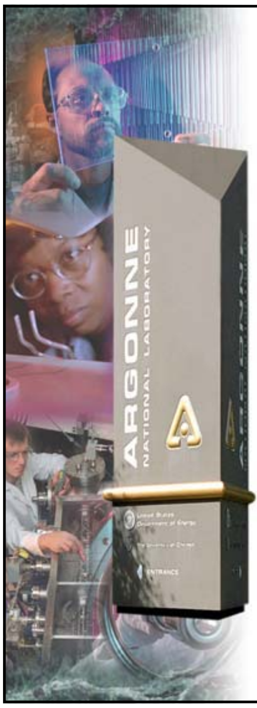

Experimental Nuclear Structure Part I

Filip G. Kondev
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Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation", Trieste, Italy

April 4-15th, 2005

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline

I) Lecture I: Experimental nuclear structure physics

- **reactions used to populate excited nuclear states**
- **techniques used to measure the lifetime of a nuclear state**
  - ***Coulomb excitation, electronic, specific activity, indirect***
- **techniques used to deduce J^{π}**
  - ***ICC, angular distributions, DCO ratios etc.***

II) Lecture II: Contemporary Nuclear Structure Physics at the Extreme

- **spectroscopy of nuclear K-Isomers**
- **physics with large γ–ray arrays**
- **gamma-ray tracking – the future of the γ–ray spectroscopy**

Have attempted to avoid formulas and jargon, and material covered by other lecturers – will give many examples

Please feel free to interrupt at any time!

Some Useful Books

"Handbook of nuclear spectroscopy", J. Kantele,1995

"Radiation detection and measurements", G.F. Knoll, 1989

"In-beam gamma-ray spectroscopy", H. Morinaga and T. Yamazaki, 1976

"Gamma-ray and electron spectroscopy in Nuclear Physics", H. Ejiri and M.J.A. de Voigt, 1989

"Techniques in Nuclear Structure Physics", J.B.A. England, 1964

"Techniques for Nuclear and Particle Physics Experiments", W.R. Leo, 1987

"Nuclear Spectroscopy and Reactions", Ed. J. Cerny, Vol. A-C

"Alpha-, Beta- and Gamma-ray Spectroscopy", Ed. K. Siegbahn, 1965

"The Electromagnetic Interaction in Nuclear Spectroscopy", Ed. W.D. Hamilton, 1975

Plenty of information on the Web

Input from many colleagues

C.J. Lister and I. Ahmad, Argonne National Laboratory, USA

M.A. Riley, Florida State University, USA

I.Y. Lee, Lawrence Berkeley National Laboratory, USA

D. Radford, Oak Ridge National Laboratory, USA

A. Heinz, Yale University, USA

C. Svensson, University of Guelph, Canada

G.D. Dracoulis and T. Kibedi, Australian National University, Australia

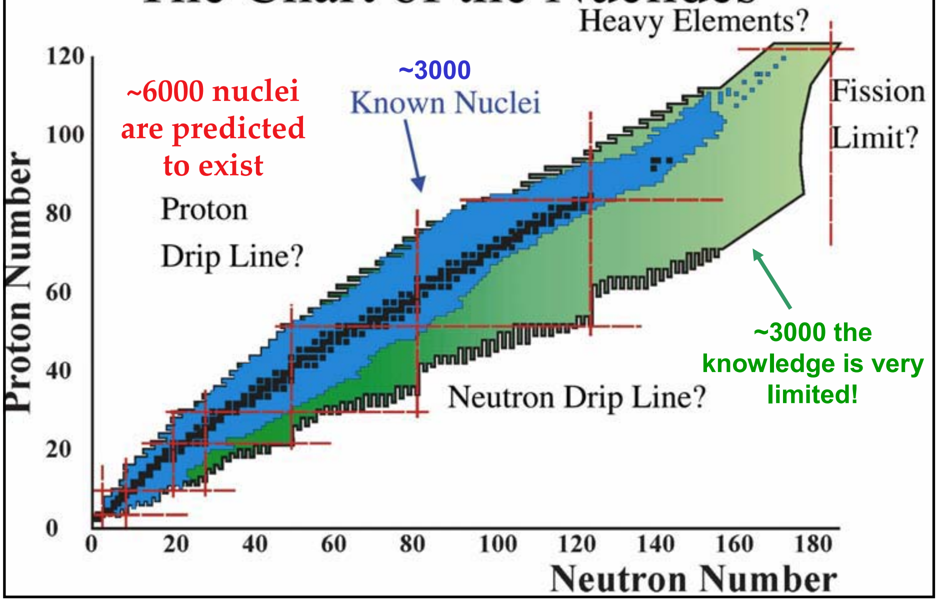
J. Simpson, Daresbury Laboratory, UK

E. Paul, University of Liverpool, UK

P. Reagan, University of Surrey, UK

and many others …

The Chart of the Nuclides



Introduction

- The nucleus is one of nature's most interesting quantal few-body systems
- It brings together many types of behaviour, almost all of which are found in other systems
- The major elementary excitations in nuclei can be associated with single-particle and collective modes.
- While these modes can exist in isolation, it is the interaction between them that gives nuclear spectroscopy its rich diversity

So to summarize …

NUCLEAR PHYSICS IS A BIG CHALLENGE

(because of complicated forces, energy scale, and sizes involved)

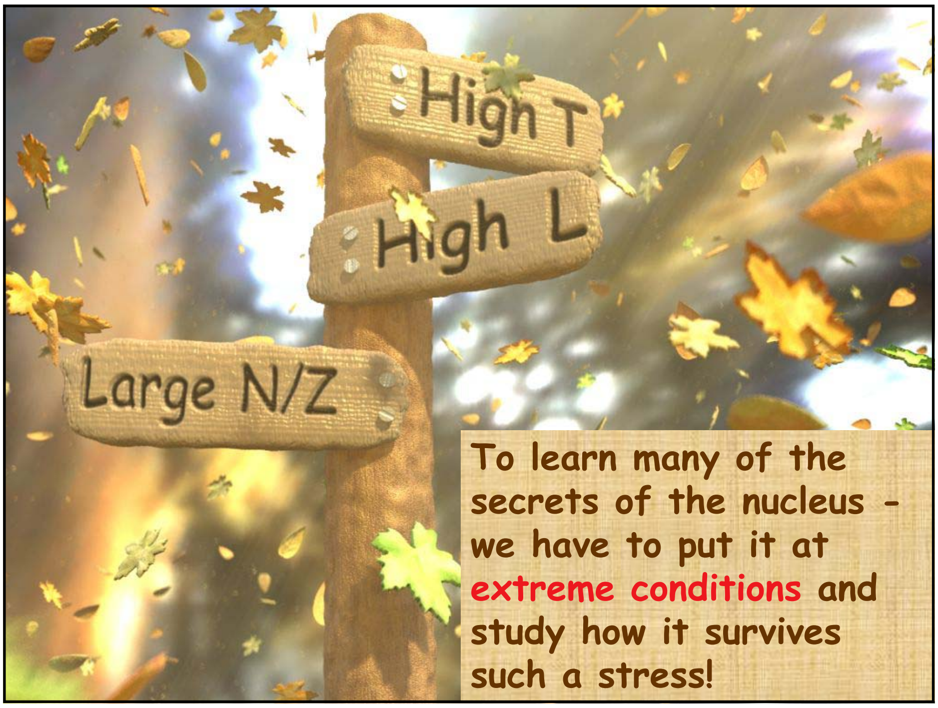
The challenge of understanding how nucleon-nucleon interactions build to create the mean field or how single-particle motions build collective effects like pairing, vibrations and shapes

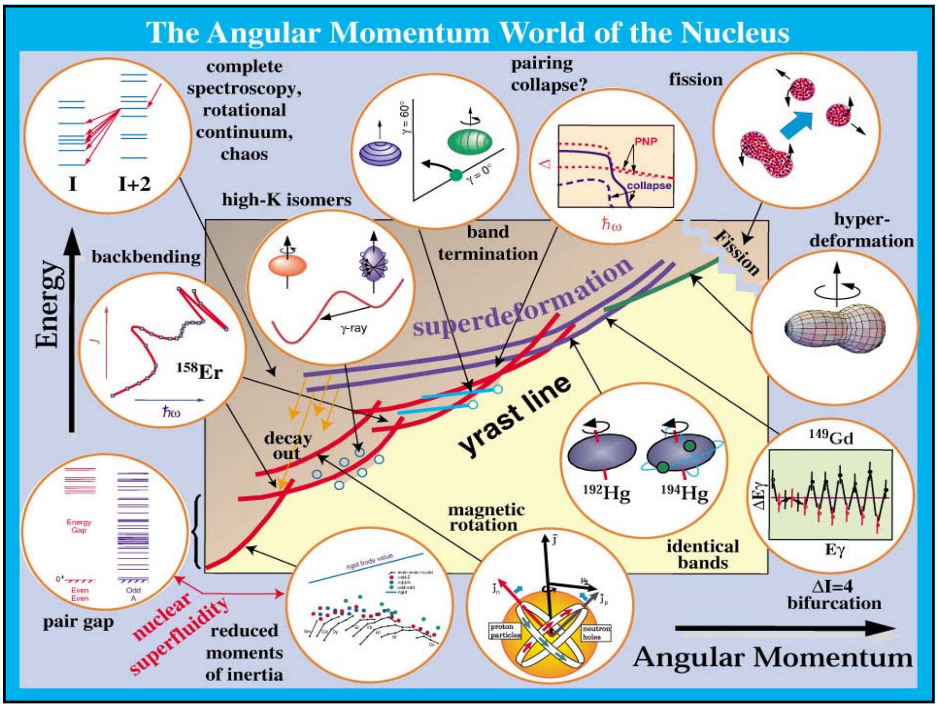
NUCLEAR PHYSICS IS IMPORTANT

(intellectually, astrophysics, energy production, and security)

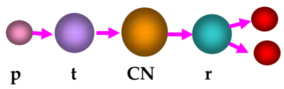
THIS IS A GREAT TIME IN NUCLEAR PHYSICS

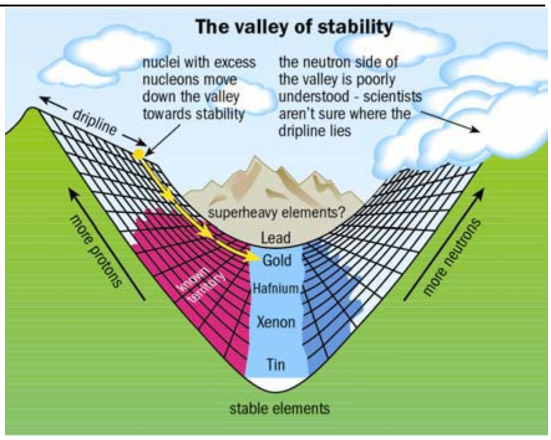
(with new facilities just around the corner we have a chance to make major contributions to the knowledge - with advances in theory we have a great chance to understand it all - by compiling & evaluating data we have a chance to support various applications and to preserve the knowledge for future generations!)





Nuclear Reactions – very schematic!



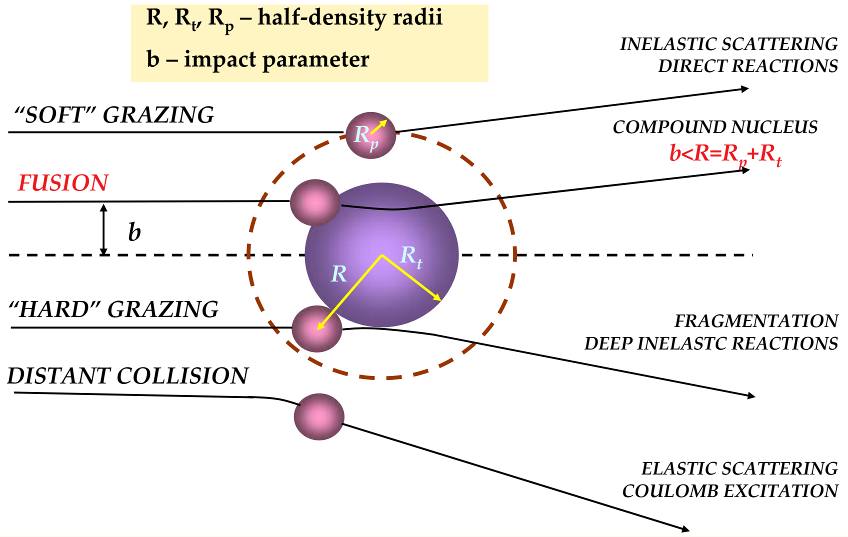


a multi-step process

- ❑ Gamma-ray induced
  - no Coulomb barrier
- ❑ Neutron induced
  - low-spin states
  - no Coulomb barrier
- ❑ Light charged particles, e.g. p, d, t, α
  - Coulomb barrier
  - low-spin states

- ❑ Heavy Ions (1970 - ????)
  - ➢ high-spin phenomena
  - ➢ nuclei away from the line of stability

Reactions with Heavy Ions – Classical Picture



Heavy Ions at the Coulomb barrier

Many properties of the collision can be quite well estimated by just using conservation of momentum and energy.

$$E_{cm} = M_t / (M_b + M_t) E_{lab}$$

Energy scale on which fusion starts is determined by Coulomb barrier, V_{cb}

$$V_{cb} = (4\pi\varepsilon)^{-1} Z_b Z_t e^2 / R = 1.44 Z_b Z_t / 1.16 [(A_b^{1/3}+A_t^{1/3}) + 2] \text{ MeV}$$

$$L_{max} = 0.22 R [\mu (E_{cm} - V_{cb})]^{1/2} \quad \hbar$$

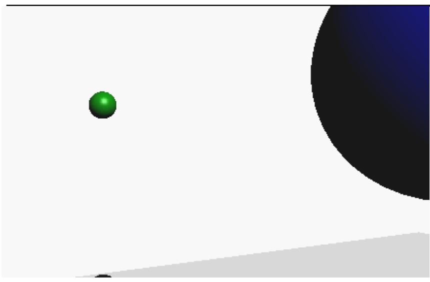
Excitation energy is usually lowered by Q-value and K.E. of evaporated particles

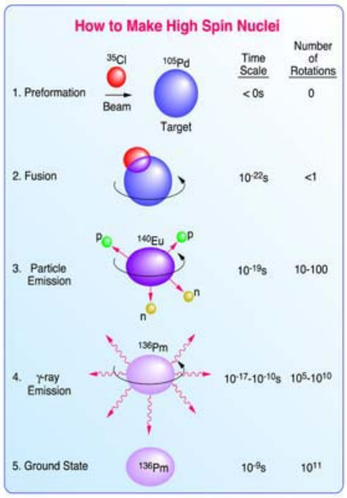
$$E^*_{residue} = E_{cm} + Q - K.E.$$

Velocity of center-of-mass frame, which is ~ velocity of fused residues

$$\beta_r^2 = 2 M_b c^2 E_{lab} / [(M_b + M_t) c^2]^2$$

HI Fusion-Evaporation Reactions





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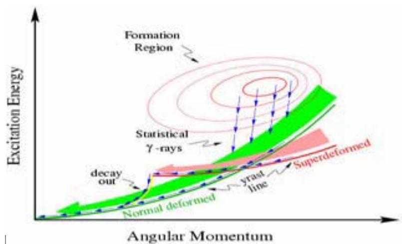
Decay of the Compound Nucleus

❑ In a typical HI fusion-evaporation reaction the final nucleus is often left with L~60-80 hbar and E_x~30-50 MeV

❑ The excited nucleus cools off by emitting γ–rays - their typical number is quite large, usually 30-40 and the average energy is ~1-2 MeV – it is not a trivial task to detect all of them - the big advantage came with the large γ–ray arrays



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Channel Selection for γ–ray spectroscopy

Detection of Light Charged Particles (α,p,n)

PLUS Efficient, flexible, powerful.....inexpensive.

MINUS Count-rate limited, Contaminant (Carbon etc, isotopic impurities) makes absolute identification of new nuclei difficult.

CROSS SECTION LOWER LIMIT ~100 μb that is, ~10^{-4}

Detection of Residues in Vacuum Mass Separator

PLUS True M/q, even true M measurement. With suitable focal plane detector can be ULTRA sensitive. Suppresses contaminants.

MINUS Low Efficiency

CROSS SECTION LOWER LIMIT ~100 nb that is ~10^{-7}

Detection of Residues in Gas Filled Separator

Improves efficiency of vacuum separators, at cost of mass information and clenliness. In some cases (heavy nuclei) focal plane counters clean up the data for good sensitivity.

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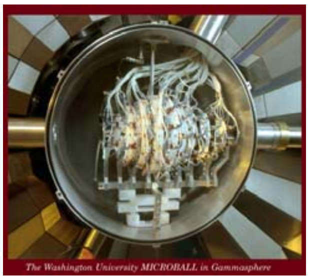
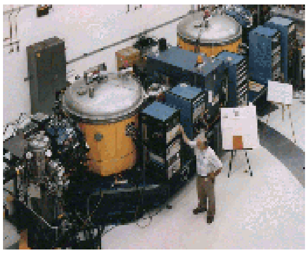
Some Channel Selection Detectors



Argonne FMA

USA



Light charged-particle detector

Microball – 96 CsI with photo diodes

USA

Jyvaskyla

RITU

Europe

16

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Calculate Reaction Rates

Reaction Yield/sec. $Y = N_b\, N_t\, \sigma$

$N_b = i_b / e\, q$

with i_b = electric current in amps, q = charge state, $e = 1.6\ 10^{-19}$ c

$N_t = [N_a / A]\, \rho x$

with N_a = Avagadros #, A = Mass # of tgt, ρ = density in g/cc, x = thickness (cm).

σ= Cross Section in cm^2 .... note 1 barn is 10^{-24} cm

Accumulated data: D = Y x TIME x Efficiency

Typical "far from stability" near barrier experiment may have:

i_b = 100 nA, q=10, A=100, $\rho x = 10^{-3}$ & σ=1 barn - produces $3\text{x}10^5$ reactions/sec

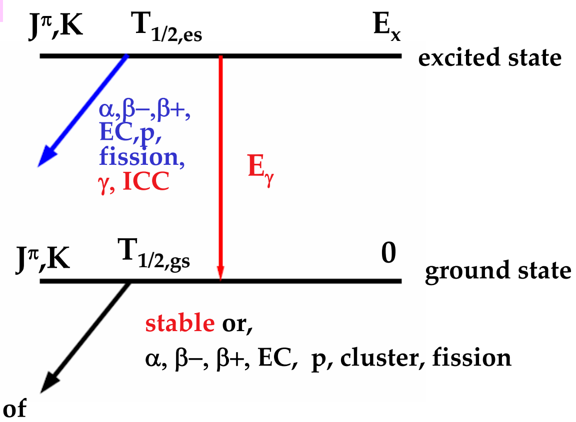
BUT

If partial cross section is 100 nb and efficiency is 10%...... rate is 10 /hour, 10 pb gives ~ 1 every 10 weeks!!!.....the present situation for producing the heavies elements.

The basic knowledge

What we want to know

- **Excitation energy**
- **Quantum numbers and their projections**
- **Lifetime**
- **Branching ratios**



How

- **By measuring properties of signature radiations**

What is Stable?

A surprisingly difficult question with a somewhat arbitrary answer!
CAN'T Decay to something else, BUT

CAN'T Decay is a Philosophical Issue

- Violation of some quantity which **we believe** is conserved such as Energy, Spin, Parity, Charge, Baryon or Lepton number, etc.

DOESN'T Decay is an Experimental Issue that backs up the beliefs

Specific Activity: $A = dN/dt = \lambda N$

Activity of 1 mole of material (6.02×10^{23} atoms) with $T_{1/2} = 10^9$ y ($\lambda = 2.2 \times 10^{-17}$ s) is ~0.4 mCi (1 Ci $= 3.7 \times 10^{10}$ dps) (or 13 MBq) .... a blazing source, so it is quite easy to set VERY long limits on stability.

Current limit on proton half-life, based on just counting a tank of water is $T_{1/2} > 1.5 \times 10^{25}$ yr.

Stable Nuclei: Segre's Chart

~ 280 Nuclei have Half-lives $>10^6$ years

So are (quite) stable against

Decay of their constituents (p,n,e)

Weak Decay (β^+ β^- and E.C.)

