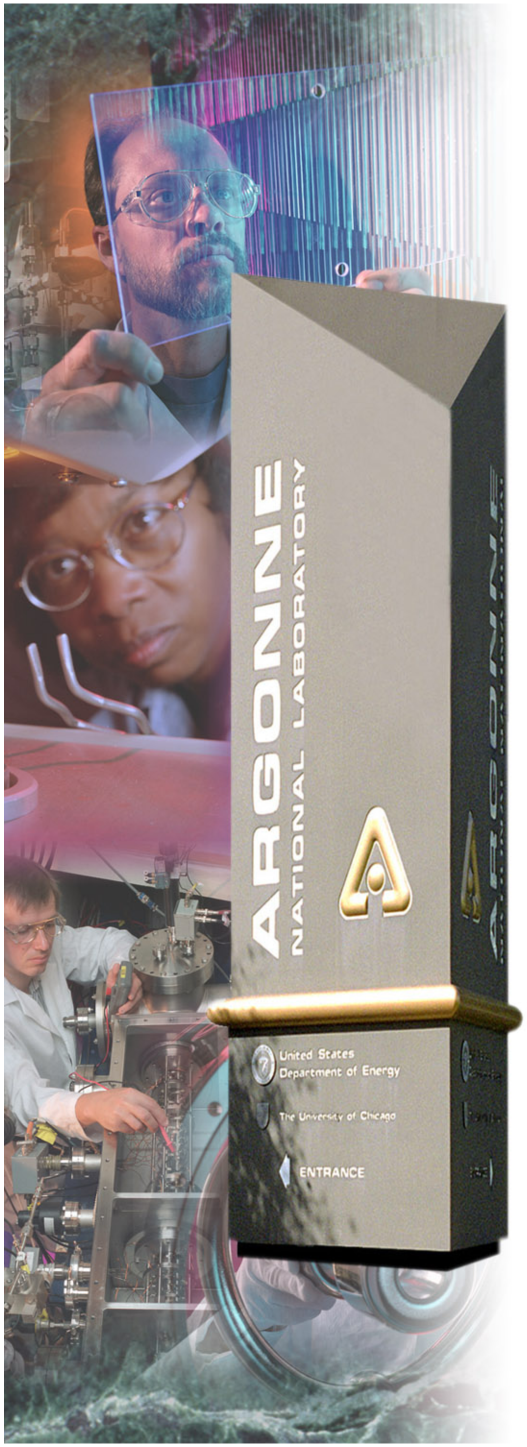

Experimental Nuclear Structure Part I

Filip G. Kondev

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

February 20th-March 3rd, 2006

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

- ❑ Introduction
- ❑ Reactions used to populate excited nuclear states
- ❑ Techniques used to measure the lifetime of a nuclear state
  - ➢ *Coulomb excitation, electronic, activity, indirect*

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 – <u>will give many examples</u>

