The Practice of Gamma-ray Spectroscopy: Here & Now

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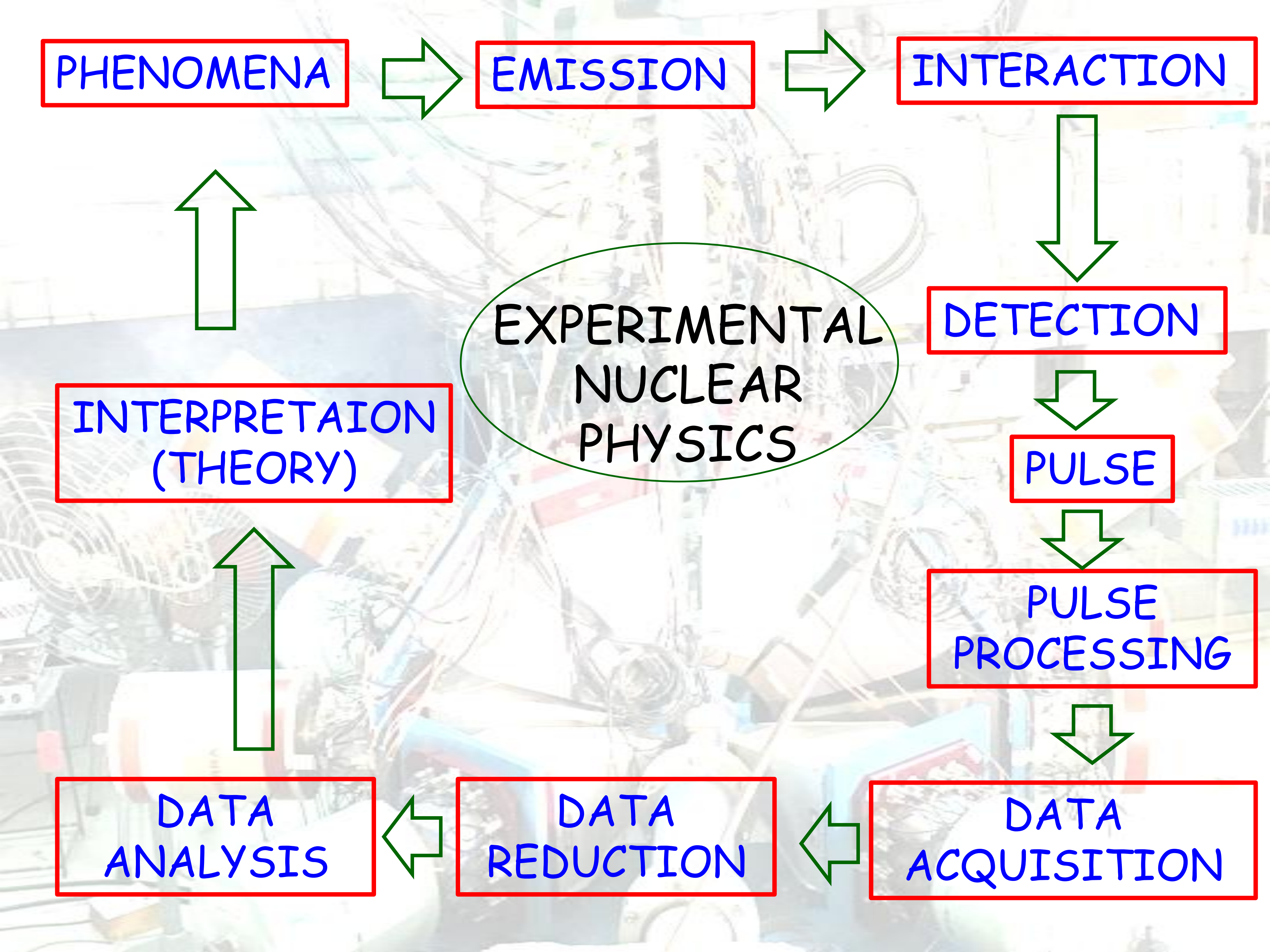
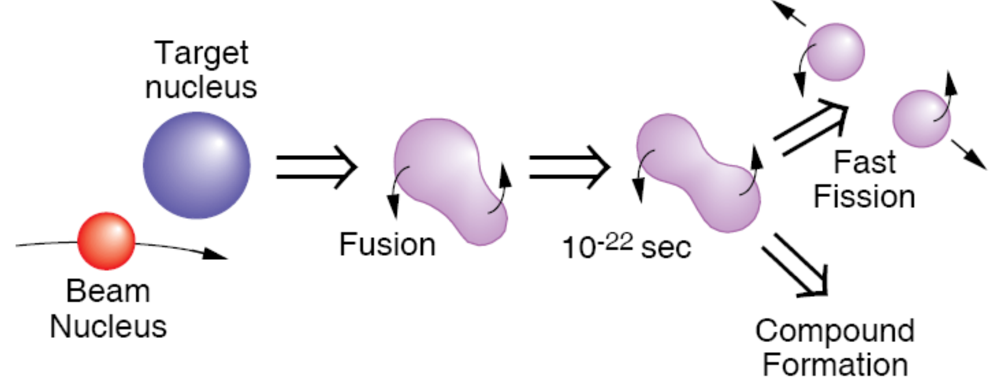

PHENOMENA
EMISSION
INTERACTION
DETECTION
PULSE
PULSE PROCESSING
DATA ACQUISITION
DATA REDUCTION
DATA ANALYSIS
INTERPRETAION (THEORY)
EXPERIMENTAL NUCLEAR PHYSICS

Production of Excited Nuclei



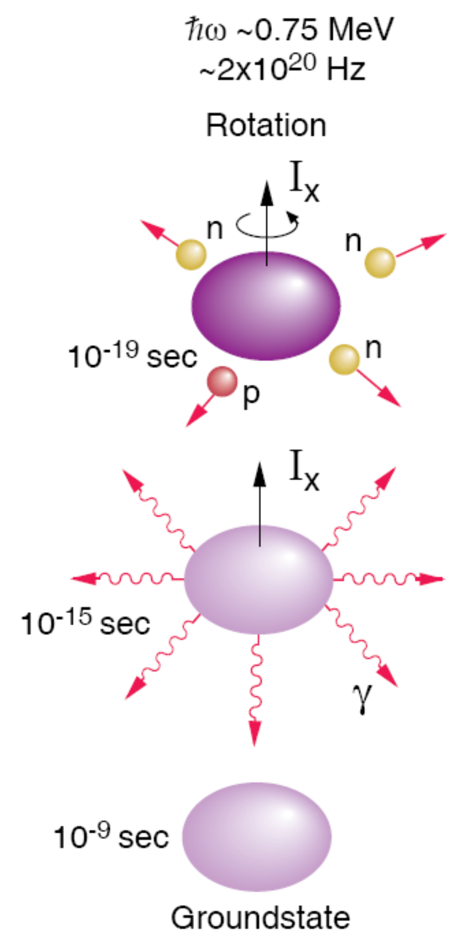
Nucleus: many-body quantum system.

Nuclear Structure Studies: nucleus at excited states (energy & angular momentum)

Angular momentum generation mechanisms: single particle & collective

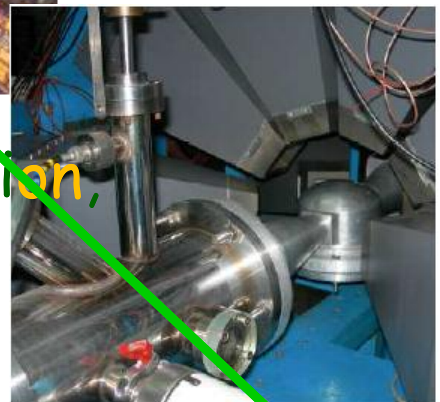
Phenomena: Bands, shapes, shells, deformations, evolutions & coexistence

Theory: Model calculations to interpret & understand the observed level structures. (Shell Model, for instance)



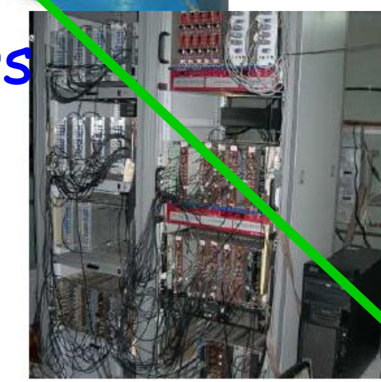
Flow of Things

beam from accelerators (cyclotron@ VECC, pelletron @ IUAC, TIFR)



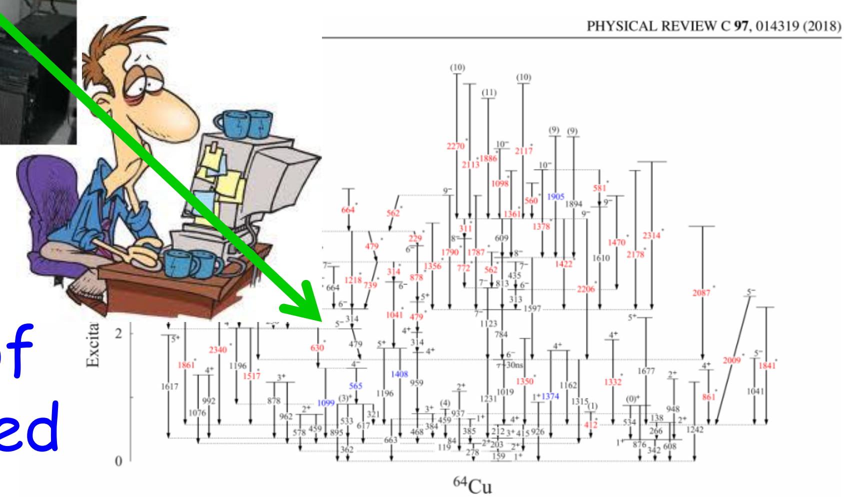
reactions, radiation, detection (HPGe)

gamma-ray interactions: photoelectric, Compton, pair-production; full energy deposition, Compton suppression for spectroscopy



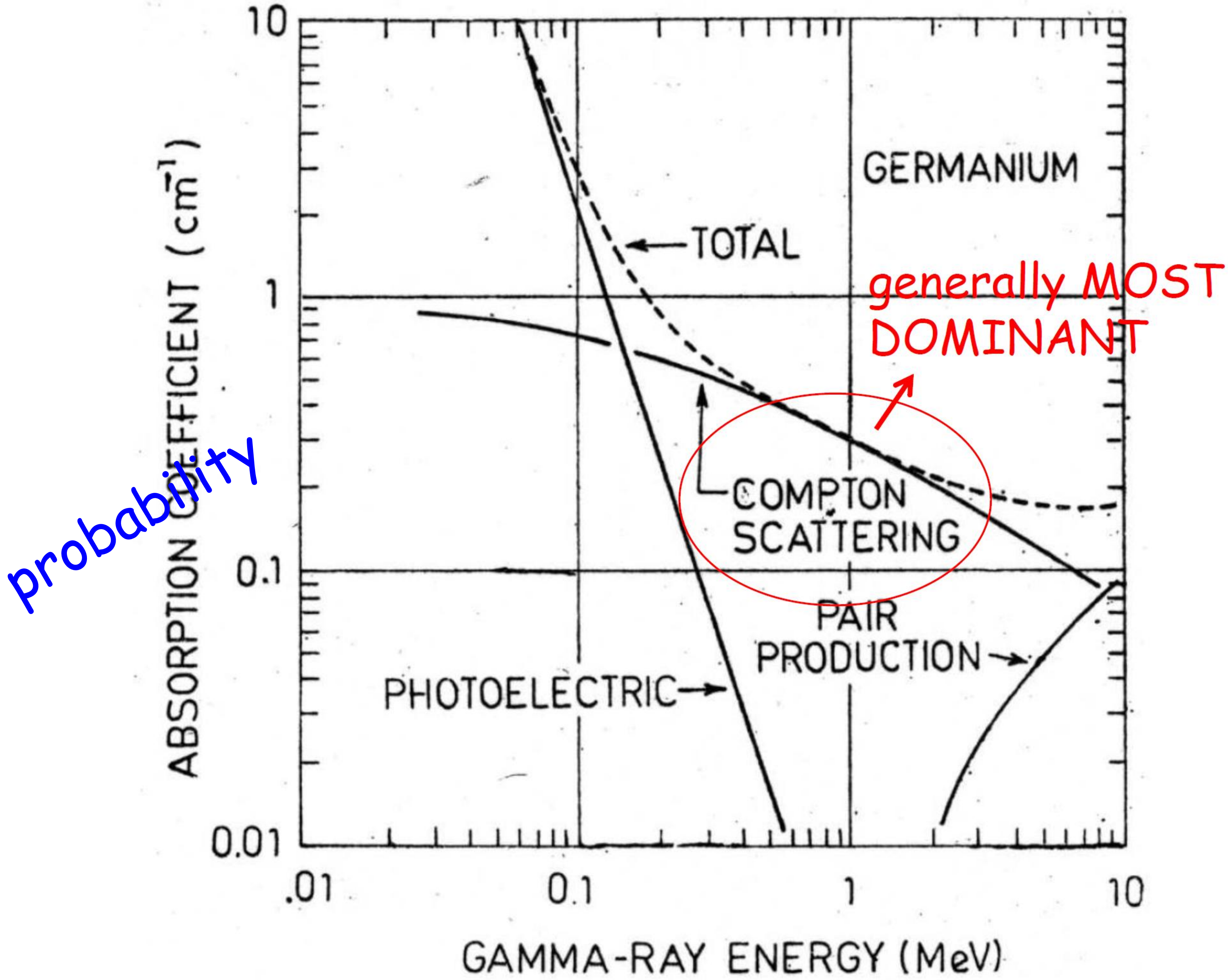
pulse from detectors processed, data recorded in acquisition system

pulse processing electronics: analog, digital



data: reduced & analyzed to extract the excitation scheme of nuclei and interpret the associated physics

