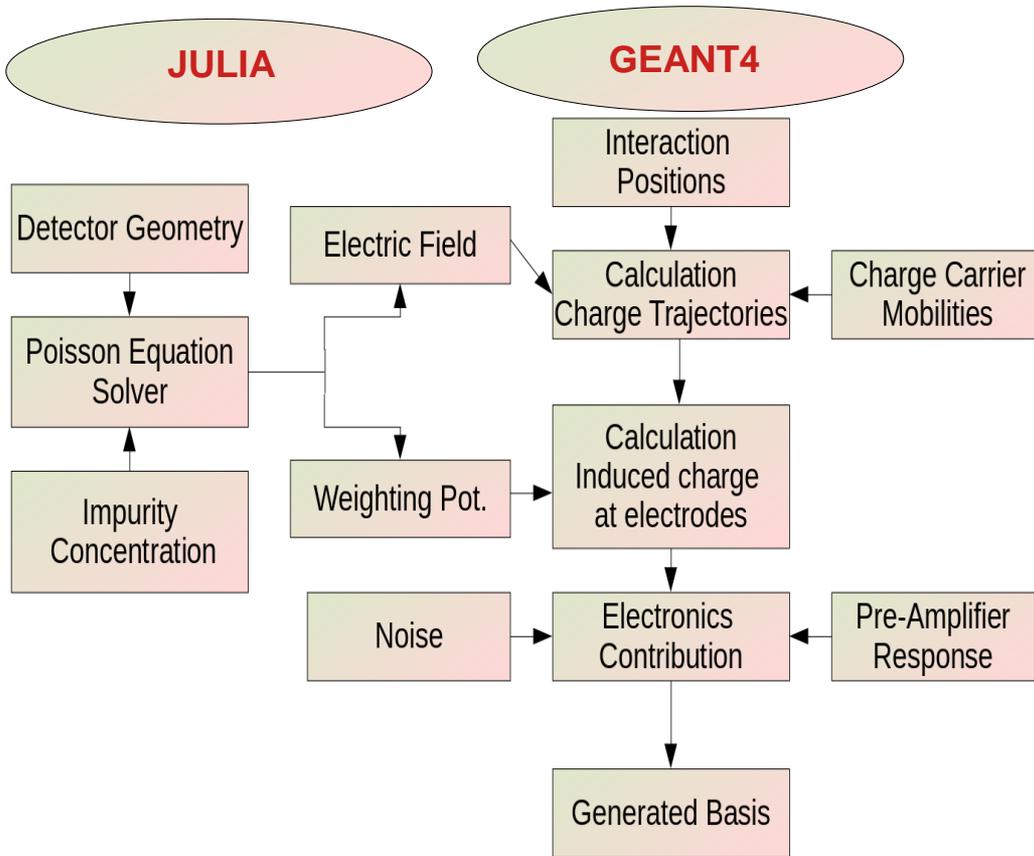
Requirements:

- Good Position resolution
- High granularity
- Parallel surfaces of particle detectors & Ge array
- Large separation between Ge in the stacks

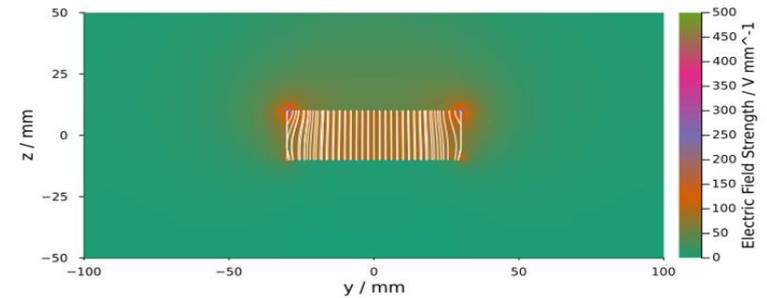
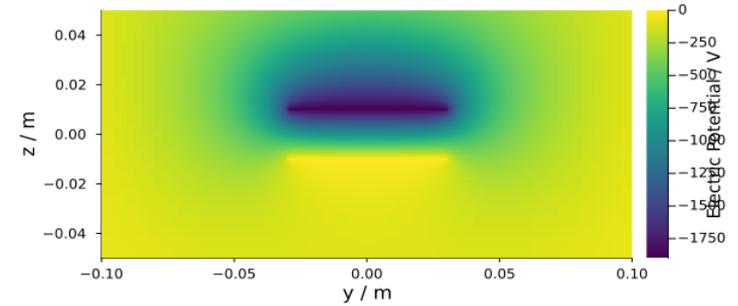