<u>Please feel free to interrupt at any time!</u>

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

R.V.F. Janssens, 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

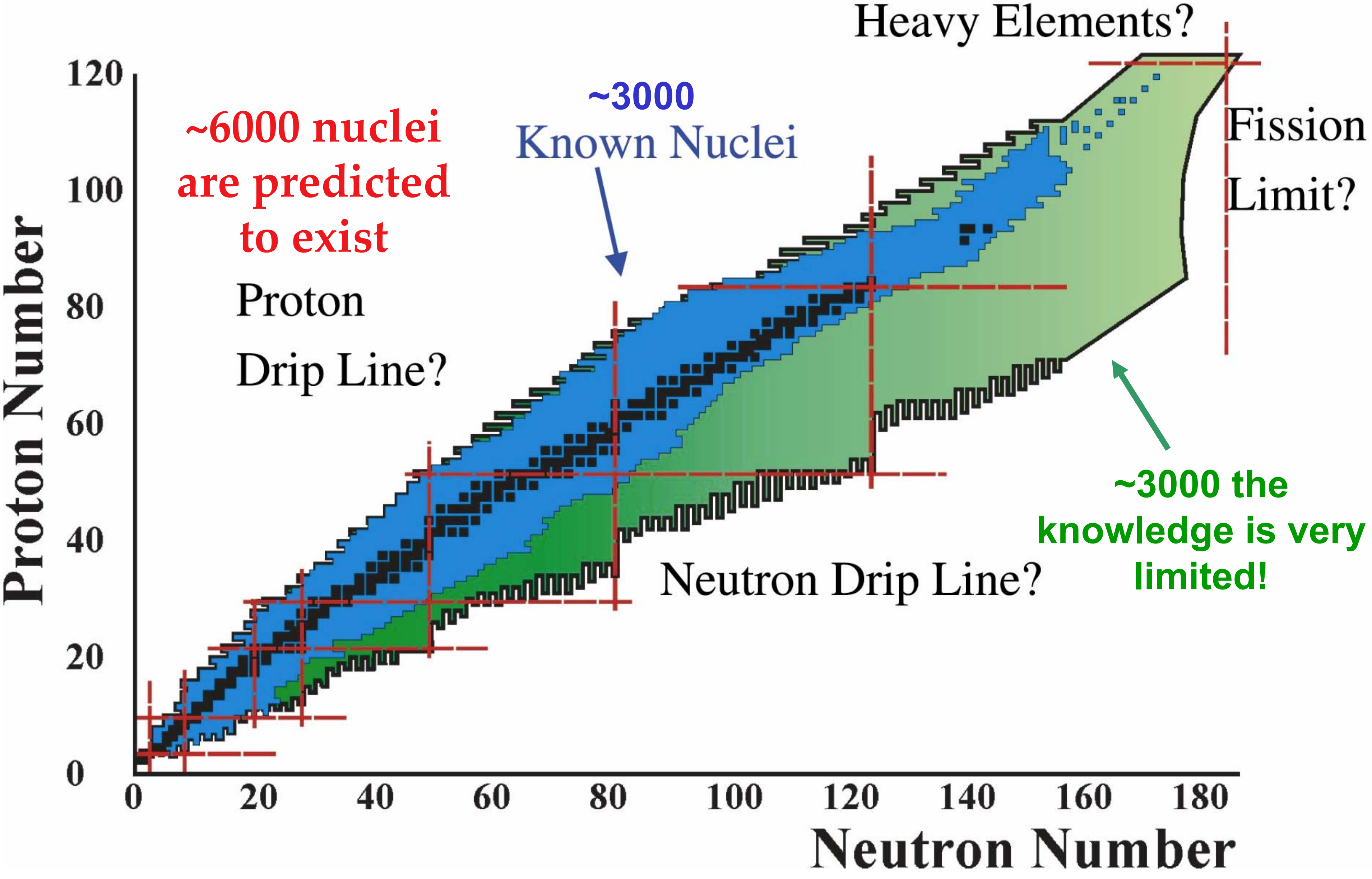
J. Simpson, Daresbury Laboratory, UK

E. Paul, University of Liverpool, UK

P. Reagan, University of Surrey, UK

and many others …

The Chart of the Nuclides



~6000 nuclei are predicted to exist

~3000 Known Nuclei

~3000 the knowledge is very limited!

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)

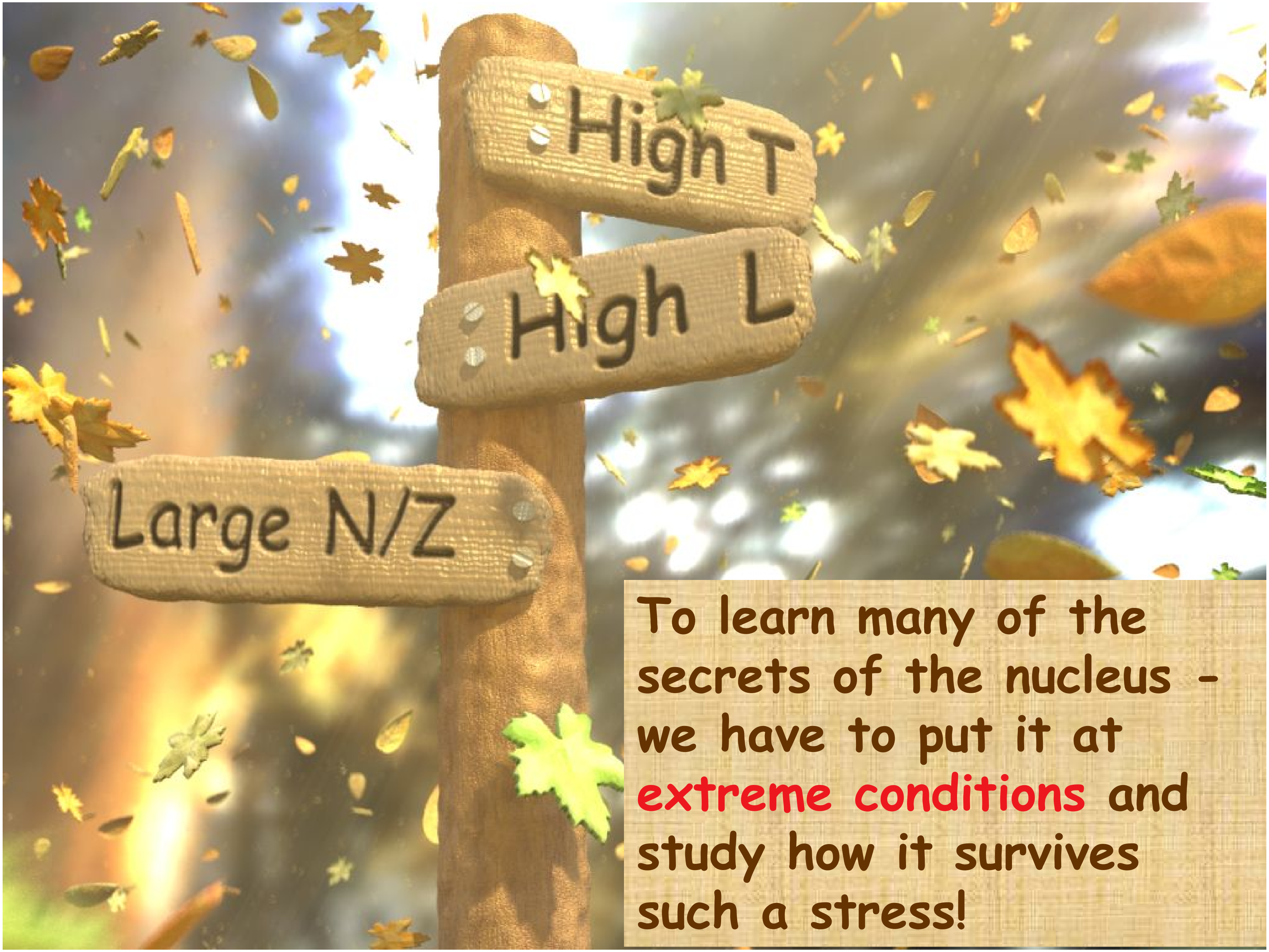
The challenge is to understand how nucleon-nucleon interactions build to create the mean field or how single-particle motions build collective effects like pairing, vibrations and shapes

NUCLEAR PHYSICS IS IMPORTANT

(intellectually, astrophysics, energy production, and security)