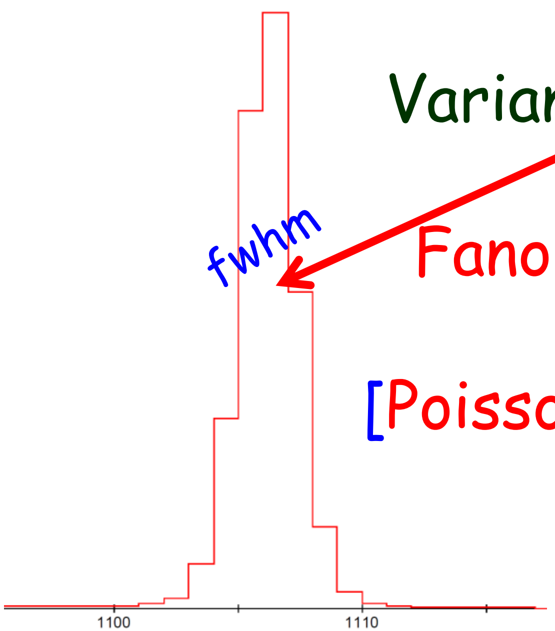
Interaction of Gamma-rays with Matter



Radiation Detectors: General Properties

Incident Radiation Energy
-> Charge Carriers -> Transit of Carriers under Electric Field
-> Collection of Charge Carriers -> Pulse -> Processing ->
Amplitude Read-out ->
Incident Radiation Energy

Number of Charge Carriers ~ energy resolution of the detector (spectroscopy) -> width of the transition peak



Variance/fluctuations in the number of charged carriers:
Fano factor (F) = (observed variance) / (E/W)

[Poisson predicted variance on the no. of carriers = no. of charge carriers = (E/W)]
Good energy resolution -> small F

Radiation Detectors: General Properties

Transit of charge carriers in the electric field -> time of collection -> rise time of the pulse -> timing characteristics of the detector

Example:

Gas Detectors: electron-ion pair are charge carriers

+ve ion-slow -> collection ~ ms

electrons–fast -> collection ~ us

Operate the detector in PULSE MODE

(each individual DETECTION is DISCERNED)

for SPECTROSCOPIC applications

(Current Mode operation: average current flow in the detector…..field applications, particularly for higher count-rates)

Radiation Detectors: General Properties

Can be based on different detection media

gas (oldest, still used, particularly for particles-fission fragments)

liquid (scintillators, example of usage – neutron detection)

solid (widely used in contemporary nuclear physics measurements)

Use of solid state detectors are of great advantage in the detection of radiation

densities of solids ~ 1000 times that of gas

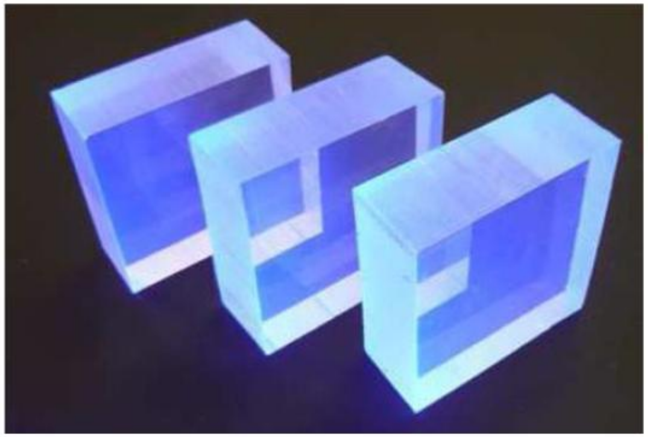
(larger number of interaction points in smaller dimensions)

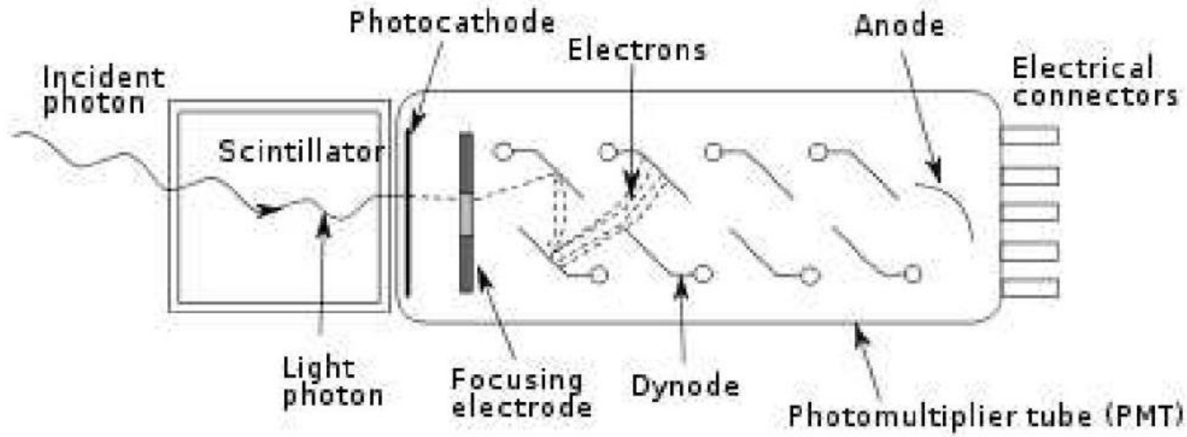
particularly significant for gamma-ray detection

Solid State Detectors

Scintillators

Poor energy resolution and do not befit spectroscopic applications.





Average energy / carrier (electron) ~ 100 eV.

no. of charge carriers in a typical radiation interaction ~ maximum few thousands.

Statistical fluctuations on such "small" number imposes a limitation on the energy resolution obtained.

NaI(Tl): 6-7% at 662 keV

Solid State Detectors
Semiconductors

Widely used in spectroscopic applications, owing to the superior energy resolution.

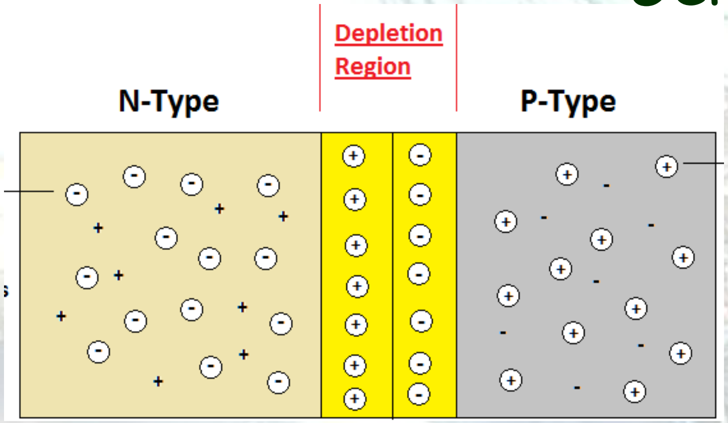
Fundamental information carriers: electron (e) – hole (h) pairs.

Si: for charged particle & Ge: for γ-rays (Why ?)

Energy required to produce an e-h pair in Si/Ge: W ~ 3 eV (compare with
30 eV for an electron-ion pair in gas detector;
100 eV for an electron in the scintillator)

more no. of carriers -> better resolution
(as much as ~ 0.2% at 1 MeV)

Semiconductor Detectors
General characteristics



Based on properties created near the junction of a p-type and a n-type semiconductor: the depletion region .

It is "depleted" in the concentration of electrons & holes.
(only charge remaining: ionized donor sites & filled acceptor sites -> immobile)

e-h pairs created by the passage of radiation are swept out of the depletion region by the existing electric field and the motion constitutes the electrical signal.

Thermal generation of e-h pair ? Leakage current ?

Semiconductor Detectors
General characteristics

Unbiased pn-junction, no external voltage applied: can operate as radiation detector, IN PRINCIPLE, but with VERY VERY POOR PERFORMANCE.

The contact potential across the junction ~ 1V -> electric field is too small to make the charge carriers move rapidly -> loss of carriers due to trapping & recombination.

Thickness of depletion region ~ small -> high capacitance -> poor noise characteristics

THUS, junctions used as radiation detectors are REVERSE BIASED -> enhances the potential difference across the junction

Reverse Biased p-n Junction

Reverse bias accentuates the potential difference across the junction -> extend to greater distances on either side of the junction

-> thickness of the depletion region is increased
[$d = (2\,\varepsilon V/eN)^{1/2}$, N is dopant concentration]

-> capacitance (depletion region <-> charged capacitor) =
$\varepsilon/d \cong (e\,\varepsilon\,N/2V)^{1/2}$
decreases with increase in reverse bias -> improved detector performance

-> operated with largest possible applied reverse bias to achieve a FULLY DEPLETED DETECTOR
[$V_d = eNT^2/2\,\varepsilon$, T is the wafer thickness]

Germanium Detectors for Gamma-ray Spectroscopy

Si/Ge of normal purity can produce depletion region ~ few mm's, insufficient for gamma-ray detection.

Depletion depth -> $d = (2\ \varepsilon V/eN)^{1/2}$, N is dopant concentration (low N, greater d for same applied V)

How low in N do we think of ? 10^{10} atoms/cm^3 ! (compare with Avogadro's number……)

Possible in Ge but not in Si ->

High Purity Germanium (HPGe) detectors

for gamma-ray spectroscopy.

Operational Characteristics of HPGe Detectors

Reverse Bias

As in case of semiconductor detectors, these are operated under reverse biased condition.

Typical dimensions of crystals are ~ few cm & corresponding bias ~ few thousand V.

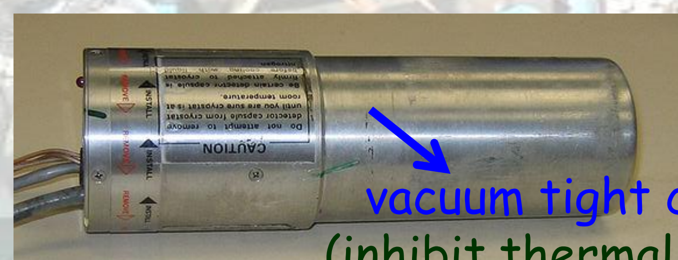
Temperature

Small band gap (0.7 eV) of Ge results in a substantial thermally induced leakage current, at room temperature.

They are operated at liquid nitrogen temperature (77 K), to suppress the leakage current.

dewar to hold LN_2

LN_2 in thermal contact with the crystal.



vacuum tight cryostat (inhibit thermal exchange with the surroundings)

Efficiency Characteristics of HPGe Detectors

Efficiency ~ Energy Dependent

(intuitive)

At a given incident gamma-ray energy

Absolute Efficiency =

No. of full energy counts/ No. of photons emitted

Intrinsic Efficiency =

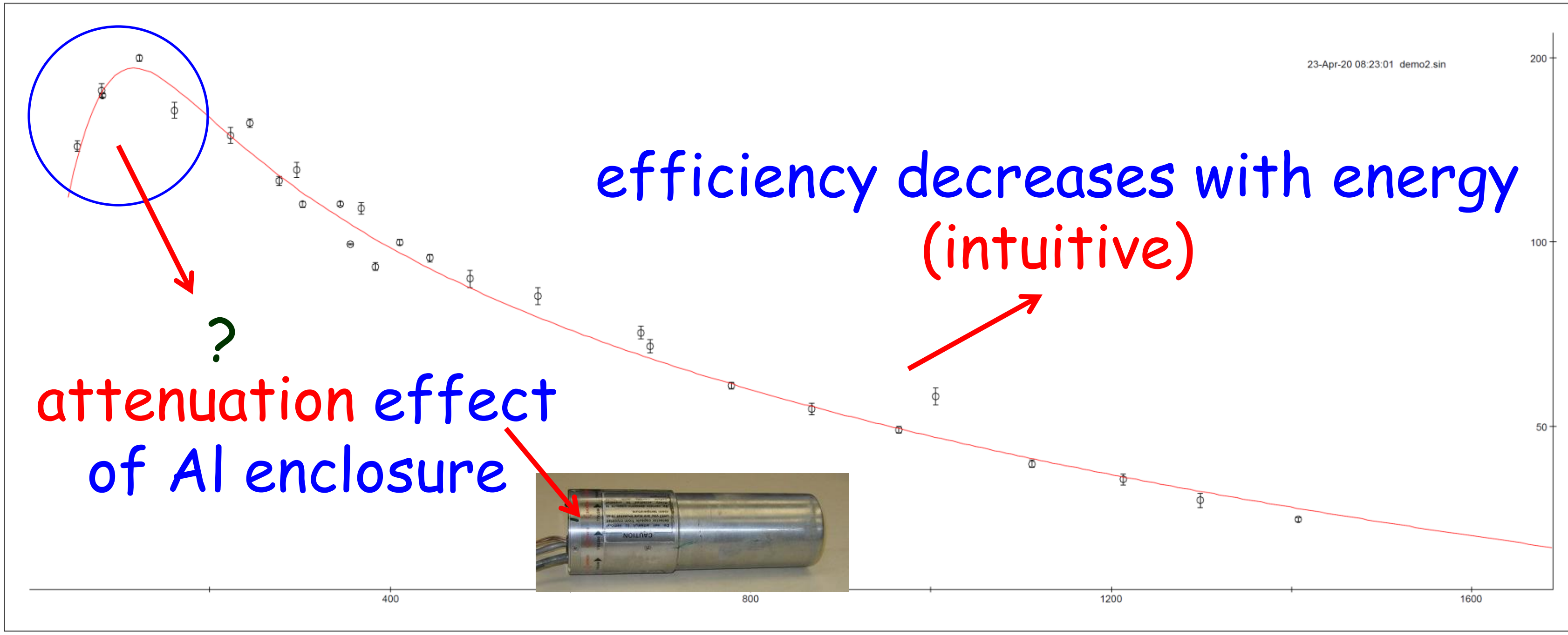
No. of full energy counts/ No. of photons incident