Pulse Shape Analysis: Position information, Interaction depth

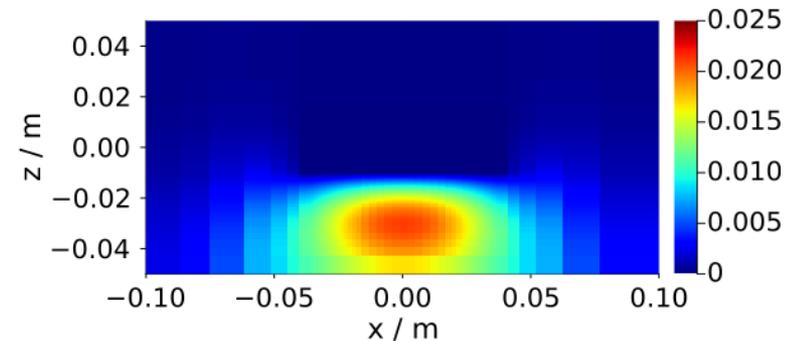
Simulation Framework



Electric Potential @ $x = 0.0$ m

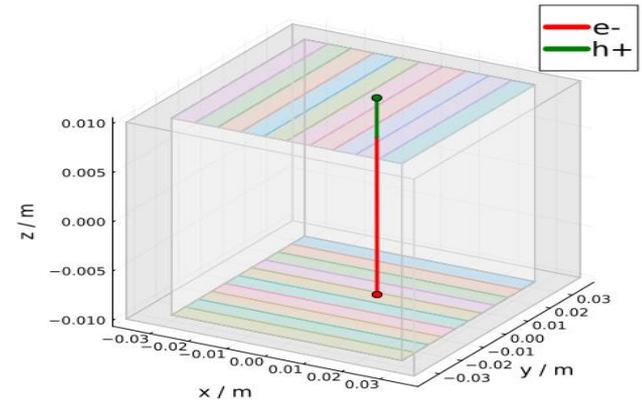
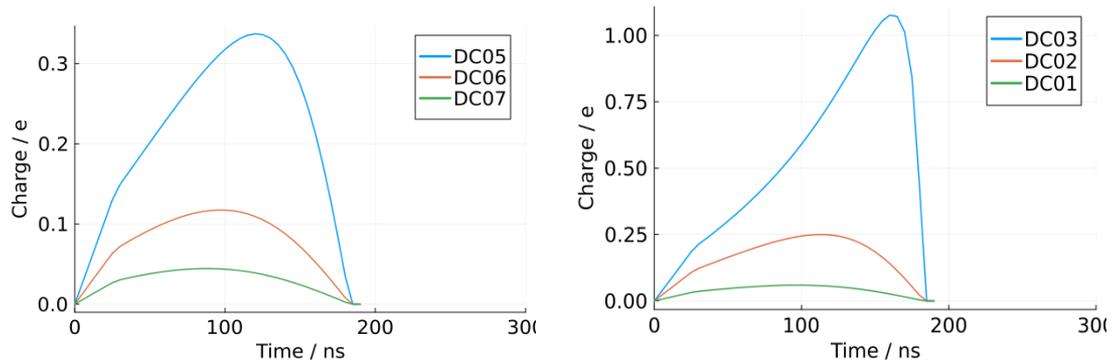