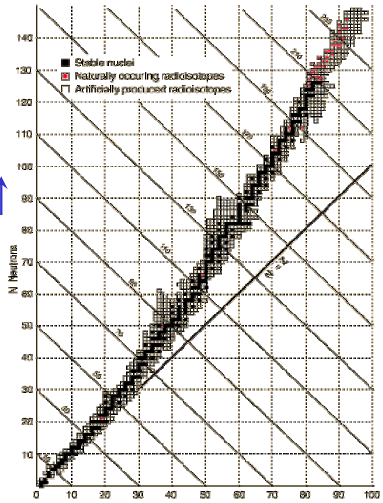
α,p,n decays

More complex cluster emission

Fission

(Mostly because of energy conservation)

N ↑



Atomic Number, Z →

Mean Lifetime

$$f_{decay}(t) = \frac{Ae^{-\lambda t}}{\int_0^\infty Ae^{-\lambda t}dt} = \lambda e^{-\lambda t}$$

Probability for decay of a nuclear state (normalized distribution function); λ – decay constant

$$P_n(t) = \int_0^t \lambda e^{-\lambda t'}dt'$$

Probability that a nucleus will decay within time *t*

$$1 - P_n(t) = 1 - \int_0^t \lambda e^{-\lambda t'}dt' = e^{-\lambda t}$$

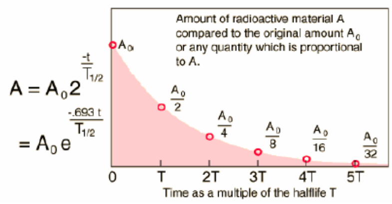
Probability that a nucleus will remain at time *t*

$$<t> = \tau = \int_0^\infty t e^{-\lambda t}dt = \frac{1}{\lambda}$$

The average survival time (mean lifetime - τ) is then the mean value of this probability

Half-life & Decay Width

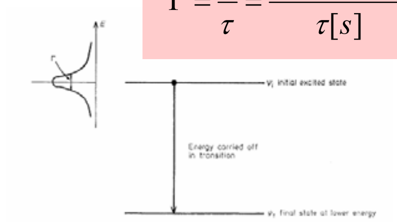
$T_{1/2}$: the time required for half the atoms in a radioactive substance to disintegrate



relation between $\tau, T_{1/2}$ and λ $\tau = \frac{T_{1/2}}{\ln 2} = \frac{1}{\lambda}$

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.58\times10^{-16}}{\tau[s]} \text{ [eV]}$$

$$\Gamma \propto |<\psi_1 | M | \psi_2>|^2$$



Determine the matrix element describing the mode of decay between the initial and final state

log ft values

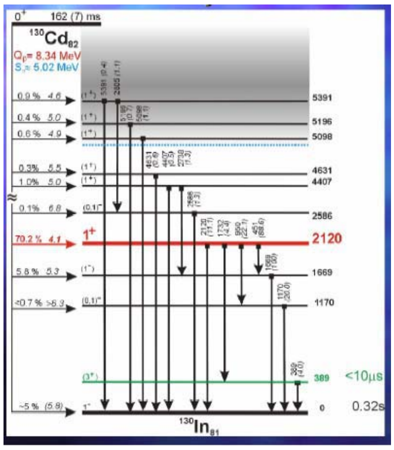
$$\log ft = \log f + \log t$$

$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}}{BR_i}$ partial half-life of a given β− (β+,EC) decay branch

$f \equiv f_\beta \equiv f_n, n = 0,1,2\ldots$

statistical rate function (phase-space factor): the energy & nuclear structure dependences of the decay transition

Decay Mode	Type	**log *ft***
β–	allowed	$\log f_0^-$
β–	1st-forb	$\log f_0^- + \log(f_1^- / f_0^-)$
EC+β+	allowed	$\log(f_0^{EC} + f_0^+)$



$f_0^-, f_1^-, etc.$ N.B. Gove and M. Martin, Nuclear Data Tables 10 (1971) 205

Hindrance Factor in α–decay

$$|I_i - I_f| \leq L \leq |I_i + I_f|$$

$$\pi_i \pi_f = (-1)^L$$

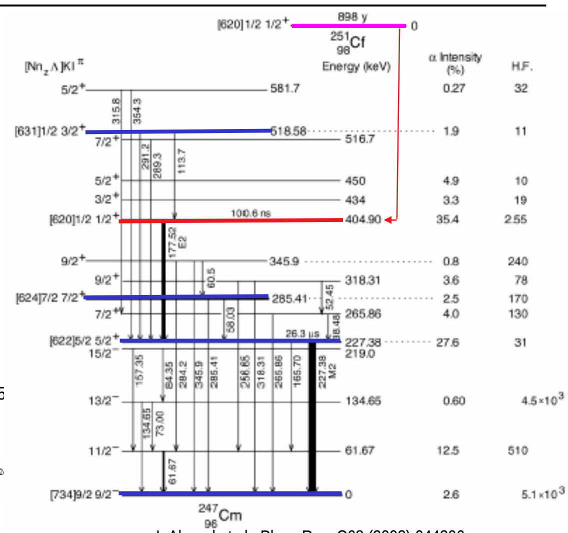
Strong dependence on L

L=0 - unhindered decay (fast)

$$HF_i = \frac{T_{1/2}^{Exp}(\alpha_i)}{T_{1/2}^{Theory}} = \frac{T_{1/2}^{Exp} / BR_i}{T_{1/2}^{Theory}}$$

$T_{1/2}^{Theory}$ M.A. Preston, Phys. Rev. 71 (1947) 865

$$t_{1/2}^{\alpha} = \ln 2 \frac{r_0}{2v} \frac{\mu^2(H_i^2+K_i^2)+\tan^2\alpha_0(C_i^2+S_i^2)+2\mu\tan\alpha_0(C_iK_i - S_iH_i)}{\mu^2\tan\alpha_0(H_iC_i+K_iS_i)Q_i} e^{+2\ldots}$$



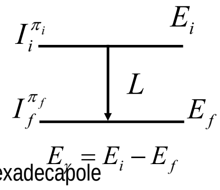
I. Ahmad et al., Phys. Rev. C68 (2003) 044306

γ–ray decay

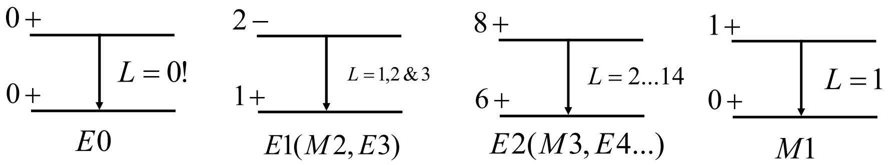
$$|I_i - I_f| \le L \le |I_i + I_f|$$

$$\Delta\pi(EL) = (-1)^L \qquad \Delta\pi(ML) = (-1)^{L+1}$$

electric multipole — magnetic multipole



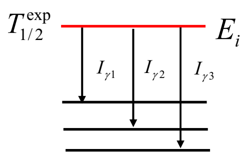
dipole	quadrupole	octupole	hexadecapole	
E1:L=1,yes	E2:L=2,no	E3:L=3,yes	E4:L=4,no	E5:L=5,yes
M1:L=1,no	M2:L=2,yes	M3:L=3,no	M4:L=4,yes	M5:L=5,no



Partial lifetime & Transition Probability

$$T_{1/2}^{\gamma} = T_{1/2}^{\exp} \times \frac{\sum I_{\gamma_i} \times (1+\alpha_{Ti})}{I_\gamma}$$

partial half-life



$$P_\gamma(XL : I_i \to I_f) = \frac{\ln 2}{T_{1/2}^{\gamma}} = \frac{8\pi(L+1)}{L[(2L+1)!!]^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(XL : I_i \to I_f)$$

partial γ–ray Transition Probability — reduced Transition Probability

$$B(XL : I_i \to I_f) = \frac{\left|\langle I_i | M(XL) | I_f \rangle\right|^2}{2I_i + 1}$$

contains the nuclear structure information

Hindrance Factor in γ–ray decay

$$F_{W(N)} = \frac{B(XL)_{Theory}}{B(XL)_{Exp}} = \frac{T^{\gamma}_{1/2}(XL)_{Exp}}{T^{\gamma}_{1/2}(XL)_{Theory}}$$

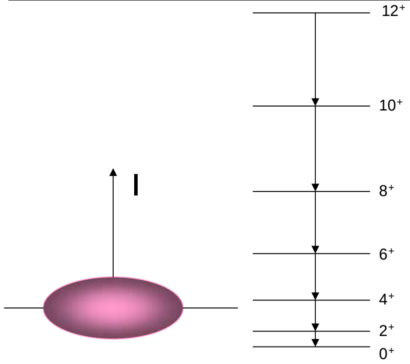
... usually an upper limit, but ...

Hindrance Factor: Weisskopf (W): based on spherical shell model potential

Nilsson (N): based on deformed Nilsson model potential

EL	$B(EL)_W, e^2 fm^{2L}$	$T^{\gamma}_{1/2}(EL)_W$, sec	ML	$B(ML)_W, \mu_N^2 fm^{2L-2}$	$T^{\gamma}_{1/2}(ML)_W$, sec
E1	$0.06446 A^{2/3}$	$6.762 A^{-2/3} E_\gamma^{-3} \times 10^{-15}$	M1	1.7905	$2.202 E_\gamma^{-3} \times 10^{-14}$
E2	$0.0594 A^{4/3}$	$9.523 A^{-4/3} E_\gamma^{-5} \times 10^{-9}$	M2	$1.6501 A^{2/3}$	$3.100 A^{-2/3} E_\gamma^{-5} \times 10^{-8}$
E3	$0.0594 A^{2}$	$2.044 A^{-2} E_\gamma^{-7} \times 10^{-2}$	M3	$1.6501 A^{4/3}$	$6.655 A^{-4/3} E_\gamma^{-7} \times 10^{-2}$
E4	$0.06285 A^{8/3}$	$6.499 A^{-8/3} E_\gamma^{-9} \times 10^{4}$	M4	$1.7458 A^{2}$	$2.116 A^{-2} E_\gamma^{-9} \times 10^{5}$
E5	$0.06929 A^{10/3}$	$2.893 A^{-10/3} E_\gamma^{-11} \times 10^{11}$	M5	$1.9247 A^{8/3}$	$9.419 A^{-8/3} E_\gamma^{-11} \times 10^{11}$

Quadrupole Deformation



I=Jω

^{156}Dy

$E_I = \hbar^2/2J \; I(I+1)$

B(E2) ~ 200 W.U.

deformed nucleus

$$B(E2) = \frac{8.16\times10^{13}}{E_\gamma^5[keV]\tau_\gamma[ps]}[e^2b^2]$$

$$B(E2;KI_i \rightarrow KI_f) = \frac{5}{16\pi}Q_0^2\langle I_iK20|I_fK\rangle^2$$

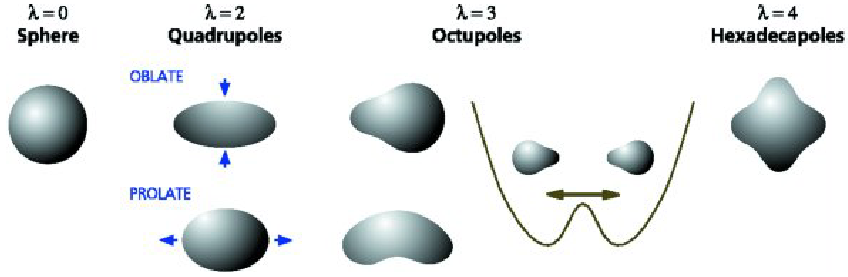
(from collective models)

$$\beta_2 \approx -7\sqrt{\frac{\pi}{80}} + \sqrt{\frac{49\pi}{80} + \frac{7\pi Q_0}{6eZr_0^2A^{2/3}}}$$

$$\tau_\gamma[ps] = (1.58\pm0.28)\times10^{14}E_{2_1^+}^{-4}[keV]Z^{-2}A^{2/3}$$

$$\beta_2 = \frac{466\pm41}{A\times\sqrt{E_{2_1^+}[keV]}}$$

Octupole Deformation

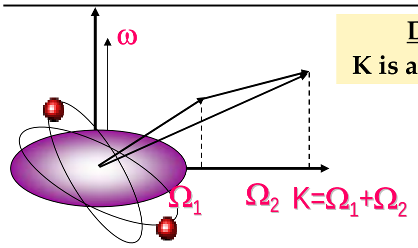


$$\tau_{E3}[s] = 0.012264 \times E_{3_1^-}^{-7} \times [B(E3)\uparrow]^{-1}$$

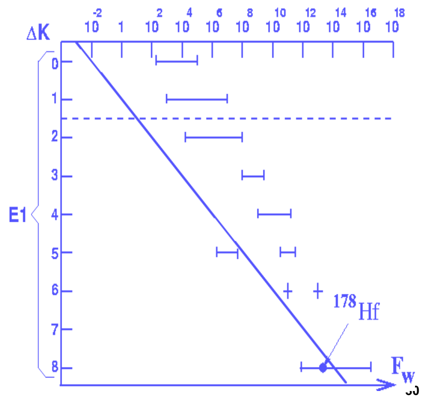
$$E_{3_1^-}[MeV]; B(E3)\uparrow [e^2 fm^6]$$

$$\beta_3 = \frac{4\pi}{ZR^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

K-forbidden decay

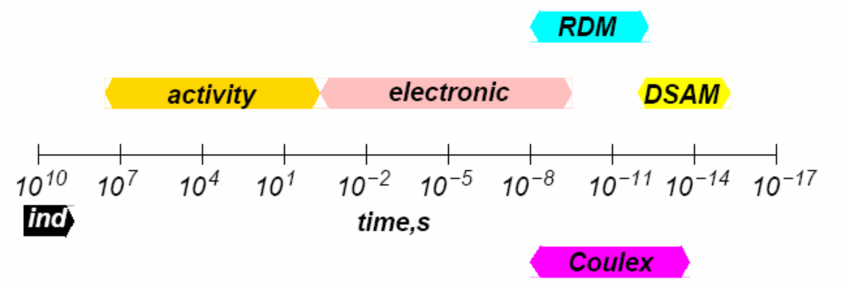


Deformed, axially symmetric nuclei
K is approximately a good quantum number
each state has not only
J$^\pi$ but also *K*



- The solid line shows the dependence of F_W on ΔK for some E1 transitions according to an empirical rule: log F_W = 2{|ΔK| - λ} = 2ν
- i.e. F_W values increase approximately by a factor of 100 per degree of K forbiddenness
- $f_\nu=(F_W)^{1/\nu}$ – reduced hindrance per degree of K forbiddenness

Experimental techniques



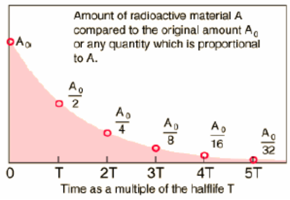
- Direct width measurements
- Inelastic electron scattering
- Blocking technique
- Mossbauer technique

Specific Activity

Time Range: a few seconds up to several years

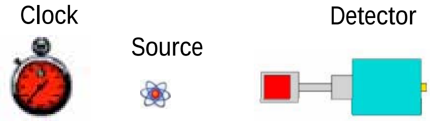
$$A = \lambda N = \lambda N_0 e^{-t/\tau}$$

- Statistical uncertainties are usually small
- Systematic uncertainties (dead time, geometry, etc.) dominate



usually want to follow at least 5 x $T_{1/2}$

Tag on specific signature radiations (α, β, ce or γ) in a “singles” mode

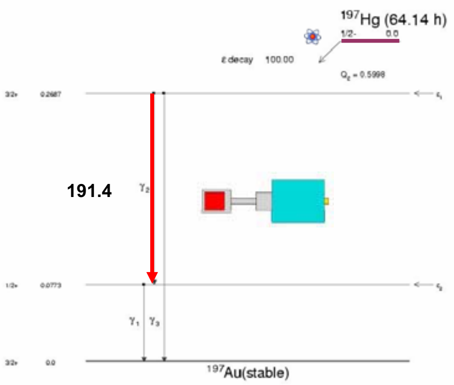


Specific Activity: Example 1

PHYSICAL REVIEW C, VOLUME 63, 047307

Half-lives of Au, Hg, and Pb isotopes from photoactivation

K. Lindenberg, F. Neumann, D. Galaviz, T. Hartmann, P. Mohr, K. Vogt, S. Volz, and A. Zilges
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 9, D-64289 Darmstadt, Germany



- More than 270 spectra were measured
- Followed 4 x $T_{1/2}$

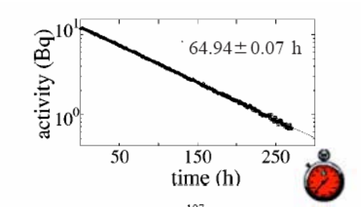
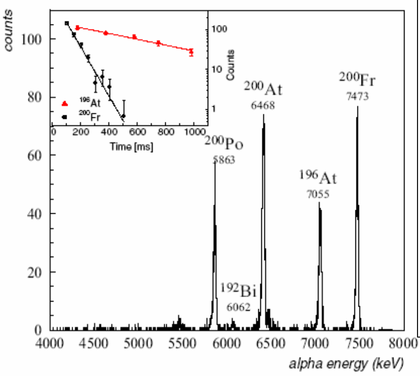
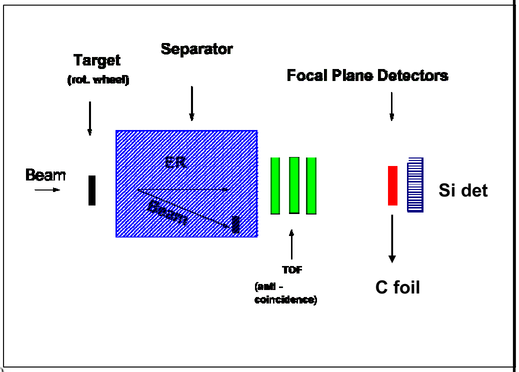


FIG. 3. Decay curve of ^{197}Hg at E_γ=191.4 keV.

Specific Activity: Example 2



Isotope	Energy (keV)	$T_{1/2}$	Reference
^{200}Fr	7473(12)	49(4) ms	this work
	7500(30)	570^{+270}_{-140} ms	[4]
	7468(9)	19^{+13}_{-6} ms	[5]



1 GeV pulsed proton beam on 51 g/cm2 ThCx target

on-line mass separation (ISOLDE)/CERN

H. De Witte et al., EPJ A23 (2005) 243

Very long-lived cases – Example 1

Time Range: longer than 10^2 yr

$$A = \lambda N \qquad T_{1/2} = \ln 2 \frac{N_{182}}{A_{182}}$$

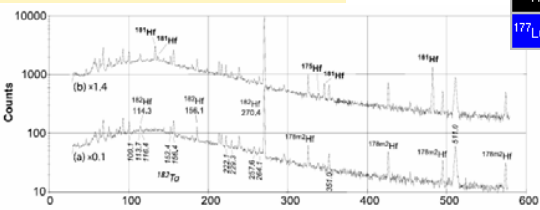
the number of atoms estimated by other means, e.g. mass spectrometry

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

New Half-Life Measurement of ^{182}Hf: Improved Chronometer for the Early Solar System

C. Vockenhuber,[1,*] F. Oberli,[2] M. Bichler,[3] I. Ahmad,[4] G. Quitté,[2] M. Meier,[2] A. N. Halliday,[2] D.-C. Lee,[5] W. Kutschera,[1] P. Steier,[1] R. J. Gehrke,[6] and R. G. Helmer[6]

^{180}W	^{181}W	^{182}W	^{183}W	^{184}W	^{185}W	^{186}W
^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta	^{183}Ta	^{184}Ta	^{185}Ta
^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf	^{182}Hf	^{183}Hf	^{184}Hf
^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu	^{181}Lu	^{182}Lu	^{183}Lu



Material	Atomic abundance (%) ^{174}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{182}Hf
Helmer 1	≈ 0.0058	4.791	0.605	29.06	25.77	39.64	0.124
Helmer 2	≈ 0.00014	4.377	0.149	17.15	31.30	46.91	0.112
Natural	0.16	5.21	18.60	27.30	13.63	35.10	

TABLE II. The half-life of ^{182}Hf from the two measurements. All uncertainties are 1σ uncertainties.

Material	Method	Half-life ($\times 10^6$ yr)	Uncorrelated uncertainty ($\times 10^6$ yr)	Total uncertainty ($\times 10^6$ yr)
Helmer 1	Neutron activation + activity measurement	9.034	±0.241	±0.251
Helmer 2	Isotope dilution + activity measurement	8.896	±0.057	±0.089
	Weighted mean	8.904	±0.056	±0.088

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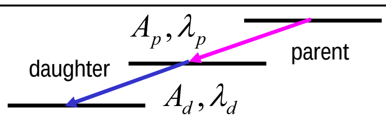
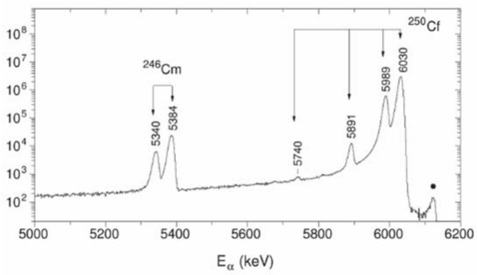
Very long-lived cases – Example 2

$$\frac{A_p(t)}{A_d(t)} = \frac{\lambda_d}{\lambda_d - \lambda_p}\left(1 - e^{-(\lambda_d - \lambda_p)t}\right)$$



^{250}Cf —α, 13 y→ ^{246}Cm —α, 4747 y→ ^{242}Pu —α, 510^5 y→

$T_{1/2}(^{250}$Cf$)$=13.05 (9) y



- *Mass separated samples (1975!)*
- *Parent/daughter activity*
- *Alpha counting technique*

$T_{1/2}$ = 4747 (46) years / Compared to values ranging from $T_{1/2}$=2300 up to 6620 years

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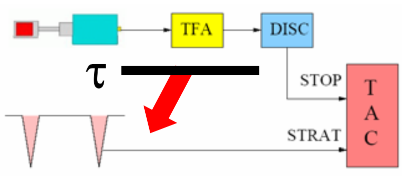
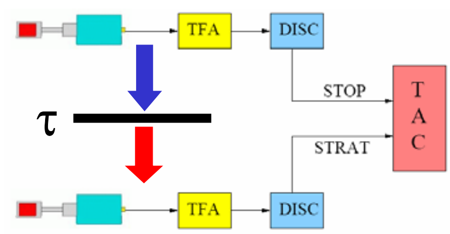
Electronic techniques

Time Range: tens of ps up to a few seconds

The "Clock" - TAC, TDC (START/STOP); Digital Clock





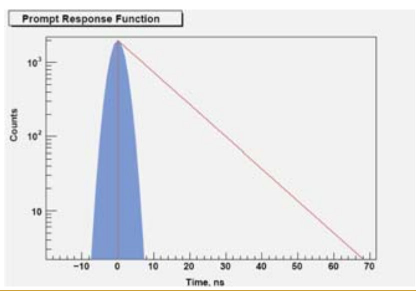
"singles" – E_γ-time, E_α-time

"coincidence" – $E_{\gamma 1}$-$E_{\gamma 2}$-Δt ; $E_{\alpha 1}$-$E_{\gamma 1}$-Δt
$E_{\alpha 1}$-$E_{\alpha 2}$-Δt

Difficulties at the boundary: e.g. for very short– and very long-lived cases!

