Detectors for Nuclear Physics

Vandana Nanal
Tata Institute of Fundamental Research
Mumbai, India

Plan

- Basic concepts
- Examples of advanced/unique detector setups in India
- Detectors for experiments with RIB (DEGAS, PARIS)
- Detectors for hypernuclei
- Cryogenic detectors & Low background setups
- Some recent novel detector development efforts in India

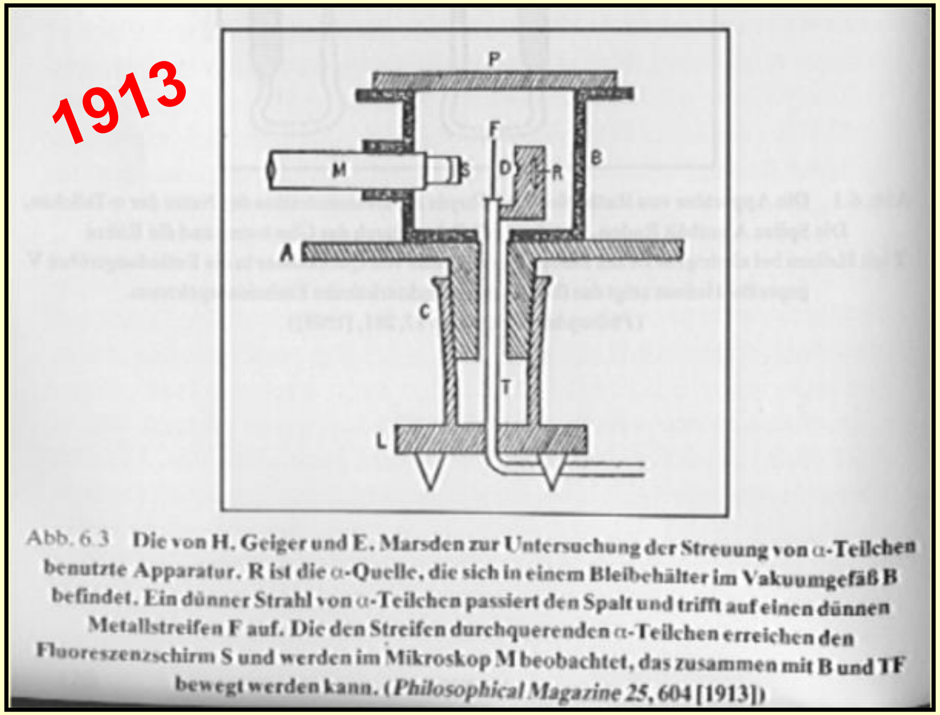
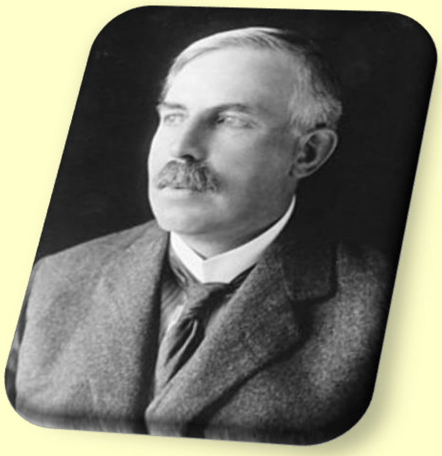


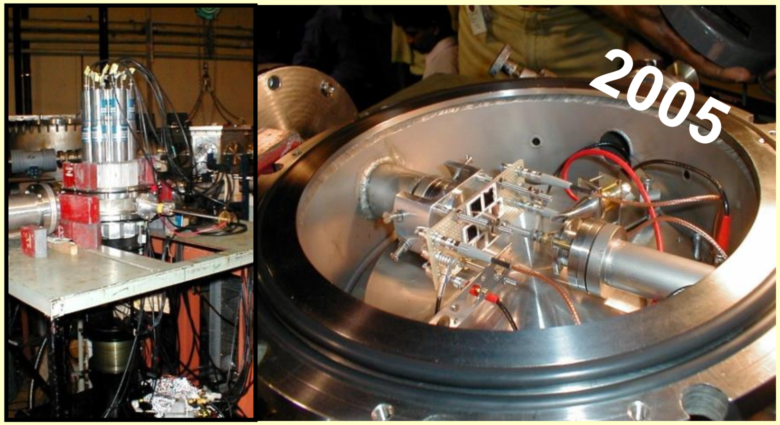
Abb. 6.3 Die von H. Geiger und E. Marsden zur Untersuchung der Streuung von α-Teilchen benutzte Apparatur. R ist die α-Quelle, die sich in einem Bleibehälter im Vakuumgefäß B befindet. Ein dünner Strahl von α-Teilchen passiert den Spalt und trifft auf einen dünnen Metallstreifen F auf. Die den Streifen durchquerenden α-Teilchen erreichen den Fluoreszenzschirm S und werden im Mikroskop M beobachtet, das zusammen mit B und TF bewegt werden kann. (*Philosophical Magazine* 25, 604 [1913])



Ernest Rutherford

Set up for ^{8}Be gamma-decay experiment

(V.M. Datar et al. @PLF, Mumbai)



Nuclear Physics experiments

Fixed target/source

Normal and Inverse kinematics (forward focused)

non-relativistic and relativistic (Doppler corrections)

Radiation damage

Task list for detectors…

Identify the Reaction products & complete kinematic measurements

-measure E/momentum, angle, mass

-correlations, time differences

-large solid angle coverage (4π)

-high granularity

(Signal processing – high density, high count rate, data filtering)

Radiations & preferred Detectors

- Charged particles (p, α, HI) - Silicon detectors, gas detectors, diamond detectors

  -have to be detected in vacuum

- Electrons – (organic, inorganic) scintillators, Si/Ge detectors, Microchannel Plates, Cerenkov radiation detectors, GEM
- Photons – scintillators (inorganic), High purity Ge Detectors

  -low interaction probability

- Neutrons – plastic scintillators

  -difficult to detect/shield

- Neutrinos

  -most difficult to detect

Overview of properties of detectors

- **Gas detectors** : good timing, poor energy resolution, need thin windows, large sizes, typical ionization potential ~10-25 eV
- **Scintillation detectors** : good timing, moderate energy resolution, large size/odd shapes, very high efficiency, typical ionization potential ~30 eV
- **Semiconductor detectors** : good energy resolution, moderate timing, expensive, more prone to radiation damage, excitation energy ~ 2 eV
- **Cryogenic detectors :** measure phonon signal, very good energy resolution (insulators, superconductors)
  - **Superconducting detectors** : few meV for quasi-particle excitation, Wide choice of materials, very good energy resolution

Some examples of advanced detector setups @ INDIA

Three major accelerator centres

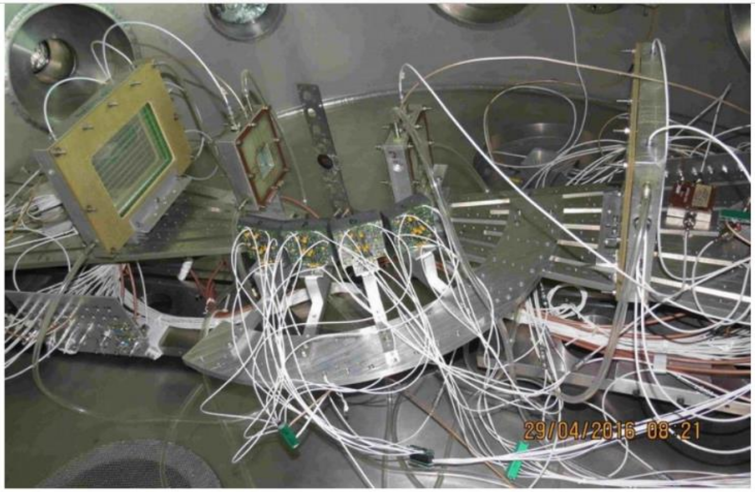
- BARC- TIFR Pelletron Linac Facility @ Mumbai
- Inter University Accelerator Centre (IUAC)@ New Delhi
- VECC @ Kolkata

&

- reactor based experiments (n,f), (n, γ) etc.
- Low background experiments (UG lab)

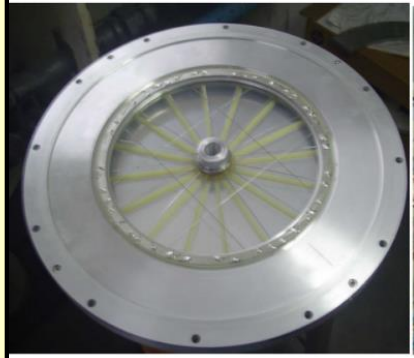
(Mass separators, ion traps, ….)

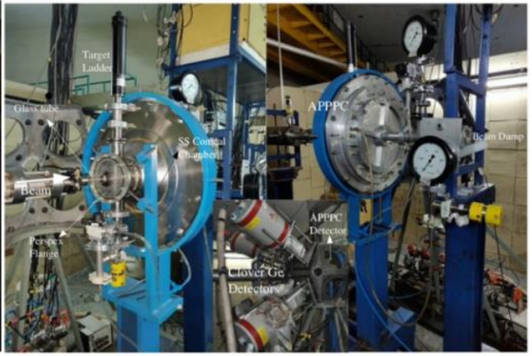
Detectors for heavy ions



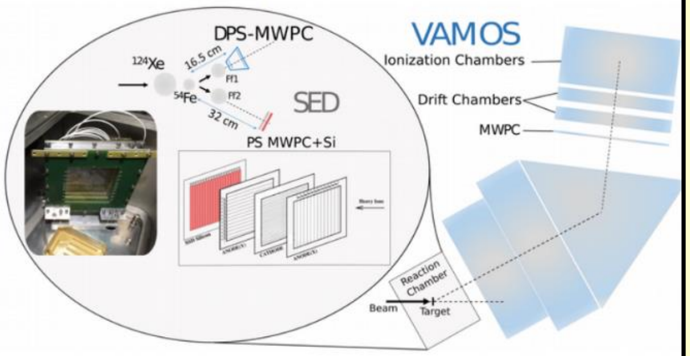
Double Arm fission TOF set up at GPSC-IUAC
Rev. Sci. Instrum. 92, 033309(2021)

Hybrid Telescope Array for Quasi-elastic scattering and Fission angular Distribution
NIM A 903 (2018) 326–334





Annular Proportional counter for Coulex
NIM A 922 (2019) 209



Integrated MWPC-SSD Detector system
at VAMOS (GANIL, France)
PHYSICAL REVIEW C 106, 044607 (2022)

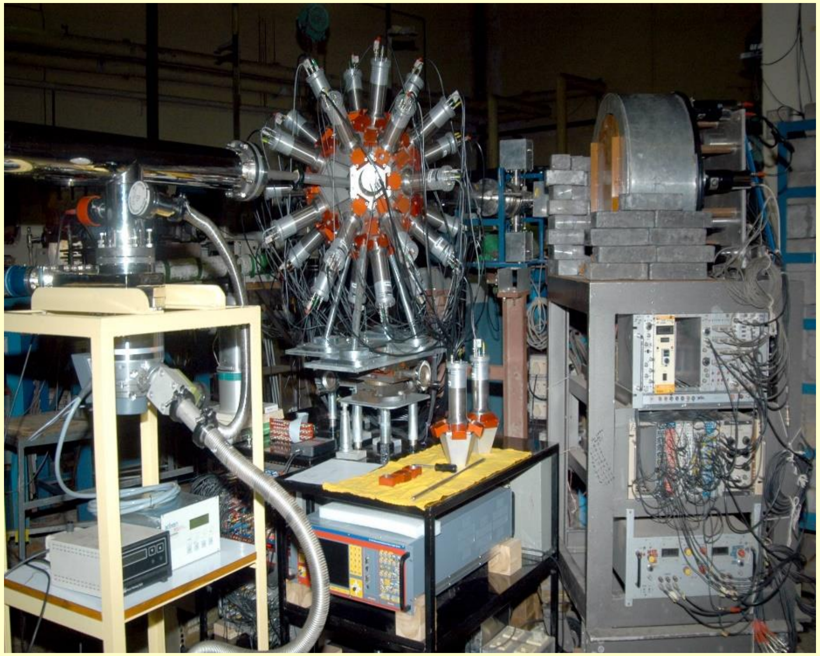
Detector Lab, IUAC (New Delhi)