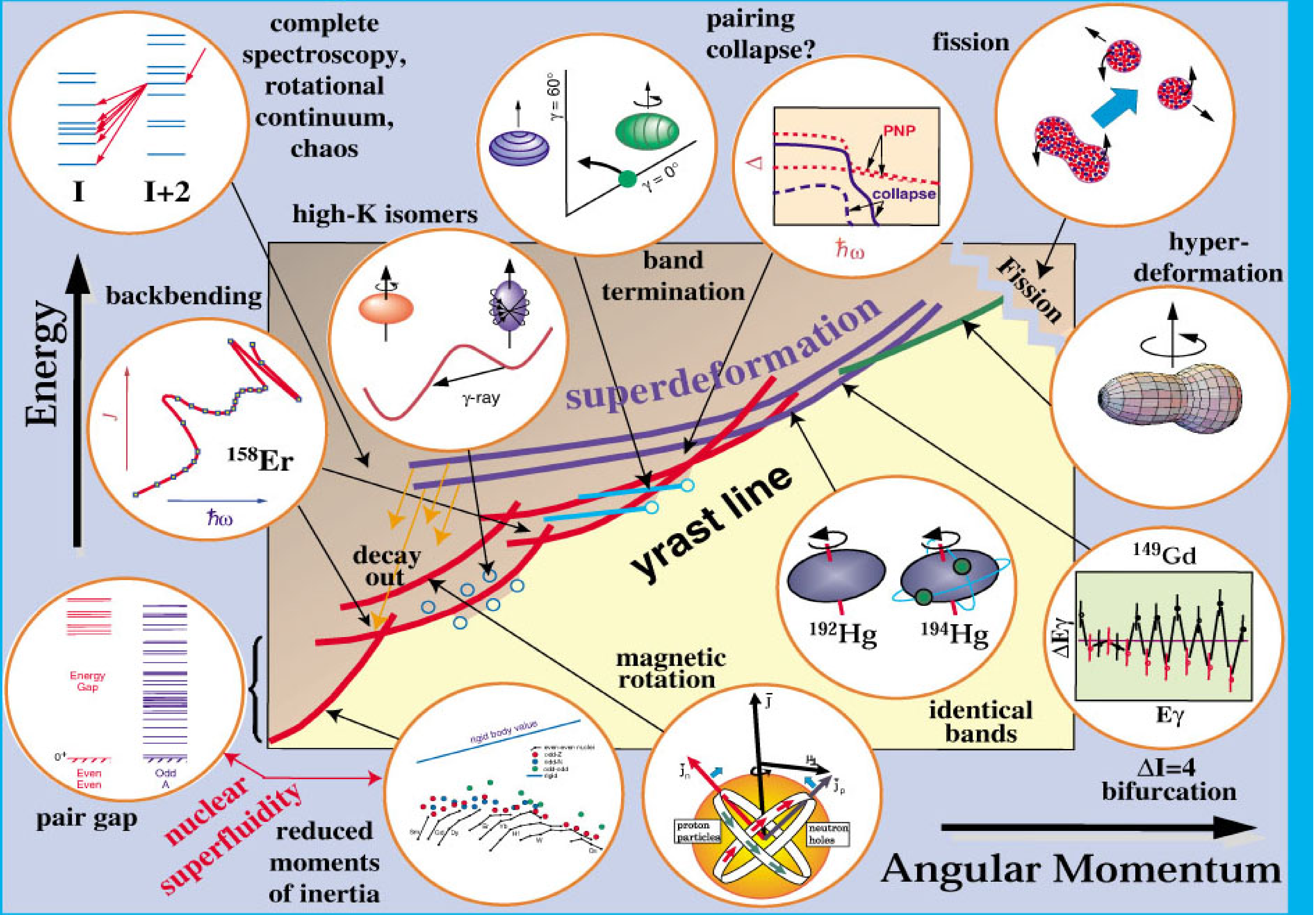
THIS IS A GREAT TIME IN NUCLEAR PHYSICS

(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!)



To learn many of the secrets of the nucleus - we have to put it at extreme conditions and study how it survives such a stress!

The Angular Momentum World of the Nucleus



complete spectroscopy, rotational continuum, chaos

pairing collapse?