Prompt Response Function

- all detectors and auxiliary electronics show statistical fluctuations in the time necessary to develop an appropriate pulse for the "clock"
  - depend on the characteristics of the detectors: e.g. light output for scintillators, bias voltage, detector geometry, etc.
  - instrumental imperfections in the electronics – e.g. noise in the preamplifiers



Some typical values

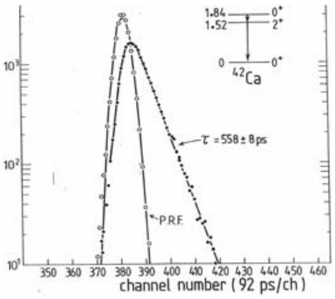
Detector	FWHM, ps
plastic scintillators	~100
BaF_2	~100
Si	~200
Na(I)	~500
Ge	0.6-9 ns

Prompt Response Function: Ge detectors

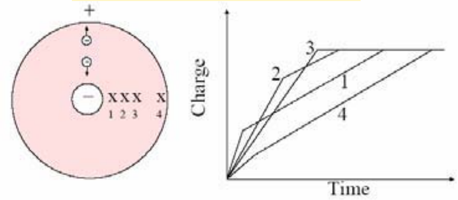
$$F(x,\lambda) = \int_{-\infty}^{\infty} f(t,\lambda) P(x-t)dt$$

$f(t,\lambda) = \lambda e^{-\lambda t} (t \geq 0) or = 0 (t < 0)$ **decay**

PRF $P(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(z/\sigma)^2}$



a schematic illustration

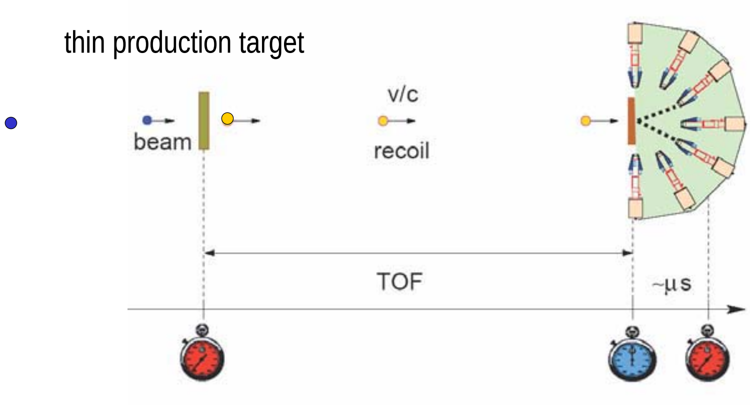


PRF depends on:

- the size of the detector
- the energy of the γ–ray

Recoil-shadow technique

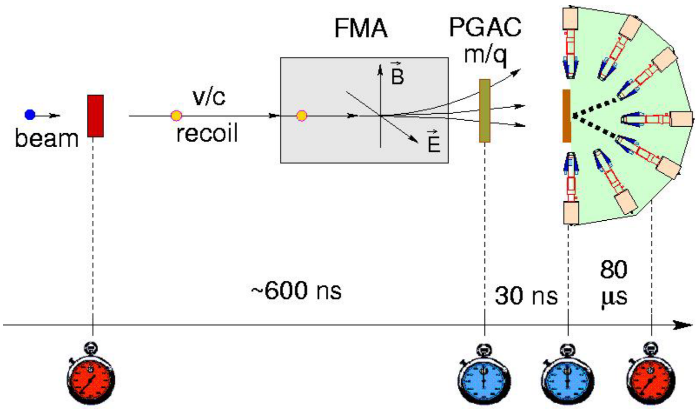
the shortest lifetime that can be measured is limited by the TOF



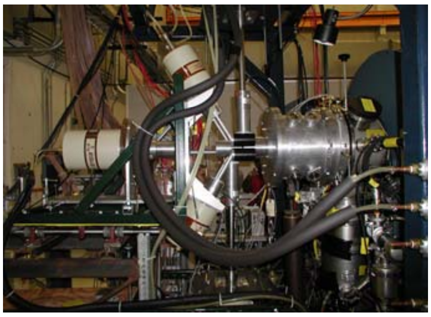
One example: ^{140}Dy experiment at ANL

^{54}Fe + ^{92}Mo @ 245 MeV

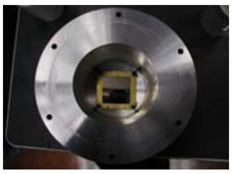
α2n channel, mass 140 only 5% from the total CS



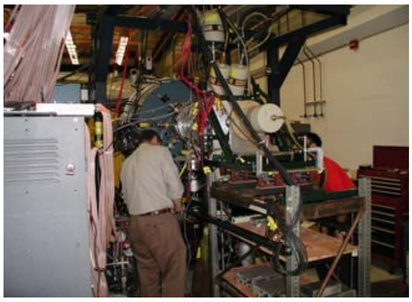
Some of the equipments used …



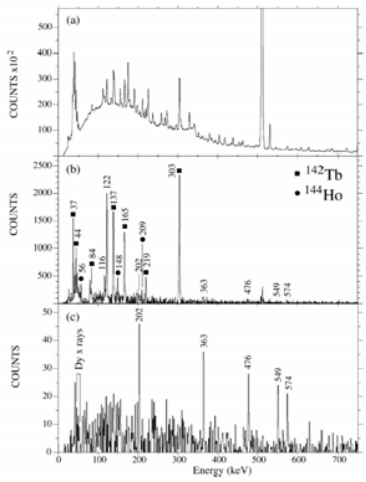
1 70% Gammasphere HpGe detector
4 25% Golf-club style HPGe detectors
2 LEPS detectors
1 2"x2" Large Area Si detector

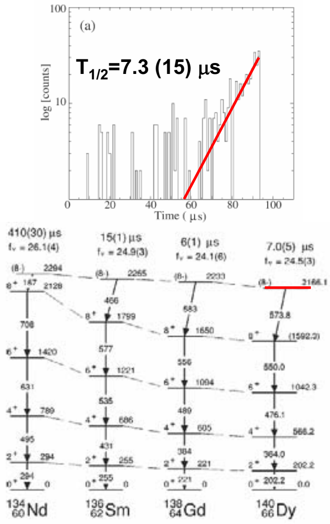


2"x2" Si Detector



^{140}Dy: Experimental Results





Similar results by the ORNL group, Krolas et al., PRC 65, 2002

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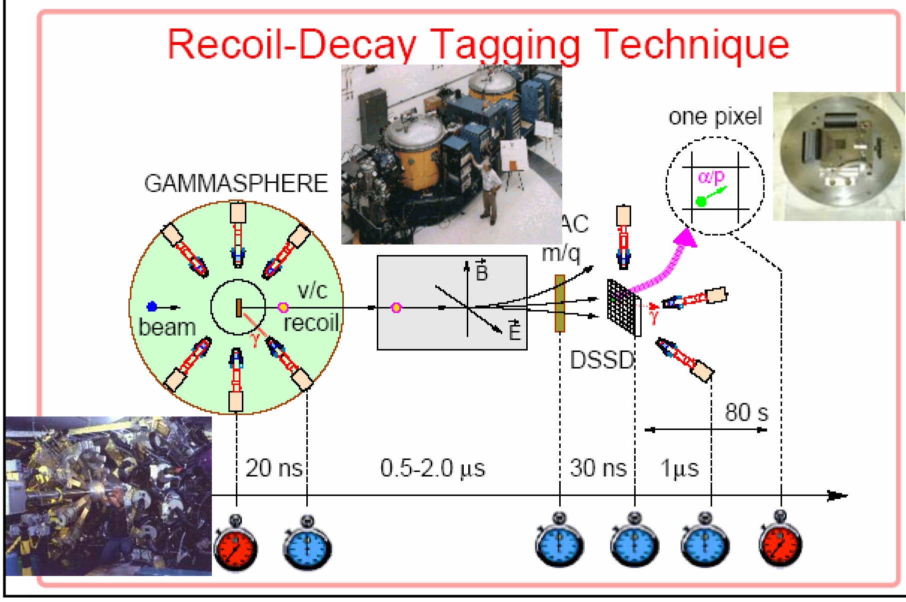
Pioneering Science and Technology

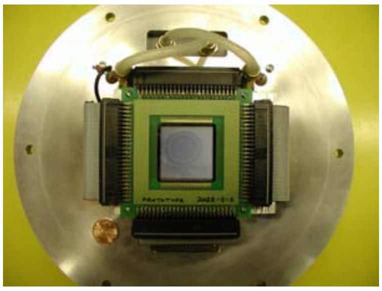
D.M. Cullen et al., Phys. Lett. B529 (2002)

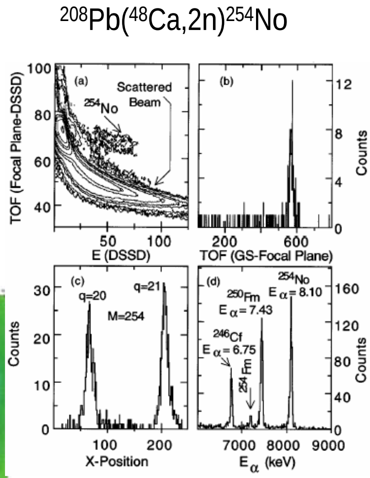
Office of Science U.S. Department of Energy

Recoil-decay tagging

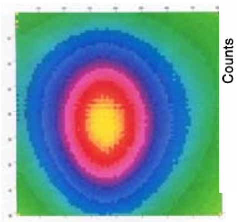


The Heart of RDT: the DSSD





80 x 80 detector 300 μm strips,
Each with high, low, and delay line amplifiers, for implant, decay, and fast-decay recognition.



Data from DSSD showing implant pattern 40 cm beyond the focal plane

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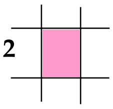
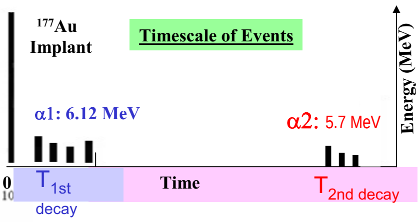
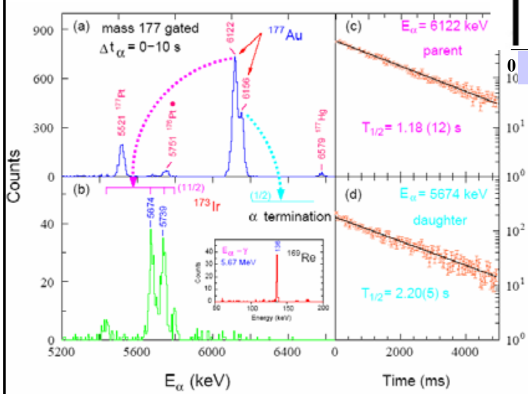
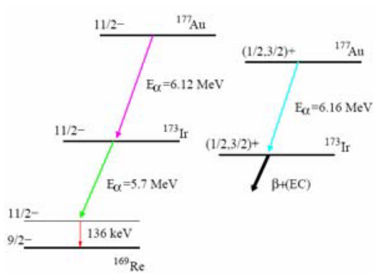
α–α (parent-daughter) correlations

Implantation->Decay 1->Decay 2 within a single pixel









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F.G. Kondev et al. Phys. Lett. B528 (2002) 221

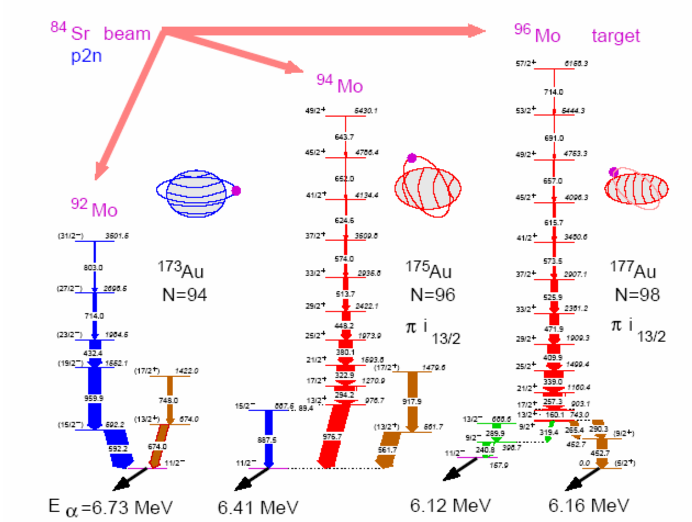
Neutron deficient nuclei

Severe complications

- Charged particle emission:
  → The fusion-evaporation cross section is fragmented into many channels.
  → It limits the absolute production.

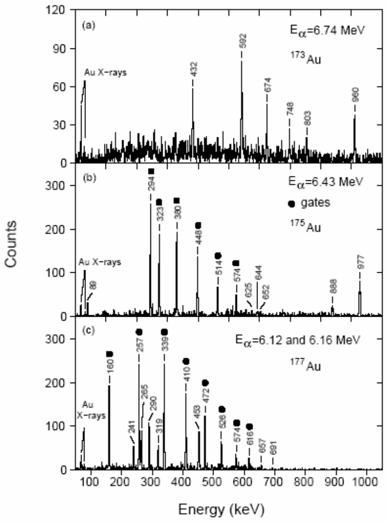
- Fission process: *fissibility parameter* ~ Z^2/A
  → Depletion of the high-*l* values.
  → It limits the population of residues at high angular momentum.
  → Huge, unwanted background.

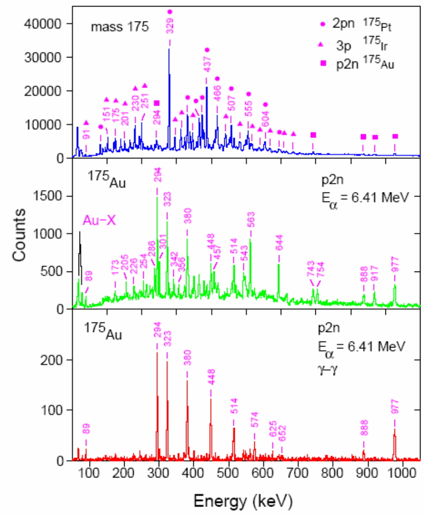
Odd-Z Au (Z=79) isotopes



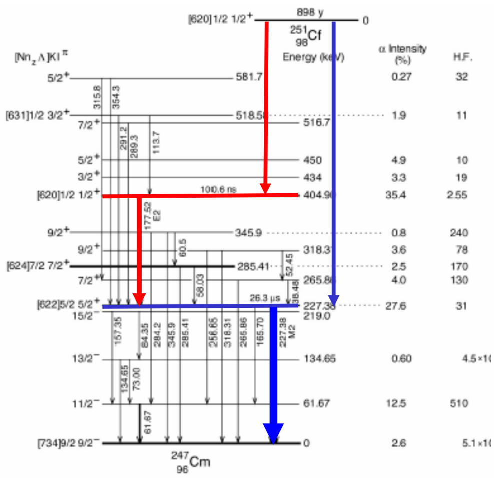
F.G. Kondev et al. Phys. Lett. B528 (2002) 221

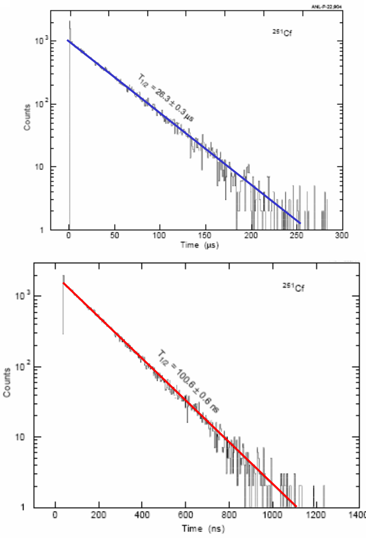
Odd-Z Au (Z=79) isotopes –sample spectra





α–γ correlations

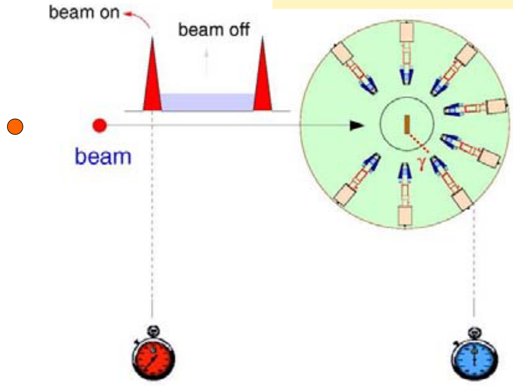




I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

Pulsed beam technique

the shortest lifetime that can be measured is limited by the width of the pulsed beam



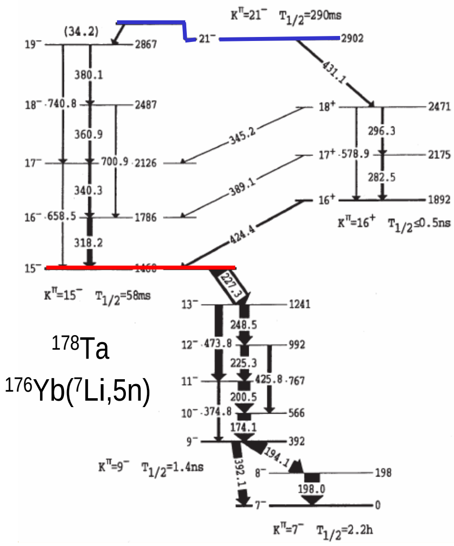
- ❑ Less effective, but …
  - ✓ well defined "clock"
  - ✓ sensitive to in-beam and decay events

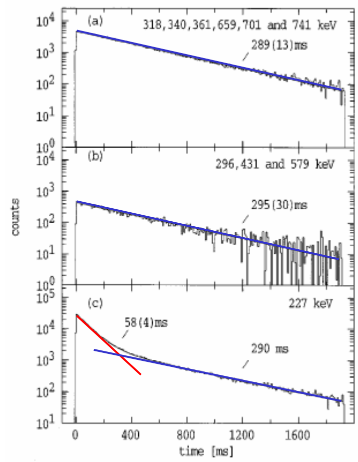
❑ "singles": γ–time

❑ coincidence: γ–γ–time

the longest lifetime that can be measured is limited by the time interval between the beam pulses

Pulsed beam: γ–time





reveals the time history of levels above the 58 ms isomer !

F.G. Kondev et al. Phys. Rev. C54 (1996) R459

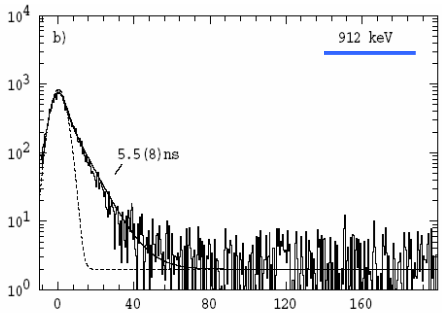
Pulsed beam: γ–time (short-lived)

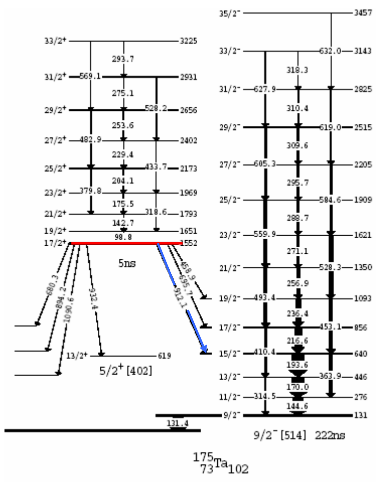
The importance of PRF

In γ–time measurements PRF depends on E_γ for a single transition

^{175}Ta

^{170}Er(^{10}B,5n)





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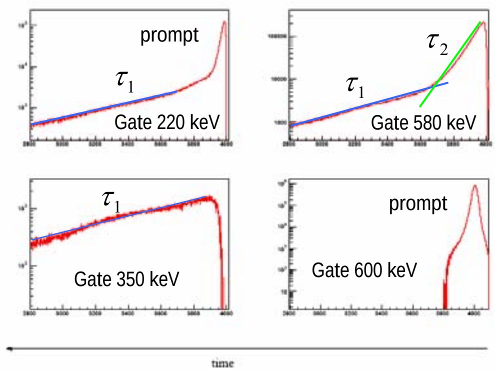
Pioneering Science and Technology

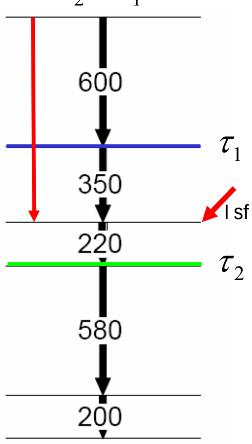
F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

Office of Science U.S. Department of Energy

Limitations: Pulsed beam γ–time

- Complicated when more than one isomer is presented
- Complicated because of contaminations
- Limited time range – e.g. TAC (Ortec 567) – 3 ms
- Rate dependent time distortions





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Pioneering Science and Technology

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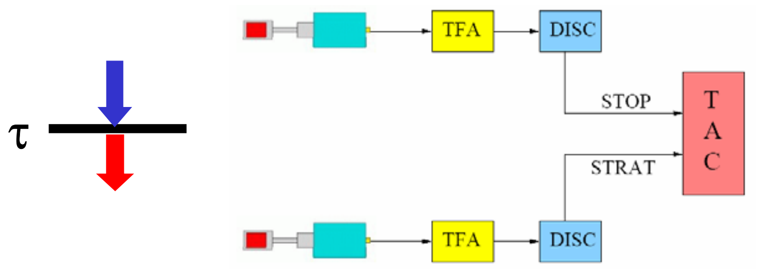
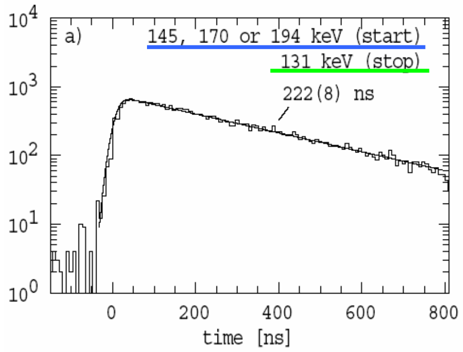
Pulsed beam: γ–γ–time technique

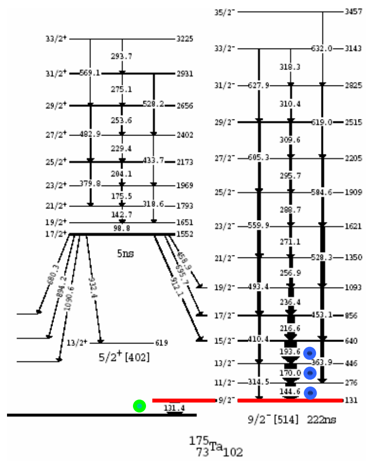


"coincidence" – $E_{\gamma1}$-$E_{\gamma2}$-Δt ; $E_{\alpha1}$-$E_{\gamma1}$-Δt
$E_{\alpha1}$-$E_{\alpha2}$-Δt

γ–γ–time: decay of the 9/2- isomer in ^{175}Ta

^{175}Ta
^{170}Er(^{10}B,5n)





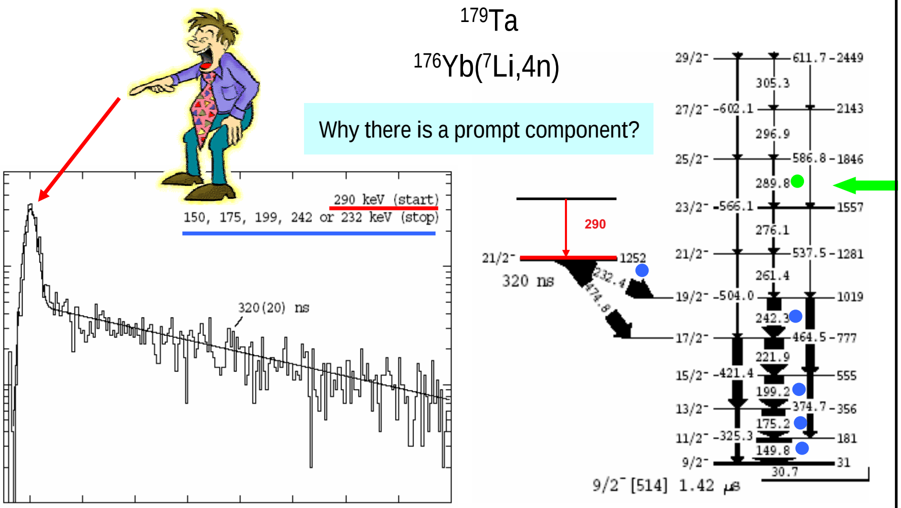
F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

γ–γ–time: decay of the 21/2- isomer in ^{179}Ta

^{179}Ta

^{176}Yb(^{7}Li,4n)

Why there is a prompt component?