Absolute Efficiency

= Solid Angle Coverage ($\Omega/4\pi$) * Intrinsic Efficiency

[Ω = area of the detector (face)/r^2, r being the radius of the sphere centered on the gamma-ray source]

Efficiency Characteristics of HPGe Detectors



Efficiency calculated at different energies using standard radioactive sources

Area = Intensity * Efficiency

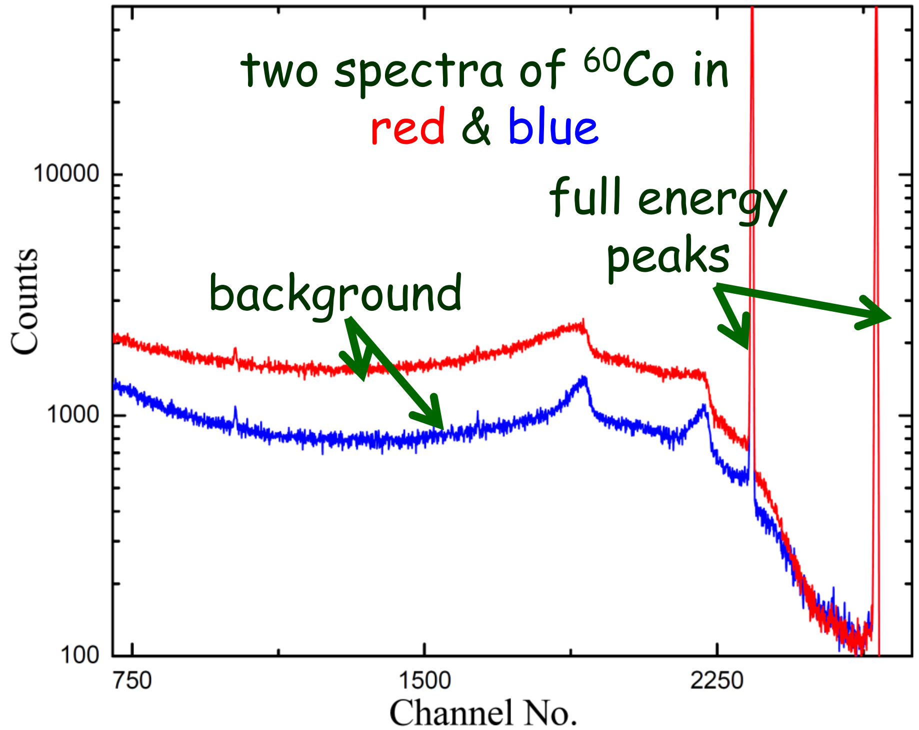
(intensity -> relative intensity -> relative efficiency)

Fitted with a function to extract efficiency at all energy values.

Gamma-ray Spectrum of HPGe Detectors

Full Energy Peaks
Deposition of the complete incident energy in the detector medium.

Background
Compton interactions in the detector medium -> incomplete deposition of incident energy. (Unwanted !)

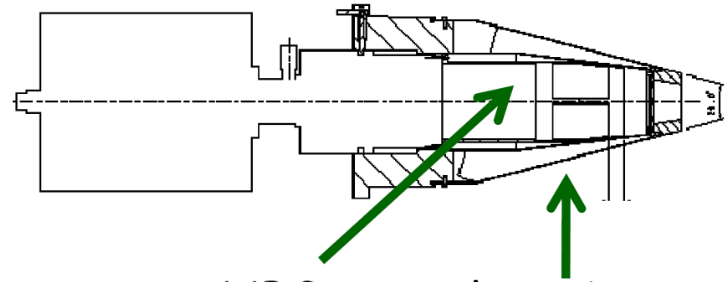


Gamma-rays
From the sources / nuclei produced in an experiment
(full energy peaks & partial depositions primarily owing to Compton interaction)

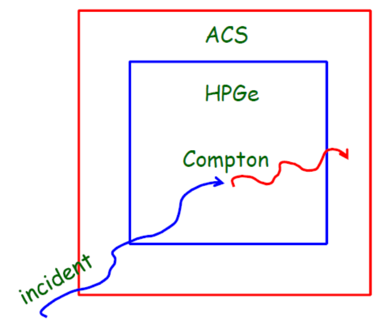
From atmospheric /cosmic origin
(very high energies -> partial depositions -> background)

Background Suppression

Cosmic background: passive shielding with high-Z canopy (Pb, W) / rock coverage in underground labs



Experimental background: Compton suppression implemented through use of Anti Compton Shield (ACS) in conjunction with HPGe



Reject events corresponding to coincident signals from BOTH HPGe AND ACS

ACS: scintillator (high efficiency) detector. BGO, NaI(Tl) [ACS has NO SPECTROSCOPIC PURPOSE. It is only to detect the presence of Compton scattered gamma-ray]

Quality of Suppression:
Peak-to-Total Ratio (P/T) characterizes a gamma-ray detection setup

Quality of Compton Suppression

Peak-to-Total Ratio (P/T) (w.r.t. to ^{60}Co spectrum) =

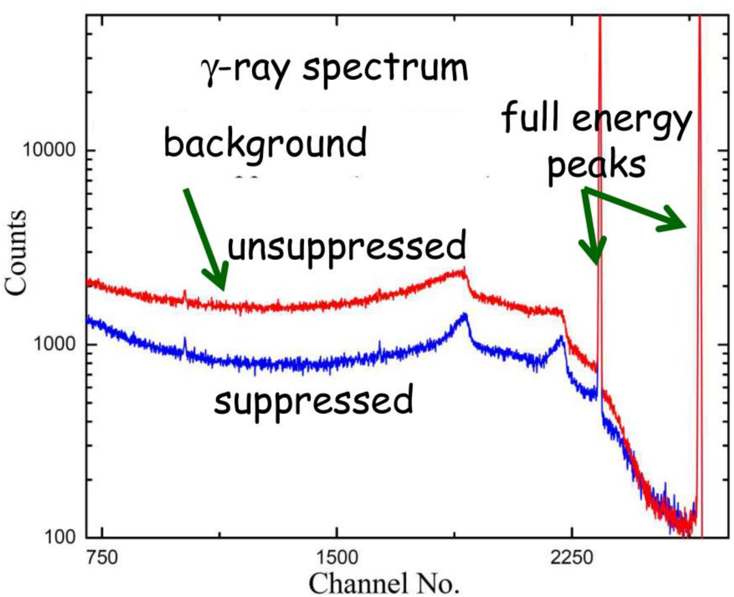
[Area(1173.2) + Area(1332.5)] / Counts(100 to 1350)

$(P/T)_{Suppressed} > (P/T)_{UnSuppressed}$

$[(P/T)_{UnSuppressed} / (P/T)_{Suppressed} \sim 0.5]$

Because $(T)_{Suppressed} < (T)_{UnSuppressed}$

Compton Suppression is not expected to affect peak areas (P)



Shortfalls in Suppression Logic

Compton scattered gamma-rays might not interact in the ACS.

(Compton event in HPGe gets recorded)

ACS might detect independent gamma-rays.

(Full energy event may be rejected)

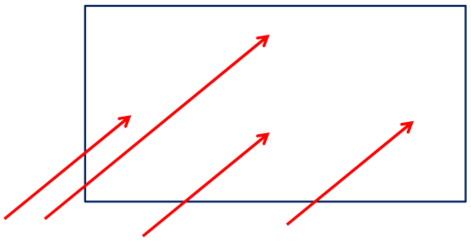
Improving the Efficiency of HPGe Detectors

LARGE Crystals (!) -> More interaction points -> Greater probability of interaction -> Higher efficiency

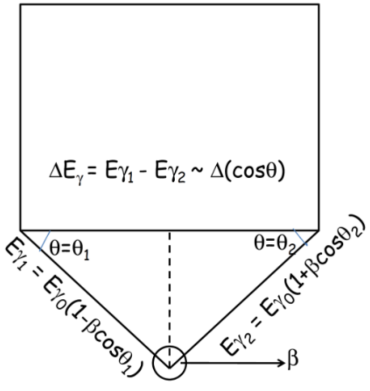
BUT

(1) Technological challenge to fabricate large HPGe crystals. That'll make them very expensive.

(2) Larger crystal -> more interaction points -> pulses of varied rise times -> detrimental to the timing characteristics



(3) Doppler broadening that afflicts the energy resolution (even when we are not asking for it !)



But larger volume -> better efficiency. So ?

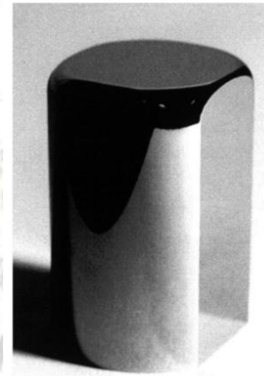
Composite HPGe Detectors: Clover

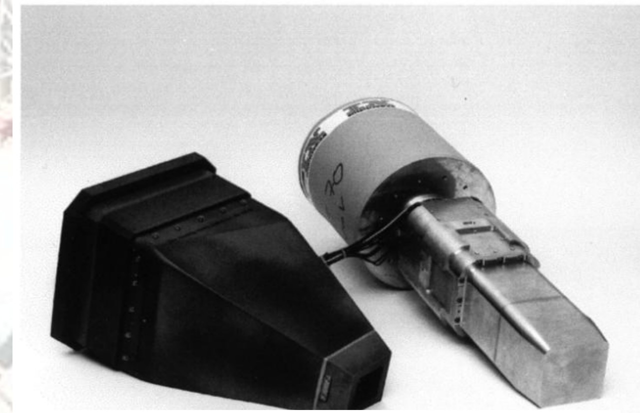
Clover detector. Four HPGe crystals (each 50 mm x 70 mm) mounted on a common cryostat.

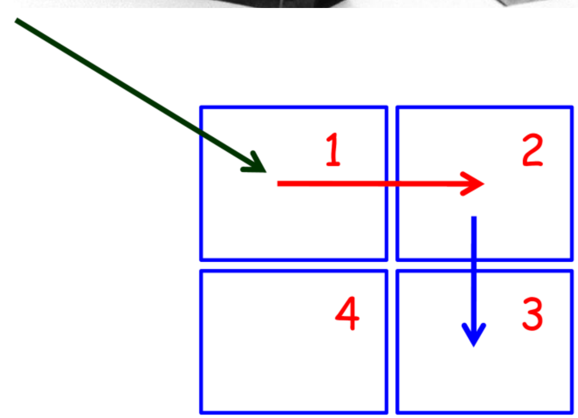
Photopeak Efficiency:
Not just four times but six times a single crystal HPGe at ~ 1 MeV

Addback:
Reconstructing the photopeak from Compton scattering between individual crystals

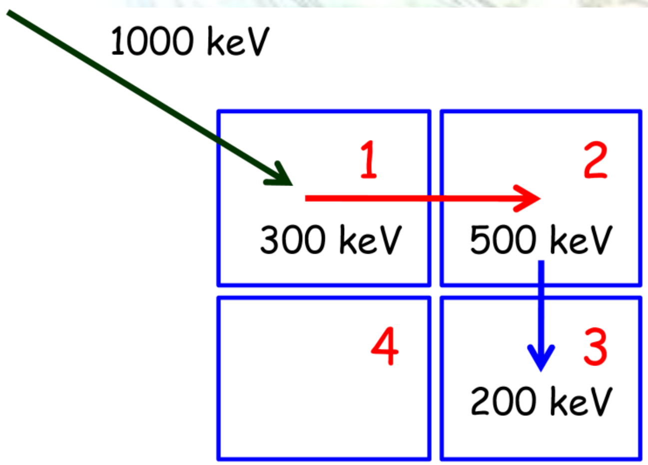
Time CORRELATED Sum
Identifying energy deposition by a single incident gamma-ray in multiple crystals