Weighting Potential @ $y = 30.0$ mm



Signal Generation

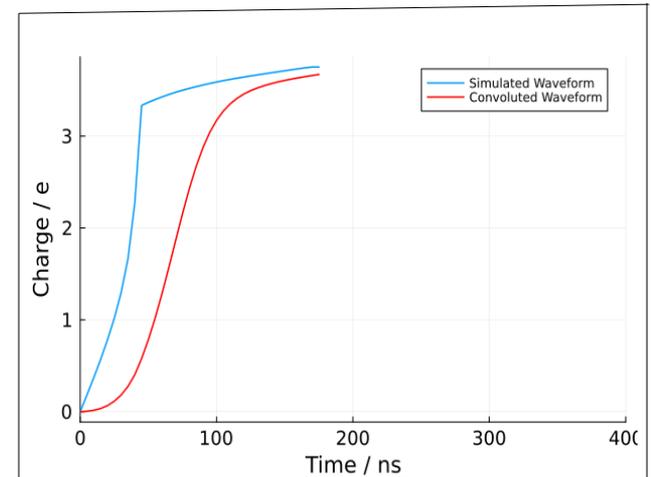
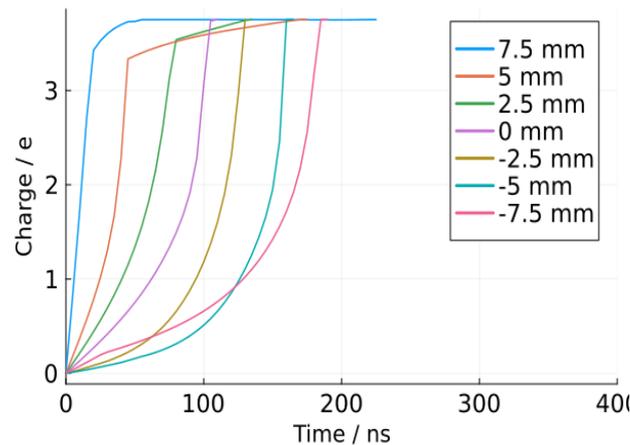
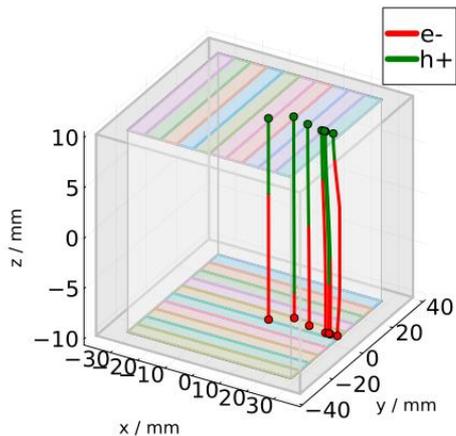
Transient charges for an interaction in DC strip



Electronics Contribution

The general shape of pre-amplifier response function:

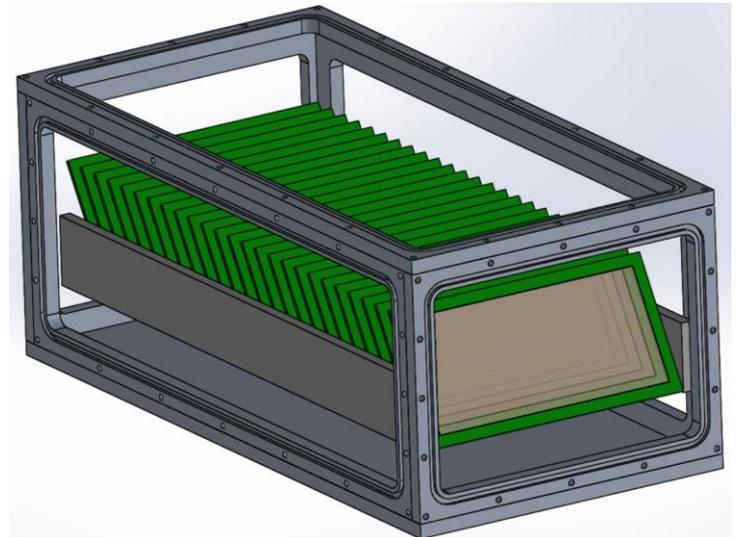
Signal generation



Tilted Electrode Gas Ionization Chamber (TEGIC)