fission

high-K isomers

backbending

band termination

hyper-deformation

superdeformation

yrast line

decay out

Energy

magnetic rotation

identical bands

ΔI=4 bifurcation

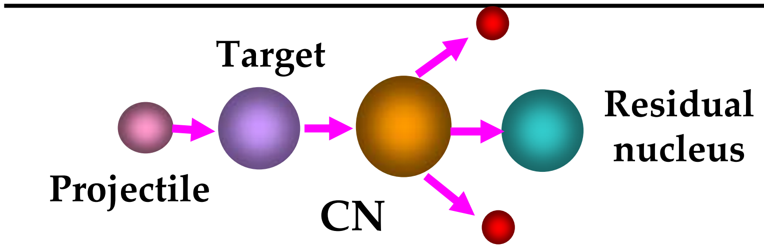
pair gap

nuclear superfluidity

reduced moments of inertia

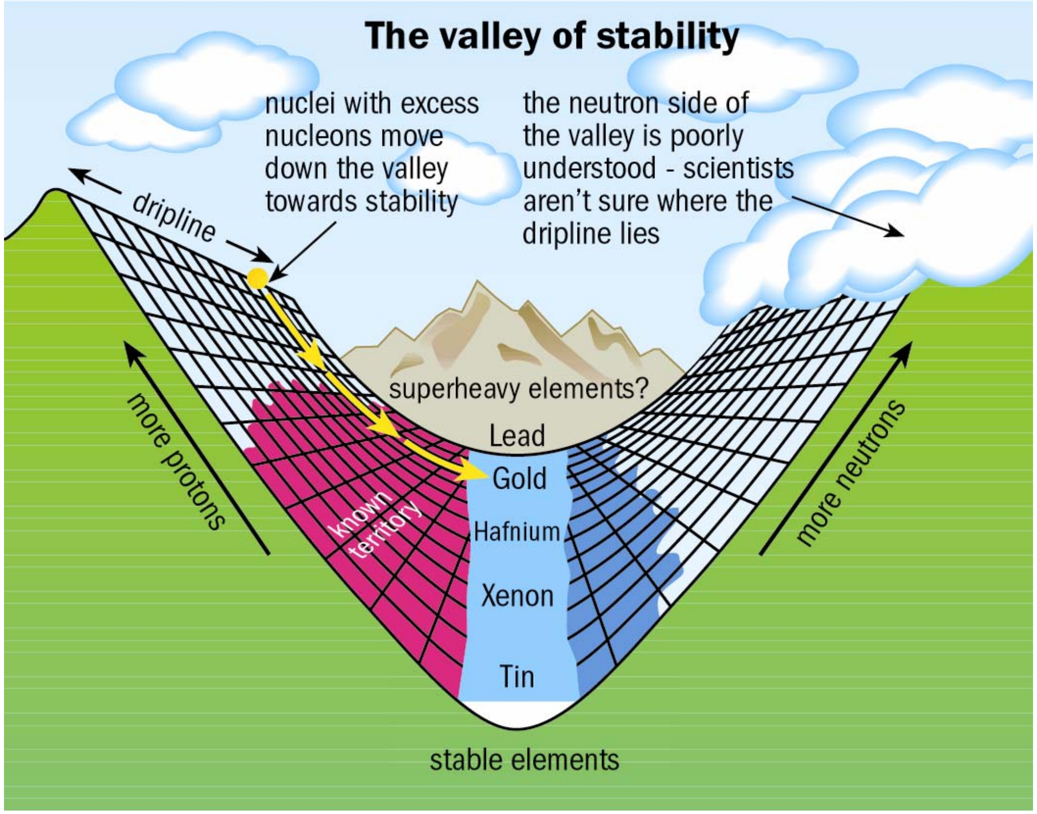
Angular Momentum

Nuclear Reactions – very schematic!



a multi-step process

- ☐ Gamma-ray & neutron induced
  - ✓ no Coulomb barrier
  - ✓ low-spin states
- ☐ Light charged particles - p, d, t, α
  - ✓ Coulomb barrier
  - ✓ low-spin states

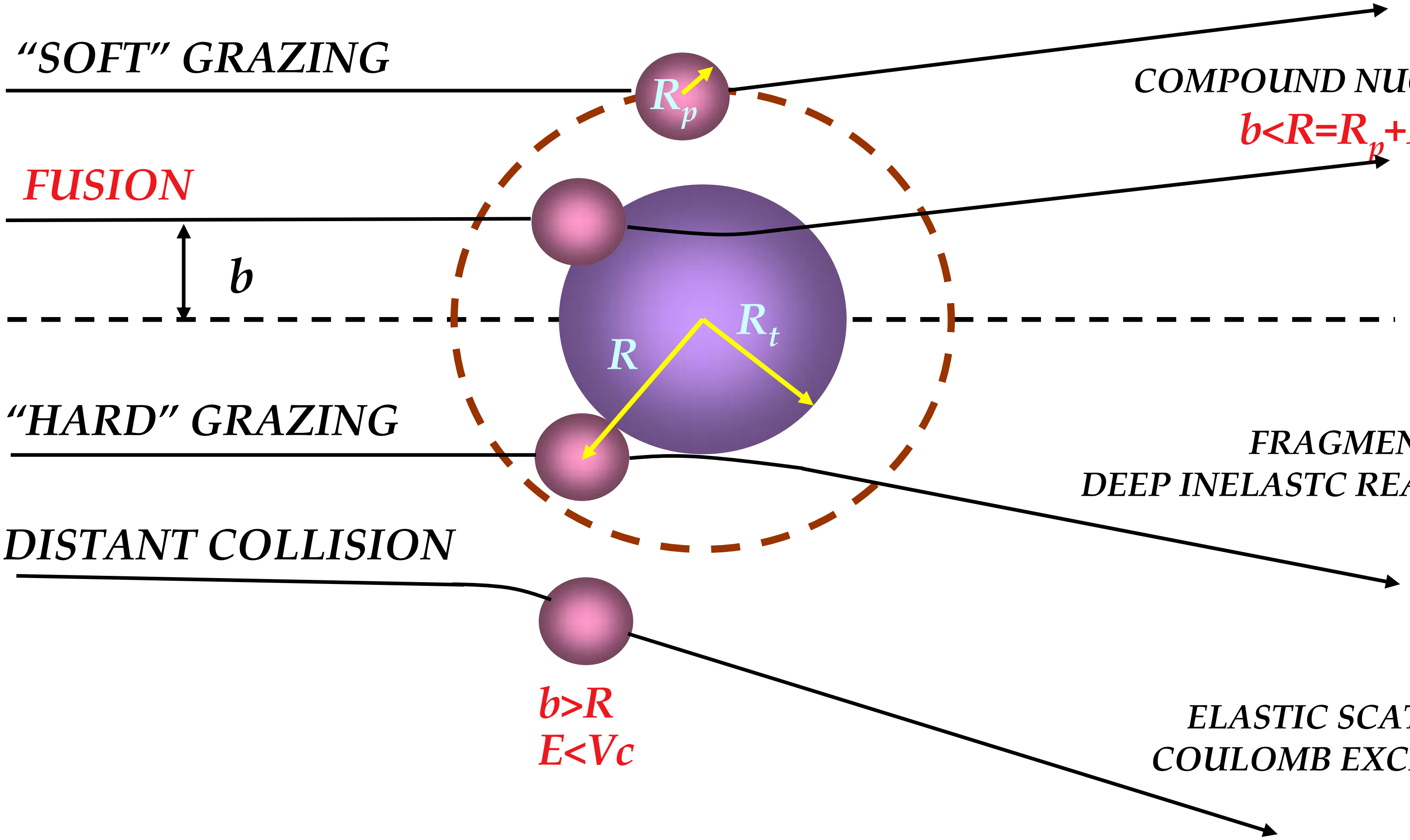


- ☐ **Heavy Ions** (1970 - ????)
  - ✓ high-spin phenomena
  - ✓ nuclei away from the line of stability