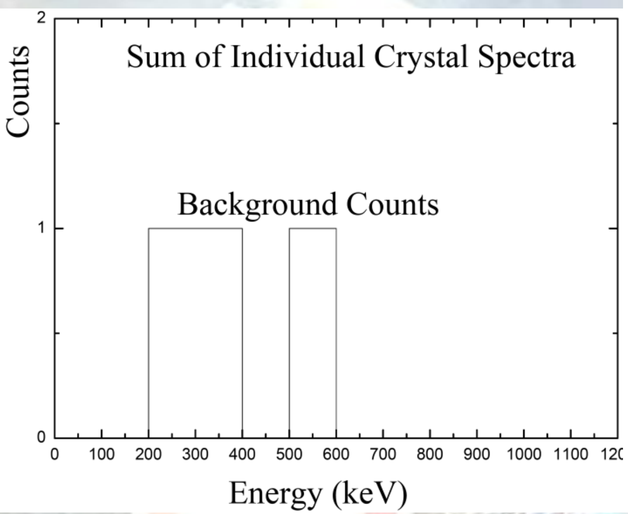


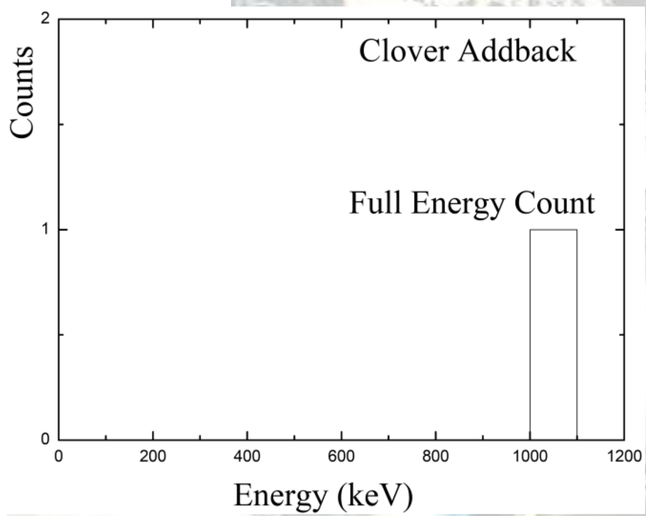


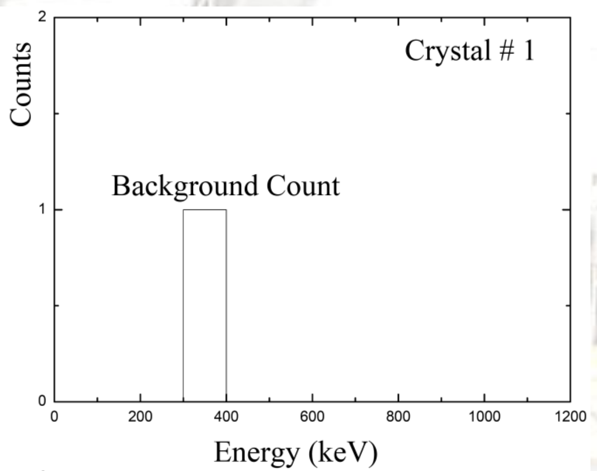


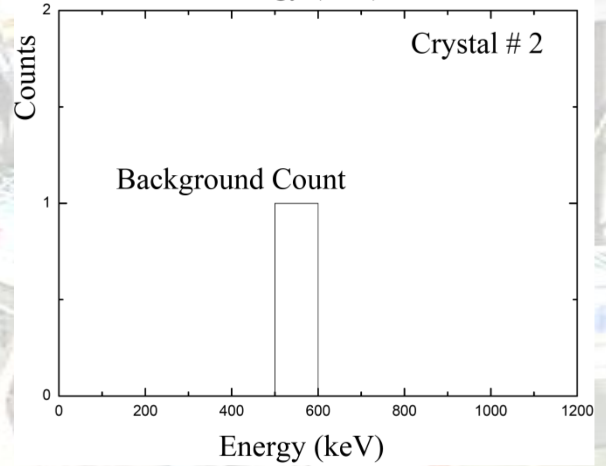
Addback Illustration

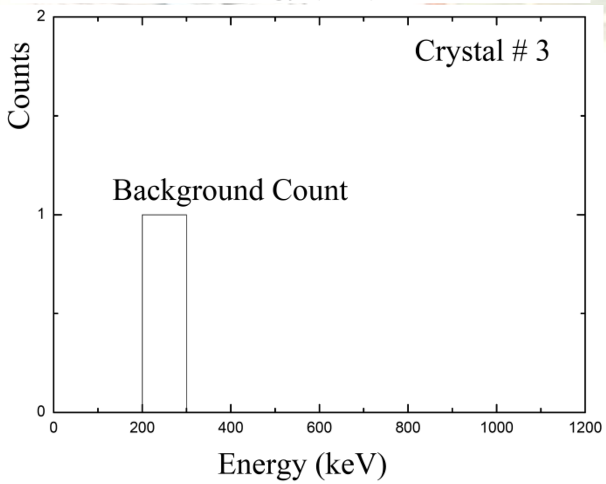








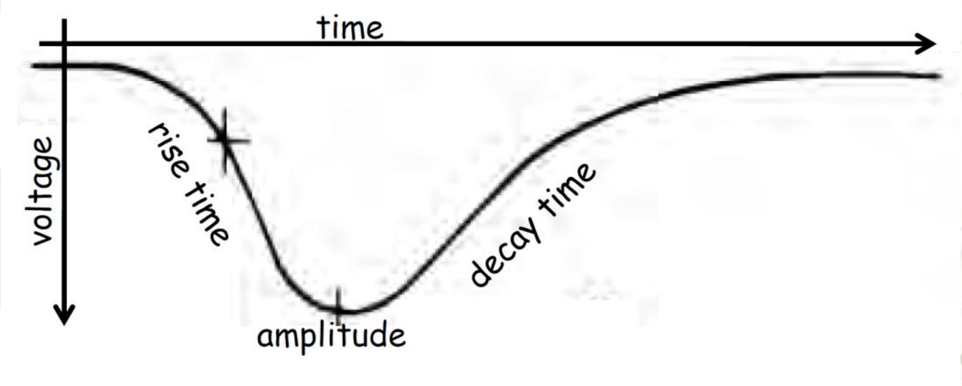




Addback is NOT "just" sum. It is TIME CORRELATED SUM.

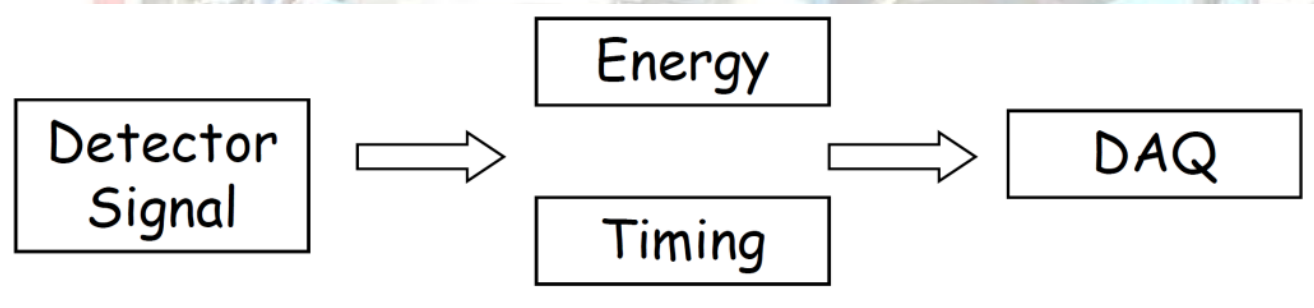
We just don't add spectra in addback. That would be TIME UNCORRELATED SUM.

Pulse from the detector ->
to be processed for energy & timing information

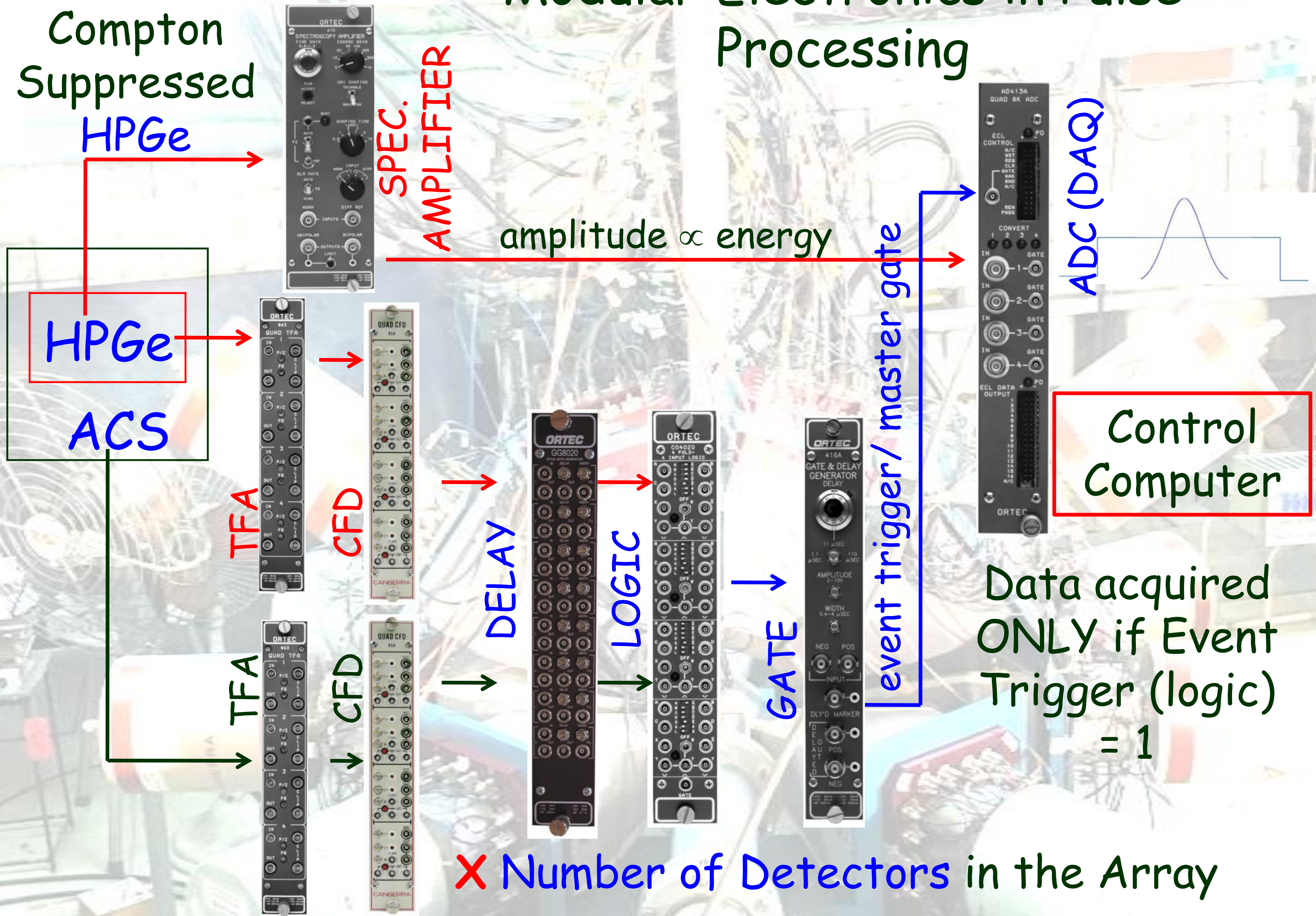


amplitude ->
energy deposited in the detection

rise time ->
time marker for detection



Modular Electronics in Pulse Processing



Digital Revolution in Gamma-ray Spectroscopy

Detector Signal ⇨ Digitization ⇨ Firmware: Recursive Algorithms (Filter) & Validation ⇨ (Time Stamped) Data

Nuclear Instruments and Methods in Physics Research A 345 (1994) 337–345
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy

Valentin T. Jordanov *, Glenn F. Knoll
Department of Nuclear Engineering, The University of Michigan, 2355 Bonisteel Blvd, Ann Arbor, MI 48109, USA

Fast, compact, efficient acquisition systems for contemporary experimental facilities

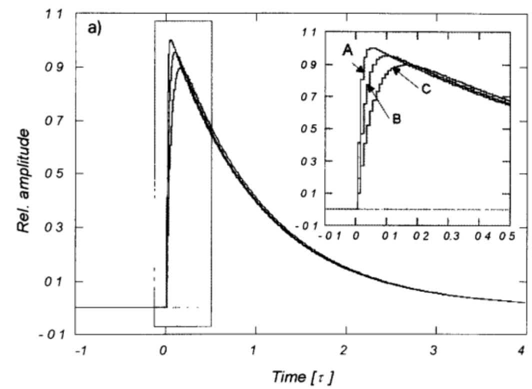
Nuclear Instruments and Methods in Physics Research A 353 (1994) 261–264