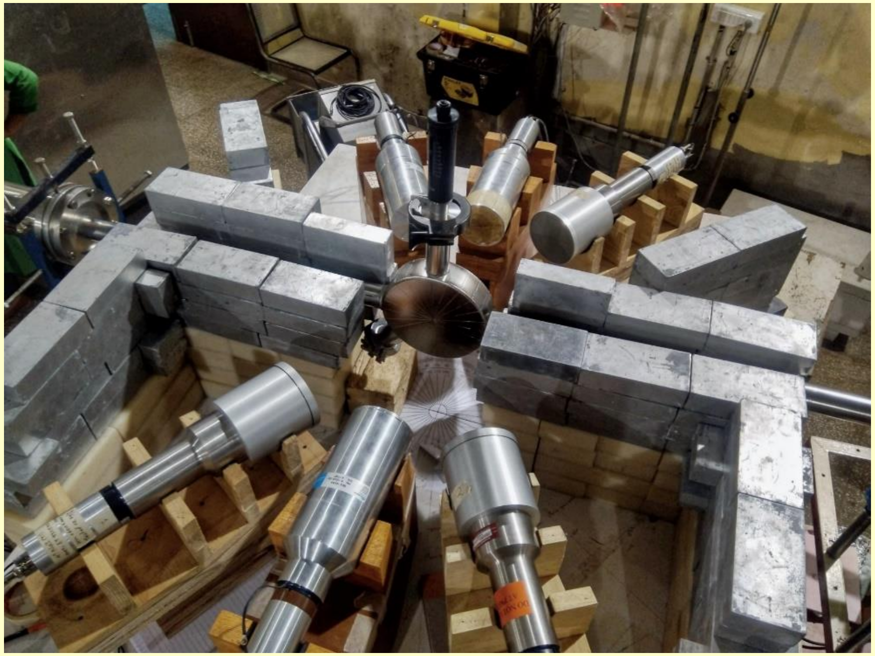
https://www.iuac.res.in/detector-lab

Courtsey : A. Jhingan (IUAC)

Scintillator detector arrays : NaI(Tl) & $LaBr_3Ce$

Planar Geometry, Compact 4π array, Square array

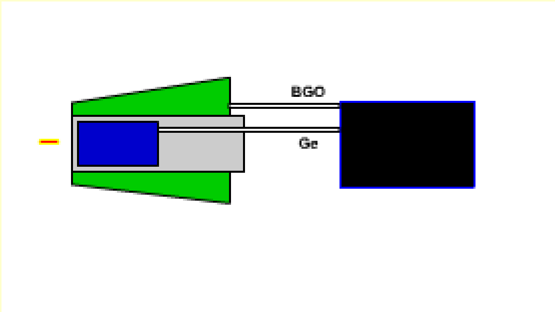


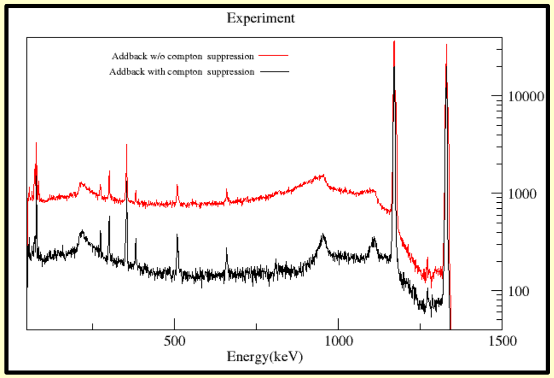


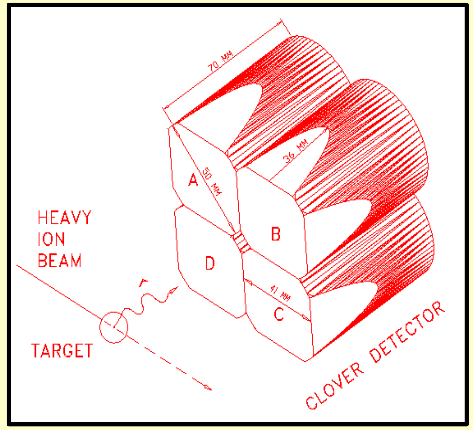
- *Reaction dynamics studies - spin gated Evaporation Residue cross sections of ^{186}Pt*
- *Nuclear Astrophysics - First measurements of $^{10}B(p,\gamma)^{11}C$ absolute capture cross sections at Interstellar Medium energy.*

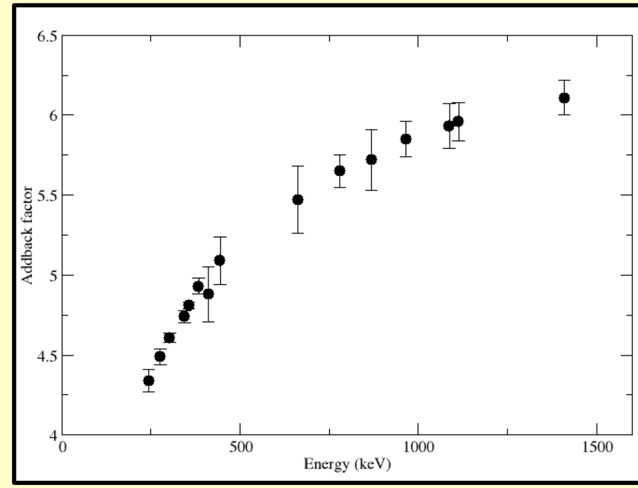
Courtsey : I. Mazumdar (TIFR)

Clover detector

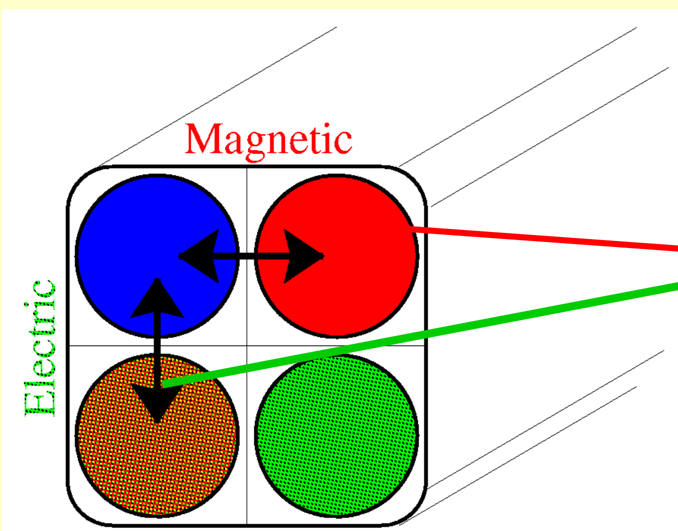


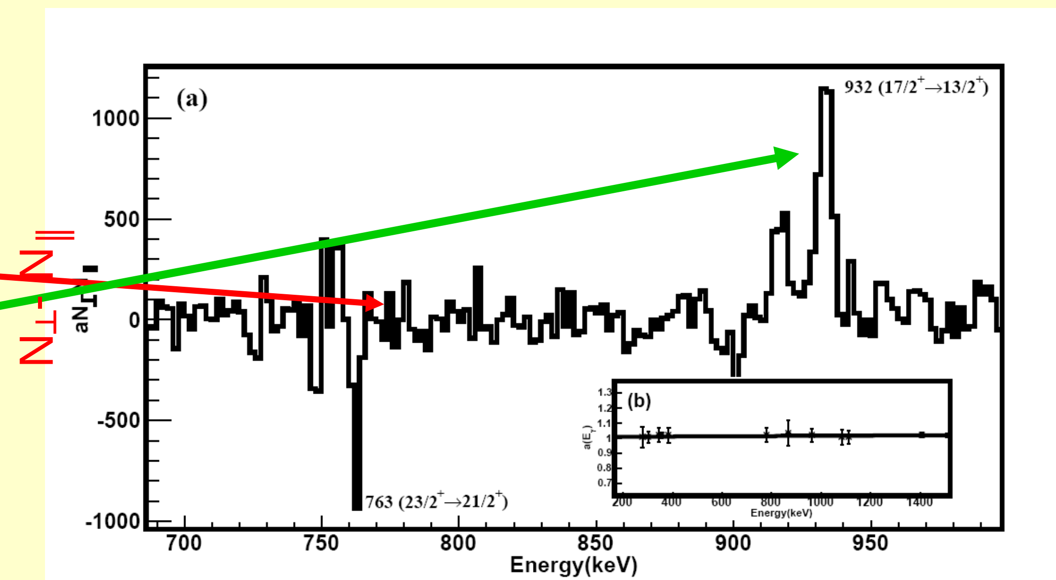






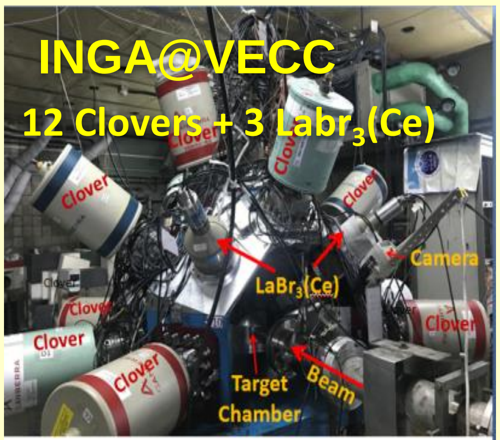
Polarisation measurement



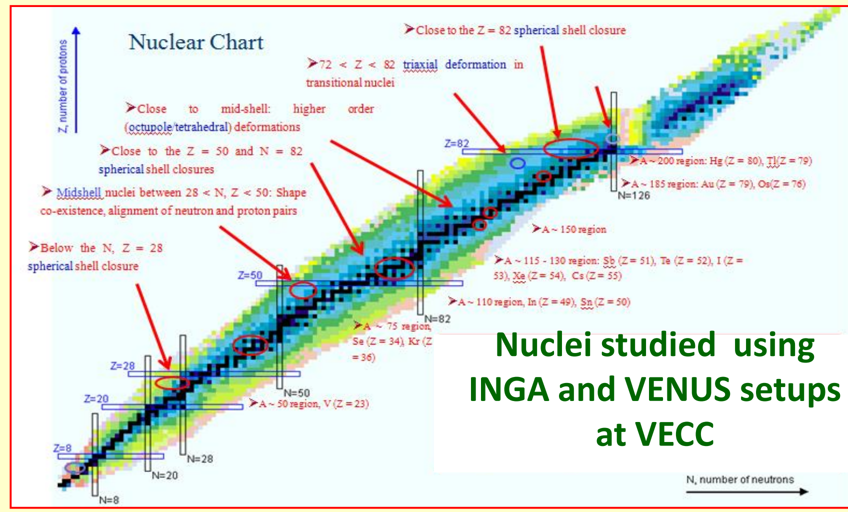


Gamma Detector Array

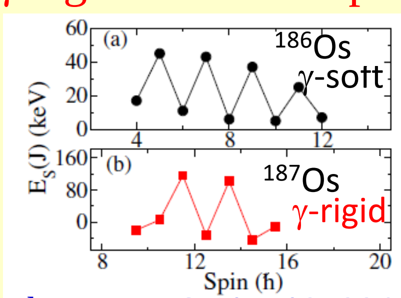
- **VE**CC array for **Nu**clear **S**pectroscopy (**VENUS**): Compton suppressed clover detectors in horizontal plane.
- Modular structure for easy maneuvering and positioning.
- Versatility in number of detectors, their angles, target-detector distance and use of ancillary detectors..