- ❖ TEGIC Electrodes tilted at an angle w.r.t. normal to the beam trajectory Allows different trajectory for charge carriers and beam particles
- ❖ Reduced drift length for charge carriers with same active length Faster induced charge Count rates $\sim 10^6$ pps
- ❖ Reduced probability of recombination/loss of charge carriers
- ❖ Reduced space charge electric field distortion effects Improved energy and DZ resolutions
- ❖ Design established at BIG-RIPS (RIKEN) and ORN

Detector made out of aluminium sheets



CAD drawing of the detector

TEGIC)

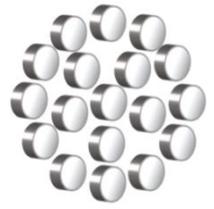
- ❖ Design Features TEGIC (IUAC – GSI)
- ❖ 21 electrodes: 10 anodes and 11 cathodes
- ❖ Electrodes: 3 μm mylar (aluminized on both sides)
- ❖ stretched and pasted on FR frames.
- ❖ Active area of frame: 25 x 12 cm^2 .
- ❖ Inter-electrode separation: 2 cm
- ❖ Active Length: 40 cm
- ❖ Housed in aluminium cuboid chamber: 60 x 38 x 24 cm^3
- ❖ Gas Medium: CF_4 or P-10 at 1 atm.
- ❖ Detector to be operated at reduced field of 0.25 – 1 $\text{V}/\text{cm}/\text{mbar}$



Testing of TEGIC with UNILAC – SIS at FRS Test run sanctioned: S. Pietri (LEC, FAIR-GSI)

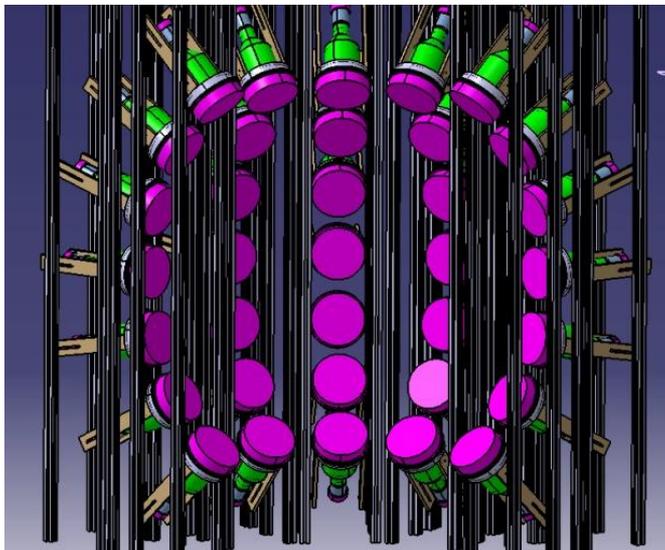
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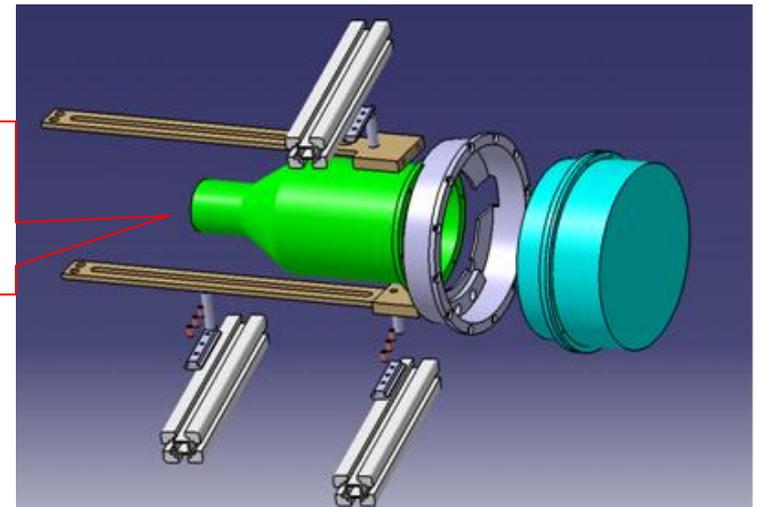
Objective