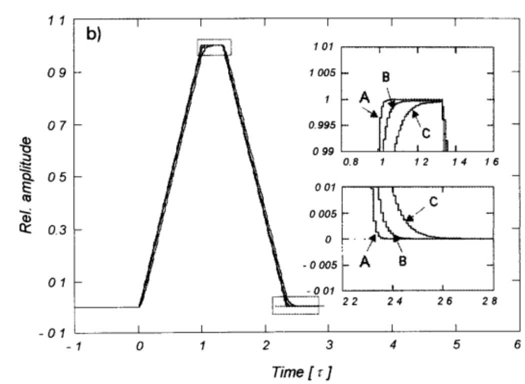
ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

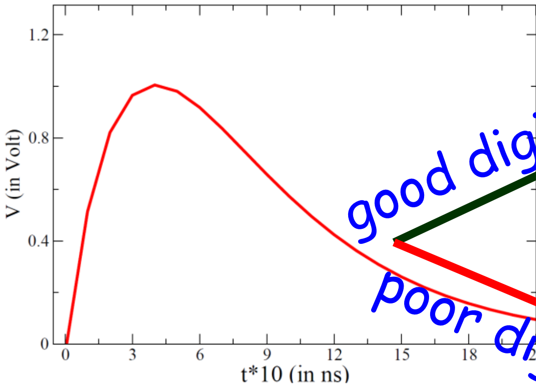
Digital techniques for real-time pulse shaping in radiation measurements

Valentin T. Jordanov [a,*], Glenn F. Knoll [b], Alan C. Huber [a], John A. Pantazis [a]
[a] *Amptek Inc., 6 De Angelo Dr., Bedford, MA 01730, USA*
[b] *The University of Michigan, Department of Nuclear Engineering, Ann Arbor, MI 48109, USA*



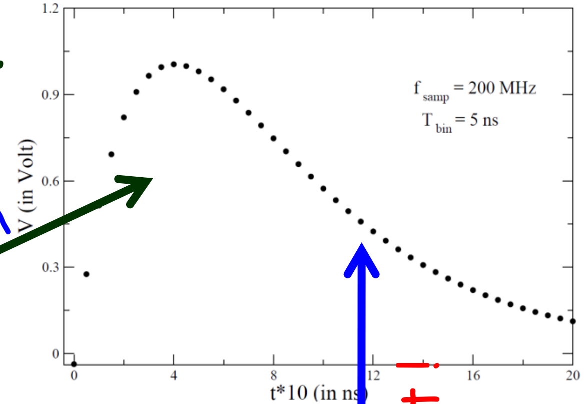


A Naive Look ....

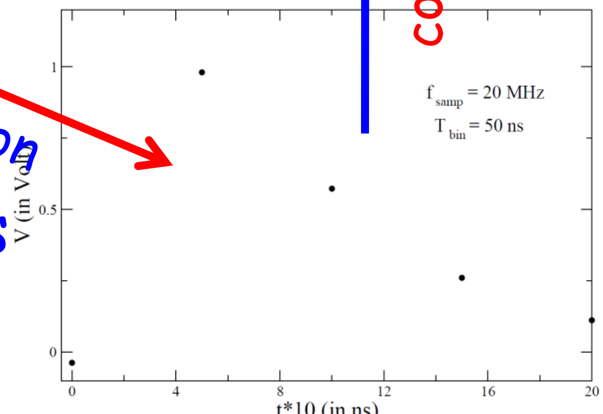


good digitization

poor digitization



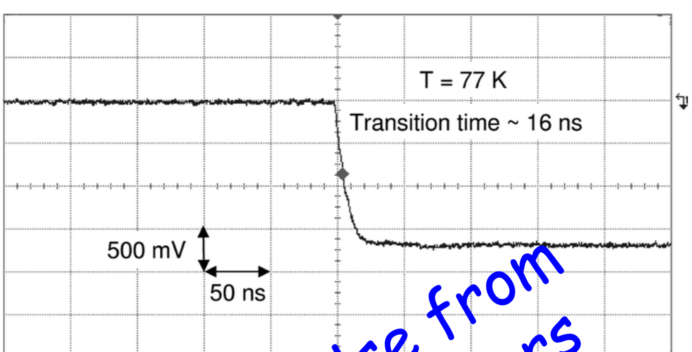
cost !



faster sampling using faster digitizer; faithful representation of the pulse

slow sampling; poor representation of the pulse

digitization: discreteness
("numberification" !!)

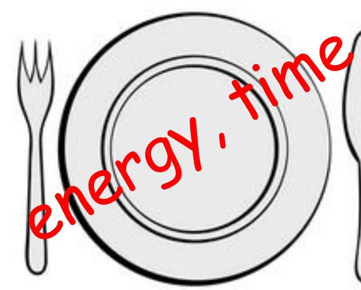


pulse from detectors

50, 125, 76, 800, 1000, 23......

numbers

recursive algorithms



energy, time

Data Format

List Mode
EVENT-BY-EVENT information recorded in data files

Remember
Event is the fulfillment of a user defined condition

For each event ->
which detectors have fired, what are the respective energies (channel numbers), time correlation info

Data files are STRUCTURED/ORGANIZED into EVENTS.
They are read event wise, for subsequent reduction and data analysis

Appropriate for multi-detector setups, multi-parameter acquisition and generally used in actual experiments

Measurements in Gamma-ray Spectroscopy

Gamma-ray energies
(calibration of the data)

Gamma-Gamma coincidence relationships
(from gamma-gamma matrix)

Gamma-ray multpolarities: dipole, quadrupole....
(angular distribution/correlation measurements)

Gamma-ray electromagnetic character: electric, magnetic..
(polarization measurements)

↓

Level Characteristics
Energies, Sequence, Spins, Parities
[Level lifetimes from Doppler effect on transition peaks]

Gamma-ray Spectroscopy Now

HPGe detectors with superior energy resolution for spectroscopy. Large arrays of detectors to optimize the efficiency.

Setup of one or different kind of detectors, depending on the physics being addressed

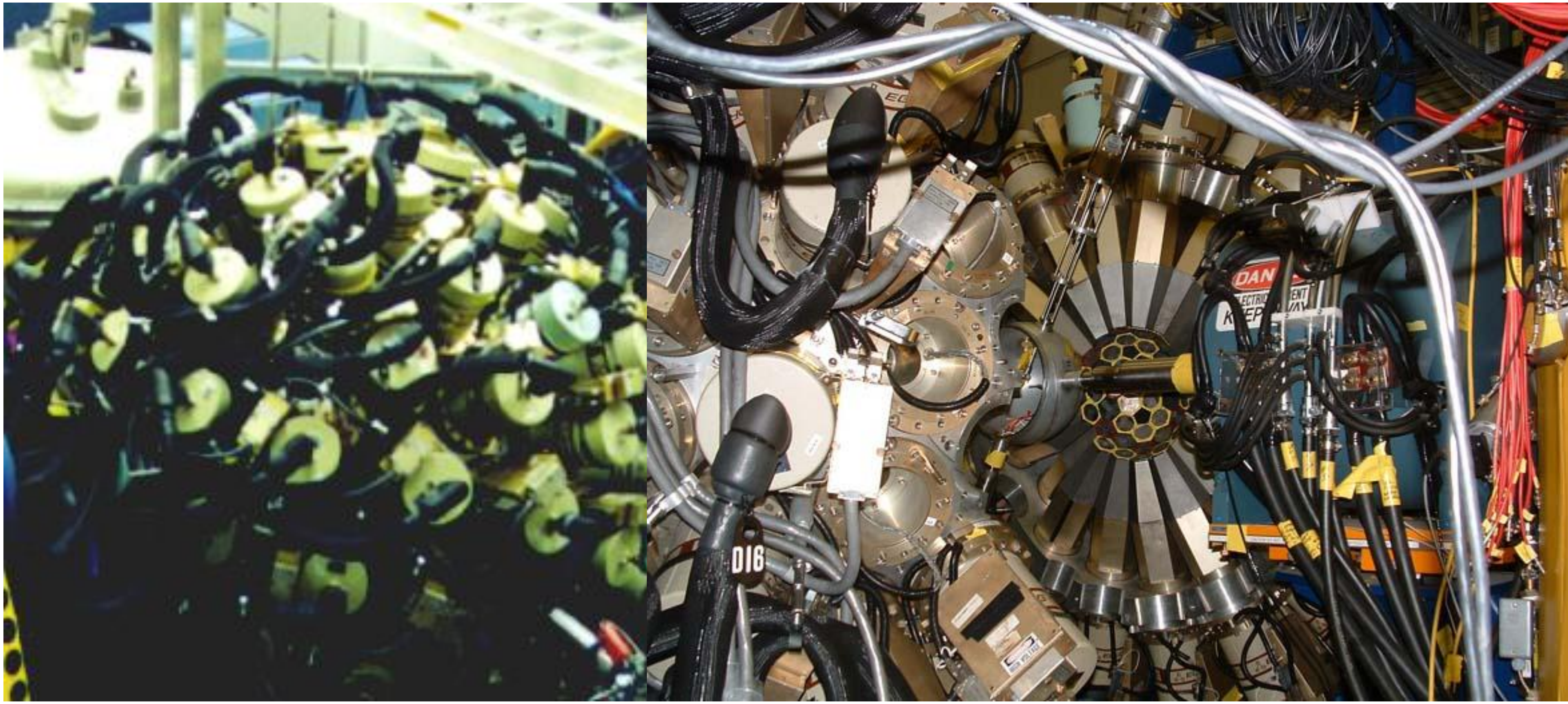
Efficient background reduction. Compton suppression using ACS.

Compact electronics, data acquisitions capable of handling more event rates.

Coincident measurements for unambiguous identification and assignments. (Typical in γ-ray detector array)

Advances in detector technology, pulse processing techniques. Advent of modern detectors.

GAMMASPHERE@ANL, USA



110 Compton Suppressed HPGe detectors +
Auxiliary Detectors (charged particles, neutrons, FMA)

Setup at Argonne Tandem Linac Accelerator System (ATLAS) @ Argonne National Laboratory (ANL)

Indian National Gamma Array (INGA)

National facility for gamma spectroscopy.

Operational since ~ 2000

An array of Compton Suppressed Clover detectors + available ancillary detection systems.

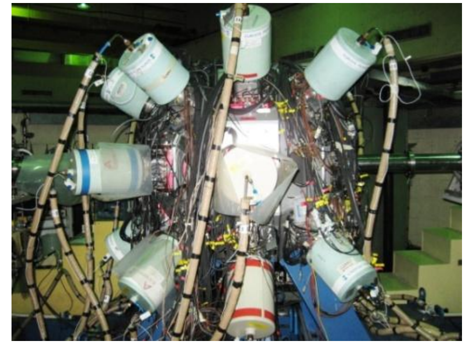
Resources from BARC, UGC-DAE CSR, SINP, IUAC, VECC and TIFR.

Setup at the three accelerator facilities in the country at IUAC, VECC and TIFR.

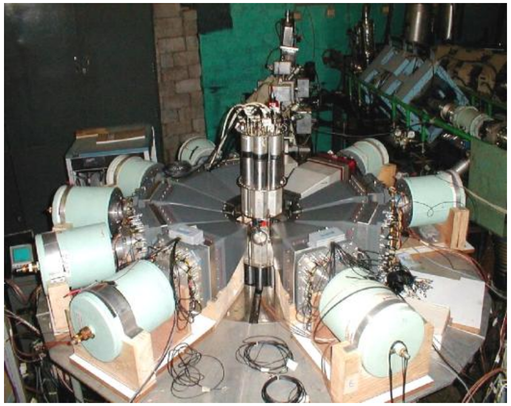
Experiments carried out by research groups from universities & institutes in the country & abroad.
150+ publications, 40+ Ph.Ds

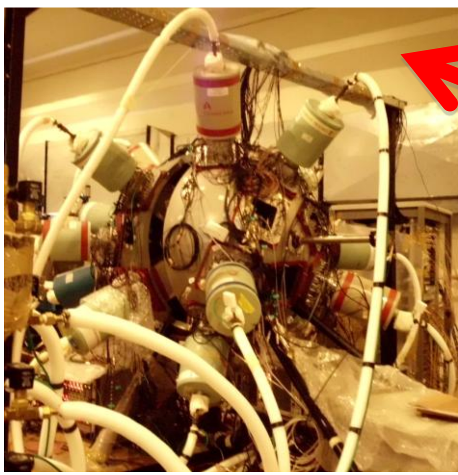
Partially Funded by DST (IR/S2/PF-03/2003/I, II, III)