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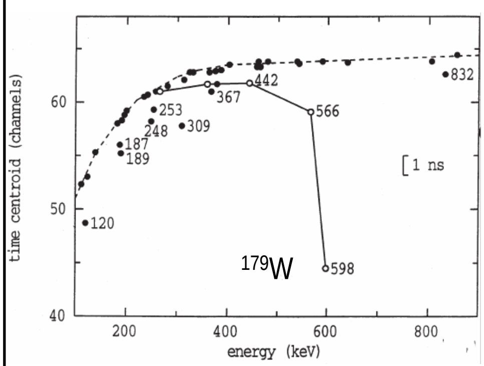
Centroid-shift technique: γ–time

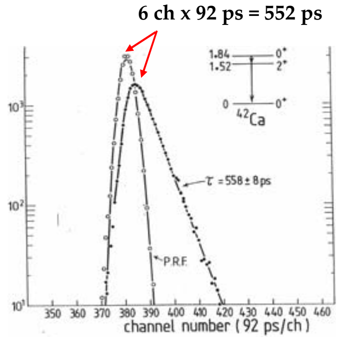
Time Range: near PRF

$$F(x,\lambda)=\int_{-\infty}^{\infty} f(t,\lambda)P(x-t)dt \qquad M_r(F(t))=\int_{-\infty}^{\infty} t^r F(t)dt \qquad \tau = M_1(F(t)) - M_1(P(t))$$

Introduced by Z. Bay, Phys. Rev. 77 (1950) 419



6 ch x 92 ps = 552 ps



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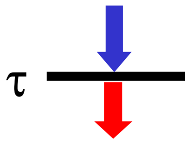
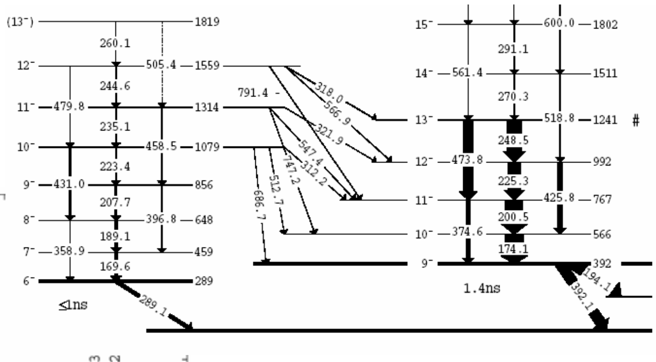
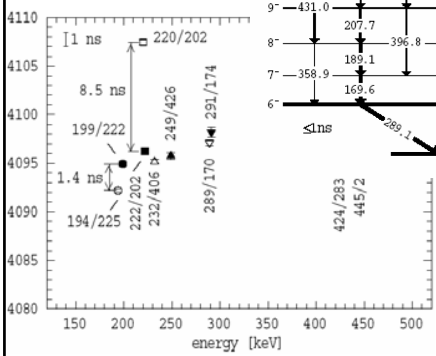
Centroid-shift technique: γ–γ–time







Must be more careful!

The PRF depends on both $E_{\gamma 1}$ and $E_{\gamma 2}$

F.G. Kondev et al. Nucl. Phys. A632 (1998) 473

Coulomb excitations

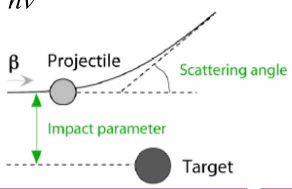
Time Range: up to hundreds of ps

$$E < V_{cb}$$

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} >> 1$$

^{19}F(1 MeV) on ^{238}U η~1.6

^{40}Ar(152 MeV) on ^{238}U η~130



Observables
- Number of gamma rays detected (N_γ)
- Number of beam particles detected (N_{beam})
- Energy of de-excitation gamma ray (E_γ)

Experimental results
- Coulomb excitation cross section (σ)
- Reduced transition probability B(E2,↑)
- Energy of excited state

$$\sigma = \frac{N_\gamma}{\varepsilon} \frac{1}{N_{target} N_{beam}}$$

$$\sigma_{0\to 2} \approx \left(\frac{Z_{target} e^2}{\hbar c}\right)^2 \frac{\pi}{e^2 b_{min}^2} B(E2, 0^+ \to 2^+)$$

Details in: Winther and Alder, Nucl. Phys. A **319** 518 (1979).

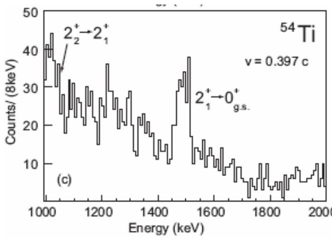
Intermediate energy Coulomb excitations

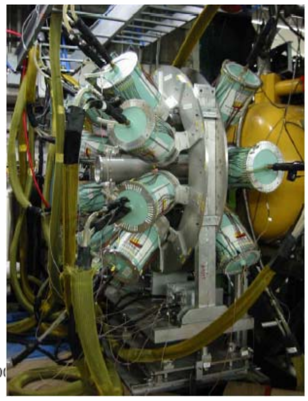
Primary beam: ^{76}Ge @ 130 MeV/nucl.
Secondary beam: ^{54}Ti @ 88 MeV/nucl.
β=0.406
^{197}Au target thickness: 257.67 mg/cm^2
Θ_{max} = 3.20° (CM)
Number of ^{54}Ti particles detected: 91.665E6

SeGA
(**Se**gmented **G**ermanium **A**rray)—Eighteen 32-fold segmented HP germanium detectors

Measured for ^{54}Ti
- E_γ = 1497(4) keV
- $\sigma(\theta<\Theta_{max})$ = 83(15) mb
- $B(E2,\uparrow)$ = 357(63) e^{2}fm^4

$\tau = 1.5(3)\,ps$





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Deduction of Transition Multipolarity

<u>Basic techniques</u>

- ❑ Internal conversion electrons
- ❑ Angular distributions
- ❑ Angular correlations (DCO ratios)
- ❑ Gamma-ray polarization

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Internal conversion electrons

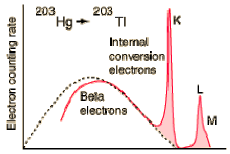
$$\alpha^{tot} = \frac{I_{ce}}{I_\gamma} = \alpha_K + \alpha_L + \alpha_M + \ldots$$

$I_i^{\pi_i}$ —— E_i

L

$I_f^{\pi_f}$ —— E_f

$$E_\gamma = E_i - E_f$$
$$E_i = E_\gamma - B_i, i = K, L, \ldots$$



Intensity ratio

∞	E0
1	Low energy isomers
10^{-1} <	50< Z
10^{-2} - 10^{-3}	30<Z < 50
10^{-4} - 10^{-5}	Z < 30

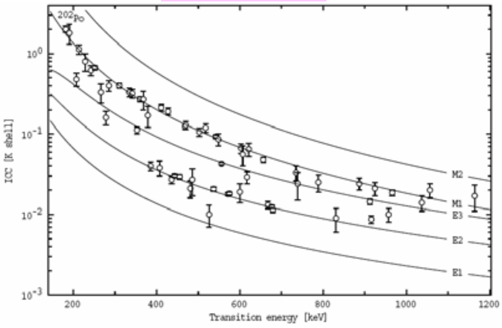
$$\alpha_K(EL) \propto Z^3 \left(\frac{L}{L+1}\right)\left(\frac{2m_e c^2}{E}\right)^{L+5/2}$$

Important for heavy nuclei, where inner electron shells are closer to the nucleus

Important for low-energy transitions

Internal conversion electrons

Sensitive to L



allows deduction of the mixing ratios

$5/2-$ —— E_i

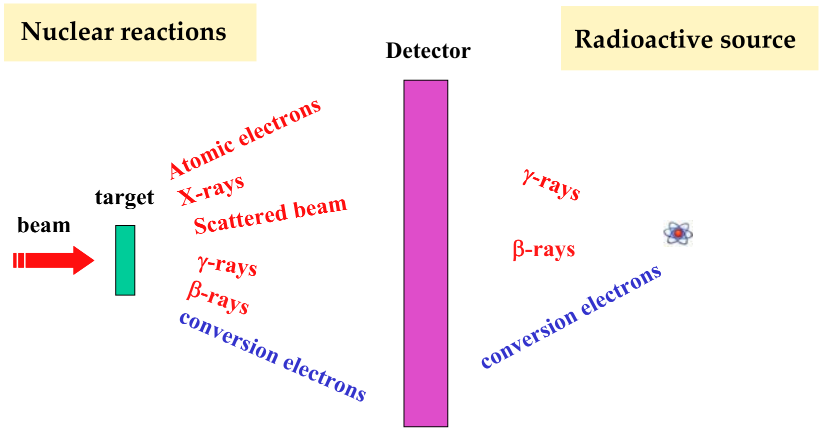
$M1+E2$

$3/2-$ —— E_f

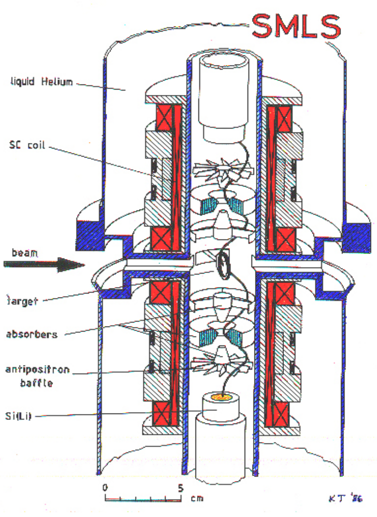
$1 \le L \le 4$ $\quad M1, E2, M3, E4$

$$\delta^2 = \frac{I_\gamma(E2)}{I_\gamma(M1)} \qquad \alpha^{M1/E2} = \frac{\alpha_{M1} + \delta^2 \alpha_{E2}}{1+\delta^2} \qquad \delta^2 = \frac{\alpha_{M1} - \alpha^{\exp}}{\alpha^{\exp} - \alpha_{E2}}$$

Direct ICC measurements



Basic electron transporters

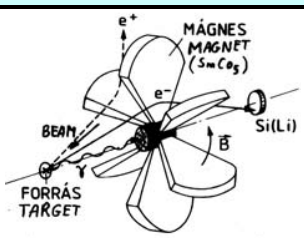


Superconducting solenoid

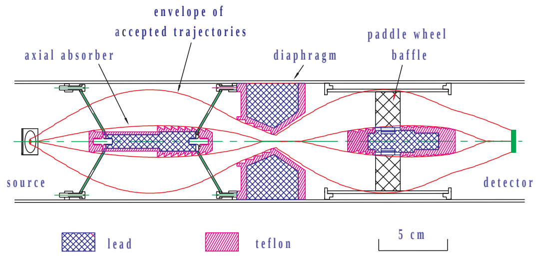
- Broad-range mode – 100 keV up to a few MeV
- Lens mode – finite transmitted momentum bandwidth (Δp/p~15-25%) – high peak-to-total ratio

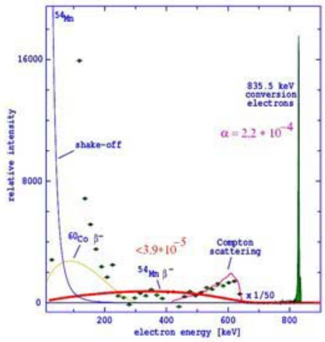
Mini-orange (looks like a peeled orange)

- transmission > 20%
- small size and portability, but poorer quality



Superconducting Solenoid Spectrometer

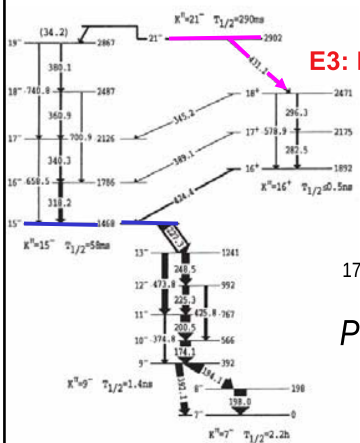




Conversion electron measurements

$\alpha_K(431) = 0.056(7)$
$\alpha_L(431) = 0.033(4)$
$\frac{K}{L}(431) = 1.7(2)$

$\alpha_K^{th}(431) = 0.008(E1); 0.022(E2); 0.058(E3); 0.067(M1); 0.21(M2)$
$\alpha_L^{th}(431) = 0.001(E1); 0.006(E2); 0.032(E3); 0.010(M1); 0.040(M2)$
$\frac{K}{L}(431) = 6.7(E1); 3.9(E2); 1.9(E3); 6.5(M1); 5.2(M2)$

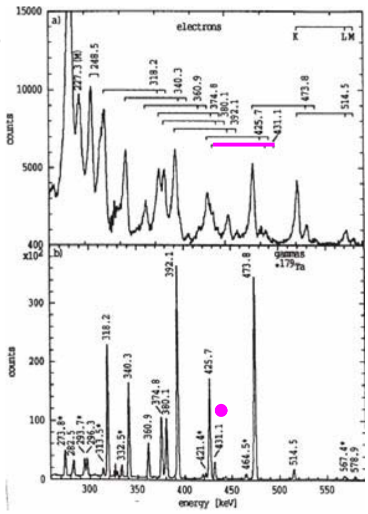


E3: L=3, π=yes

^{178}Ta

^{176}Yb(^{7}Li,5n)

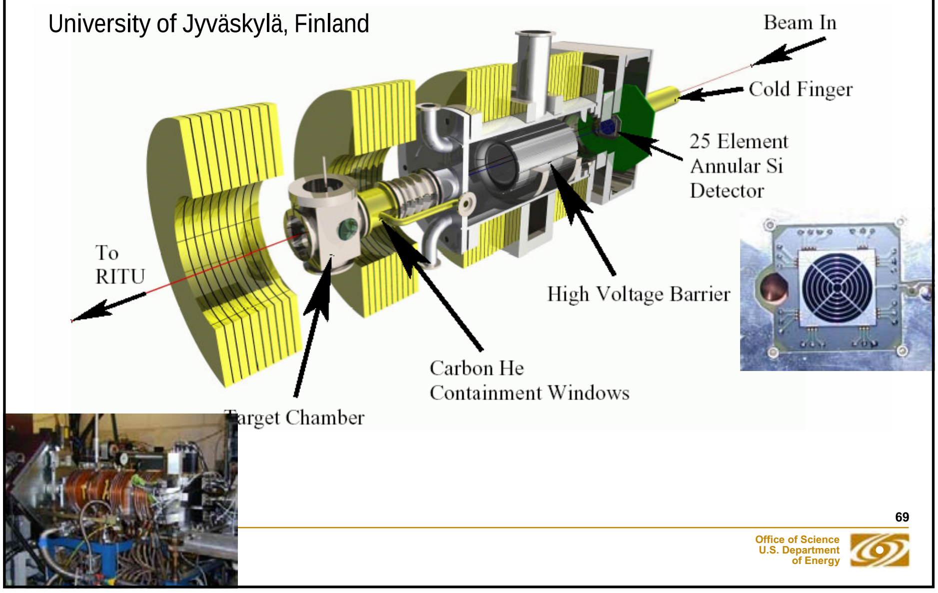
Pulsed-beam technique



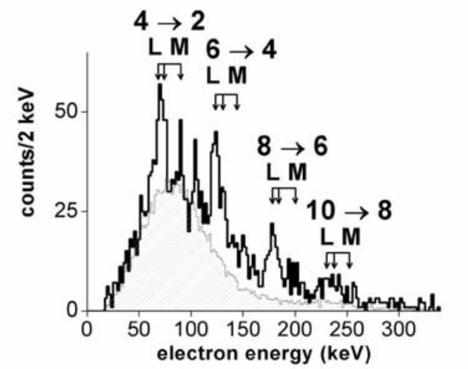
F.G. Kondev et al. Nucl. Phys. A632 (1998) 473

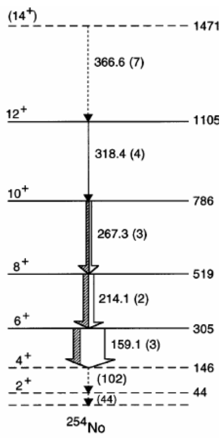
The SACRED Electron Spectrometer

University of Jyväskylä, Finland



Recoil-gated CE spectrum from $^{208}Pb(^{48}Ca,2n)^{254}No$





P.A. Butler et al.,PRL 89 (2002) 202501

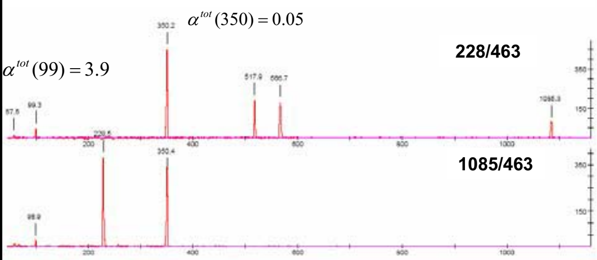
ICC from total intensity balances –example 1

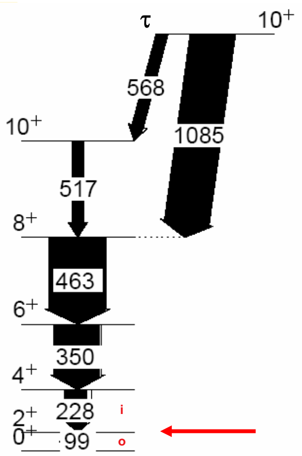
Works well for γ–rays with energies below about 250 keV

In out-of-beam (or decay) coincidence data

$$I^{tot}_{\gamma_i} = I_{\gamma_i}\times(1+\alpha_i^{tot}) \equiv I^{tot}_{\gamma_o} = I_{\gamma_o}\times(1+\alpha_o^{tot})$$

$$\alpha_o^{tot} \equiv (I_{\gamma_i}\varepsilon_o / I_{\gamma_o}\varepsilon_i)\times(1+\alpha_i^{tot})-1$$





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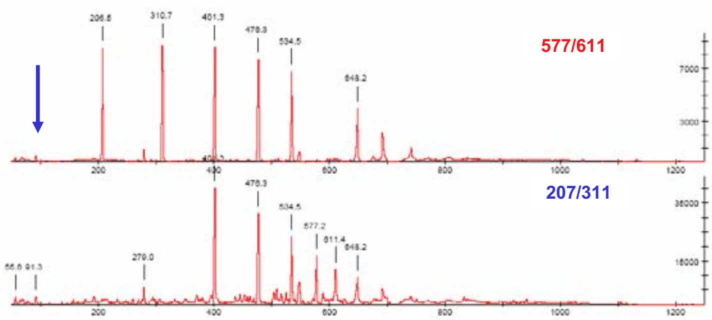
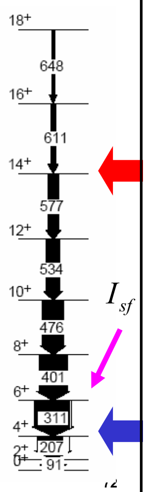
ICC from total intensity balances –example 2

In-beam: only when gating from "above"

$$I^{tot}_{\gamma_i} = I_{\gamma_i}\times(1+\alpha_i^{tot}) \equiv I^{tot}_{\gamma_o} = I_{\gamma_o}\times(1+\alpha_o^{tot})$$

$$I^{tot}_{\gamma_i} = I^{tot}_{\gamma_o} + I_{sf}$$





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Angular Distributions

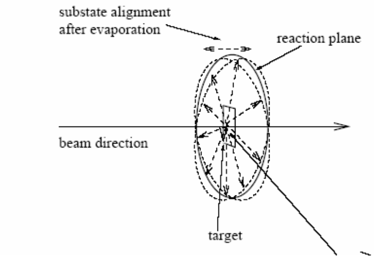
The gamma-rays emitted from nuclear reactions exhibit angular distributions:

$$W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$

$$A_{22} = \alpha_2 A_2^{\max};\ A_{44} = \alpha_4 A_4^{\max}$$

$$\alpha_k(J_i) = \rho_k(J_i)/B_k(J_i)$$

$$\rho_k(J) = \sqrt{(2J+1)} \times \sum_m (-1)^{J-m} < J, m, J-m \,|\, k0 > P_m(J)$$

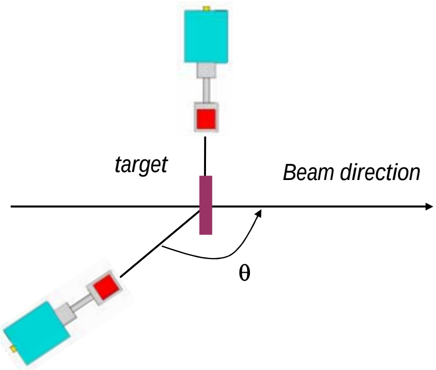


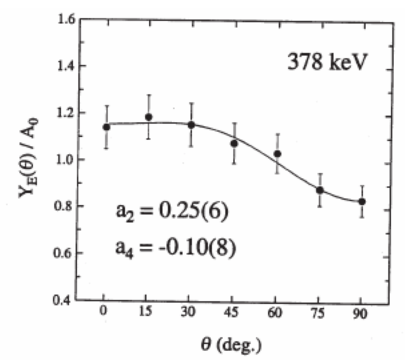
The orientation of the nucleus will be slightly attenuated by the emission of evaporated particles (n,p,α) and γ–rays.

$$P_m(J) = \frac{\exp(-m^2/2\sigma^2)}{\sum_{m=-J}^{J} \exp(-m^2/2\sigma^2)}$$

Angular Distributions: Experiment

Measure: the γ-ray yield as a function of θ





Using a single detector – "singles" mode – contaminants

Using a large gamma-ray array – "coincidence" mode - you must be careful!

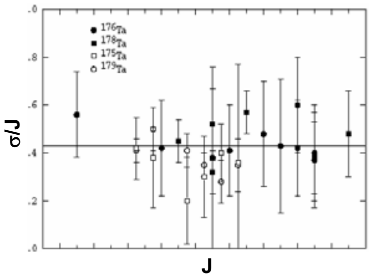
How to determine the mixing ratios?