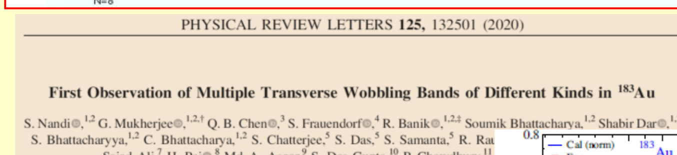
Collaboration
SINP,
UGC-DAE-CSR
&VECC, Kolkata



γ-rigid triaxial shape in ^{187}Os



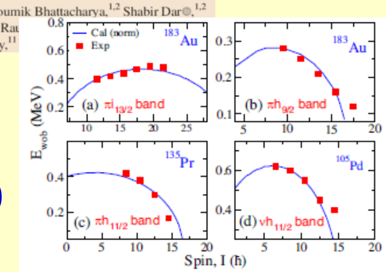
Phys. Rev. C 105, 034336 (2022)


PHYSICAL REVIEW LETTERS 125, 132501 (2020)

First Observation of Multiple Transverse Wobbling Bands of Different Kinds in ^{183}Au

S. Nandi, G. Mukherjee, Q. B. Chen, S. Frauendorf, R. Banik, Soumik Bhattacharya, Shabir Dar, S. Bhattacharyya, C. Bhattacharya, S. Chatterjee, S. Das, S. Samanta, R. Rai, Sajad Ali, H. Pai, Md. A. Asgar, S. Das Gupta, P. Chowdhury,

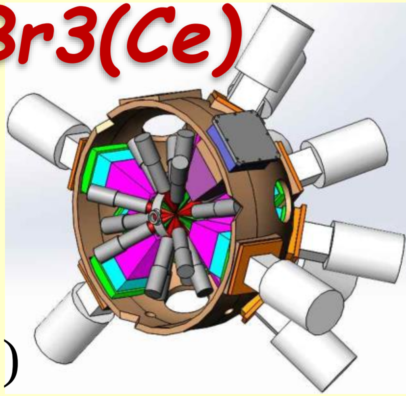
Multiple wobbling bands in ^{183}Au



Phys. Rev. Lett. 125, 132501 (2020)

Courtsey : Chandana Bhattacharya (VECC)

Hybrid Array of HPGe Clover – LaBr3(Ce)

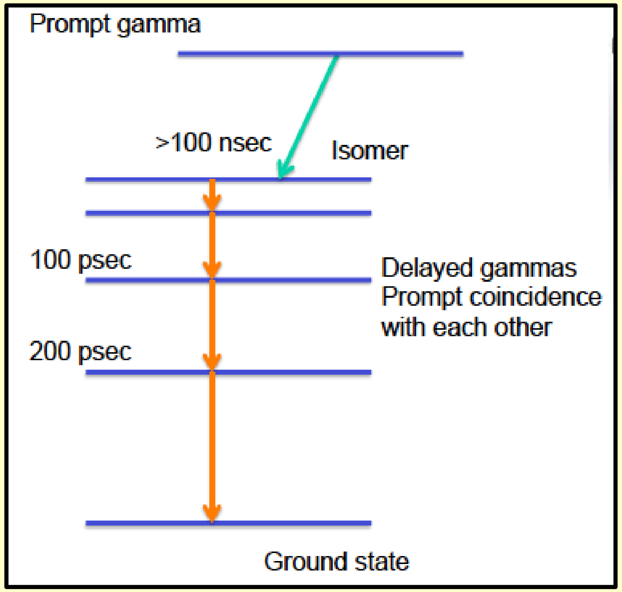


HPGe for enhanced, highly selective decay path isolation

&

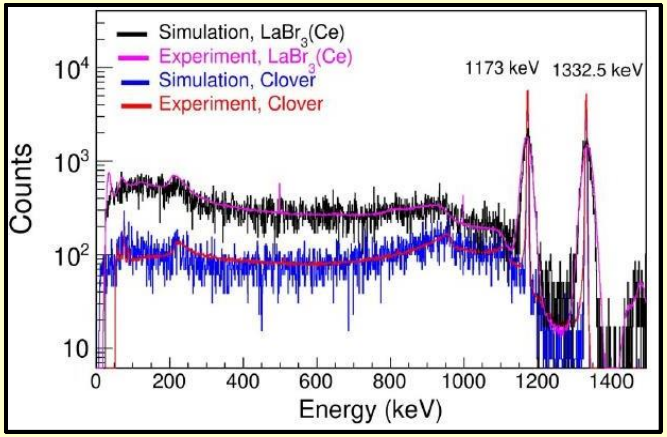
LaBr3(Ce) for gated sub-nanosecond lifetime measurements

(With other ancillary detectors/set-up (CsI(Tl), Si detectors, plunger)



Some examples of Physics cases:

Isomer depletion, Lifetime measurements for E1 decays, Octupole shapes, Gamma bands, Wobbling mode, Test of K-hindrance, Collectivity in heavy nuclei,



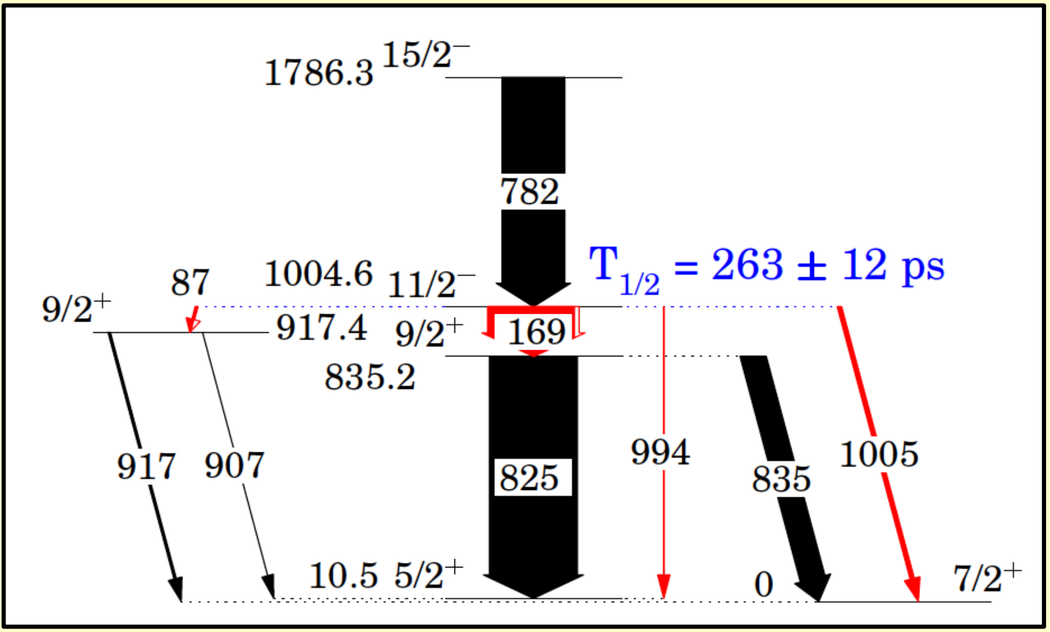
Experiments performed in collaboration

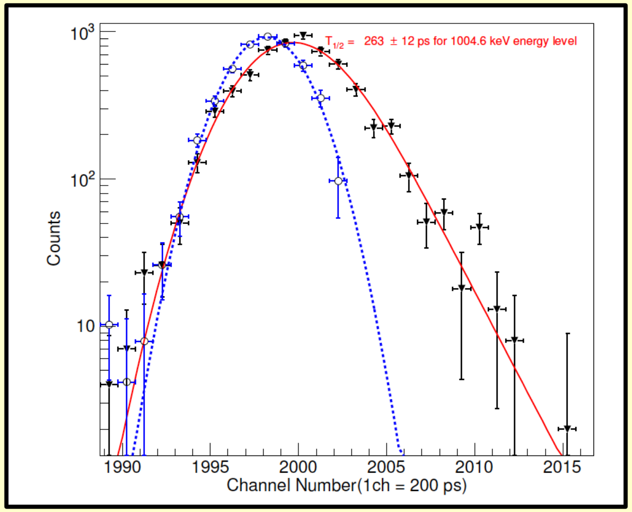
TIFR, PU, IIT Ropar, BARC, VECC, GG Univ, Presidency Univ

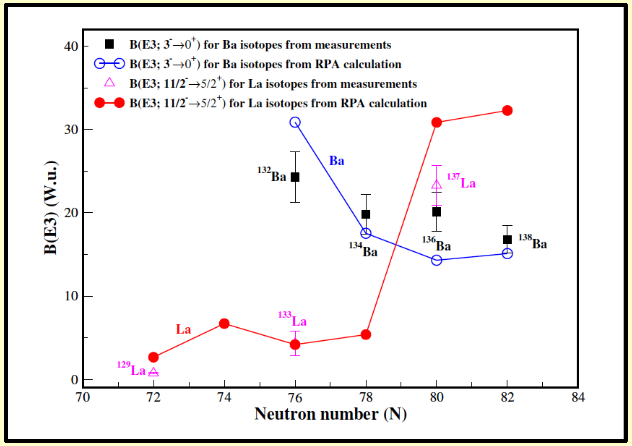
B. Das et al., J. of Instrum. Soc. of India **51**, 44 (2021).

Courtsey : R. Palit (TIFR)

Measuring Lifetime in ^{137}La to study octupole correlations







The measured lifetime of 1004.6-keV state is 263(12) ps

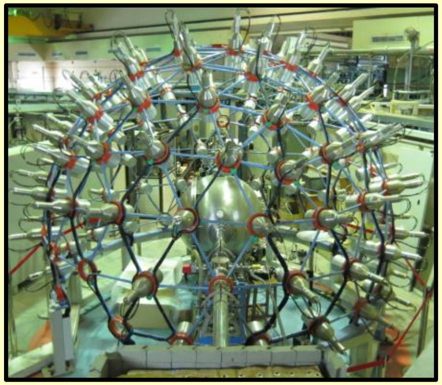
Md S R Laskar et al., PRC104, Letter 011301 (2021)

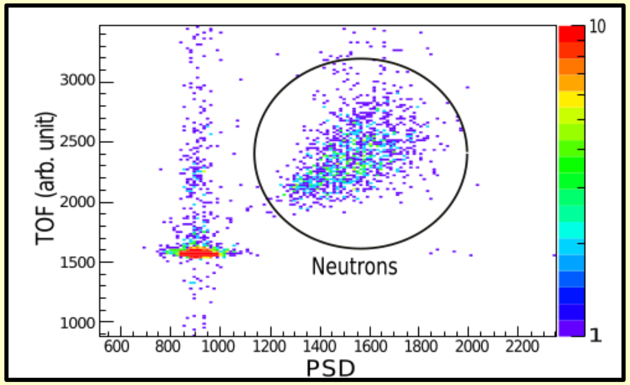
Courtsey : R. Palit (TIFR)

National Array of Neutron Detectors (NAND@IUAC)