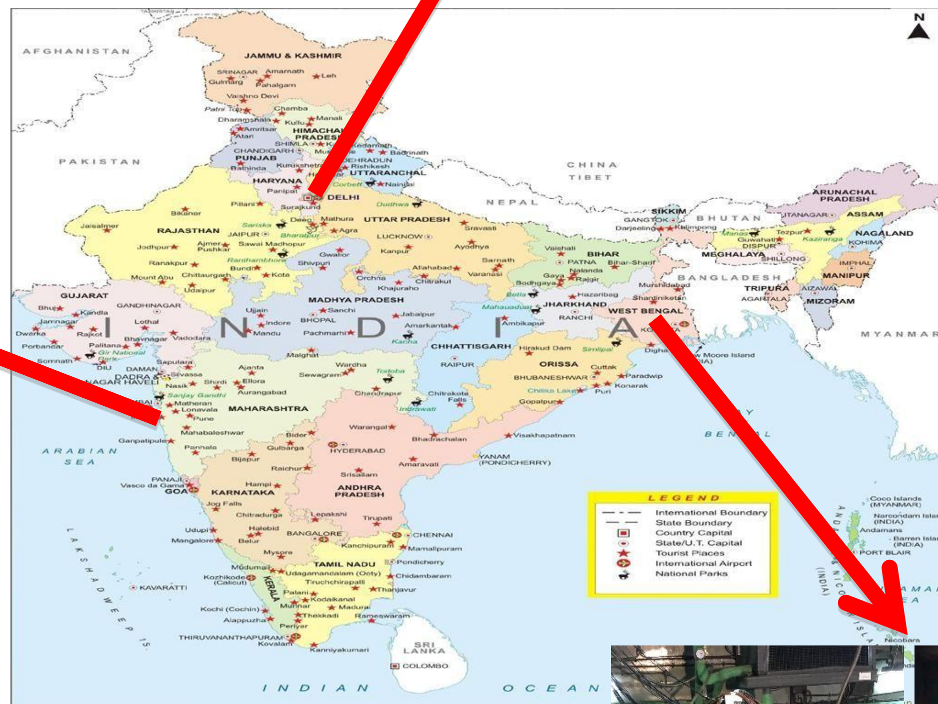
INGA Campaigns



IUAC (2002-04, 2007-09, 2016-)



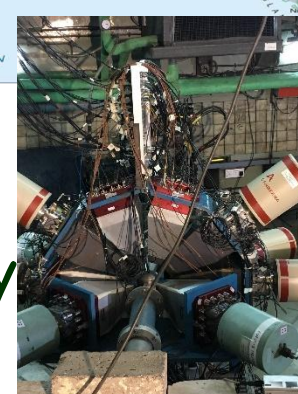


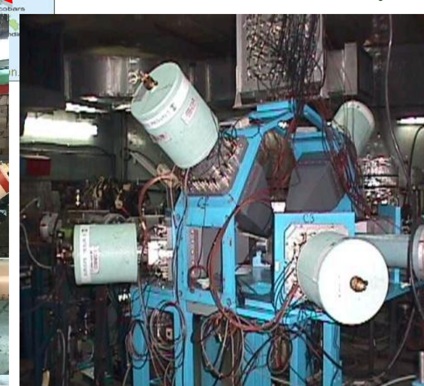


VECC (2004-06, 2017-21)

TIFR (2000-01, 2009-13)

35+ User Groups from within & outside the country





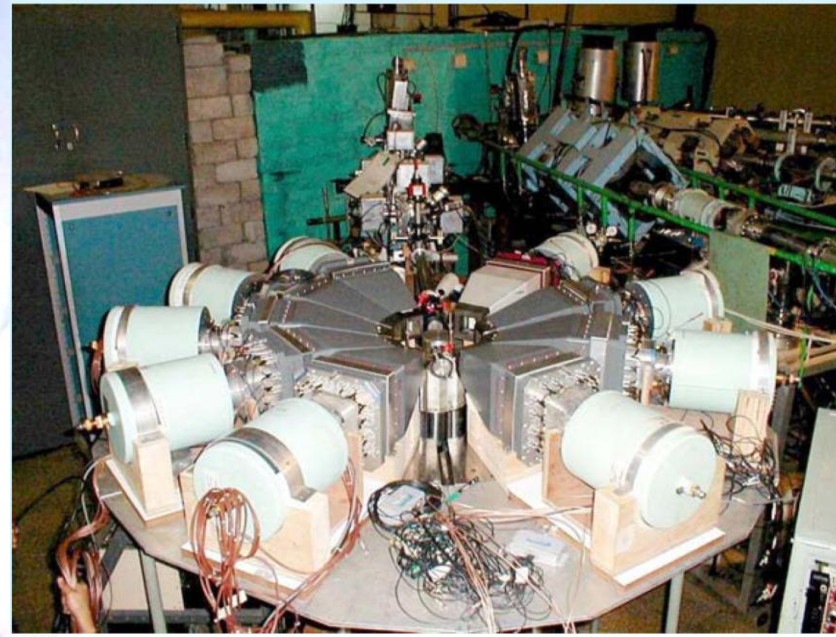
https://www.tifr.res.in/~nsg/INGAC.php

INGA at TIFR (2000-02)

Nine Compton suppressed Clover detectors

Commercial electronics

DAQ: LAMPS (BARC)



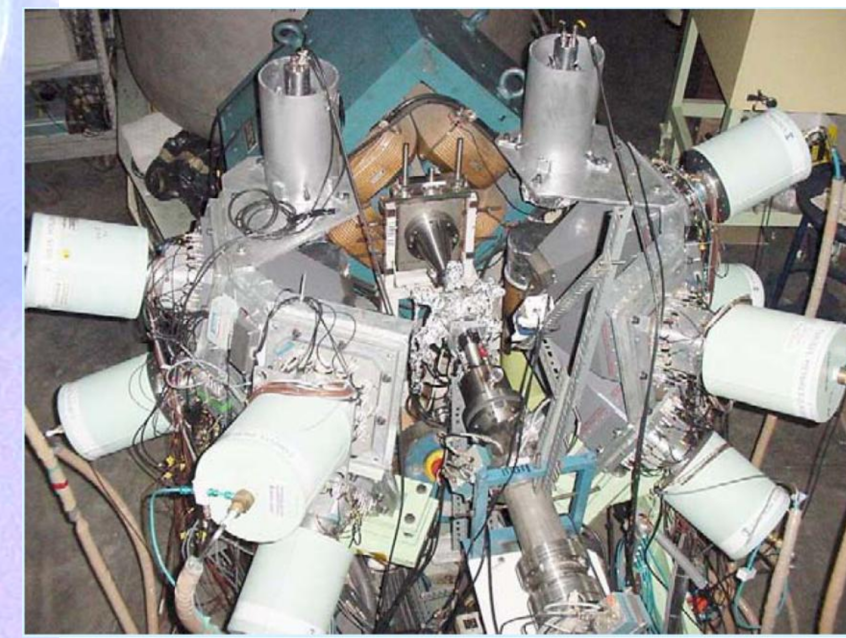
INGA at IUAC (2002-04)

Eight Compton suppressed Clover detectors +

Charged Particle, Neutron Detectors + Heavy Ion Reaction Analyzer (HIRA)

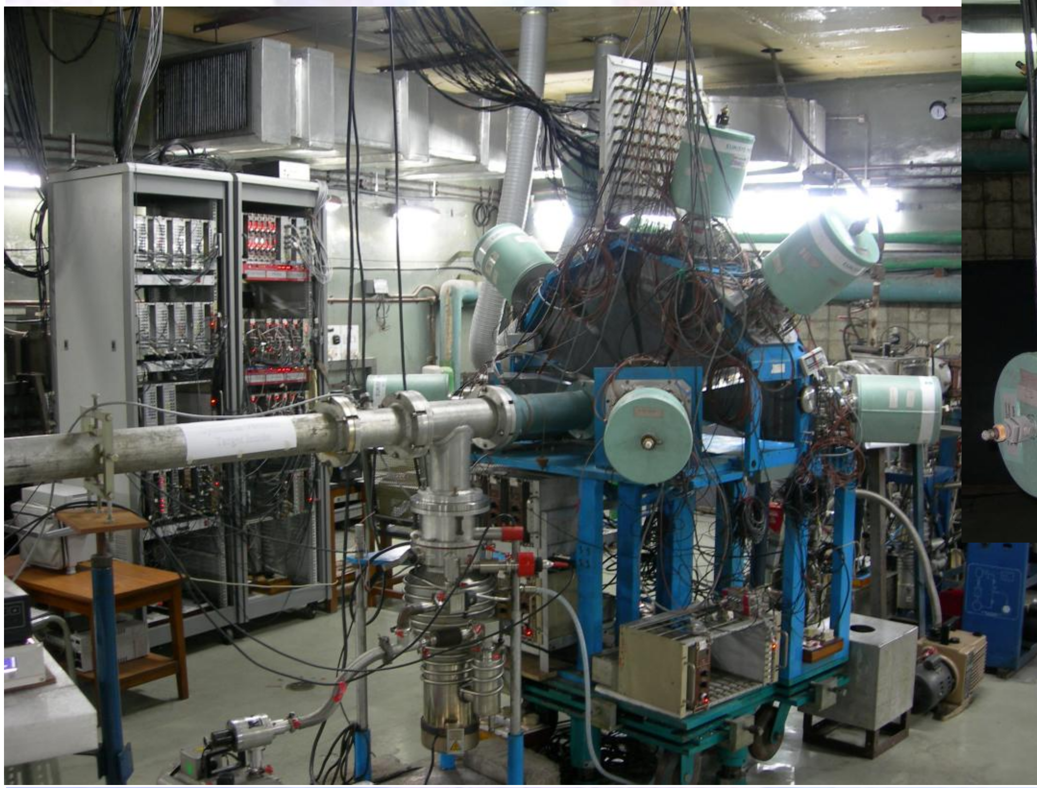
Commercial electronics

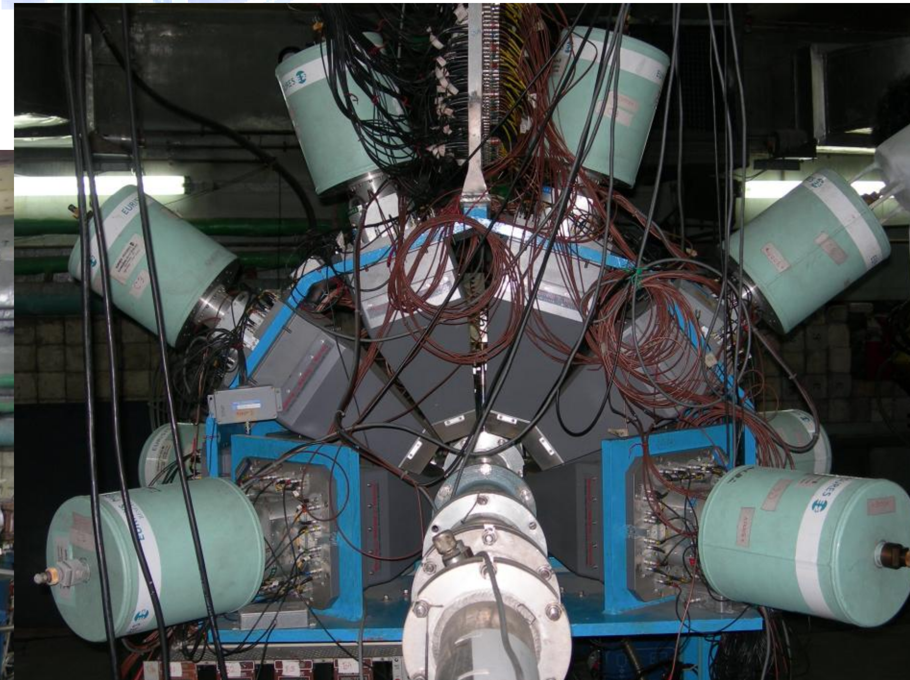
DAQ: CANDLE (IUAC)



INGA at VECC, Kolkata (2004-06)