Reactions with Heavy Ions – Classical Picture

R, R_t, R_p – half-density radii

b – impact parameter



INELASTIC SCATTERING
DIRECT REACTIONS

"SOFT" GRAZING

COMPOUND NUCLEUS

$b<R=R_p+R_t$

FUSION

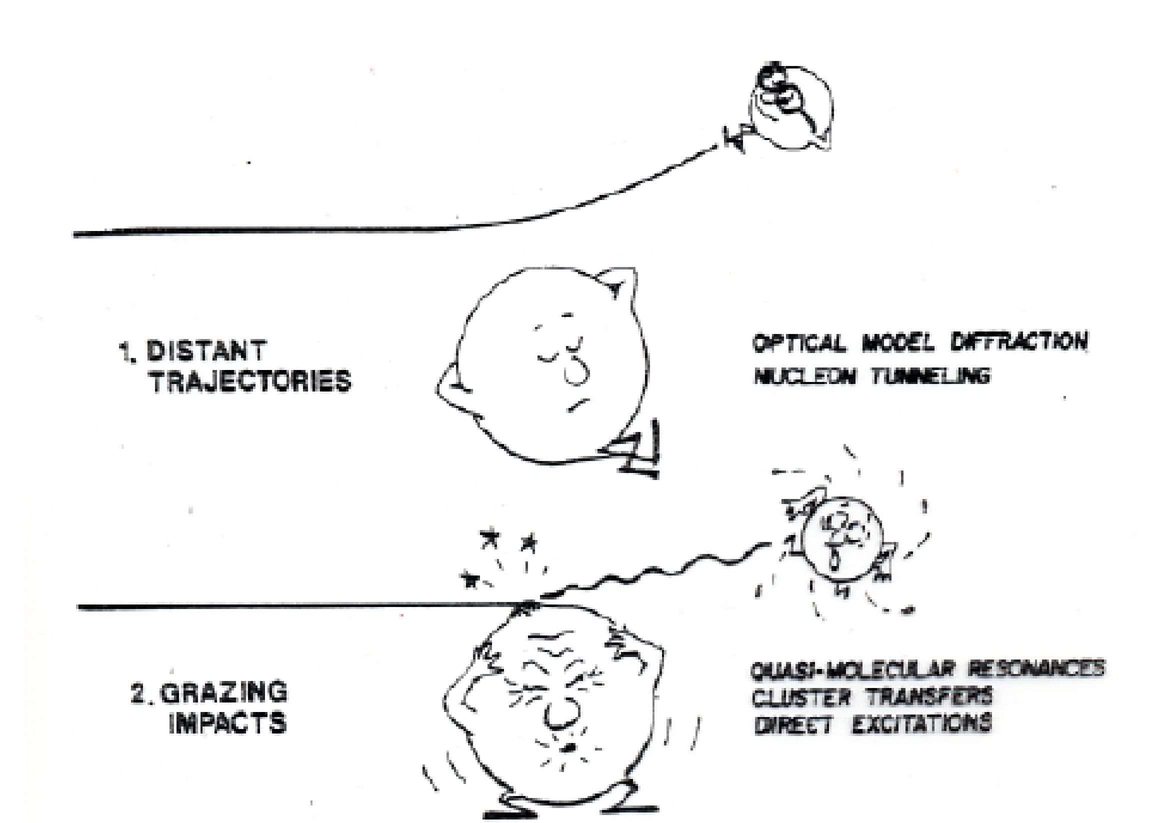
"HARD" GRAZING

FRAGMENTATION
DEEP INELASTC REACTIONS

DISTANT COLLISION

$b>R$
$E<Vc$

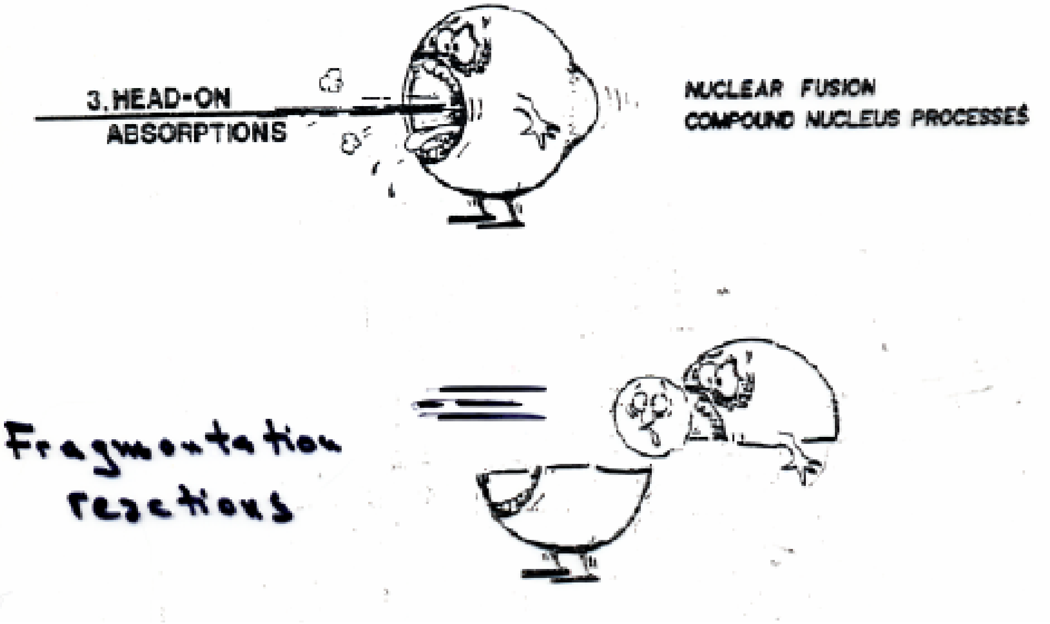
ELASTIC SCATTERING
COULOMB EXCITATION



Distant Collision

Soft grazing

Fusion



Hard grazing

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}

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

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

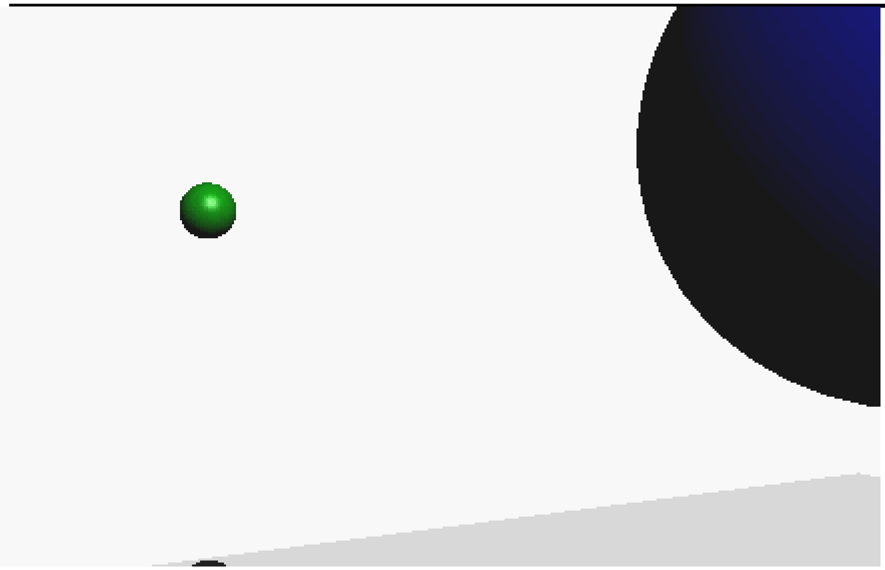
Excitation energy is usually lowered by Q-value and K.E. of evaporated particles