100 liquid scintillator cells (5"x5" BC501A), coupled to 5" PMT

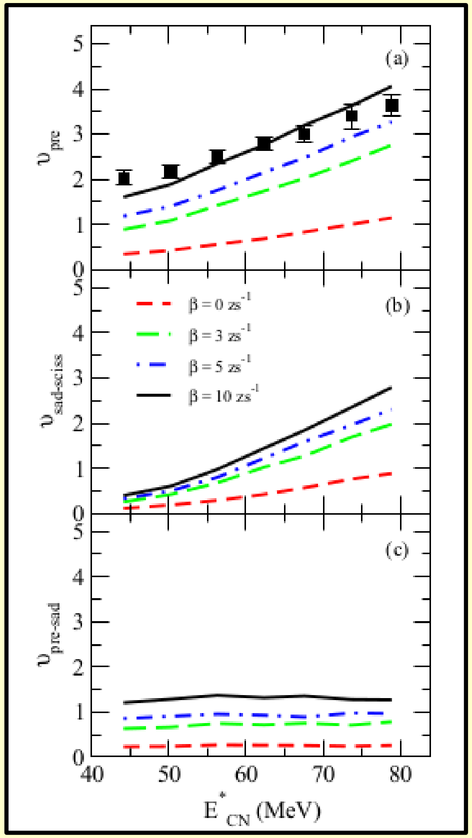
Study of fusion-fission & quasi-fission dynamics through neutron multiplicity & mass distribution -coincidence measurements of neutron and fission fragments





Nuclear dissipation at high excitation energy and angular momenta in reaction forming ^{227}Np

^{30}Si +^{197}Au (44-78 MeV) Measured pre-scission neutron multiplicity indicates a strong fission hindrance



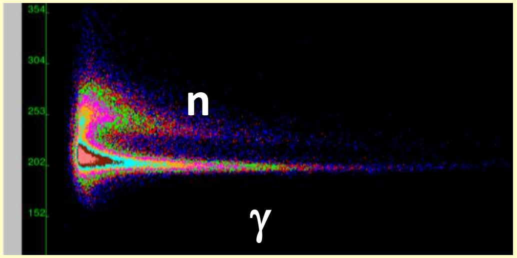
Courtsey: P. Sugathan (IUAC)

M. Shareef et al. PRC **99**, 024618 (2019)

Neutron TOF array@VECC

- Nuclear reaction dynamics studies
- Neutron energy Measurement using TOF detector
- Neutron Multiplicity measurement to get the Information of Excitation of the system
- Study of exotic structure of nucleus using multi particle correlation

Pulse shape discrimination



Courtsey : Chandana Bhattacharya (VECC)

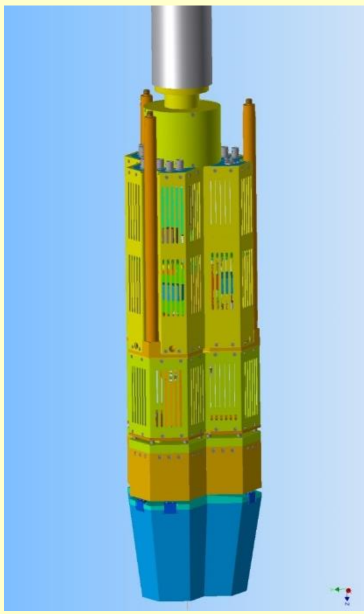
Examples of advanced detector setups @ RIB facility

FAIR@GSI, SPIRAL,SPIRAL2@GANIL

DEGAS at NuSTAR@FAIR
(Indian Contribution)

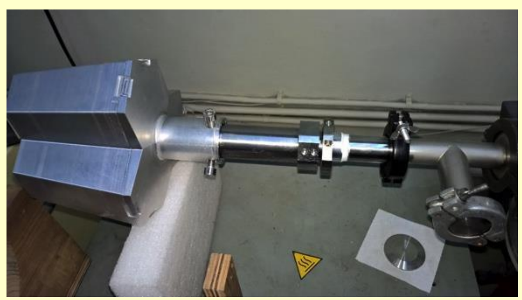
Detector at FAIR for the study of formation of heavy elements in the Universe

A very complex and complicated device



- Encapsulated HPGe crystals in the cryostat with electrical cooling.
- The detector consists of 38 producible components Cu, stainless steel, Al
- High vacuum

Developed at GSI in collaboration with Ferchau GmbH, Germany, Partial production at TIFR, Mumbai, India.

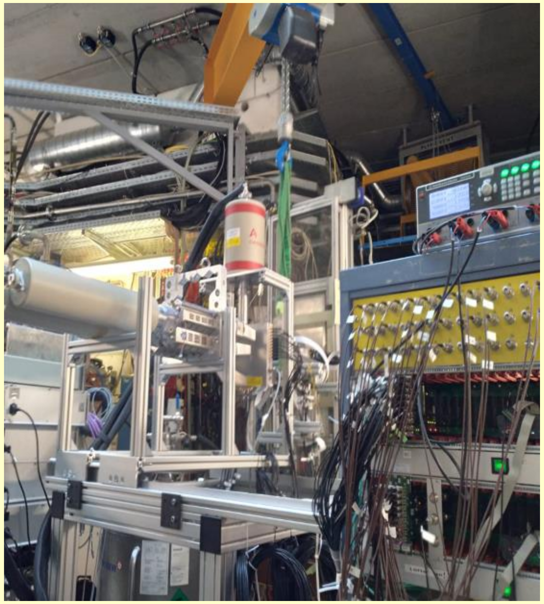


Fabrication, First mechanics test, TIFR, February 2016

In-kind contract finalized -- Various components of DEGAS, HPGe detector with Imaging, BGO catcher with SiPM

Courtsey : R. Palit (TIFR)

Planar HPGe detector: Implant detector for decay spectroscopy of heavy nuclei at DESPEC/FAIR setup

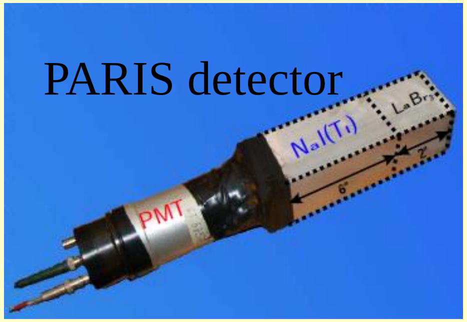


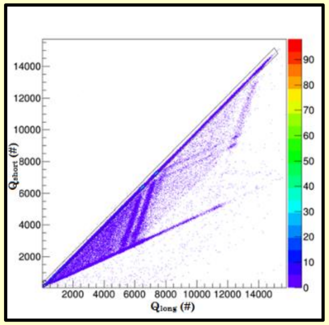
R. Palit et al., S506 experiment at GSI/FAIR

- ➢ Interested to measure low energy γ-rays from isomeric decay.
- ➢ Sensitive to the Internal conversion electrons (ICE).
- ✓ Response of HPGe detector and its electronics to **35 GeV heavy ion implantation**.
- ✓ Study of damage due to implantation.
- ➢ Response of DEGAS detector kept in downstream direction.
- ➢ Decay of milli-second isomer of ^{184}Pt inside the detector ($I^{\pi} = 8^{-}$, $E_x = 1840.3$ keV, $E\gamma = 49$ keV)

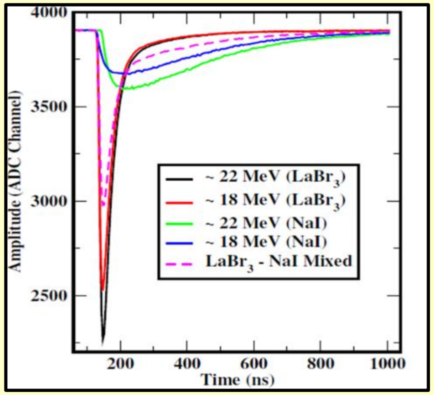
Courtsey : R. Palit (TIFR)

PARIS –Photon Array for studies with Radioactive Ion and Stable beams

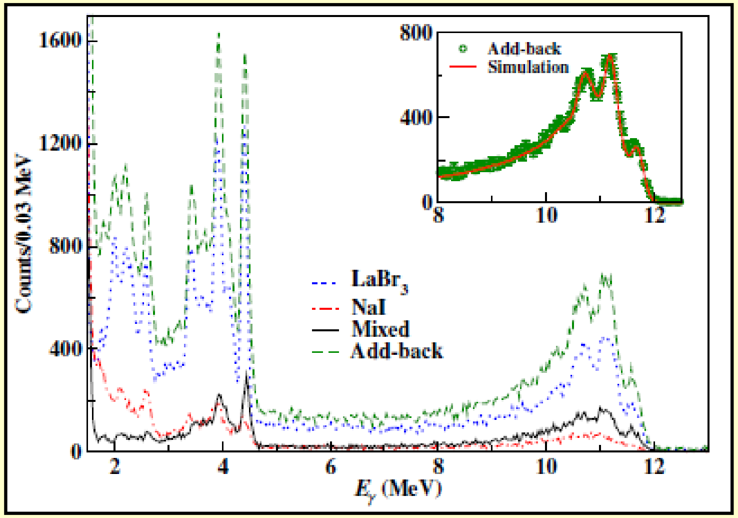




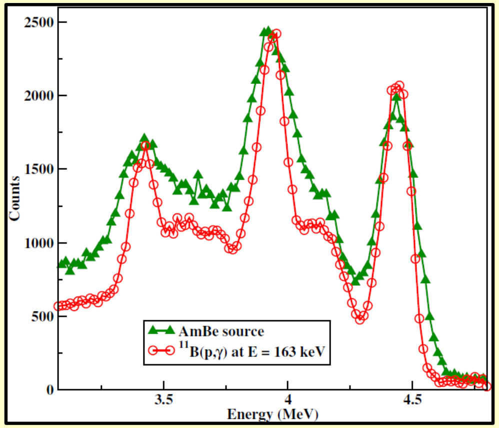
^{11}B (p,γ) @163 keV with V1720E digitizer (250 MHz, 12 bit ADC)



~ 50% enhancement in photopeak without any significant effect on resolution (2.9% -3.4%)



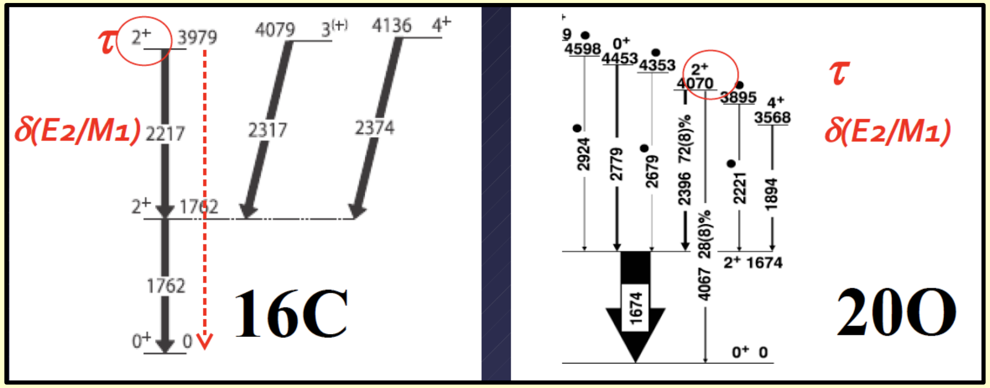
Intrinsic Broadening of AmBe Source demonstration of phoswich resolution