8-10 Compton suppressed Clover Detectors



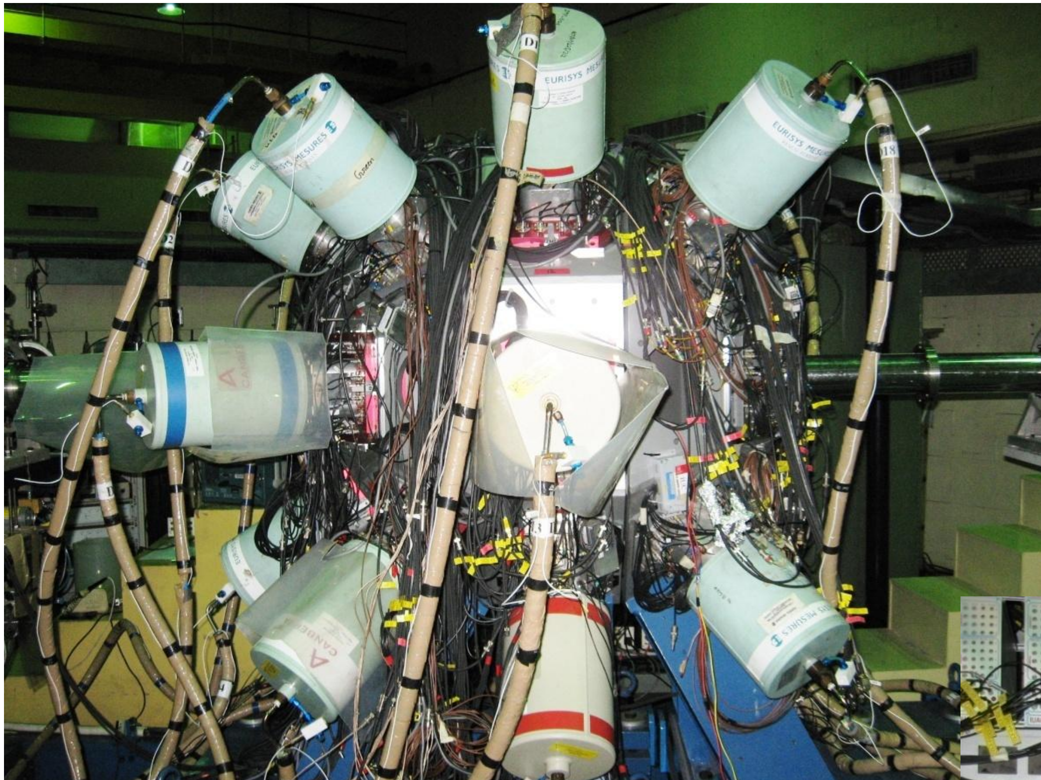


Setup at Cave-II of Room Temperature Cyclotron (RTC) @ VECC

FIRST Use of Clover electronics module designed and fabricated at IUAC

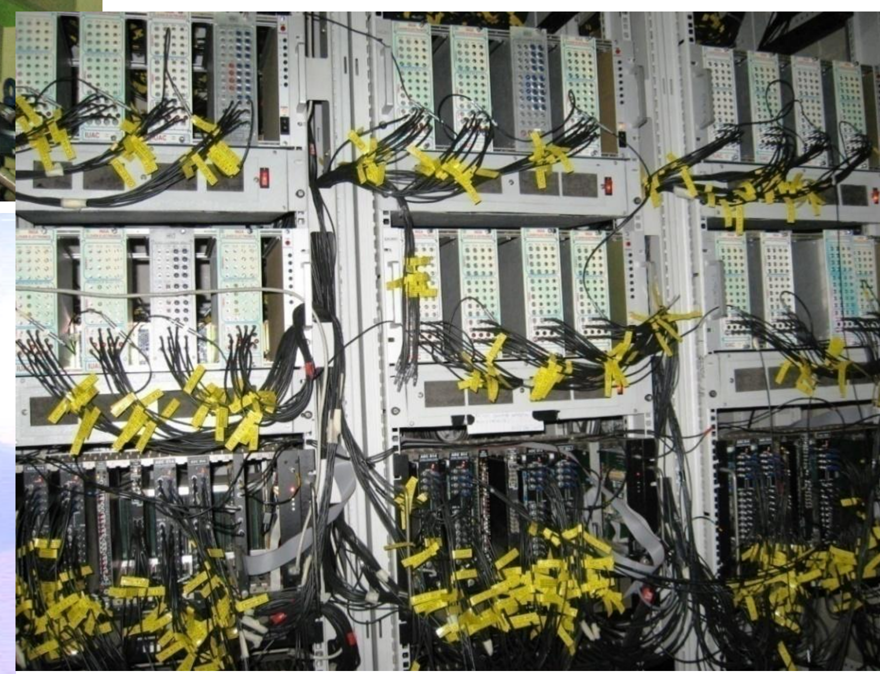
R. Raut et al. ,
Proc. DAE-BRNS Symp. Nucl. Phy. 47B, 578(2004).

INGA at IUAC, New Delhi (2007-09, 2016-)



Around 22 Compton suppressed Clover detectors.

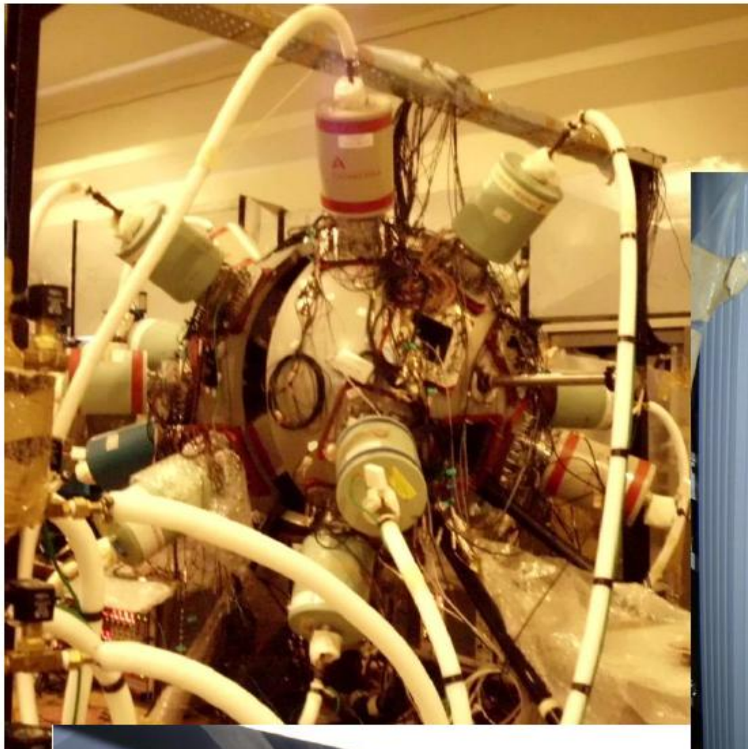
Full energy peak efficiency ~ 5% [@ 1 MeV]



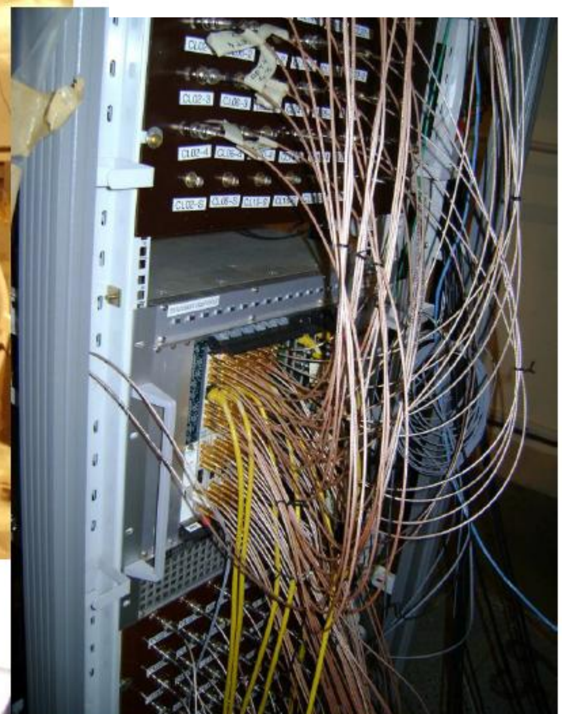
Compact electronics setup using the Clover modules designed and fabricated at IUAC

Muralithar et al. [NIM A 622, 281(2010)]

INGA at TIFR, Mumbai (2009-2013)



Around twenty Compton suppressed Clover detectors.



Digitizer (Pixie-16 XIA) based pulse processing electronics + data acquisition system.

The beginning of the DIGITIZER ERA in Indian Gamma-ray Spectroscopy Efforts

Palit et al. [NIM A 680, 90(2012)]

Digital INGA@VECC

December, 2017 to February, 2021

6-7 CS HPGe clovers -> clovers + LEPS -> more clovers & LEPS -> 12 clovers + $LaBr_3$ -> 11 clovers + LEPS ………

digital pulse processing & DAQ: PIXIE-16 digitizers (XIA LLC) + firmware conceptualized by NP Group @ UGC-DAE CSR, Kolkata Centre

CS detector multiplicity trigger (all detectors) -> optional inclusion of detectors; in situ calibration …….

Das et al. [NIM A 841, 17(2017)]

Physics with INGA

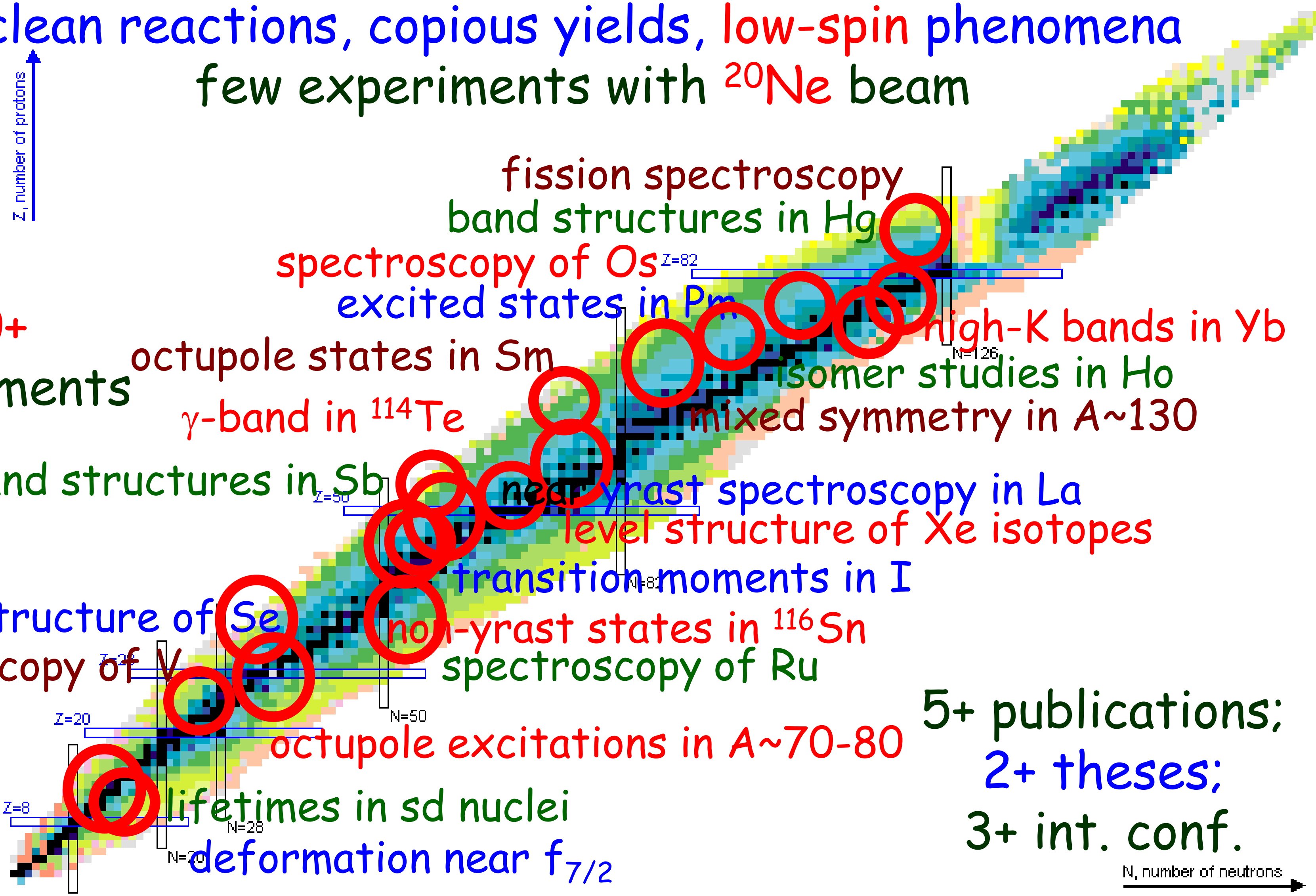
Example: VECC Campaign (2017-2021)

nuclear structure studies primarily with light-ion (α,p) beams

clean reactions, copious yields, low-spin phenomena

few experiments with ^{20}Ne beam

30+ experiments



5+ publications;

2+ theses;

3+ int. conf.