$$E_x = E_{cm} + Q - K.E.$$

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

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

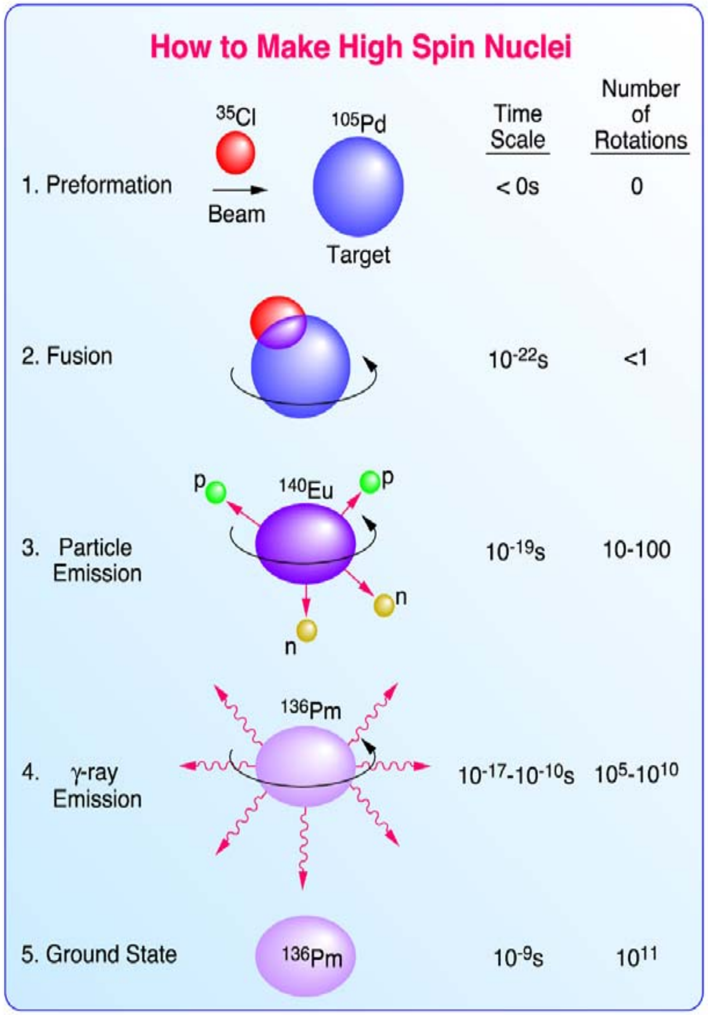
HI Fusion-Evaporation Reactions



$$\sigma_R = \pi\bar{\lambda}^2 \sum_{l=0}^{l\max}(2l+1)T_l = \pi\bar{\lambda}^2(l_{\max}+1)^2$$

$$\bar{\lambda} = \hbar / \sqrt{2\mu E_{CM}}\,, \mu = \frac{A_1 A_2}{A_1 + A_2}$$

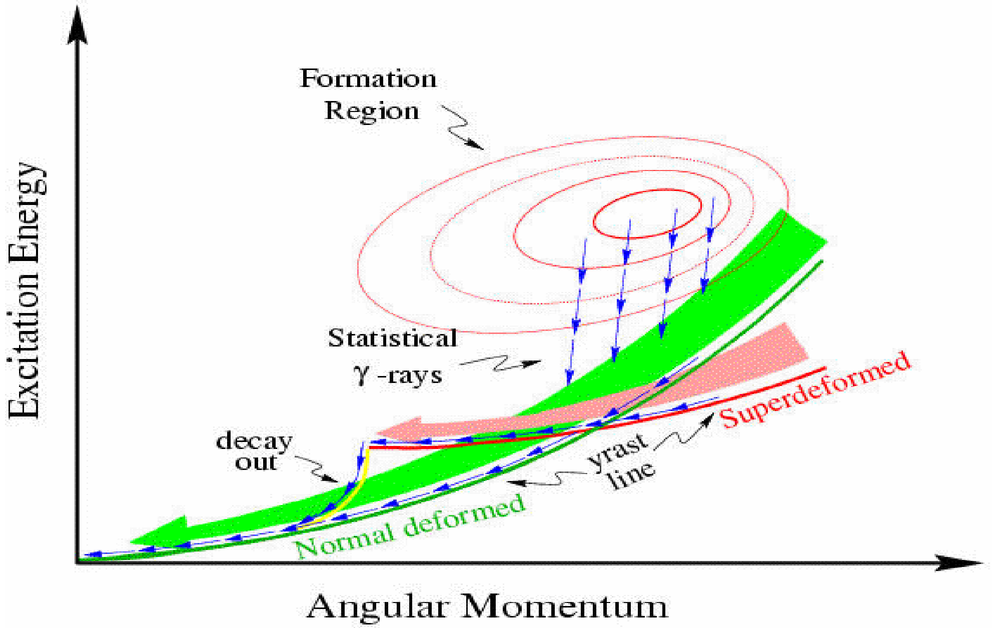
$$l_{\max}^2 = \left(\frac{2\mu R^2}{\hbar^2}\right)\left(E_{CM} - V_C\right)$$