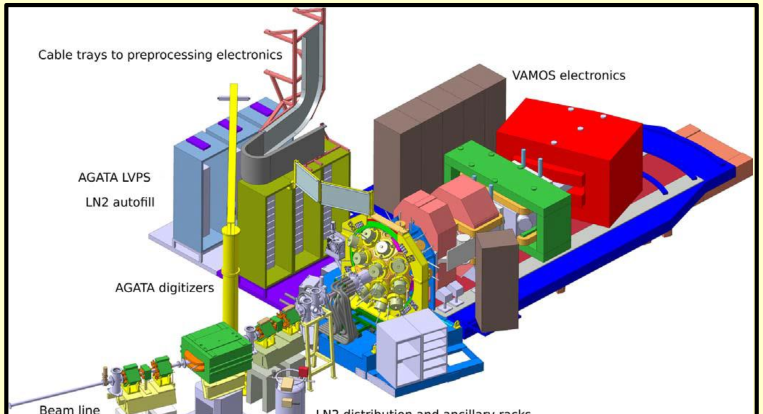


The broadening due to source recoil ~ 2%

C. Ghosh *et al.*, JINST P05023 (2016)

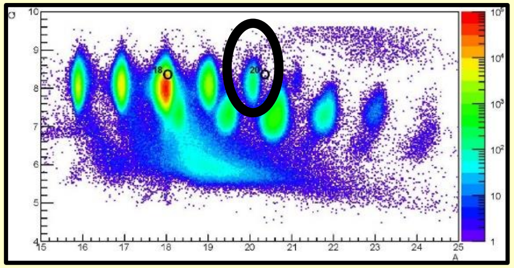
Lifetime measurements of excited states in neutron-rich C and O isotopes

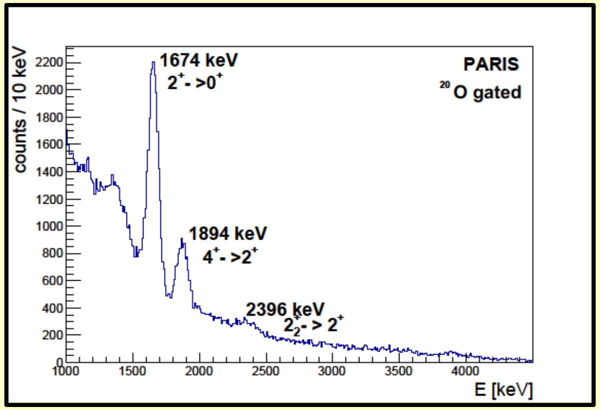




E. Clement et al. NIMA **885**, 1(2017)

S. Leoni, B. Fornal, M. Ciemala et al.,
PARIS (2 clusters), 2 large $LaBr_3$, **AGATA, VAMOS**





Courtsey : A. Maj(PARIS project manager)

HYPERBALL –J
for Probing Hypernuclei

Pulse tube refrigerator

compact detector→close mounting→ high efficiency

cooling below 85 K→to minimise n-induced damage

Flexible geometry

Fast ACS – PWO

Cooling PWO ~-20 C??

- *γ–γ coincindences of hypernuclei*
- 5-7% efficiency

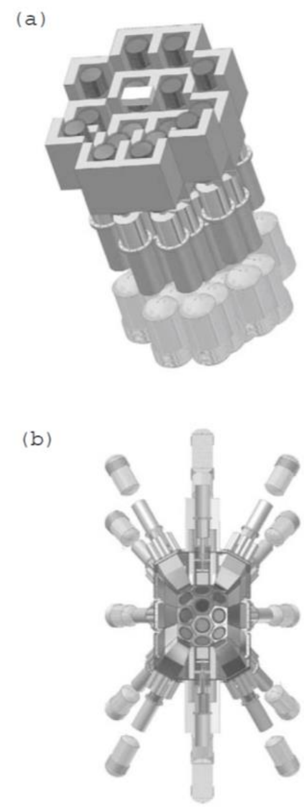


Fig. 1. Two configurations for the Hyperball-J array. Beam axis goes through the center from left to right. (a) Wall type. Half apparatus (lower part) is shown together with a target at the enter. (b) Ball type with 30 detectors (Ball(30) in Table 1).

Proceedings of the IX International Conference on Hypernuclear and Strange Particle Physics (pp.25-28) 2007

Detectors for rare decays

Cryogenic detectors

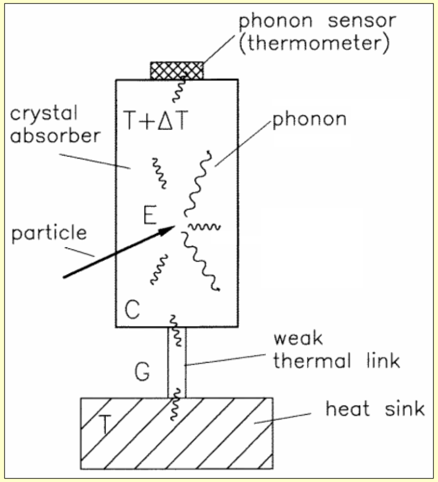
Low background detectors

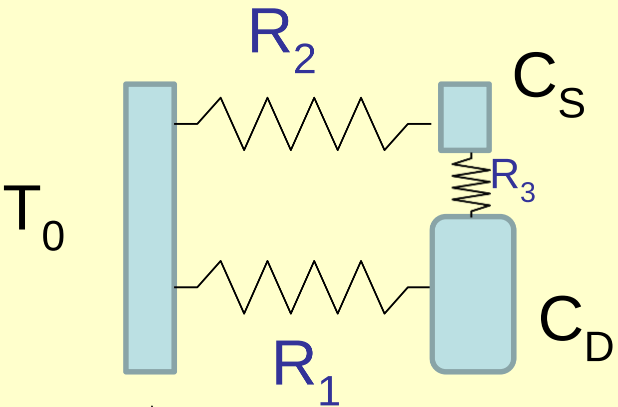
Low Temperature calorimetry

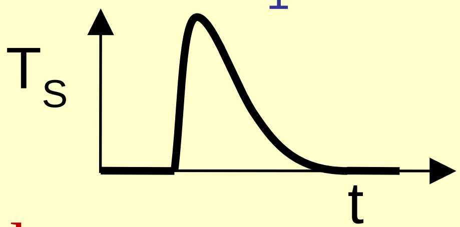
Energy of particle → Thermal energy in detector

→ measurable temperature rise if net heat capacity is very low

Bolometer Schematic







- $\Delta T = E/C_D$
- System returns to equilibrium with a time constant $\tau = C/G$)
- Ideally, $R_3 \approx 0$
  - C_D should be small
  - $C_S << C_D$
  - Large R_1 and R_2 (weak heat link)

Resolution of Bolometer

- Limited by Thermodynamical fluctuation noise $\{\delta E=(kT^2C(T))^{1/2}\}$
- Depends only on operating temperature and specific heat
- Independent of incident Energy

Low Tempearture Detectors (LTD)

Wide range of applications (mostly at $T < 100$ mK)

- photons (sub mm to soft gamma rays)
- particles (α, β, heavy ions, WIMPS)

Why they are attractive

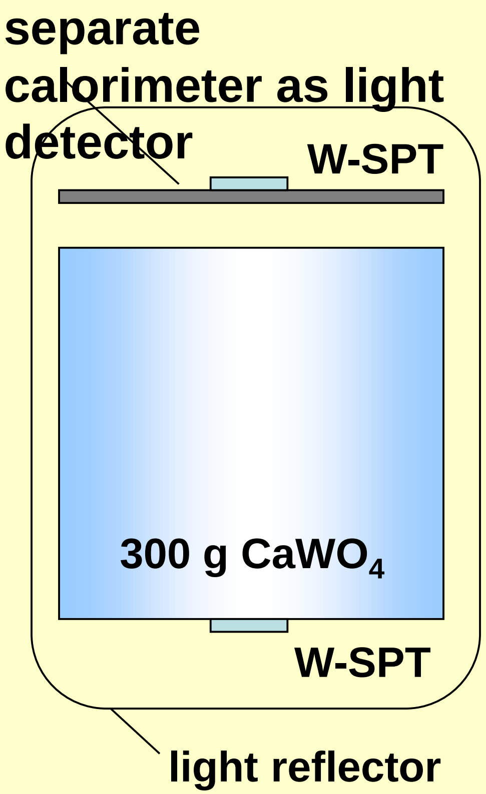
- Thermal source itself is a detector
  $\rightarrow$ devoid of dead layers, self absorption, reflection at surfaces
- High efficiency
- Resolution depends upon factors like T (temperature), C (heat capacity), G (thermal conductance of the weak link to bath), thermodynamic fluctuation noise and thermometer sensitivity; does not depend on particle or its energy

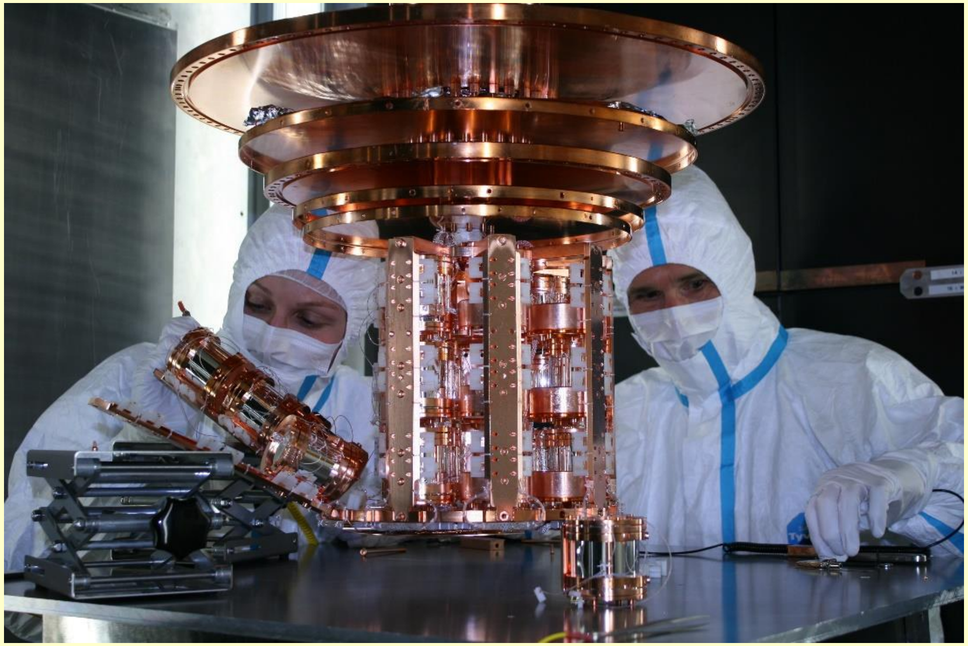
  limited by extraneous factors like noise
- Large arrays can be easily built (mg to Kg)

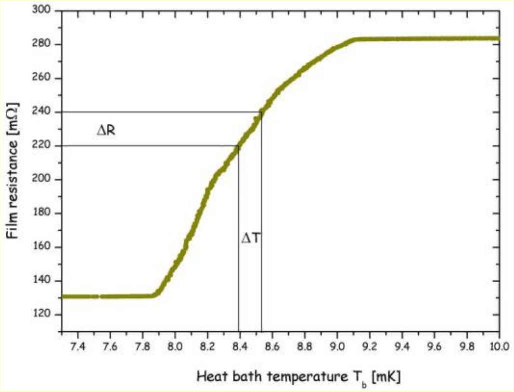
Ideal for high precision measurements & rare event studies (DBD, Dark matter)