I) If both A2 and A4 have been measured – see

E. Der Mateosian and A.W. Sunyar, ADNDT 13 (1974) 407

II) If only A2 has been measured (A4~0)

1) Determine the attenuation coefficient (α_2) for known E2 transitions depopulating levels of known spin (gs band in even-even nuclei)



$$\alpha_2 = A_2^{\exp} / A_2^{\max}$$

$$A_2^{\max} = B_2 \times F_2$$

Tabulated in E. Der Mateosian and A.W. Sunyar, ADNDT 13 (1974) 391

2) For a given transition determine:

$$A_2^{\max} = A_2^{\exp} / \alpha_2$$

3) From **E. Der Mateosian and A.W. Sunyar, ADNDT 13 (1974) 407** get δ

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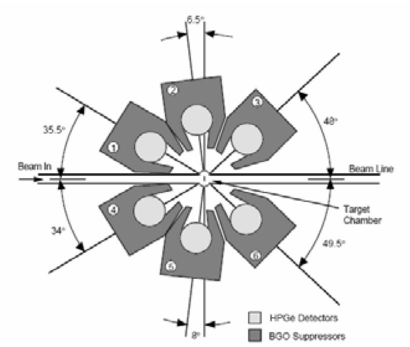
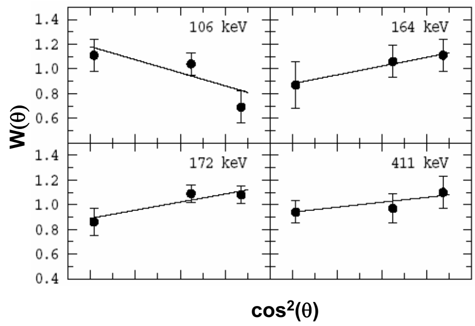
Angular Distributions: Example 1

^{175}Ta

^{170}Er(^{10}B,5n)@64 MeV





172γ: δ(AD)=0.44 -13+17; δ(RM)=0.54 -/+5

CAESAR array/Canberra (AUS)

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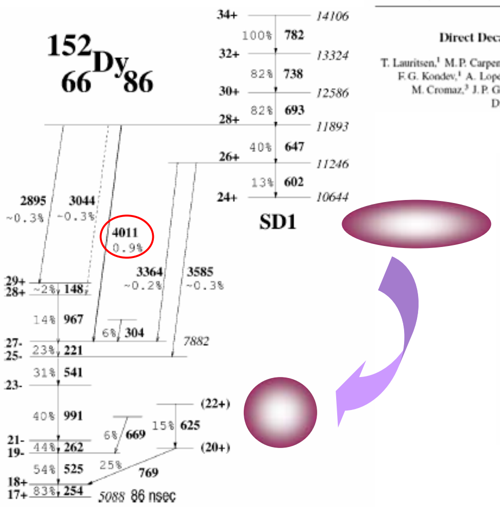
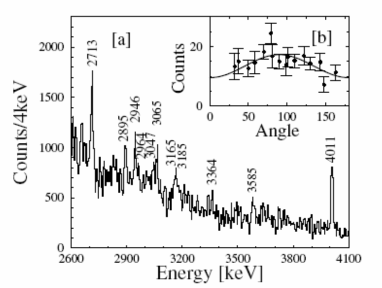
Angular Distributions: Example 2



VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

Direct Decay from the Superdeformed Band to the Yrast Line in $^{152}_{66}Dy_{86}$

T. Lauritsen,[1] M. P. Carpenter,[1] T. Døssing,[2] P. Fallon,[3] B. Herskind,[2] R. V. F. Janssens,[1] D. G. Jenkins,[1] T. L. Khoo,[1] F. G. Kondev,[1] A. Lopez-Martens,[4] A. O. Macchiavelli,[3] D. Ward,[3] K. S. Abu Saleem,[1] I. Ahmad,[1] R. Clark,[3] M. Cromaz,[3] J. P. Greene,[1] F. Hannachi,[4] A. M. Heinz,[1] A. Korichi,[4] G. Lane,[3] C. J. Lister,[1] P. Reiter,[1,5] D. Seweryniak,[1] S. Siem,[1] R. C. Vondrasek,[1] and I. Wiedenhöver[1,6]



$A_2 = -0.35(12)$ and $A_4 = -0.02(16)$

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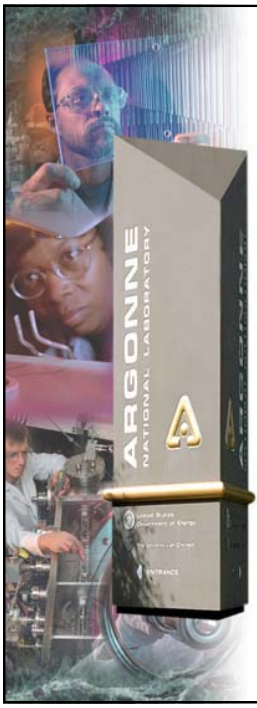


Experimental Nuclear Structure Part II

Filip G. Kondev
kondev@anl.gov

Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation", Trieste, Italy

April 4-15th, 2005

Argonne National Laboratory

A U.S. Department of Energy Office of Science Laboratory Operated by The University of Chicago

Outline

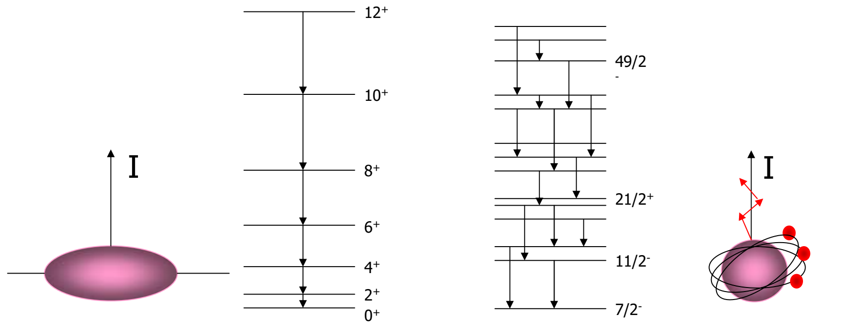
I) Lecture I: Experimental nuclear structure techniques

- reactions used to populate excited nuclear states
- techniques used to measure the lifetime of a nuclear state
  - *Coulomb excitation, electronic, specific activity, indirect*
- Techniques used to deduce J^{π}
  - *ICC, angular distributions, DCO ratios, etc.*

II) Lecture II: Contemporary Nuclear Structure Physics at the Extreme

- spectroscopy of nuclear K-Isomers
- physics with large γ–ray arrays
- gamma-ray tracking – the future of the nuclear γ–ray spectroscopy

Generation of Angular Momentum in Nuclei



$I = J\omega$ — ^{156}Dy — ^{147}Gd — $I = \Sigma\, I_j$

$E_I = \hbar^2/2J\; I(I+1)$ — $E_I = \Sigma\, e_j + \Sigma\Sigma\, V_{jk}$

B(E2) ~ 200 W.U.

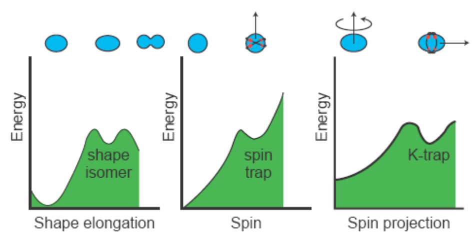
deformed nucleus — spherical nucleus

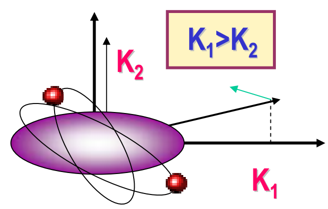
What is a Nuclear Isomer?

Nuclear Isomer – a *long-lived excited nuclear state ($T_{1/2} > 1$ ns)*
decays by emission of α, β, γ, p, fission, cluster

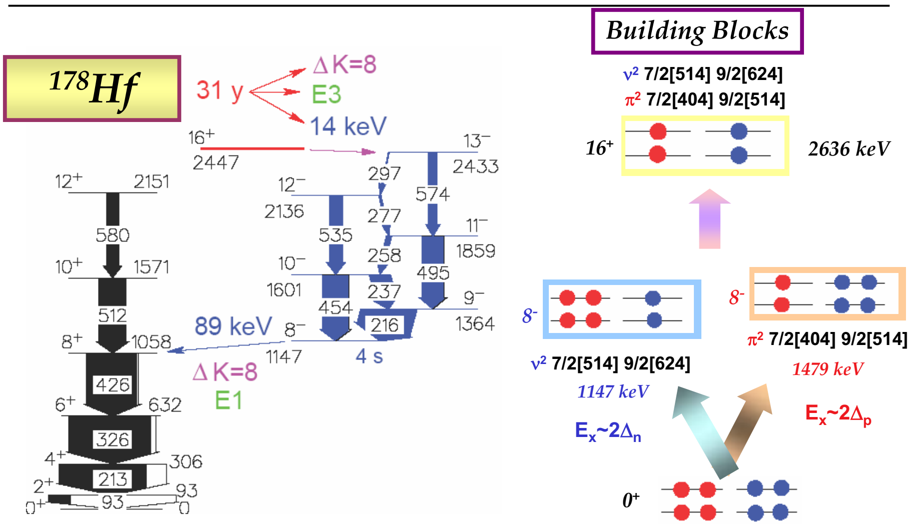
The first one discovered by O. Hahn in Berlin in 1921 – decay of ^{234}Pa (70 s)
von Weizsacker, A. Bohr & B. Mottelson

$$1/\tau \sim E_\gamma^{\,2\lambda+1}\, |\langle \psi_f \,|\, T \,|\, \psi_i \rangle|$$





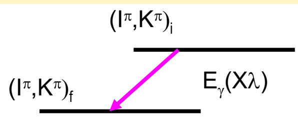
K-Isomers – the building blocks

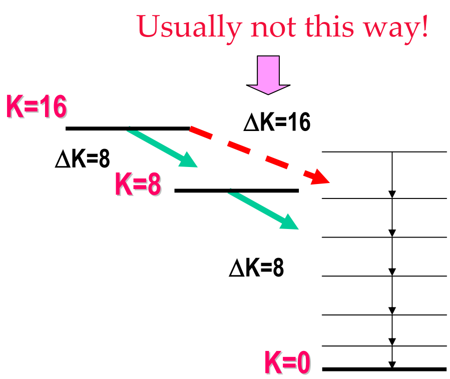


R. Helmer & C. Reich, NP A114 (1968)

K-Selection Rule and Reduced Hindrance

K-Isomer decay usually proceeds by minimizing ΔK





$\nu = \Delta K - \lambda$ – degree of K-forbiddenness

$F = \tau^{\gamma}(X\lambda)/\tau^{w}(X\lambda)$ – hindrance factor

$f_{\nu} = (F)^{1/\nu}$ – reduced hindrance per degree of K-forbiddenness – gives yardstick for "goodness" of K-quantum number

$f_{\nu} > 20$ – K-hindered decay

$f_{\nu} < 10$ - anomalous decay

Why Studying Isomers?

- **Powerful spectroscopy tool - highly selective "devices"**
- **Advanced physics**
  - ✓ The mapping of intrinsic orbitals close to and remote from the Fermi surface providing an indirect probe of deformation and potentials used in mean-field descriptions.
  - ✓ The limits to the existence of high-K states, both at high excitation energy and as a function of proton and neutron number and the competition between collective and intrinsic excitation.
  - ✓ The question of the dilution of the K-quantum number due to both random interactions in regions of high-level density, and to chance degeneracies in regions of low level density.
  - ✓ As a seniority- and configuration-dependent probe of the major residual interactions in deformed nuclei, specifically pairing and spin-spin interactions.

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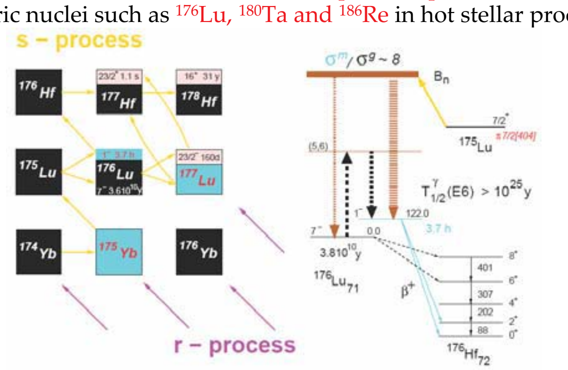
Why Studying Isomers – cont.?

- Interesting astrophysical applications: stellar thermometers and chronometers
  - ✓There is considerable interest in the role of nuclear structure effects (the precise disposition of excited states) and the possible role of the K-quantum number in the formation and possible photo-destruction of isomeric nuclei such as ^{176}Lu, ^{180}Ta and ^{186}Re in hot stellar processes.



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Why Studying Isomers? – cont.

Applications

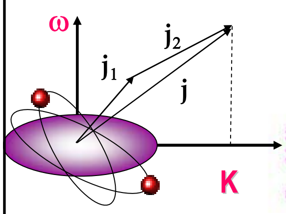
- ❑ Activation analysis
- ❑ Medicine
- ❑ Gamma-ray lasers/batteries?
- ❑ Transmutation of nuclear waste?

Exotic Studies

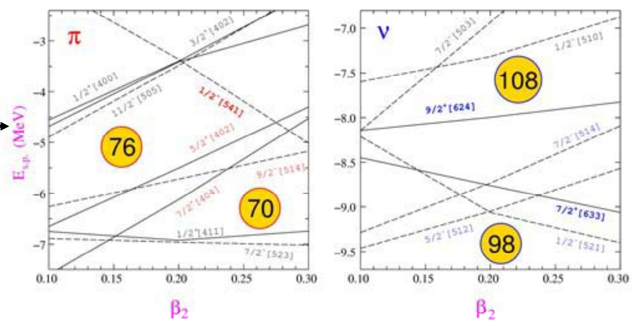
- ❑ Radioactive targets – high-spin/seniority, e.g. ^{178m2}Hf, ^{177m}Lu
- ❑ Radioactive beams – the future of nuclear knowledge

K Isomers: Where to find them?

- ❑ Deformed nuclei with axially-symmetric shape



Mass 180 region : Yb (Z=70)-Ir(Z=77)



- ❑ High-K orbitals near the Fermi surface

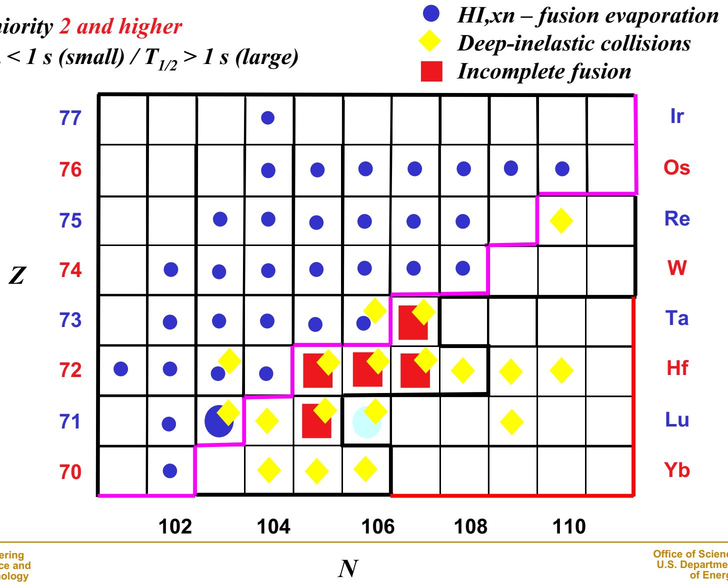
π 5/2[402], 7/2[404], 9/2[514]

ν 5/2[512], 7/2[514], 7/2[633], 9/2[624]

→ **7-qp K=49/2**

K-Isomers in the A~180 Region

- Seniority 2 and higher
- $T_{1/2} < 1$ s (small) / $T_{1/2} > 1$ s (large)

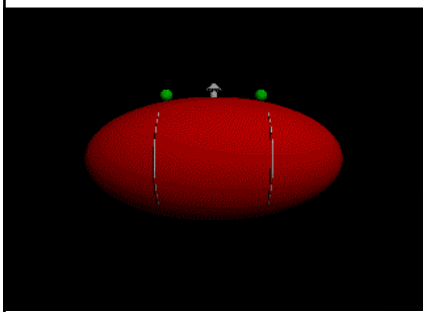


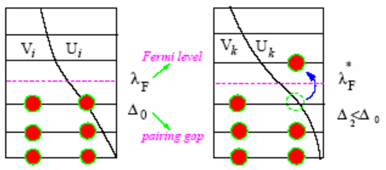
Pairing Destruction in Nuclei

In general there are **two** anti–pairing mechanisms :

(a) Coriolis anti–pairing – induced by the fast rotation

(b) Blocking – occupation of level(s) by unpaired nucleon(s)

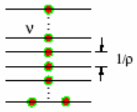




$V^2_{i(k)}\ U^2_{i(k)}$ the probability that a given state is or is not occupied

uniform levels distribution

$\Delta_\nu = [\Delta_0(\Delta_0 - \nu/\rho)]^{1/2}$



ν – the number of blocked particles (seniority)

ρ – level density near the Fermi surface

$1/\rho \sim 300$ keV and $\Delta_0 \sim 900$ keV

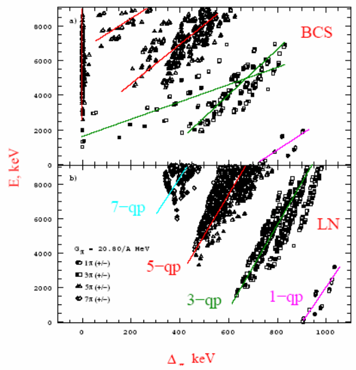
$\nu \sim 3$ $\Delta = 0$!

Pairing Gap & Seniority

illustrative example: blocked multi−quasiparticle calculations − protons $^{177}_{73}\mathrm{Ta}_{104}$

mean field − Nilsson potential *pairing* − BCS model, LN model

LN: *W. Nazarewicz et al. NP A512 (1990)*
W. Satula et al. NP A578 (1994)

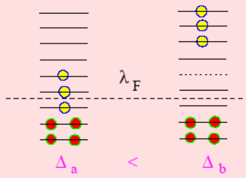


(a) Has the pairing really gone ?

(i) the number of blocked levels

seniority dependence

(ii) their location



configuration dependence

(iii) the single−particle density

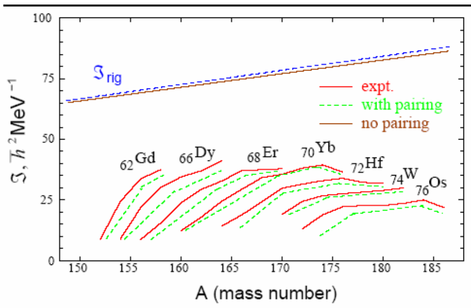
$\Delta \sim exp\,[-1/G\,\rho\,]$

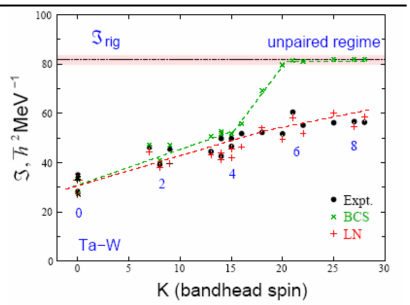
shell structure dependence

(b) How to prove it?

rotation of the MQP state comes to the rescue

Pairing & Moment of Inertia



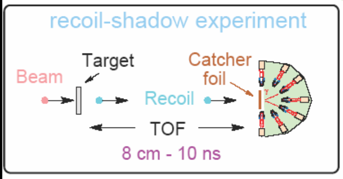


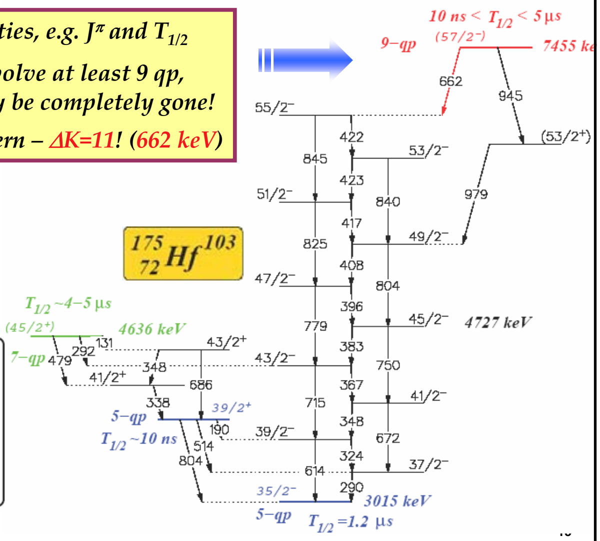
- *Implication:* yet higher seniority states would not show marked decrease in pairing
  G.D. Dracoulis et al., Phys. Lett. B419 (1998)
- *Is the rigid rotation a signature of quenched pairing?*
  ℑ is smaller than $\Im_{rig}$ due to shell effects
  S. Frauendorf et al., Phys. Rev. C61 (2000)
- *Needs an experimental confirmation !*

… at Extreme of Seniority – the case of ^{175}Hf

- *Tentative quantum properties, e.g. J^{π} and $T_{1/2}$*
- *Exotic structure - must involve at least 9 qp, a case where the pairing may be completely gone!*
- *Unprecedented decay pattern – ΔK=11! (662 keV)*

$^{48}Ca + ^{130}Te \xrightarrow{3n}$ @195 MeV

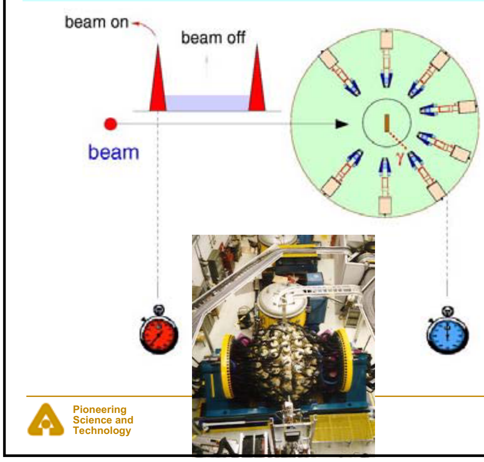




^{175}Hf Experiments at ANL and ANU/Canberra

Pulsed Beam Technique

- *Well defined "clock"*
- *Sensitive to in-beam and decay events*



ANL Experiment

^{48}Ca(^{130}Te,3n)@194 MeV

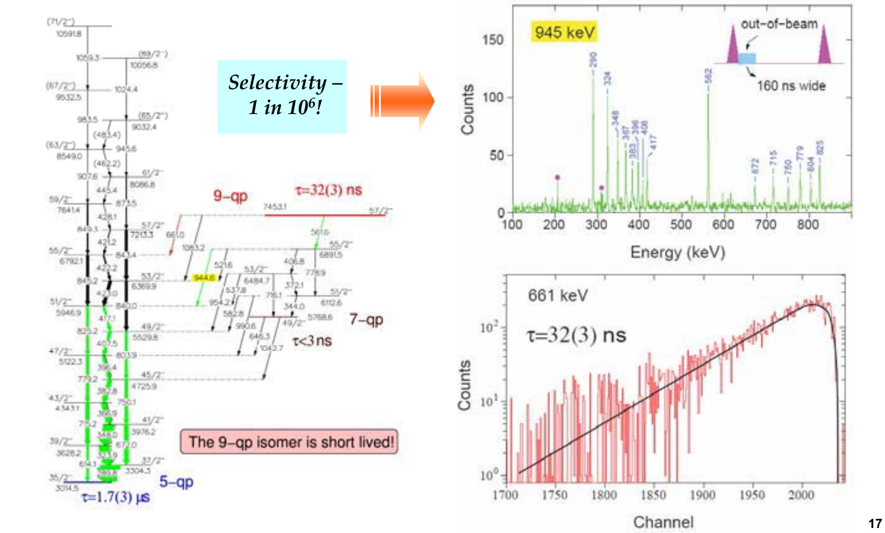
- *Pulsed beam & Gammasphere*
  1 ns on / 825 ns off
- *Thin target*
  1 ns on / 82.5 ns off