Physics with INGA: Highlights

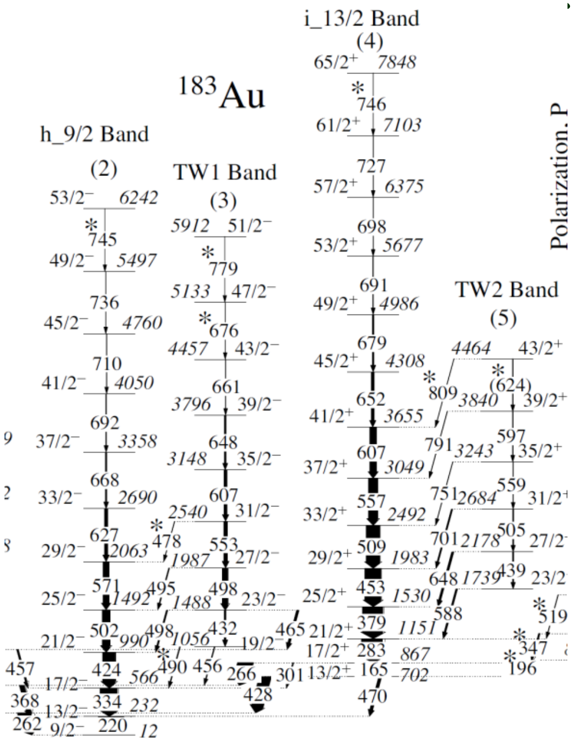
PHYSICAL REVIEW LETTERS 125, 132501 (2020)

INGA@VECC

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

S. Nandi,[1,2] G. Mukherjee,[1,2,†] Q. B. Chen,[3] S. Frauendorf,[4] R. Banik,[1,2,‡] Soumik Bhattacharya,[1,2] Shabir Dar,[1,2] S. Bhattacharyya,[1,2] C. Bhattacharya,[1,2] S. Chatterjee,[5] S. Das,[5] S. Samanta,[5] R. Raut,[5] S. S. Ghugre,[5] S. Rajbanshi,[6] Sajad Ali,[7] H. Pai,[8] Md. A. Asgar,[9] S. Das Gupta,[10] P. Chowdhury,[11] and A. Goswami[8,*]

^{169}Tm(^{20}Ne,6n)^{183}Au @ E_{lab} = 146 MeV



wobbling: triaxial nuclei

wobbling bands:
experimentally validated through ΔI = 1 E2 transitions
(identified based on measurement of multipolarity, polarization)
connecting them to the yrast bands

theoretical interpretation: PRM, HFA

Physics with INGA: Highlights

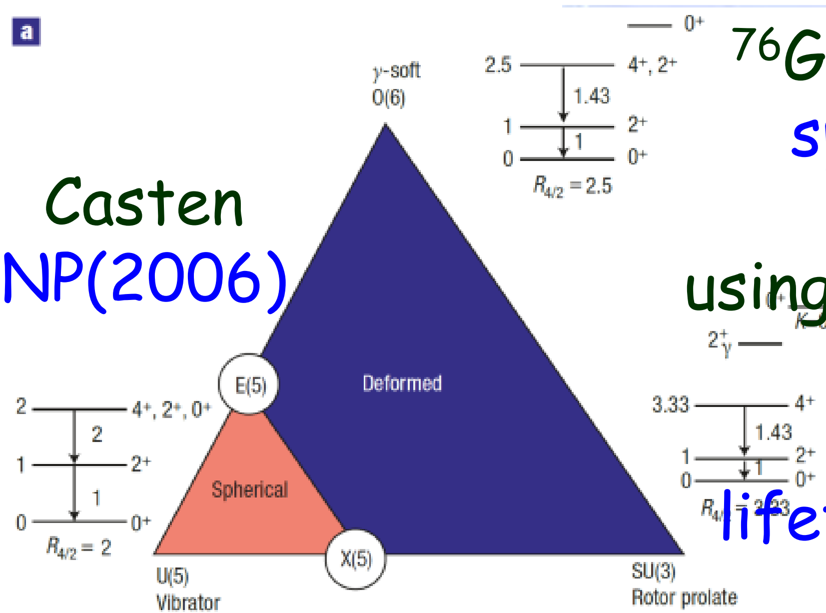
PHYSICAL REVIEW C **104**, L031302 (2021)

Letter

INGA@TIFR

Experimental evidence of exact E(5) symmetry in ^{82}Kr

S. Rajbanshi,[1,*] S. Bhattacharya,[2] R. Raut,[3,†] R. Palit,[4] Sajad Ali,[5] Rajkumar Santra,[6,7] H. Pai,[6]
F. S. Babra,[4] R. Banik,[7,8] S. Bhattacharyya,[7,9] P. Dey,[4] G. Mukherjee,[7,9] Md. S. R. Laskar,[4] S. Nandi,[7,9]
T. Trivedi,[2] S. S. Ghugre,[3] and A. Goswami[6]



Casten
NP(2006)

^{76}Ge(^{9}Be,3n)^{82}Kr @ E_{lab} ~ 31 MeV
spectroscopy & level lifetime measurements
using the Doppler Shift Attenuation Method (DSAM)

lifetime -> transition probabilities
[to indicate critical point]

theoretical interpretation: IBA model

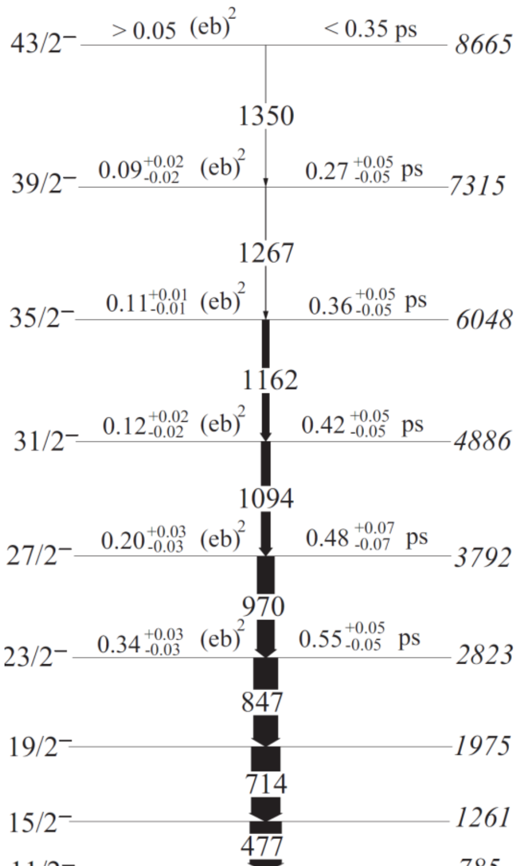
Physics with INGA: Highlights

PHYSICAL REVIEW C **103**, 024324 (2021)

INGA@IUAC

Evidence of antimagnetic rotational motion in ^{103}Pd

A. Sharma,[1,*] R. Raut,[2] S. Muralithar,[3] R. P. Singh,[3,†] S. S. Bhattacharjee,[3] S. Das,[2] S. Samanta,[2] S. S. Ghugre,[2] R. Palit,[4] S. Jehangir,[4] N. Rather,[5] G. H. Bhat,[6] J. A. Sheikh,[7] S. S. Tiwary,[8] Neelam,[9] P. V. Madhusudhana Rao,[10] U. Garg,[11] and S. K. Dhiman[1]

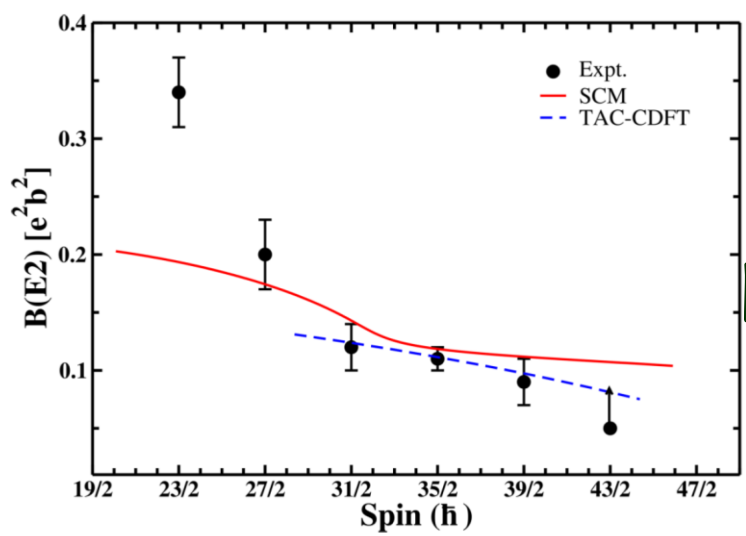


^{94}Zr(^{13}C,4n)^{103}Pd @ E_{lab} = 55 MeV

lifetime measurements using DSAM

lifetime -> B(E2) transition probabilities

decreasing B(E2) along the band: AMR



theory

TAC-CDFT, SCM [Jia et al. (2018)], TRS

Physics with INGA: Highlights

Transverse Wobbling in ^{135}Pr

J. T. Matta, U. Garg, W. Li, S. Frauendorf, A. D. Ayangeakaa,[†] D. Patel, and K. W. Schlax
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA

R. Palit, S. Saha, J. Sethi, and T. Trivedi[‡]
Tata Institute of Fundamental Research, Mumbai 400 005, India

S. S. Ghugre, R. Raut, and A. K. Sinha
UGC-DAE Consortium for Scientific Research, Kolkata 700 098, India

R. V. F. Janssens, S. Zhu, M. P. Carpenter, T. Lauritsen, and D. Seweryniak
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

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Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA and Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

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C. M. Petrache
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S. Mukhopadhyay
Bhabha Atomic Research Centre, Mumbai 400 085, India

D. Vijaya Lakshmi, M. Kumar Raju,[§] and P. V. Madhusudhana Rao
Department of Nuclear Physics, Andhra University, Visakhapatnam 530 003, India

S. K. Tandel
UM-DAE Centre for Excellence in Basic Sciences, Mumbai 400 098, India

S. Ray[¶]
Saha Institute of Nuclear Physics, Kolkata 700 064, India

F. Dönau[*]
Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany

GAMMASPHERE + INGA@TIFR
(for polarization measurements)

Next is What ?

Gamma-ray Tracking

AGATA (Europe) &
GRETINA (USA):
36-segmented HPGe

spatial coordinates & deposited energy of EACH interaction
is recorded to reconstruct
the scattering path
to decide full/partial energy absorption

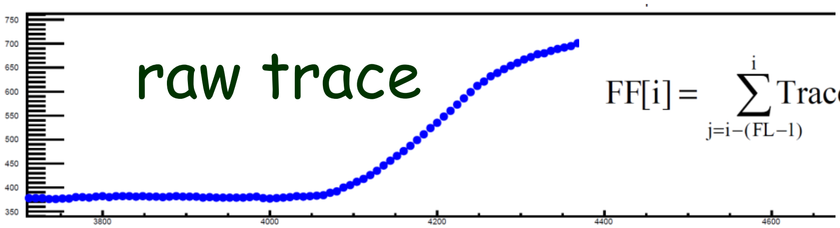
NIM A (2012,2017)

Our Endeavors towards Gamma-ray Tracking

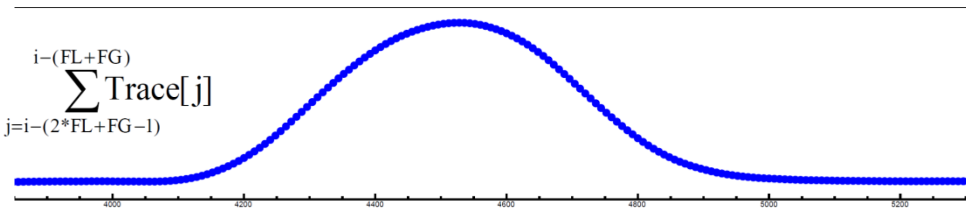
trace acquisition & analysis

merit of digital DAQ: acquisition of trace for detector pulse

understanding/optimization of pulse processing algorithms



$$FF[i] = \sum_{j=i-(FL-1)}^{i} Trace[j] - \sum_{j=i-(2*FL+FG-1)}^{i-(FL+FG)} Trace[j]$$

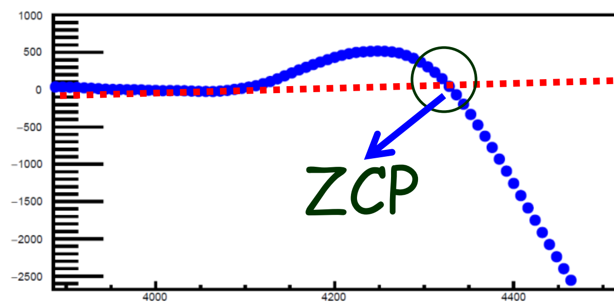


example usage of trace analysis

$$CFD[i+D] = FF[i+D]*(1-w/8) - FF[i]$$

$$f = \frac{CFDout1}{(CFDout1 + CFDout2)}$$

before ZCP   after ZCP



compare actual & calculated cfd

```
Modified FF Threshold = 520
Pulse begins at Trace Point # 518
I have hit a ZCP: Trace Point # = 541 Trace Value = 1037 FF Value = 5204.000000 CFDOut1 = 47.000000 CFDOut2 = -20.000000

TRACE REPORT

SHOWING TRACE # 24999 THAT CORRESPONDS TO SLOT # 3 CHANNEL # 4

CALCULATED CFD VALUE = 11493.253731
RECORDED CFD VALUE = 11493
FORCED TRIGGER STATUS = 0
PILEUP STATUS = 0

Do you want to read another trace ?
```

ROOT based code developed by NP Group @ UGC-DAE CSR, KC

Our Endeavors towards Gamma-ray Tracking

test setups

setup: 16-segmented HPGe clover (@VECC)

Digital DAQ (UGC-DAE CSR, KC): acquire list mode data with trace (of individual segments) acquisition enabled

Plan: to correlate detection of a particular (full) energy in a crystal with the segment(s) of detection

Collaborator: G. Mukherjee et al. (VECC)

Summary

the miles this far & the road ahead

Compton suppressed HPGe based detectors, single crystal & composites (clover), are fundamental in gamma-ray spectroscopy

Detector arrays operational in the country & around the globe
GAMMASPHERE, INGA
Fascinating physics outputs in the study of excited nuclei

Continuing developments in pulse processing & data acquisition
Use of digitizers -> more data

Gamma-ray tracking is the state-of-the-art
AGATA, GRETINA operational
initial efforts being undertaken in the country

lookup

ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Progress in Particle and Nuclear Physics 60 (2008) 283–337

Progress in Particle and Nuclear Physics

www.elsevier.com/locate/ppnp

Review

From Ge(Li) detectors to gamma-ray tracking arrays – 50 years of gamma spectroscopy with germanium detectors

J. Eberth[a,*], J. Simpson[b]

[a] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[b] *STFC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*

Gratitude

Work in Progress !