CRESST-II

Cryogenic Rare Event Search with Superconducting Thermometers



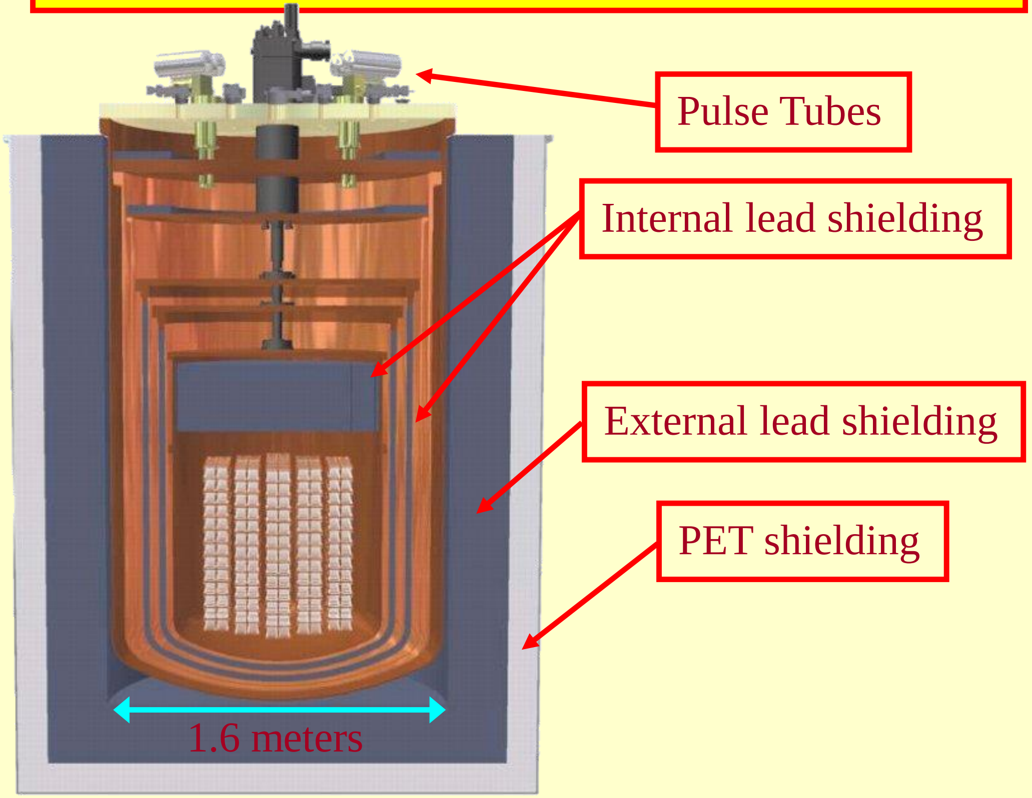




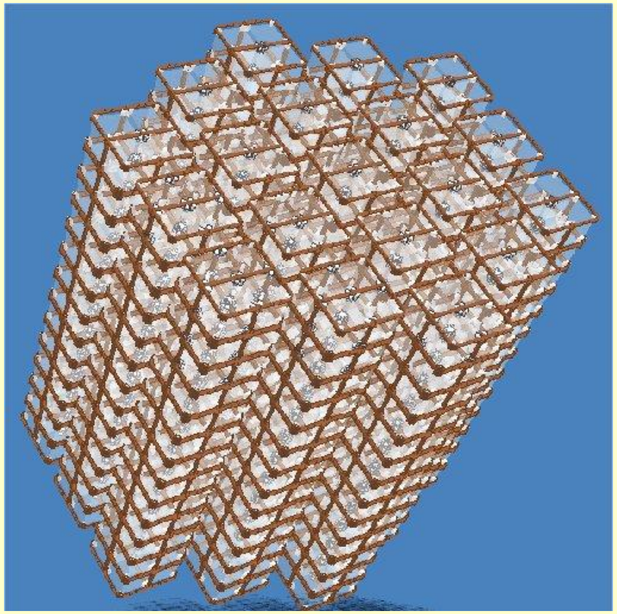
Cryogenic Underground Observatory (for) Rare Events

M = 0.75 ton
bkg~0.01 counts/(kev-kg-yr)
$T_{1/2}$ ~ 2.5 x 10^{26} yrs, $\langle m_\nu \rangle$~ 0.04 eV

203 kg ^{130}Te



Array of 988 detectors:
19 towers , 13 modules/tower
4 detectors/module



5 Pulse tube cryocoolers 1.5W @ 4.4K, 40W @ 44K

Dilution refrigerator 5μW @ 12mK, 1.5mW @ 120mK

Scintillating Bolometers

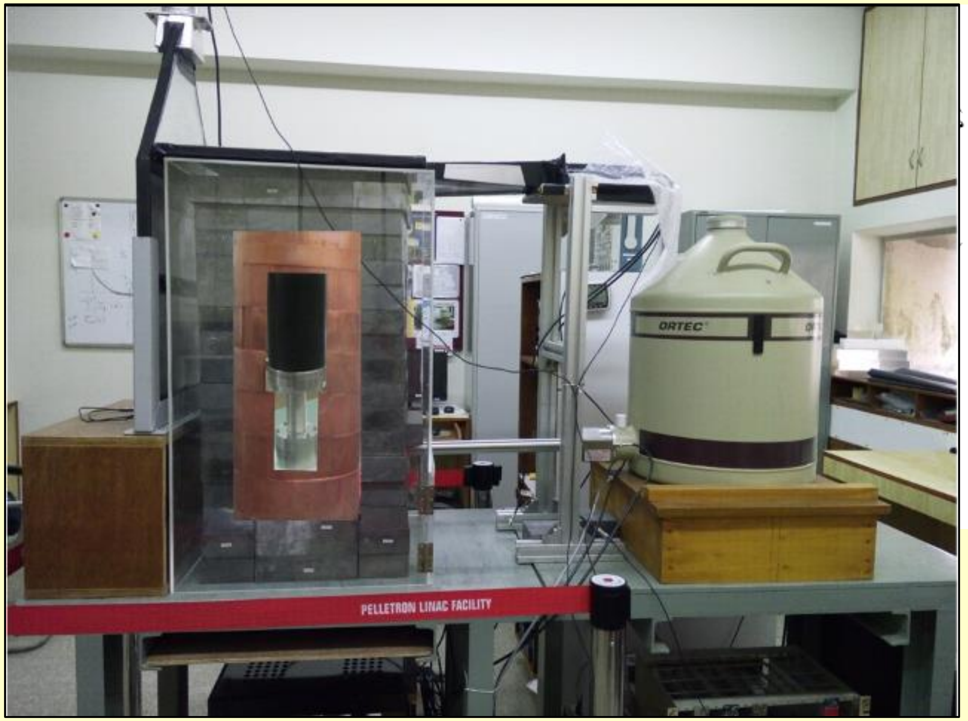
•Measure both light and phonon signals

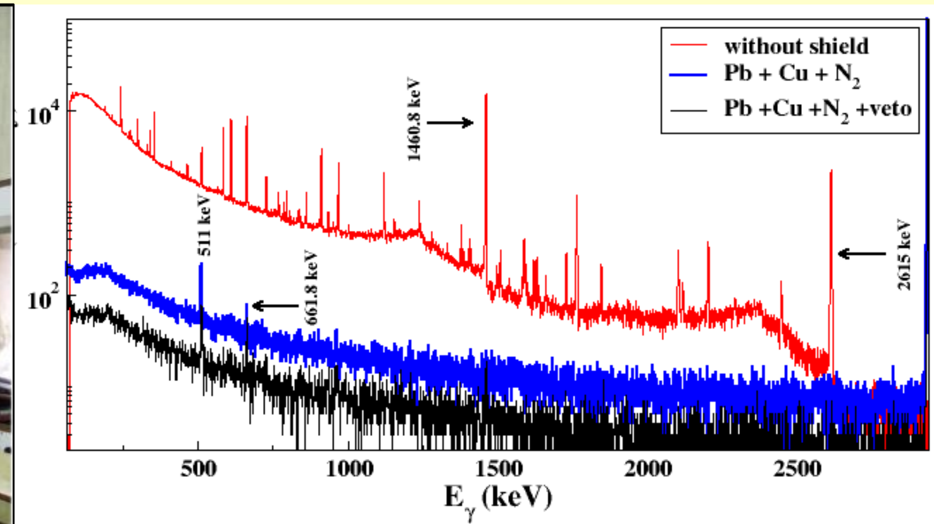
•Discrimination of nuclear recoils/alpha events from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light

- Different scintillating crystals ($CdWO_4$, CaF_2, $CaMoO_4$, $SrMoO_4$, $PbMoO_4$, ZnSe, …) have been tested
- Some of them show excellent results (for example $CdWO_4$, $CaMoO_4$ and ZnSe).

CRESST, LUCIFER, CUPID

TiLES (Tifr Low background Experimental Setup)





Sensitivity of the setup:

^{40}K – 2 ppb

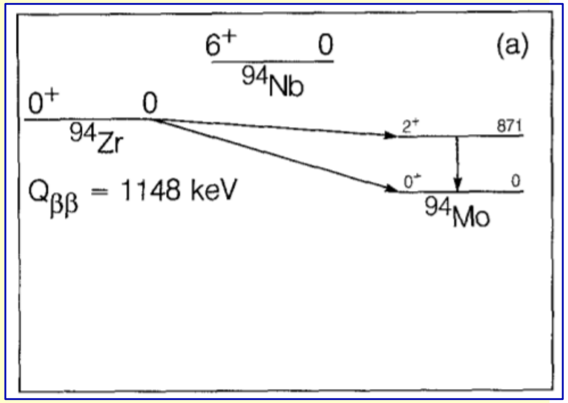
^{232}Th, ^{238}U -10 ppb

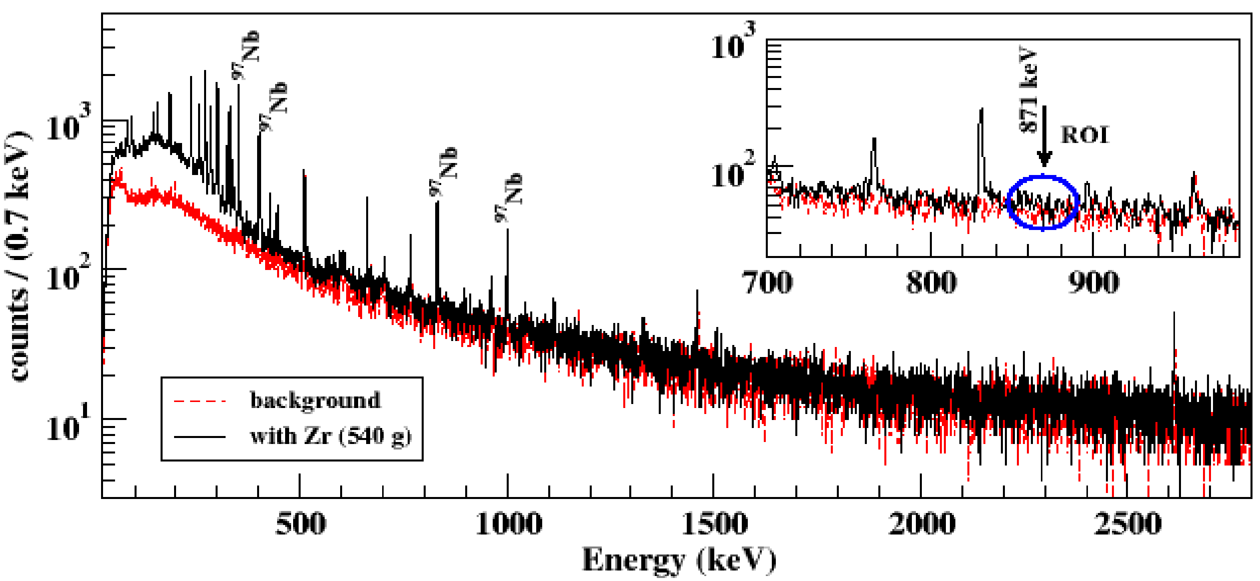
- Detector surrounded by **OFHC Cu (5 cm), Pb (10 cm) (^{210}Pb < 0.3 Bq/kg)**.
- N_2 purging system and active muon veto (plastic scintillators)
- TiLES is used for material screening such as ETP Cu, INO site rock, CsI crystals for DINO, etc.