- ❑ The MONSTER array being developed for DESPEC (DEcay SPECtrosCopy) experiments at FAIR, Germany, will consist of 100 (8"×2") liquid scintillator-based fast-neutron detectors.
- ❑ The array will be primarily used to understand the β -decay properties of neutron-rich nuclei.
- ❑ As a part of the collaboration, 41 detectors will be developed in India.
- ❑ This measurement is important not only for basic research but also for the applications like decay heat calculations in reactor design. In recent compilation work shows the scarcity of measured data and need for new experiments.



General view for the 35 detectors of
MONSTER demonstrator

Exploded
drawing view
of the detector
full assembly

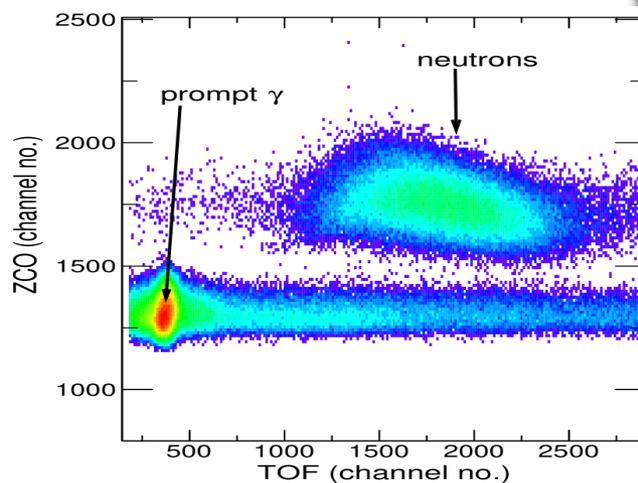
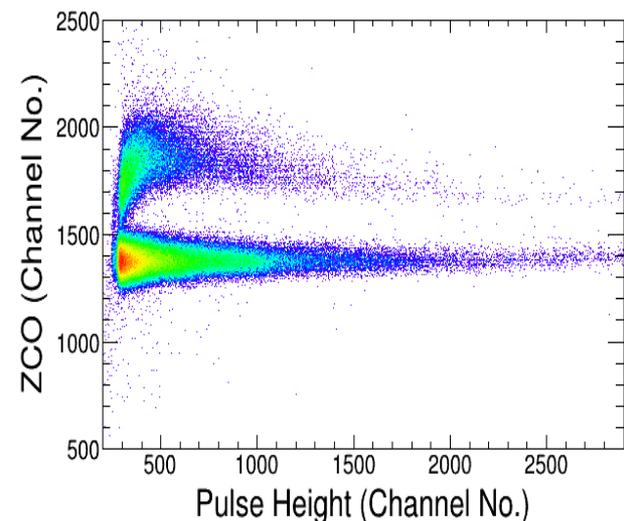