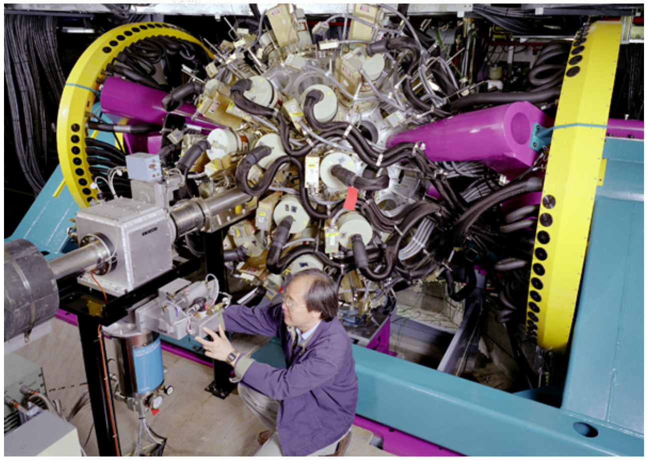


Decay of the Compound Nucleus

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

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





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, $\sim 10^{-4}$

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 $\sim 10^{-7}$

Detection of Residues in Gas Filled Separator

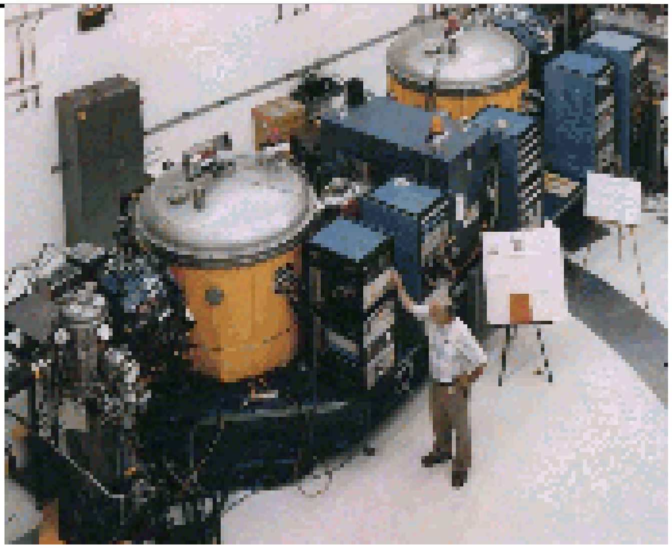
Improves efficiency of vacuum separators, at cost of mass information and cleanliness. In some cases (heavy nuclei) focal plane counters clean up the data for good sensitivity.

Some Channel Selection Detectors


The Washington University MICROBALL in Gammasphere

Argonne FMA

USA



Light charged-particle detector *Microball* **– 96 CsI with photo diodes**

USA

Jyvaskyla *RITU*

Europe

Calculate Reaction Rates

Reaction Yield: $\mathbf{Y = I_b \times N_t \times \sigma}$ [nuclei/s]

$I_b = i/(eq)$; with i - electric current [A], q - charge state, e = 1.6 10^{-19} [C]

$N_t = [N_a / A] \rho x$; with N_a = Avagadros #, A = mass, ρ = density [g/cm^3] & x = thickness [cm] of the target

σ– reaction cross section [cm^2] .... note 1 [barn] is 10^{-24} [cm^2]

Accumulated data: $\mathbf{D = Y \times Time \times Efficiency}$ [counts]

A typical "close to the line of stability" experiment may have:

i=100 [nA], q=10, A=100, ρx =10^{-3} [g/cm^2] & σ=1 [barn] and Efficiency of 10 % produces ~3.8x10^4 [counts/sec], BUT

A typical "far from the line of stability" experiment may have:

σ=100 [nb], so the accumulated data is ~14 [counts/hour];

σ=10 [pb] gives ~2 count every 10 weeks!!!.....the present situation for producing the heavies elements