Complementary Experiment at ANU

^{9}Be(^{170}Er,4n)@50 MeV

- *Pulsed beam & CAESAR array*
  (8 CS Ge detectors)
  4 μs on/60 μs off

Decay of the 57/2- Isomer



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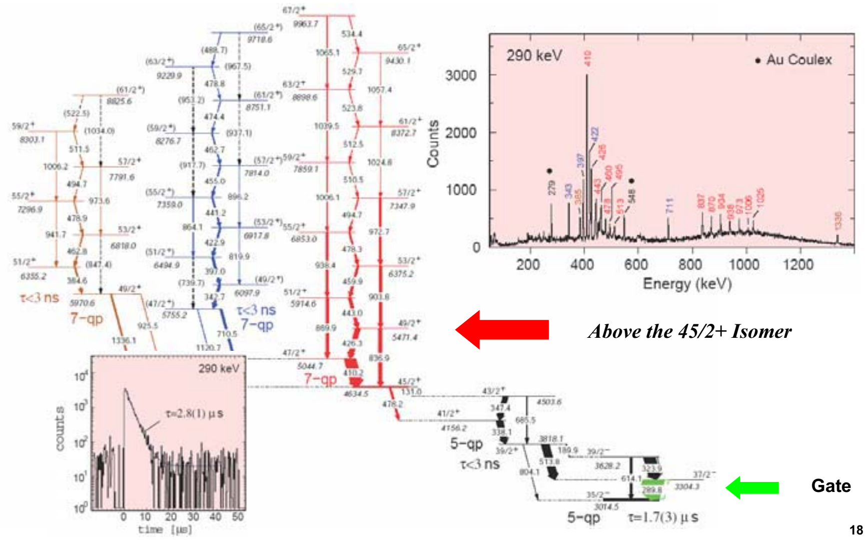
Structures above the 45/2+ Isomer



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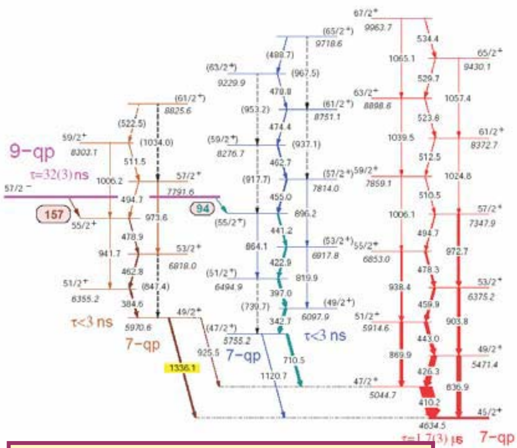
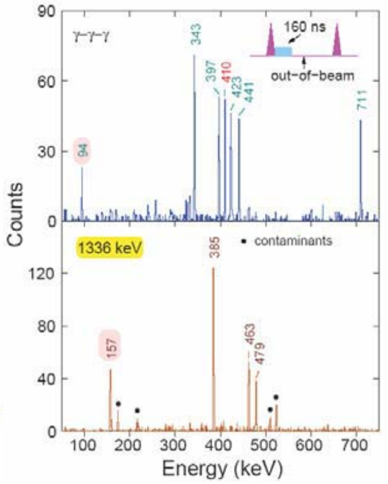
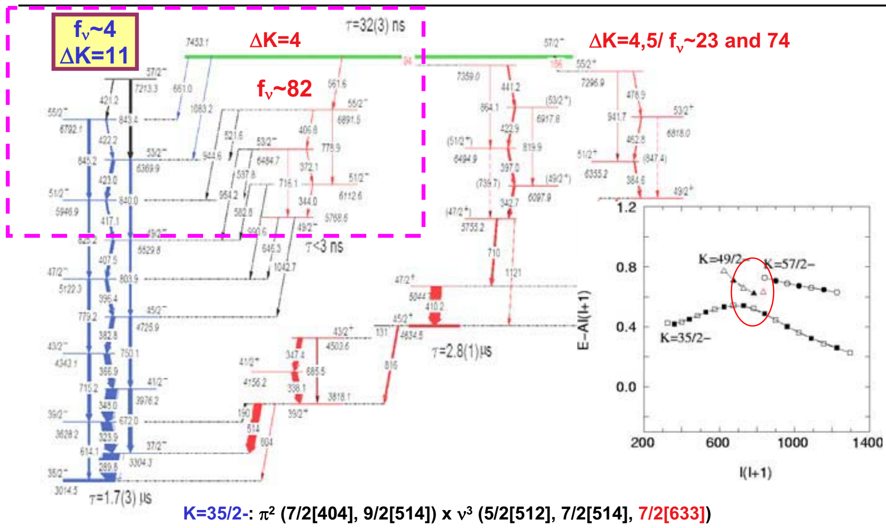
“Normal” Decay Branches





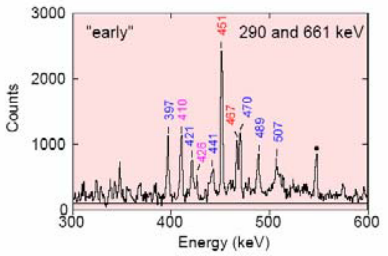
- ❑ *94 keV Mult: E1 - 18% branch*
- ❑ *157 keV Mult: E1 – 17% branch*

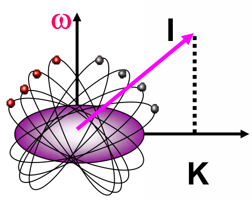
K-hindrances in the decay of the 57/2- Isomer

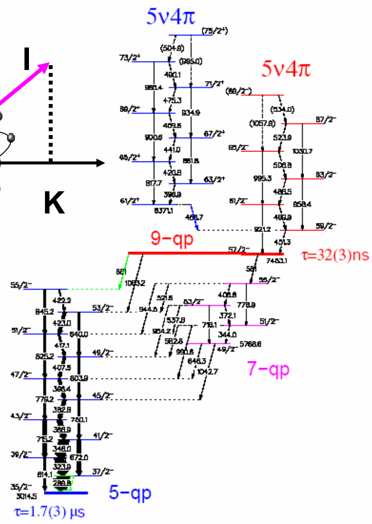


K=35/2-: π^2 (7/2[404], 9/2[514]) x ν^3 (5/2[512], 7/2[514], 7/2[633])
K=49/2-: 35/2- x ν^2 (5/2[642], 9/2[624])

Rotation of the 57/2- Isomer

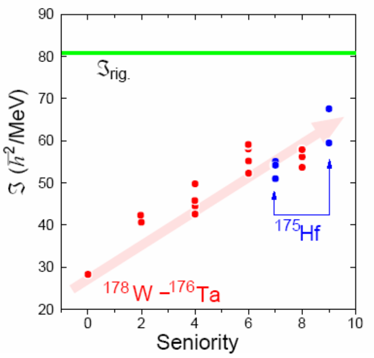


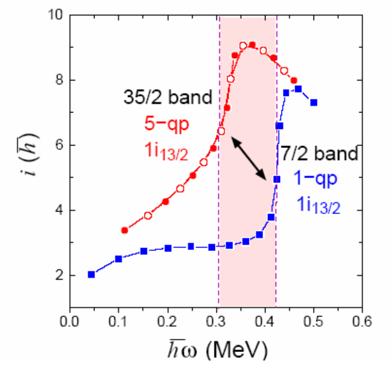




- two new 9-qp structures
- collectivity still persists
- $g_K - g_R$ – configurations

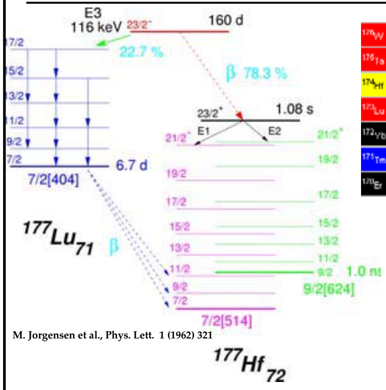
Has the Pairing Really Gone?



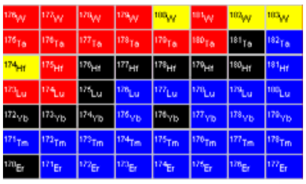


- even at 9-qp $\Im < \Im_{rig.}$
- pairing is still important
- "dynamic" vs. "static"

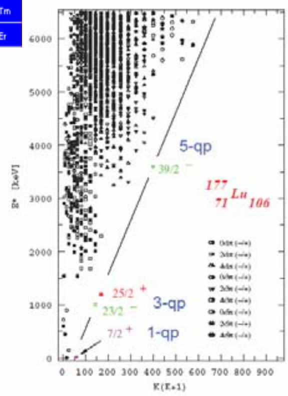
… at Extreme of Neutron number – the case of ^{177}Lu



M. Jorgensen et al., Phys. Lett. 1 (1962) 321



Deformed shell-model
- Nilsson s.p. levels
- Pairing - LN prescription

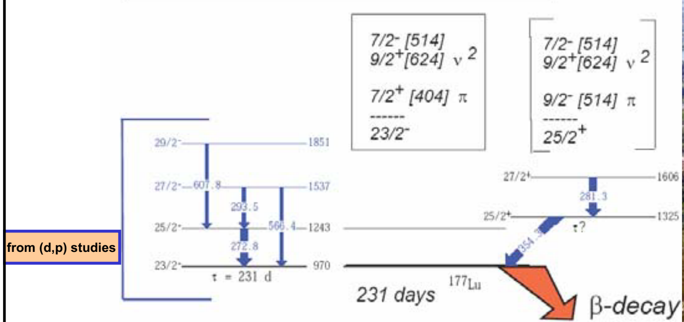


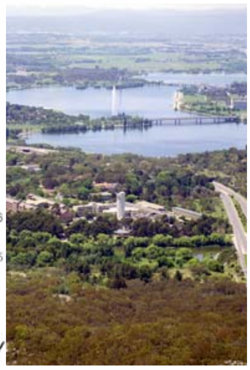
J.J. Carroll *et al.*, *Hyp. Int.* 135 (2001) 3

Isomer	Prod. factor $\sigma_{(n,\gamma)}$ [b]	Storage factor E_x [keV]	$T_{1/2}$ [y]		Triggering factor* ICS$_{trig}$ [eV b]	E_{trig} [keV]		Output factor $\langle E_\gamma \rangle$ [keV]	Overall figure of merit
^{177}Lu^m	2.8	970	0.44	427	~10^4	<100	100	230	0.056
^{178}Hf^{m2}	~10^{-6}	2,446	31	75,826	≤3 × 10^4	~10	3,000	300	0.00014

Structures Above the K^π=23/2- isomer

^{177}Lu from incomplete fusion





α–γ–γ–time coincidences 4p particle-detector array;
37 MeV 7Li ; angular momentum in 6-13 h - breakup-compound

^{176}Yb(^{7}Li,α2n) McGoram ANU PhD; to be published

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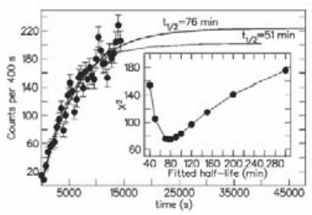
An evidence for a β– decaying isomer?

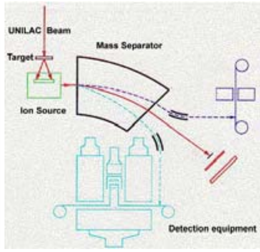
PHYSICAL REVIEW C 69, 024320 (2004)

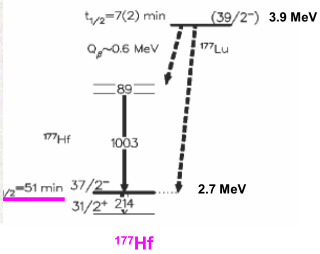
Evidence for a high-spin β-decaying isomer in ^{177}Lu

Sareh D. Al-Garni,[1,*] P. H. Regan,[1,†] P. M. Walker,[1] E. Roeckl,[2] R. Kirchner,[2] F. R. Xu,[3] L. Batist,[2,4] A. Blazhev,[2,5] R. Borcea,[2] D. M. Cullen,[6,7] J. Döring,[2] H. M. El-Masri,[1] J. Garces Narro,[1] H. Grawe,[2] M. La Commara,[2,8] C. Mazzocchi,[2,9] I. Mukha,[2,10] C. J. Pearson,[1] C. Plettner,[2] K. Schmidt,[2] W.-D. Schmidt-Ott,[11] Y. Shimbara,[12] C. Wheldon,[1,2,6] R. Wood,[1] and S. C. Wooding[1,2]

11.4 MeV/nucleon ^{136}Xe beam on ^{186}W target; thermal ion source; mass separation

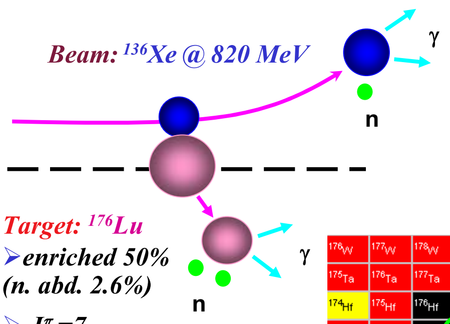






Deep Inelastic Experiment at ANL

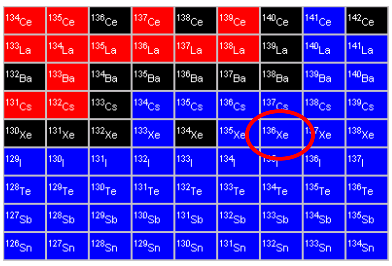
Pulsed beam & Gammasphere at ANL

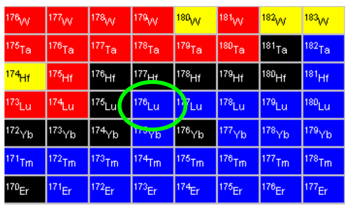


Beam: ^{136}Xe @ 820 MeV

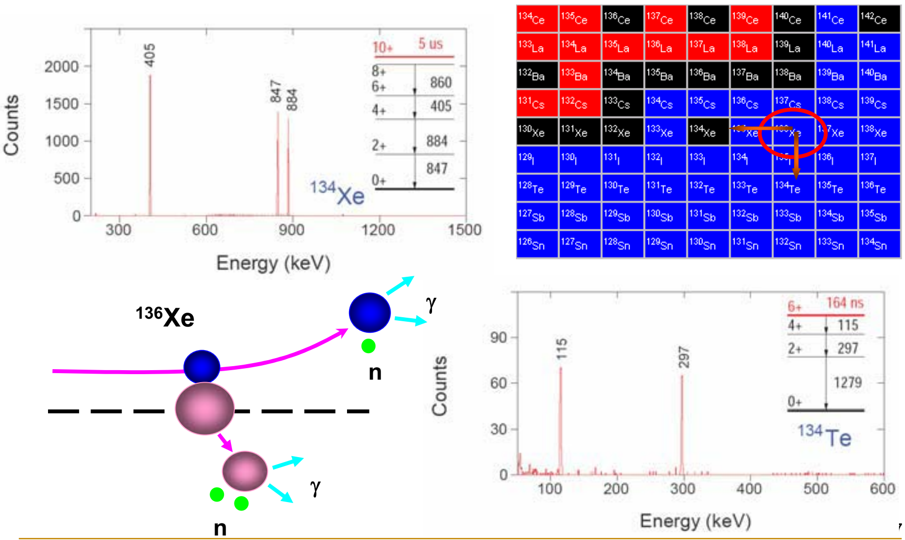
Target: ^{176}Lu
- *enriched 50% (n. abd. 2.6%)*
- *J^{π} =7-*

Target: ^{175}Lu, ^{174}Yb

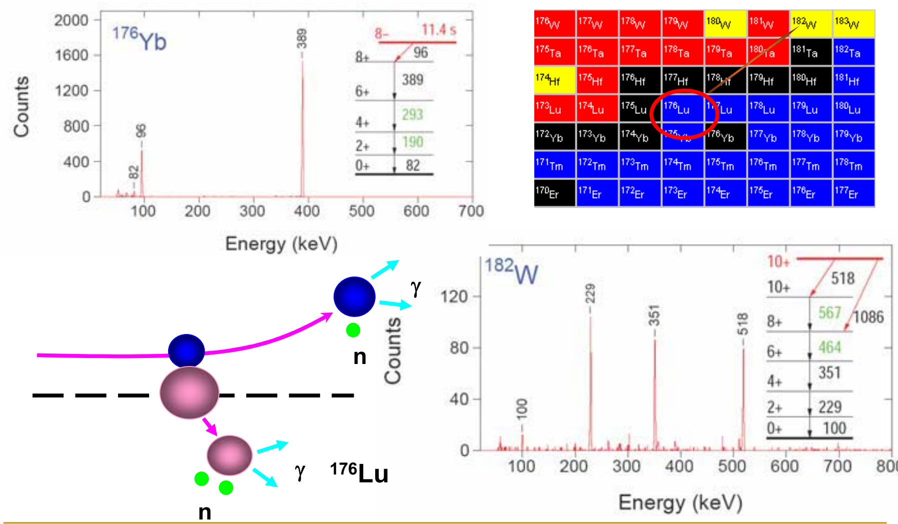




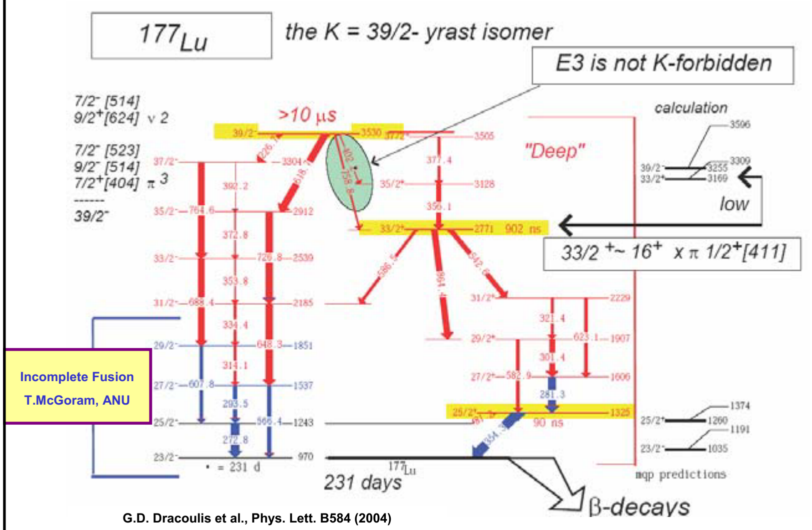
Projectile-like nuclei



Target-like nuclei

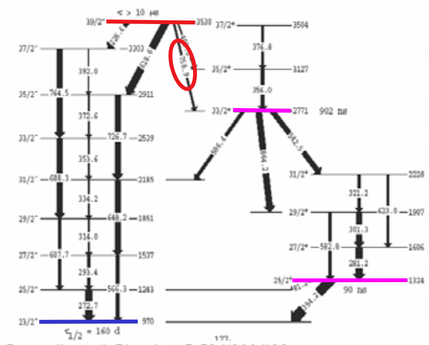


K^{π}=39/2- isomer in ^{177}Lu

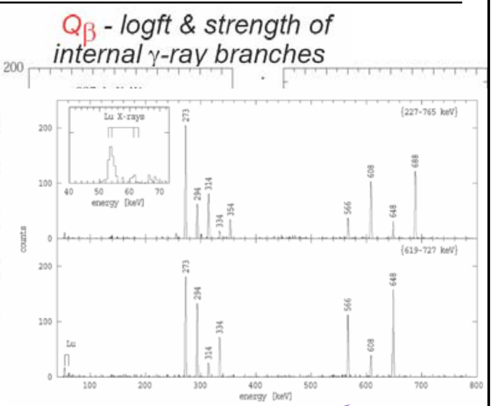


G.D. Dracoulis et al., Phys. Lett. B584 (2004)

Is this the claimed β- decaying isomer?

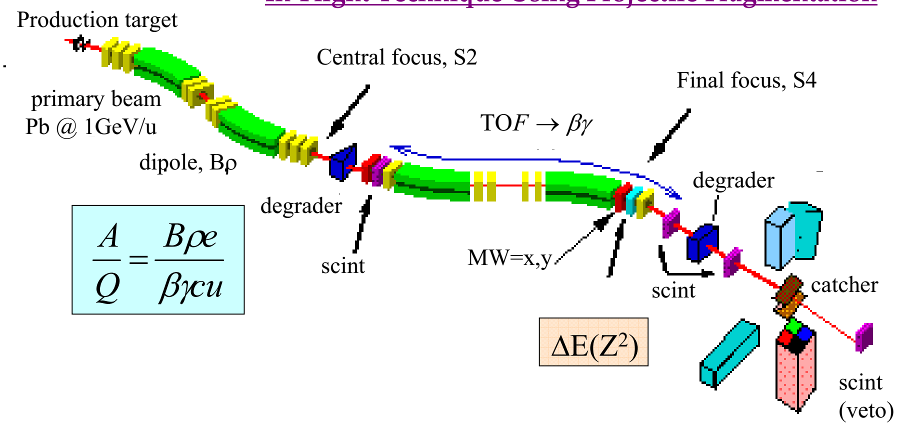


Dracoulis et al Phys Lett B 584(2004)22



- Ex=3.5 MeV (3.9 MeV)
- unambiguous γ–ray decay signature (no such gammas in the spectrum)
- unprecedented transition strength for the 759 keV, non K-forbidden, E3 transition (10^9! times retarded compared to W.u. if $T_{1/2}$=7 min)

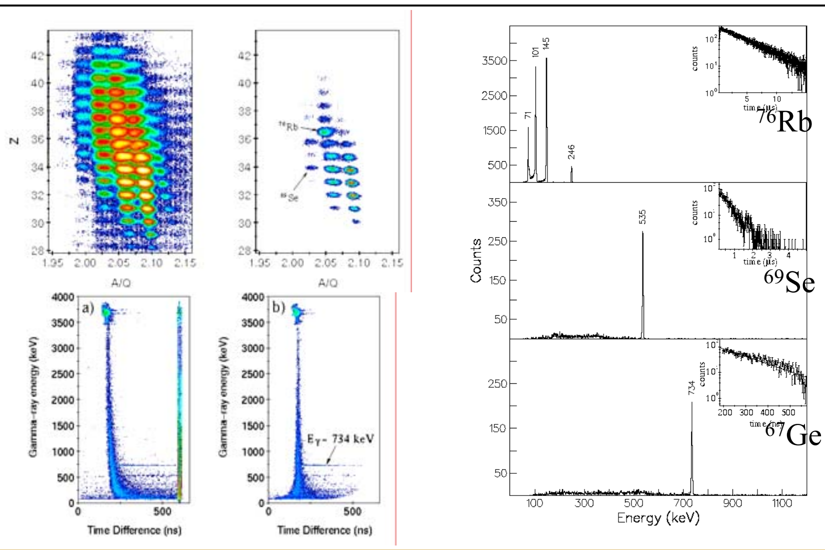
In-Flight Technique Using Projectile Fragmentation



$$\frac{A}{Q} = \frac{B\rho e}{\beta\gamma c u}$$

Use FRS@GSI or LISE3@GANIL to ID nuclei.
Transport some in isomeric states (TOF~ 300 ns).
Stop and correlate isomeric decays with nuclei id.