J. Liang et. al., Nuclear Data Sheets 168, 1 (2020).
P. Dimitriou et. al., Nuclear Data Sheets 173, 144 (2021).



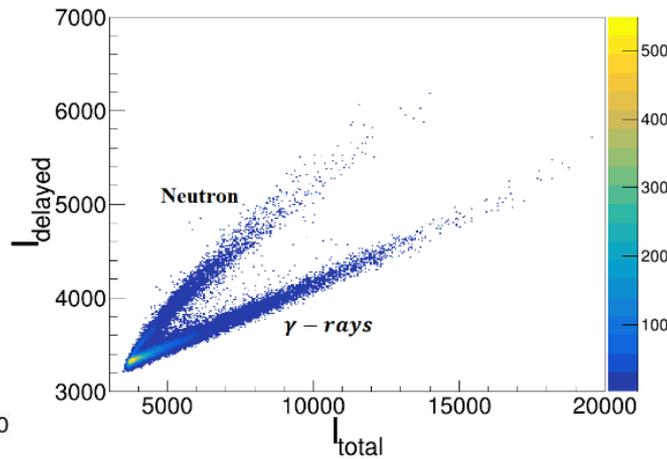
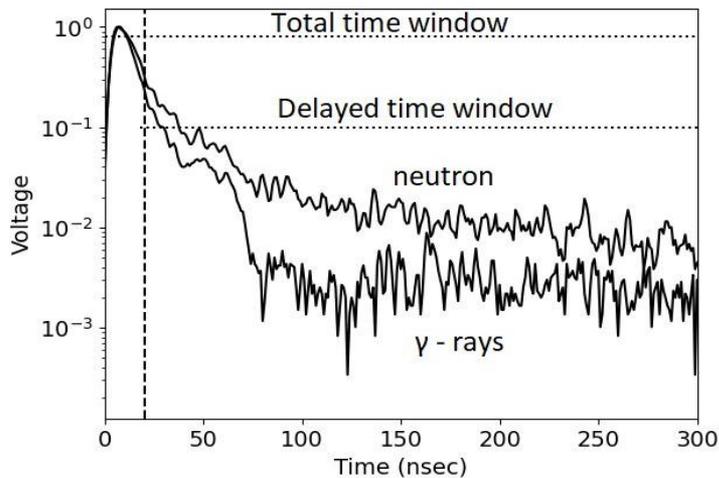
Detector Development

- ❑ 15 MONSTER modules have been fabricated at VECC
- ❑ Detailed characterization is performed with standard neutron sources.
- ❑ Procurement of components (PMT, scintillator cells etc.) for the fabrication of rest of the detectors are under progress.





- ❑ A digital DAQ system being developed using 14 bit, 1 GSamples/s digitizer card ADQ-14 of SP Devices.
- ❑ Two digital ADC cards have been procured and tested at VECC.
- ❑ Master controller and online visualization are under development in collaboration with CIEMAT.



D. Villamarin et.al., Nucl. Instr. Meth. Phys. Res. A 1055, 168526 (2023)

A. Banerjee et. al. Proc. of the DAE Symp. on Nucl. Phys. (2023)

Summary

- ▶ Overlap of Physics Interest with GSI group.
- ▶ Involvement in Research and Development of DEGAS, Pulse Shape Simulation & TEGIC detector.
- ▶ MONSTER Neutron detector modules have been fabricated and tested.
- ▶ Development of the digital DAQ in collaboration with CIEMAT is under progress.
- ▶ MOU between VECC and Bose institute has been signed.
- ▶ Request for funding for Indian participation NUSTAR/FAIR started in 2006
- ▶ Broadening the scope of collaboration in NUSTAR

Groups involved from India:

TIFR, DU, VECC, IUAC, PU, IIT Ropar, IIT Roorkee,

In Collaboration with GSI/FAIR

A wide, shallow, partially frozen lake in a snowy mountain valley. The lake is filled with ice and snow, with some water visible. The surrounding mountains are covered in snow and partially obscured by clouds. In the distance, a small settlement with green-roofed buildings is visible on the left side of the lake. The foreground shows a rocky, brownish slope with patches of snow.

Thank You

S. Mandal