N. Dokania et al. NIM A **745,** 119 (2014)

DBD to excited state in ^{94}Zr

Decay Scheme of ^{94}Zr





Gamma ray spectra of ^{nat}Zr in TiLES for t = 7d

- The current best experimental limits are **$T_{1/2} > 1.3 \times 10^{19}$ y** (68% C.L.) (***Norman et al., Phys. Lett. B 195*, 126 (1987)).**
- 540 g of ^{nat}Zr (99.5% purity) counted in the TiLES,

Double beta decay of ^{94}Zr to the 1st excited state in ^{94}Mo

***$T_{1/2} > 2.0 \times 10^{20}$ y* 68% C.L, *6.12 x 10^{19} y at 90% C.L.*.**

Systematic errors: efficiency (5%), isotopic abundance (1%) drifts in energy scale (1%) Background model fit parameters (14%)

N. Dokania et al. Eur. Phys. J. A **53,** 74 (2017)

Muon induced (n,γ) reactions

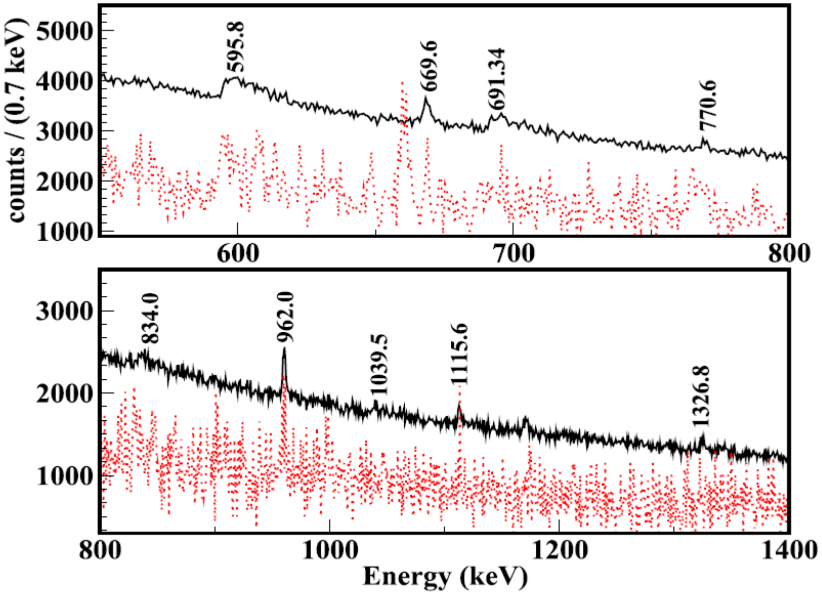


Fig. 4. Prompt (black) and chance (red) gated γ-ray spectra in the TiLES HPGe detector. The chance gated spectrum has been scaled up by an arbitrary factor (~ 330) for better viewing ($T_{\text{data}} = 329.2$ days).

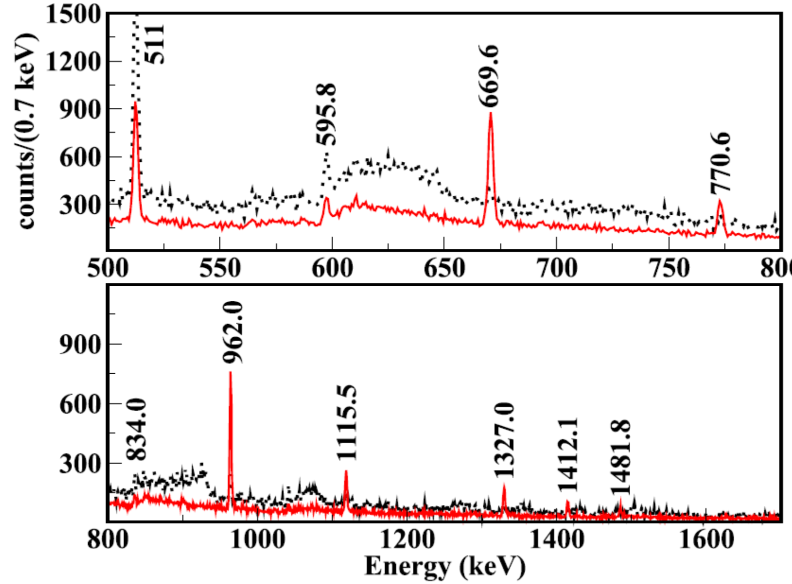


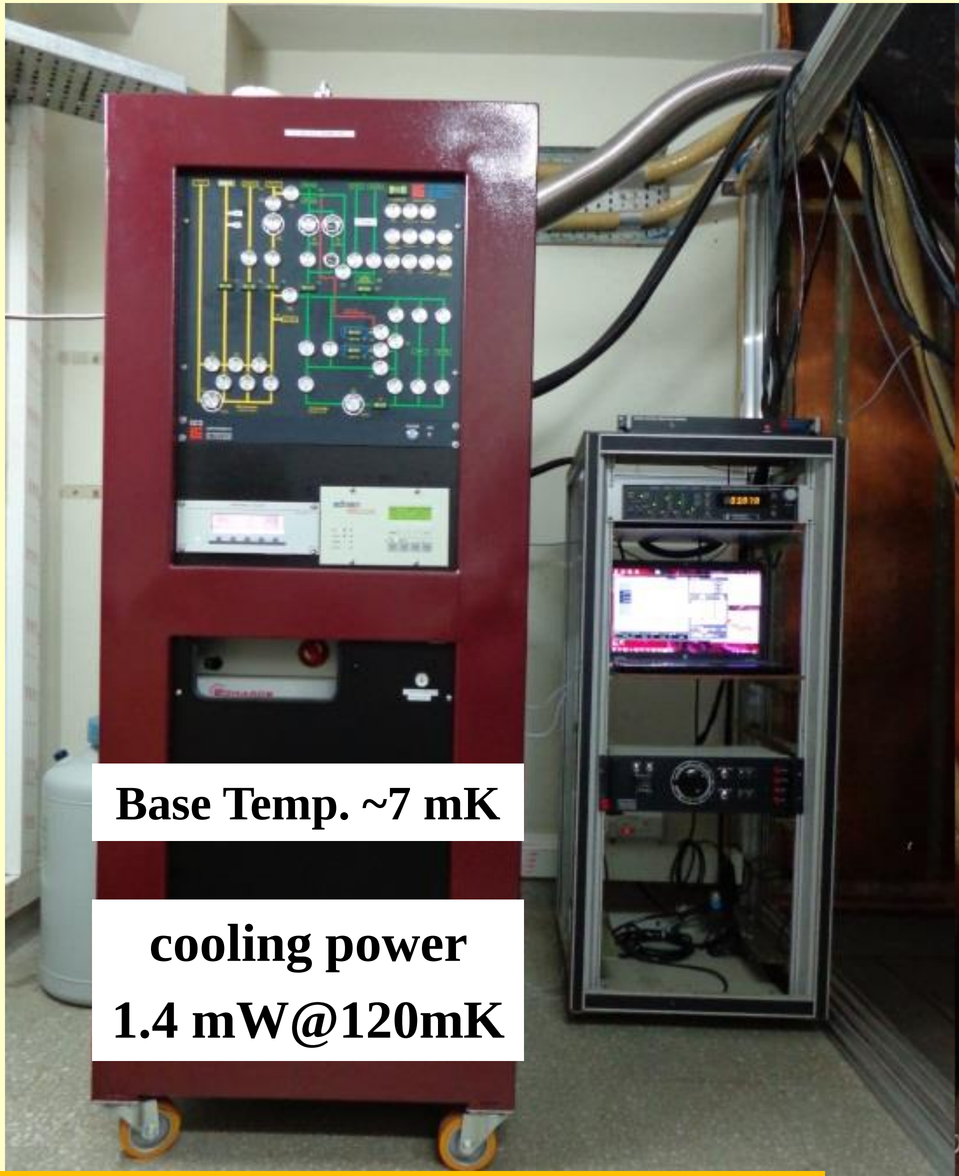
Fig. 9. A comparison of simulated γ-ray spectra generated with GEANT4.10.00 (black, dotted, scaled up by a factor of two for better visibility) and GEANT4.10.05 (red, solid) ($N_{inc}(n) = 1.435 \times 10^8$).

H. Krishnamoorthy et al. Eur. Phys. J. A **55,** 106 (2019)

Detector developments in progress in INDIA

- Cryogenic bolometer,
- Scintillators
- Thermal neutron detector
- Imaging detectors

Cryogen free dilution refrigerator installed at TIFR



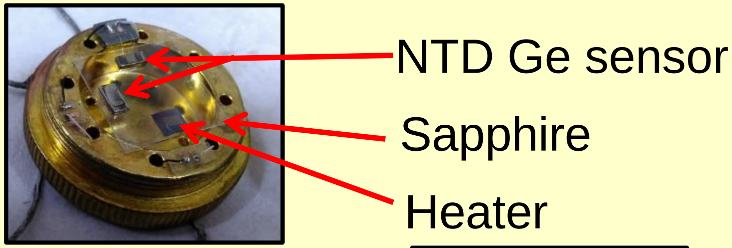
Base Temp. ~7 mK

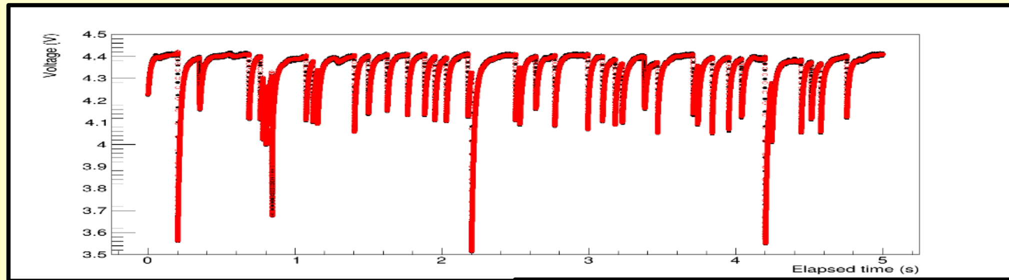
cooling power
1.4 mW@120mK

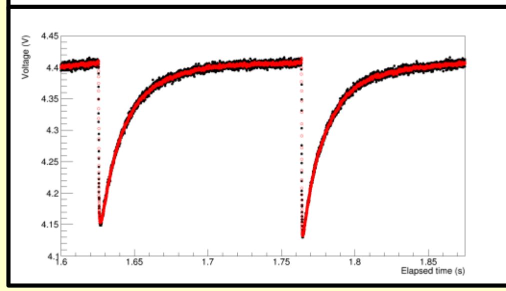
*V. Singh et. al. Pramana **81** (2013) 719*