^{92}Mo fragmentation on ^{nat}Ni target



C. Chandler et al. Phys. Rev. **C61** (2000) 044309

The future of γ–ray spectroscopy

- Historical perspective
- Principle of gamma ray tracking
- Physics opportunities
- Technical challenges
- Status of project

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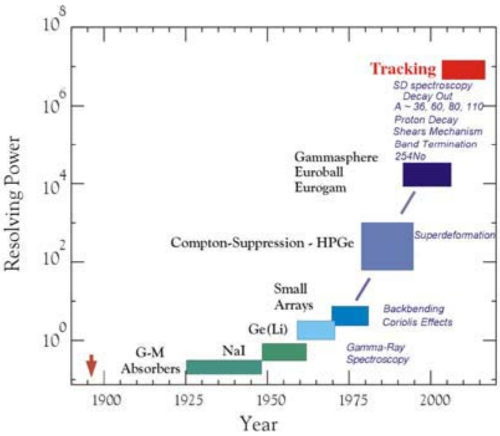
Office of Science U.S. Department of Energy

Gamma-ray Detector Development

Crucial to Nuclear Physics Research



- Advances in detector technology have resulted in new discoveries.
- Innovations have improved detector performance.
  - Energy resolution
  - Efficiency
  - Peak-to-total ratio
  - Position resolution
  - Directional information
  - Polarization
  - Auxiliary detectors
- Tracking is feasible, will provide new opportunities and meet the challenges of new facilities.

$$R \sim \left[\frac{P}{T} \times \varepsilon \times \frac{E_{spacing}}{\Delta E} \right]^n$$

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Pioneering Science and Technology

Office of Science U.S. Department of Energy

Why gamma-ray arrays?

❑ High energy resolution	ΔE_γ=2.5 keV @1.3 MeV
❑ Large P/T ratio	~60%
❑ Large photopeak efficiency	10% @ 1.3 MeV
❑ Good timing resolution	<10 ns
❑ Wide energy range	~30 keV – 20 MeV
❑ Large solid angle	~ 4π
❑ High granularity	high fold coincidences
❑ High resolving power	ability to isolate a given sequence of γ rays

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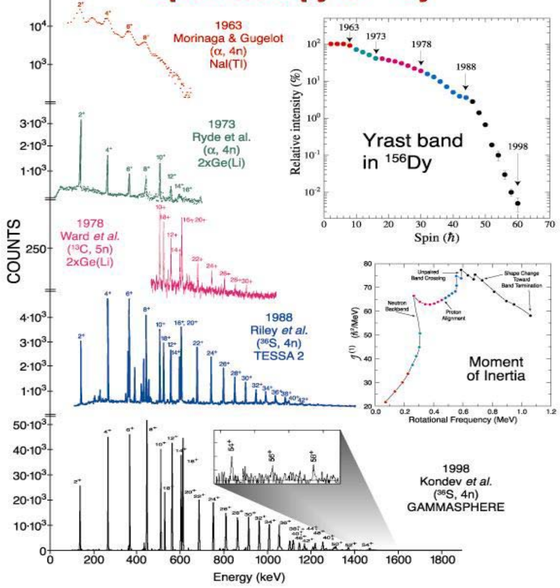
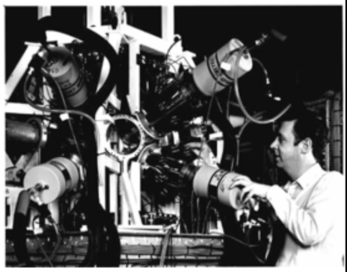
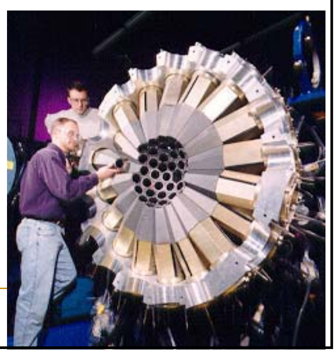
Evolution of High-Spin γ-ray Spectroscopy in ^{156}Dy

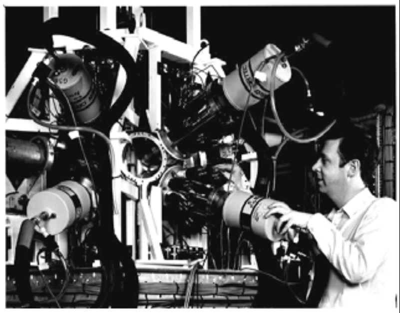






Historical Perspective

~1980 states to spin ~30
naked Ge arrays



~1980-1982 TESSA
Escape suppressed array at NBI

1983 TESSA to Daresbury
Heavier Ion beams
6 ESS using NaI(Tl)
Channel selection included, 50 element inner BGO ball

I ~ 1% sensitivity

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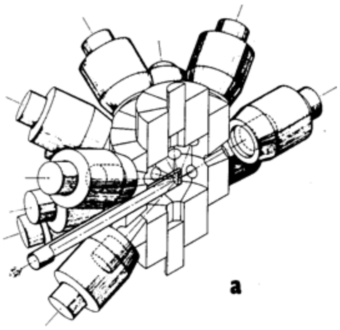
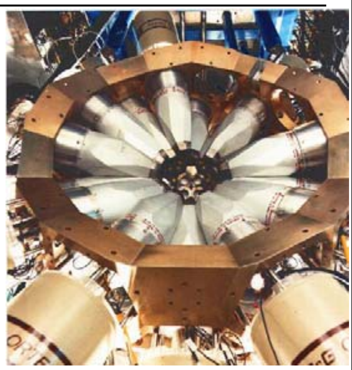
Historical Perspective – era of large arrays





~1987
BGO replaces NaI(Tl)
HERA, TESSA3

I ~ 0.1% sensitivity

~1995
Large γ–ray arrays
Eurogam, Gasp,
Gammasphere, Euroball's
I ~ 0.001% sensitivity

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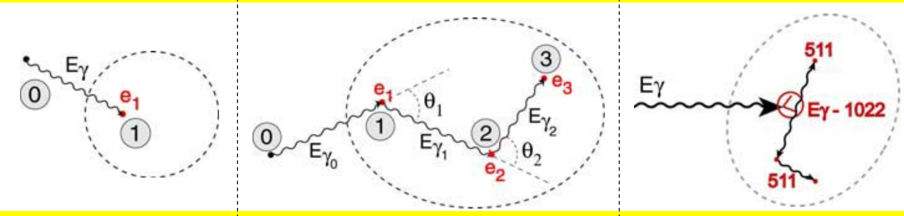
Interaction of gamma rays with matter

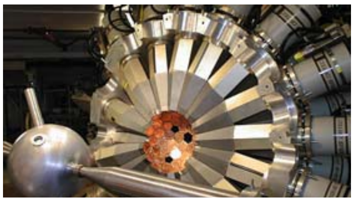
~ 100 keV | ~1 MeV | ~ 10 MeV | γ-ray energy →

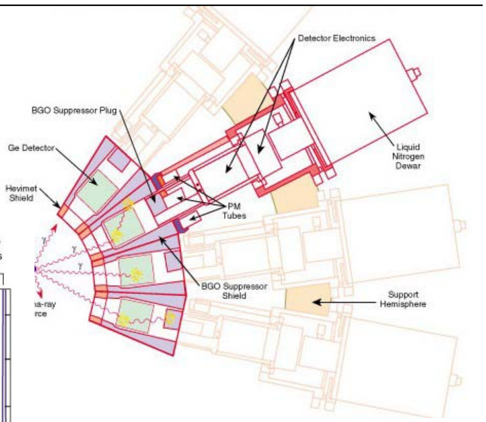
Photoelectric	Compton Scattering	Pair Production

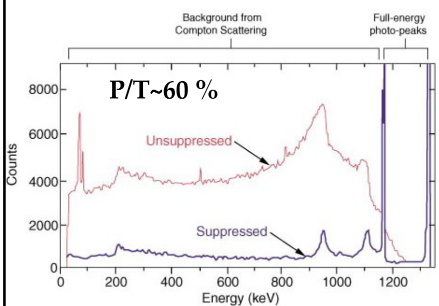


Isolated hits	Angle/Energy	Pattern of hits
Probability of interaction depth	$E_{\gamma'} = \dfrac{E_\gamma}{1+\dfrac{E_\gamma}{m_0c^2}(1-\cos\theta)}$	$E_{1st} = E_\gamma - 2\ mc^2$

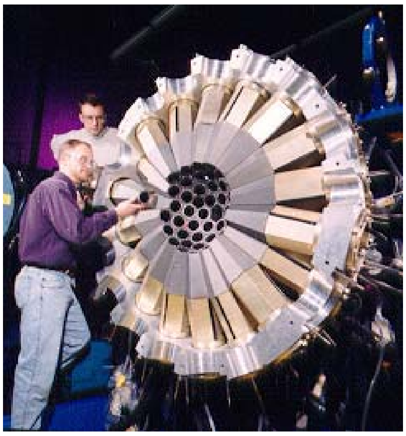
Compton Suppression – improving the peak to background ratio





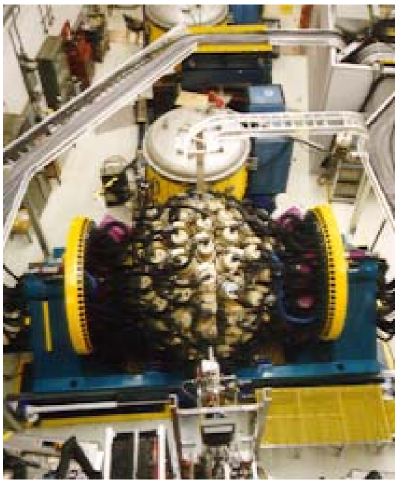


Gammasphere spectrometer



- A spectrometer with high detection sensitivity to nuclear electromagnetic radiation due to its high resolution, granularity and efficiency
- Consists of a spherical shell of 110 large volume HpGe detectors each enclosed in a BGO shield
- Funded by DOE, US

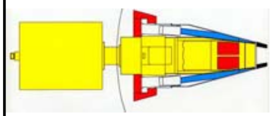
Gammasphere operation



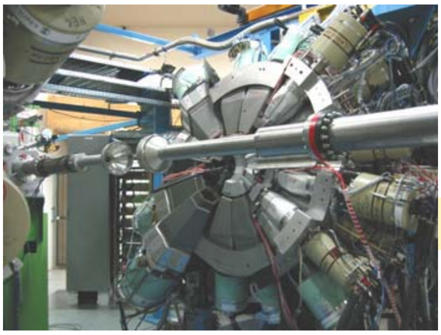
- From 1993 to 1997 GS was constructed and sited at the 88-Inch Cyclotron, LBNL
  - 130 experiments
  - super deformation
- From 1998 to 2000 GS operated at ATLAS, ANL
  - 101 experiments
  - nuclei far from stability
- From March 2000 till January 2002 at LBNL
- Since March 2002 till now GS is back at ANL

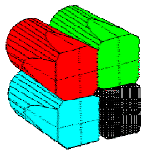
Euroball

European collaboration
France, Denmark, Germany, Italy, Sweden and the UK

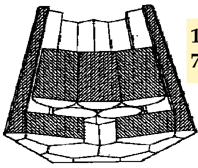


30 Large single crystal
Ge detectors





26 Clover Ge detectors
4 crystals per cryostat

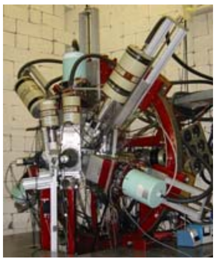


15 Cluster Ge detectors
7 encapsulated Ge crystals per cluster

239 Ge crystals
Suppression shields
Total peak efficiency ~9.4%
Intensity limit ~ 10^{-5}

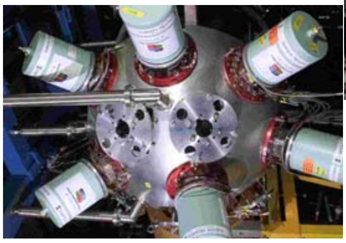
Gamma-ray arrays in US & Canada

Yrast Ball, Yale University
10 Clover
17 Ge



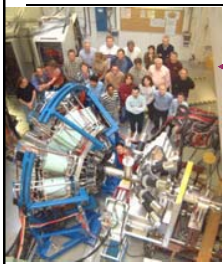
FSU Array, USA

8π, TRIUMF
~100 Ge detectors



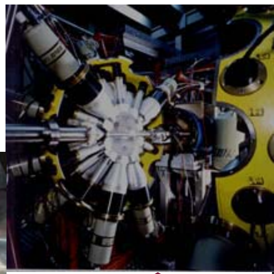
CLARION, ORNL

Gamma-ray arrays in Europe

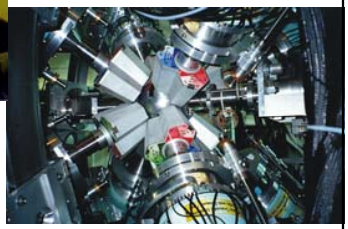


RISING, GSI

JUROGAM, JYFL



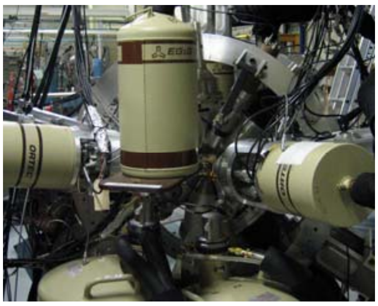
GASP, INFN

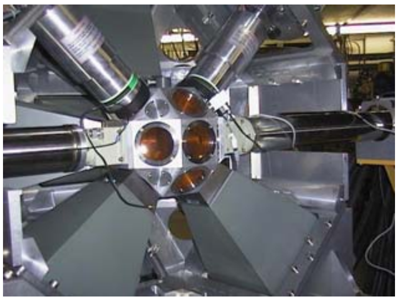


EXOGAM, Ganil

MINIBALL, RexIsolde

Australia, Asia & Africa





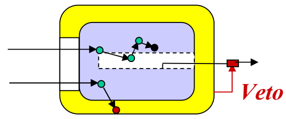
CAESAR, Australia

Afrodite, South Africa

Smaller arrays operate
in India, China and Japan

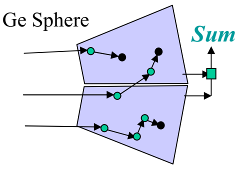
Gamma-ray Tracking Concepts

- Compton Suppressed Ge



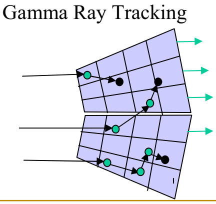
$N_{det} = 100$
Peak efficiency = 0.1
Efficiency limited

- Ge Sphere



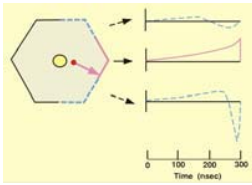
$N_{det} = 1000$ (summing)
Peak efficiency = 0.6
Too many detectors

- Gamma Ray Tracking

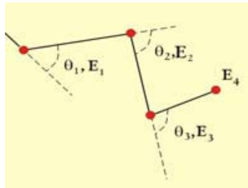


$N_{det} = 100$
Peak efficiency = 0.6
Segmentation

Pulse shape analysis in segments ➔ 3D position



Tracking of photon interaction points ➔ energy, position



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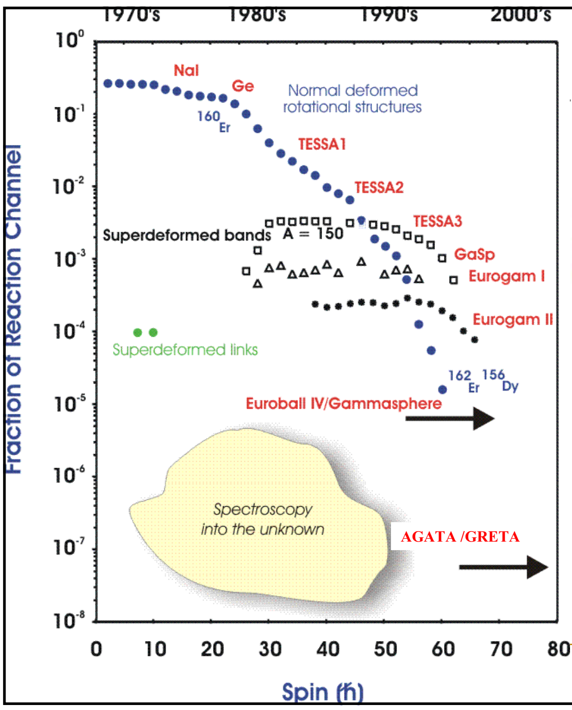
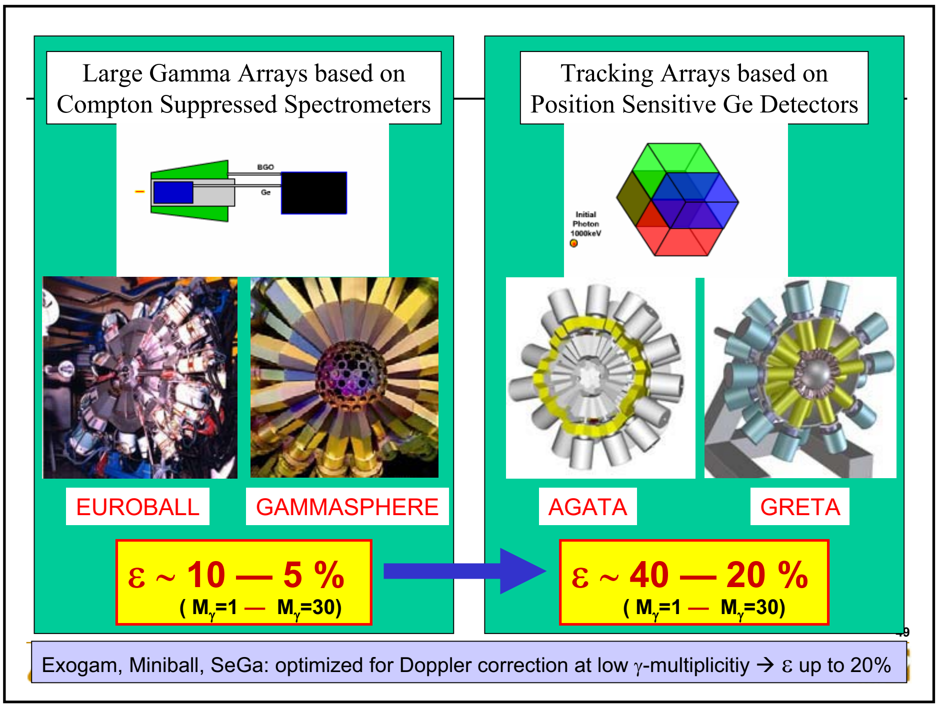


GRETINA

AGATA
ADVANCED GAMMA TRACKING ARRAY

48



GRETA/GRETINA

- **Resolving power: 10^7 vs. 10^4**
  - Cross sections down to ~1 nb
    - *Most exotic nuclei*
    - *Heavy elements (e.g. ^{253,254}No)*
    - *Drip-line physics*
    - *High level densities (e.g. chaos)*
- **Efficiency (high energy) (23% vs. 0.5% at E_γ=15 MeV)**
  - Shape of GDR
  - Studies of hypernuclei
- **Efficiency (slow beams) (50% vs. 8% at E_γ =1.3 MeV)**
  - Fusion evaporation reactions
- **Efficiency (fast beams) (50% vs. 0.5% at E_γ =1.3 MeV)**
  - Fast-beam spectroscopy with low rates -> RIA
- **Angular resolution (0.2° vs. 8°)**
  - N-rich exotic beams
    - *Coulomb excitation*
  - Fragmentation-beam spectroscopy
    - *Halos*
    - *Evolution of shell structure*
    - *Transfer reactions*
- **Count rate per crystal (100 kHz vs. 10 kHz)**
  - More efficient use of available beam intensity
- **Linear polarization**
- **Background rejection by direction**

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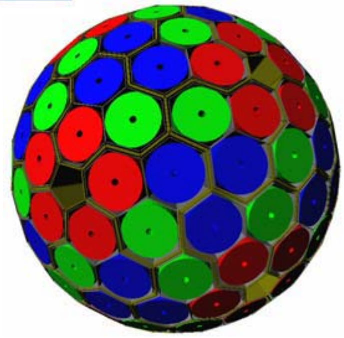
AGATA
(Advanced GAmma Tracking Array)



Main features of AGATA

Efficiency: 40% (M_γ=1) 25% (M_γ=30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

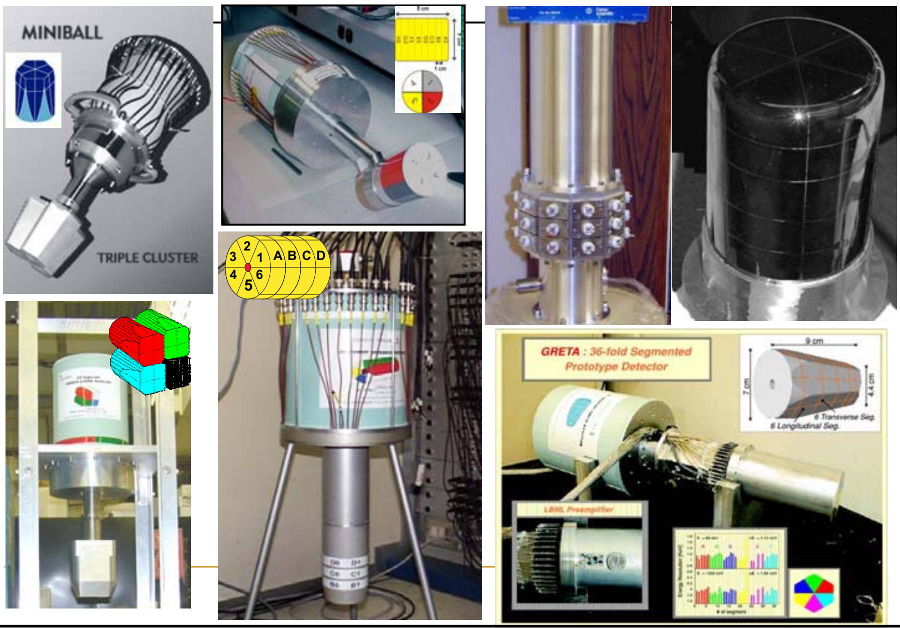
Peak/Total: 55% (M_γ=1) 45% (M_γ=30)
today ~55% 40%

Angular Resolution: ~1° →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

Rates: 3 MHz (M_γ=1) 300 kHz (M_γ=30)
today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow
- Operation of Ge detectors in position sensitive mode → γ-ray tracking