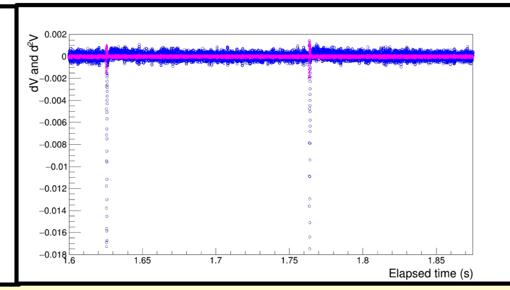
http://www.tifr.res.in/~tin.tin/

Test with blank sapphire & Sn

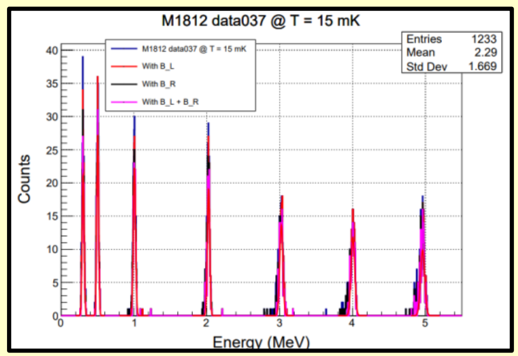


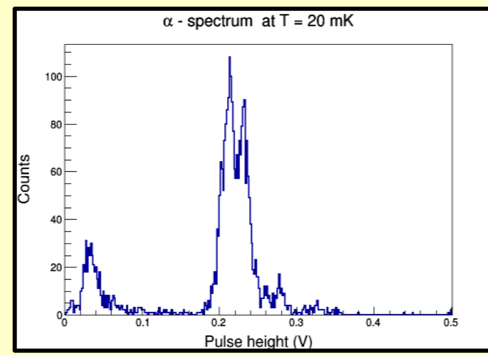




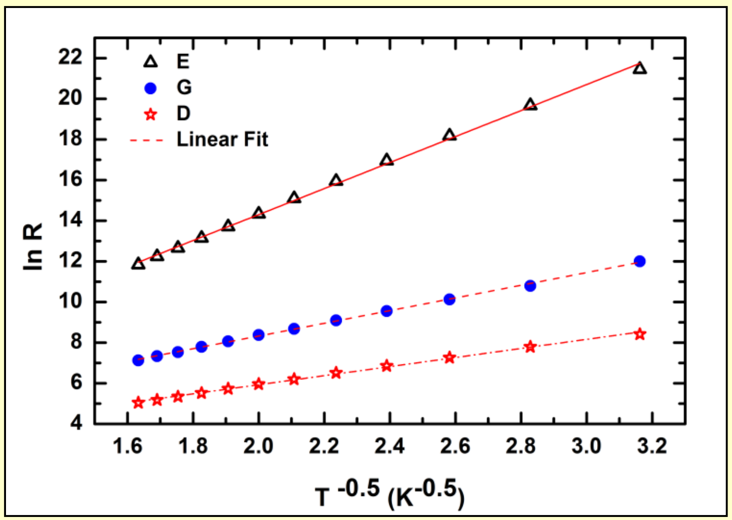


Indegenously developed NTD Ge sensor for mK thermometry





A. Garai *J Low Temp Phys*, **199**, 95 (2020)



ln R varies linearly with $T^{-0.5}$

Mathi *et al.* 10.1109/WOLTE.2014.6881014

A. Garai *et al.* Journal of Low Temp. 10.1007/s10909-015-1379-6

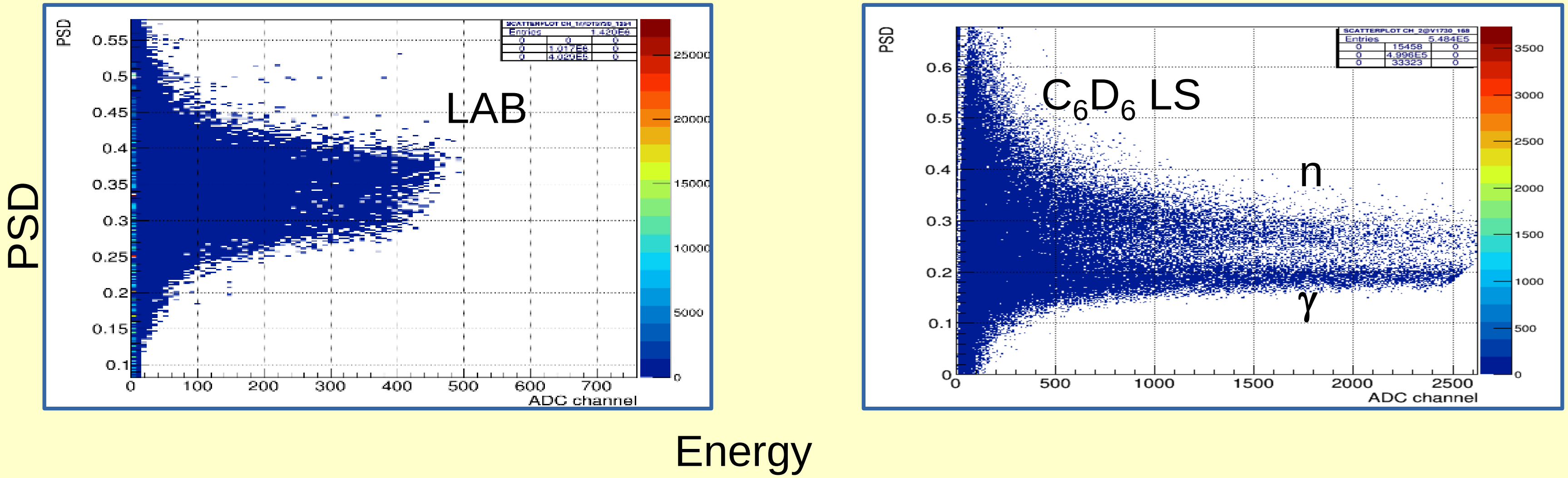
Development of new liquid scintillators

Solvents : phenyl-oxylyl ethane (PXE), linear alkyl-benzene (LAB), di-isopropylnaphthalene (DIN)

Biodegradable, relatively safe solvents, with a high flash point, very low toxicity

Well suited for large size (tonne) detectors

LAB LS & Deuterated liquid scintillators (DLS)

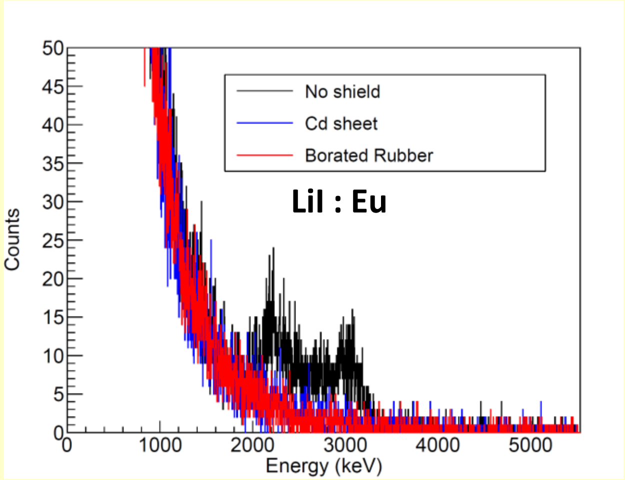


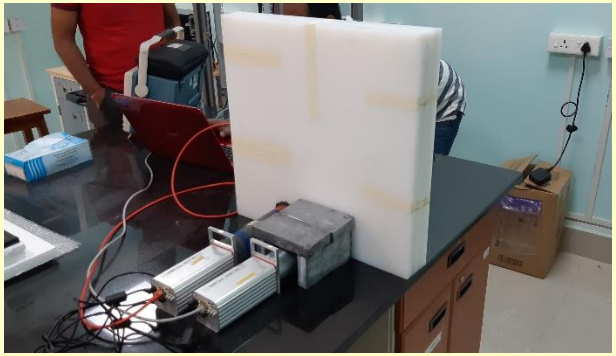
- No PSD observed in LAB LS
- DLS results very promising….

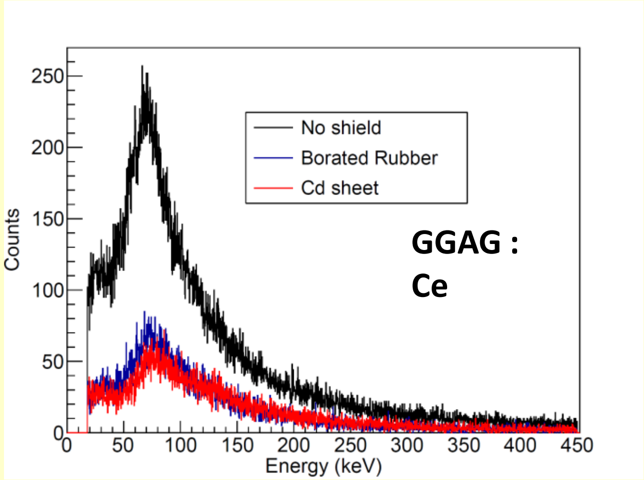
Courtsey : P.C. Rout (BARC)

Thermal neutron detectors
(for low flux thermal neutrons)

- Thermal neutron background measurement feasibility at rare event sites
- 1 mCi **Am-Be** neutron source, Fast neutrons thermalized using HDPE sheets
- Approximate thermal neutron flux ~10^{-2} $cm^{-2}s^{-1}$
- Lithium Iodide doped with Europium (LiI:Eu) and Gadolinium Gallium Aluminium Garnate doped with Cerium (GGAG:Ce) detectors
- Measurements done at NISER in collaboration with BARC colleagues



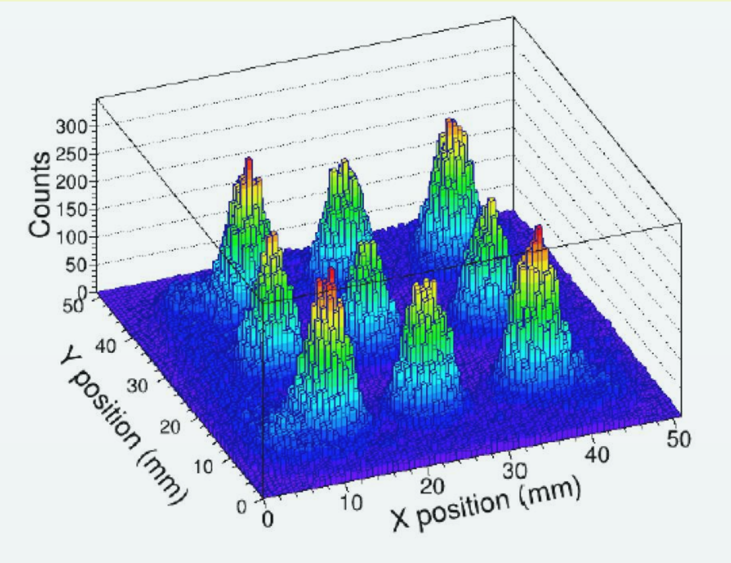




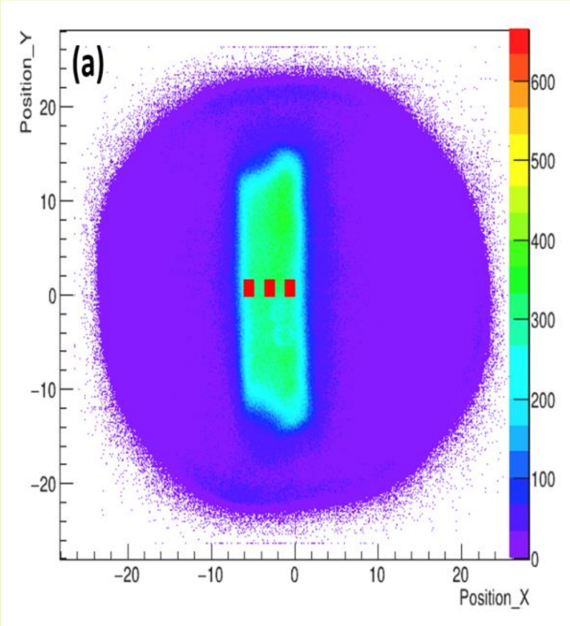
Courtsey : Bedang Das Mohanty (NISER)

Position sensitive gamma ray detectors for basic research and applications

Development of position sensitive scintillator detector
B. Das et al. EPJ Conf Series (2021)
(First prize in ANNIMA 2021 Conf)



Pulse shape study in semiconductor detector and imaging
A. Sharma et al. EPJ Conf Series (2021)



Courtsey : R. Palit (TIFR)

Summary

- *A variety of detector setups (gamma. Neutron, charge particles) developed and operational at major accelerator centres in India.*
- *Cryogenic detectors – wide range of applications for high precision measurements & rare event studies like NDBD, Dark matter*
- *Imaging, GEM, and other position sensitive detectors have wider applications in other areas*
- *In India, efforts are underway for developments of various scintillators and bolometric detectors*

Exciting times ahead

…..

…THANK YOU