Highly segmented Ge Detectors

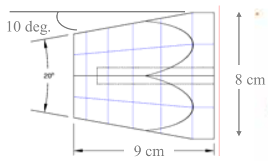


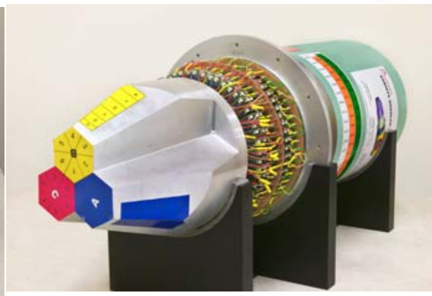
Canisters AGATA and EUROBALL

AGATA EUROBALL

GRETINA Detectors

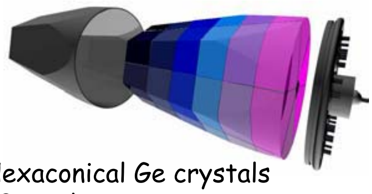
- Tapered hexagon shape
- Highly segmented $6 \times 6 = 36$
- Close packing of 3 crystals
- 111 channels of signal



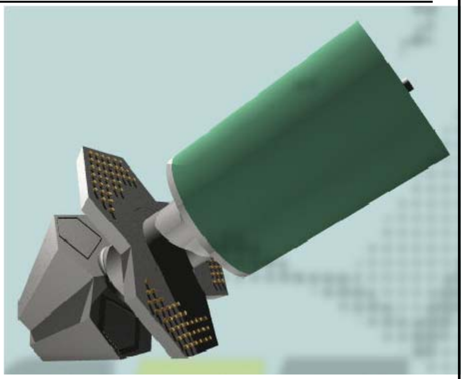


Received June 4, 2004

AGATA Detectors

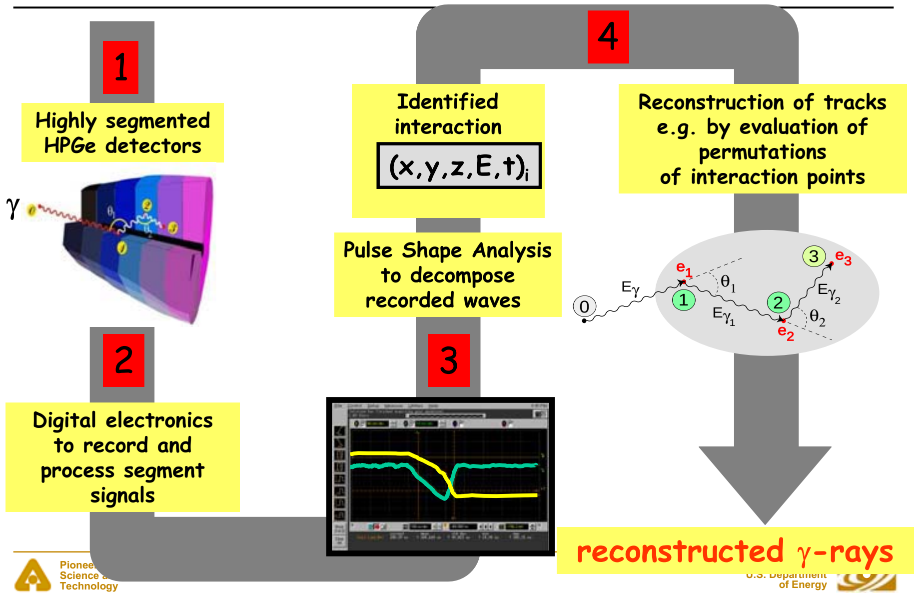


Hexaconical Ge crystals
90 mm long
80 mm max diameter
36 segments
Al encapsulation
  0.6 mm spacing
  0.8 mm thickness
37 vacuum feedthroughs



3 encapsulated crystals
111 preamplifiers with cold FET
~230 vacuum feedthroughs
LN_2 dewar, 3 litre, cooling power ~8 watts

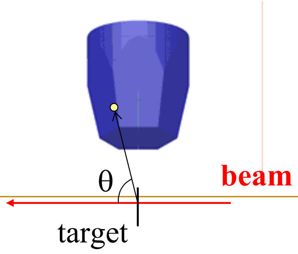
Ingredients of γ–ray Tracking



In-beam test

Experiment

- LBNL 88" Cyclotron
- Prototype II detector
- $^{82}Se + ^{12}C$ @ 385 MeV
- ^{90}Zr nuclei ($\beta \sim 8.9\%$)
- 2055 keV ($10^+ \rightarrow 8^+$) in ^{90}Zr
- Detector at 4 cm and 90°
- Three 8-channels LBNL signal Digitizer modules (24 ch.)



Analysis

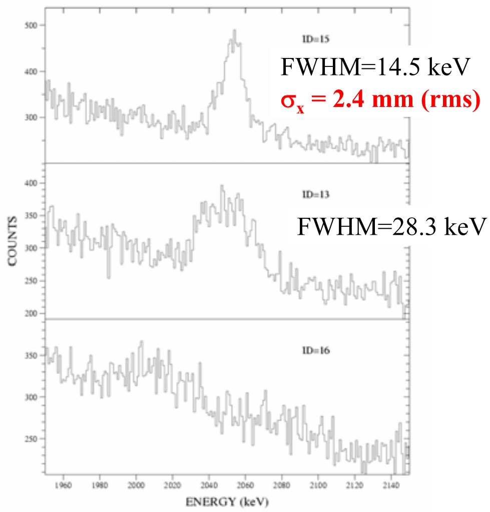
- Event building
- Calibration : cross talk
- Signal decomposition
- Doppler correction

In-beam test Results

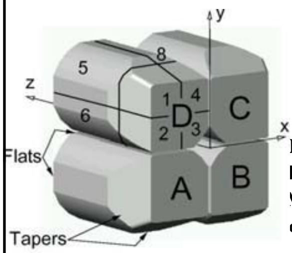
Doppler Corrected using first hit position determined by signal decomposition

Corrected using center of segment only

No correction



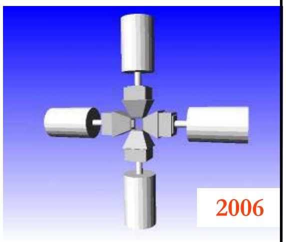
TIGRESS TRIUMF, CANADA

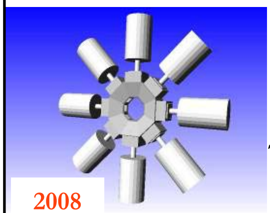


ISAC II

Nuclear Structure:

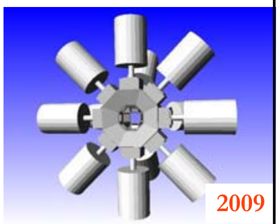
Evolution of Nuclear Shell Structure
Pairing Correlation far from Stability
Mirror Nuclei and Isospin Symmetry
oulomb Excitation with Bragg/PPAC
Fusion Evaporation reactions with CsI(Tl) and neutron detector arrays



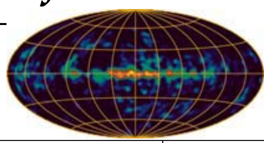


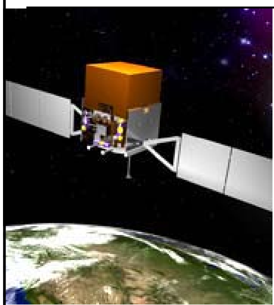
Nuclear Astrophysics:

Structure studies of astrophysically important states
Transfer reactions with EMMA/Si Array



Gamma Ray Lines of the Cosmos





Science Objective	Isotopes and Lines (MeV)
Understand Type Ia SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122)
Understand Core Collapse SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238, …***) ^{57}Co (0.122), ^{26}Al (***1.809, 0.511***)
Map the Galaxy in nucleosynthetic radioactivity	^{26}Al (***1.809, 0.511***) ^{60}Fe, ^{60}Co (***1.173, 1.332***) ^{44}Ti (0.068, 0.078, ***1.16***)
Map Galactic positron annihilation radiation	e^+–e^- annihilation (***0.511***, 3 photon continuum) SN Ia ^{56}Co positrons (***0.511***) ^{26}Al and ^{44}Ti positrons (***0.511***)
Understand the dynamics of Galactic Novae	^{13}N, ^{14,15}O, ^{18}F positrons (***0.511***) ^{7}Be (***0.478***), ^{22}Na (***1.275, 0.511***)
Cosmic Ray Interactions with the ISM	^{12}C (4.4), ^{16}O (6.1), ^{20}Ne(***1.634***), ^{24}Mg(***1.369***,2.754),^{28}Si(***1.779***), ^{56}Fe(***0.847,1.238***)
Neutron Star Mass-Radius	p-n (***2.223***)

The Concept

Position sensitive gamma ray detectors have been under development for many years

- ❑ In Space Science
- ❑ In Medical Imaging
- ❑ In Basic Nuclear Research
- ❑ In Homeland Security and Verification.

Scintillator: NaI, CsI, LSO

Semi-conductor: Si, CdZnTe, CdTe

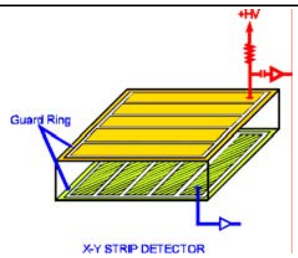
High Purity Germanium: offers the best energy resolution and timing for intermediate (40-2500 keV) radiation. Very large and efficient detectors can now be fabricated.

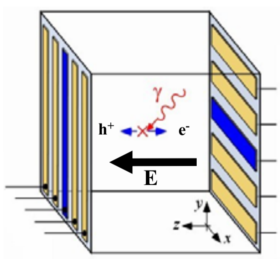
Key Question:

Can reliable, efficient, high resolution *position sensitive* germanium detectors be produced and incorporated into practical devices?

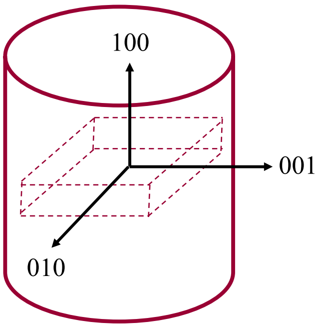
Ge Strips Detectors – an excellent choice!

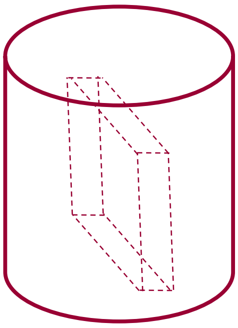
- ❑ based on the HpGe planar detector technology
- ❑ have orthogonal electrodes (strips) that provide position localization of the interactions
- ❑ operates like a conventional p-i-n diode
- ❑ pulse-shape analysis – the depth of the interactions





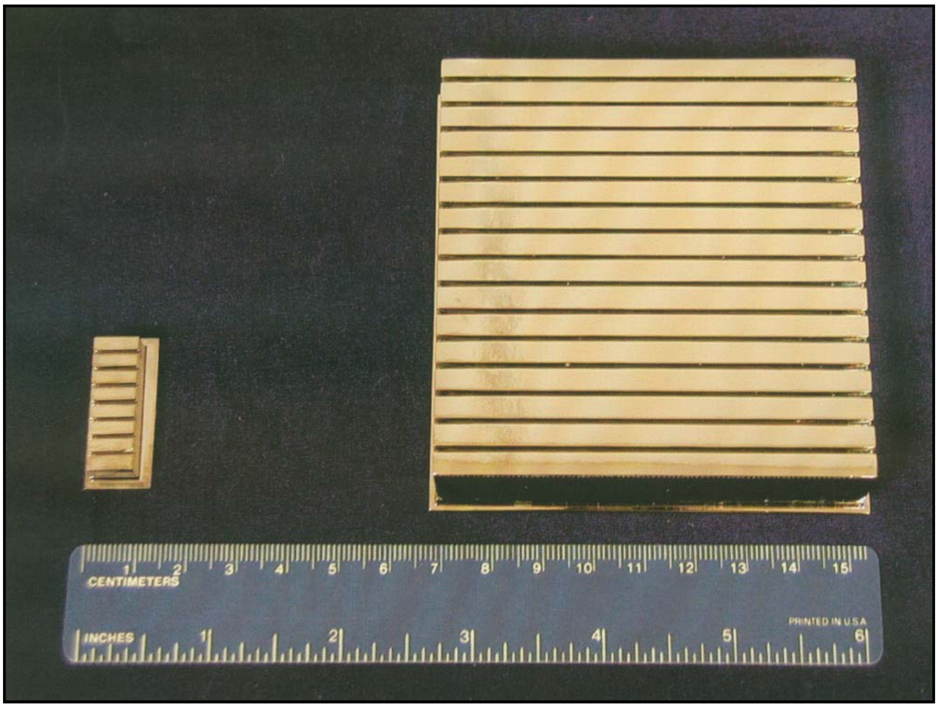
Technology: Wafer Selection



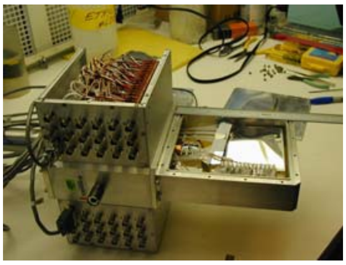


Across Boule	Along Boule
Uniform Impurities	LARGEST SIZE
LIMITED SIZE	Impurity Gradients

REAL NEED FOR FINANCING OF FACILITY TO GROW BIGGER BOULES.......(15cms)



ANL HpGe Strips Detector

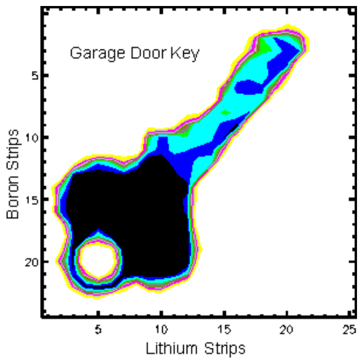


With the premier US germanium detector manufacturer, **Ortec**, we have built

- ❑ ***the biggest*** (~90 mm x 90 mm x 20 mm)
- ❑ ***the best*** (~1.0 keV at 122 keV, ~2.0 keV at 1.3 MeV)

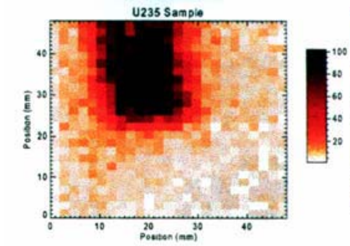
Ge strips detector in the world!

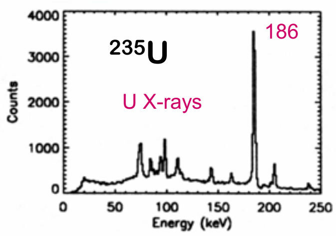
2D Imaging Capabilities



25 x 25 strip HpGeDSSD
60 keV γ-rays from ^{241}Am source

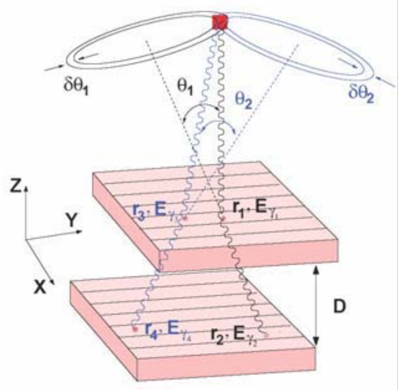
S.E. Inderhees et al., IEEE 43 (1996) 1467





Imaging and characterization

Compton Camera



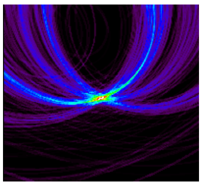
Concept

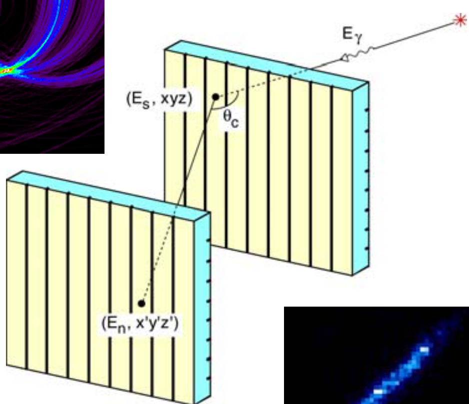
- Gamma ray Compton scatters in the first detector
- Positions and energies of individual interactions enables to determine pathway of gamma ray in the detector – *gamma-ray tracking*!
- Energies and positions define cone of incident angles (electron path is not measured)
- Cones are projected on a plane or a sphere (one circle per event) for 2D or into a cube (one cone per event) for 3D imaging

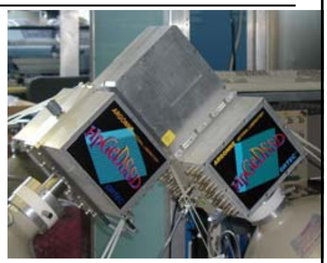
$\cos\theta_1 = [1 - m_e c^2 ((E_\gamma - E_{\gamma 1}) / E_\gamma E_{\gamma 1})]$

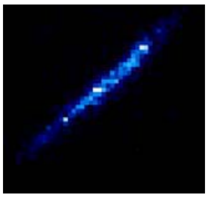
$E_\gamma = E_{\gamma 1} + E_{\gamma 2}$

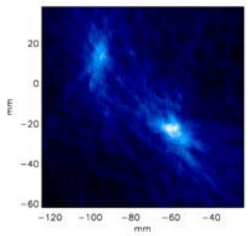
Compton Camera



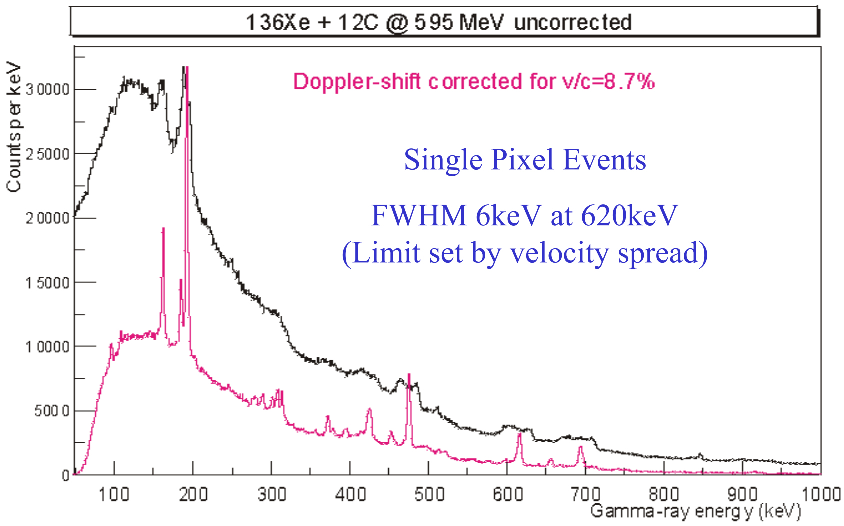








Doppler Correction



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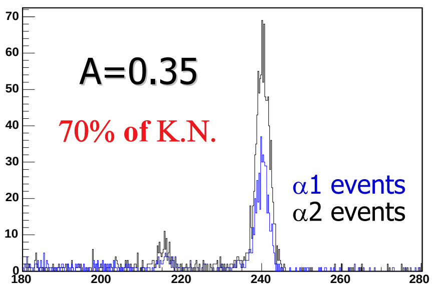
Polarization in α–γ coincidences



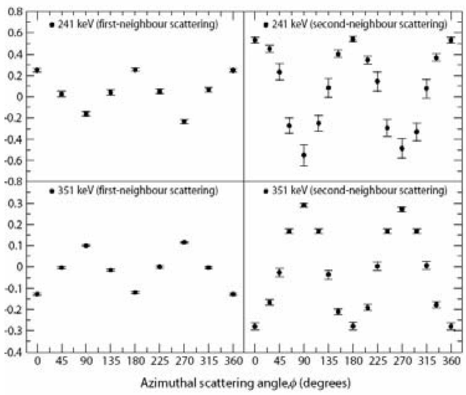
"Second Neighbor" analysis has even bigger asymmetry, and almost as much data.

16 pixels vs. 4.

"Worlds Best" figure of merit

Vertical scatters in HpGeDSSD (Boron Side)

^{228}Th 240keV (0-2-0) correlation



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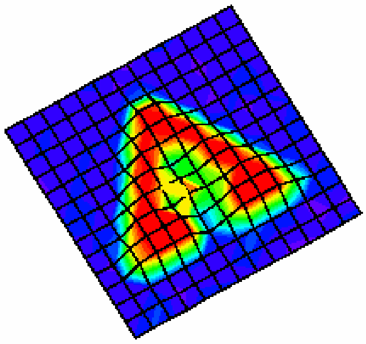
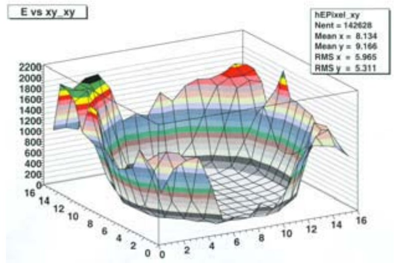
Imaging

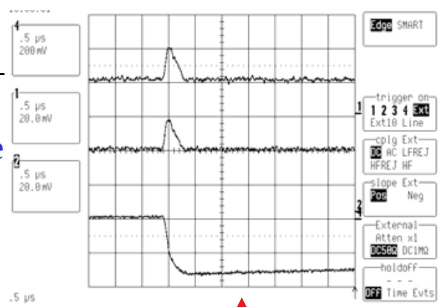


Direct Determination of materials by differential absorption

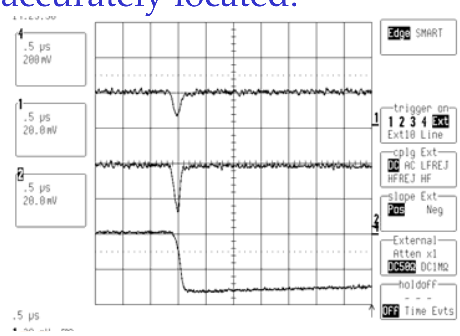


Varying source-object-detector baseline can give large magnification
This image 5mm steel ball bearing

Digital Signal Processing



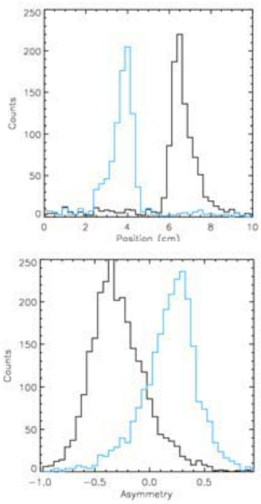
Here lies the most exciting prospect. The drifting charge created by the gamma rays induces images that allows the interaction points to be accurately located.



Shallow (Close to Electrode)
Central

Deep (Far from Electrode)
Right Side

Digital pulse processing



DEPTH
From front-back time difference of charge pulse arrival

1-2 mm
but depends on position

LATERAL
From asymmetry of induced transient signals