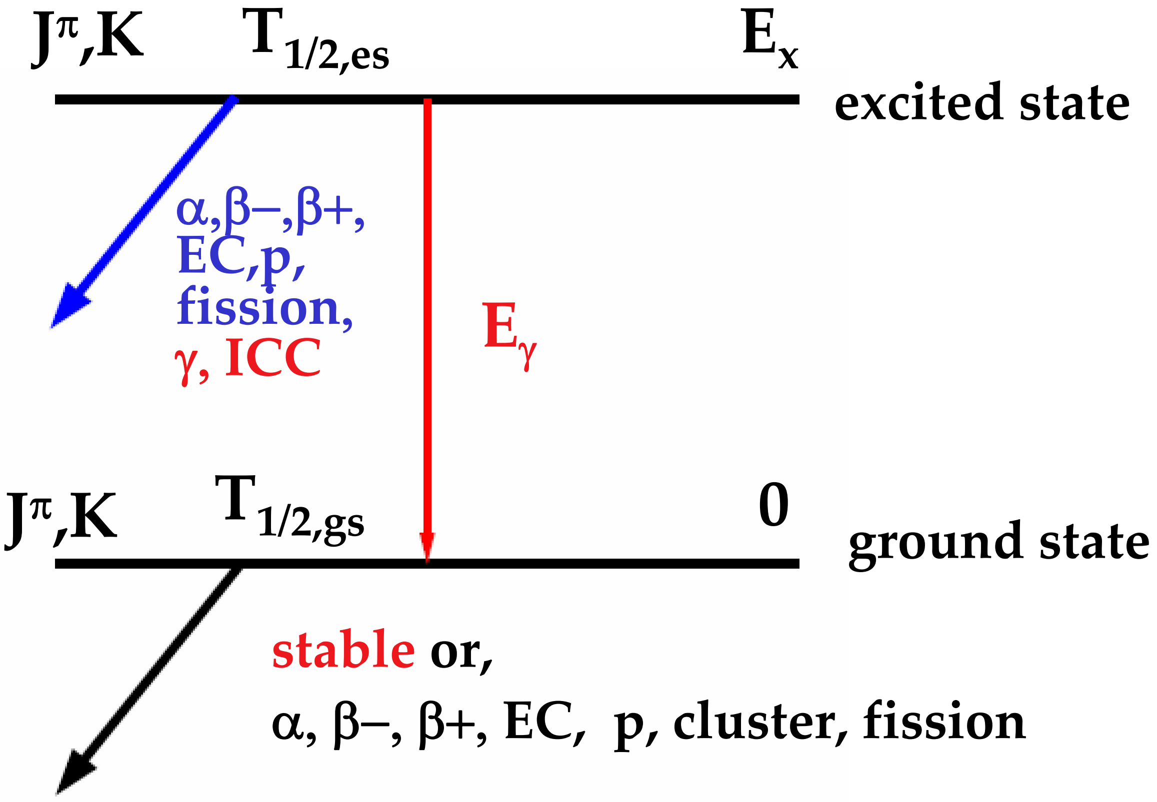
The basic knowledge

What we want to know

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

How

- ☐ By measuring properties of signature radiations



J^{π},K $T_{1/2,es}$ E_x excited state

α,β−,β+, EC,p, fission, γ, ICC

E_{γ}

J^{π},K $T_{1/2,gs}$ 0 ground state

stable or,

α, β−, β+, EC, p, cluster, fission

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

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

- ✓Activity of 1 mole of material (6.02×10^{23} atoms) with $T_{1/2} = 10^9$ y ($\lambda = 2.2 \times 10^{-17}\ s^{-1}$) 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.

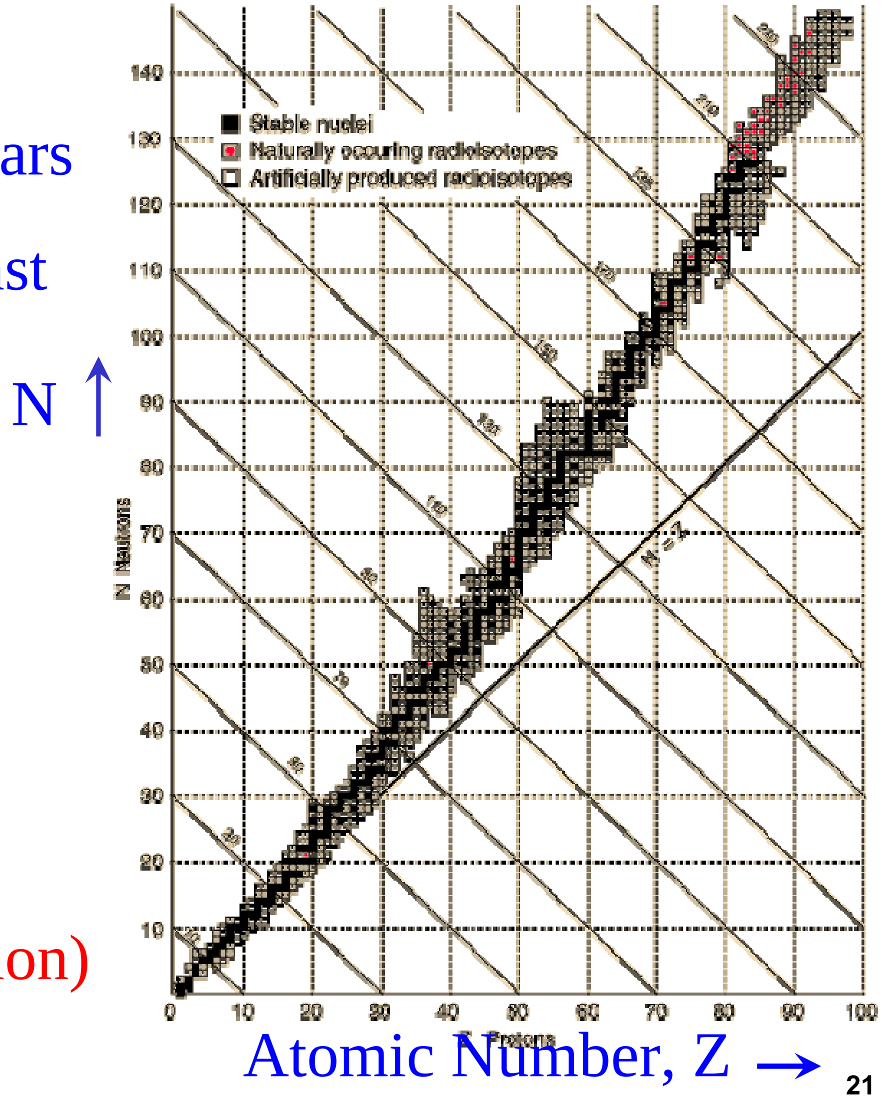
Stable Nuclei: Segre's Chart

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

So they are (quite) **stable** against

- ✓Decay of their constituents (p,n)
- ✓Weak Decay (β^+, β^- and EC)
- ✓α decay
- ✓More complex cluster emission
- ✓Fission

(Mostly because of energy conservation)



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*

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

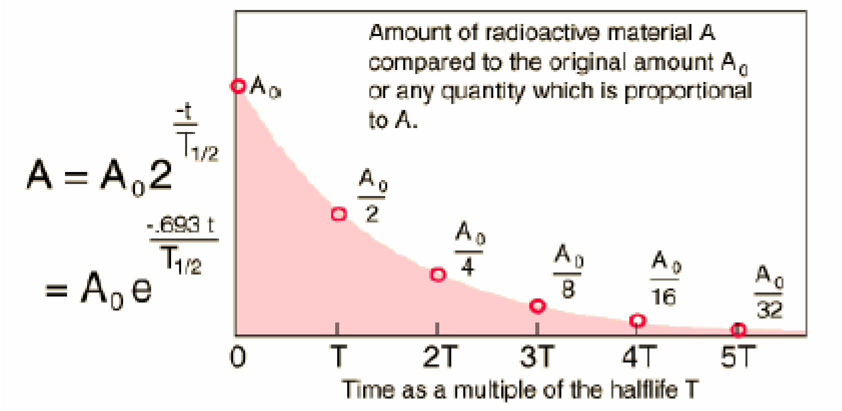
Probability that a nucleus will remain at time *t*

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

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

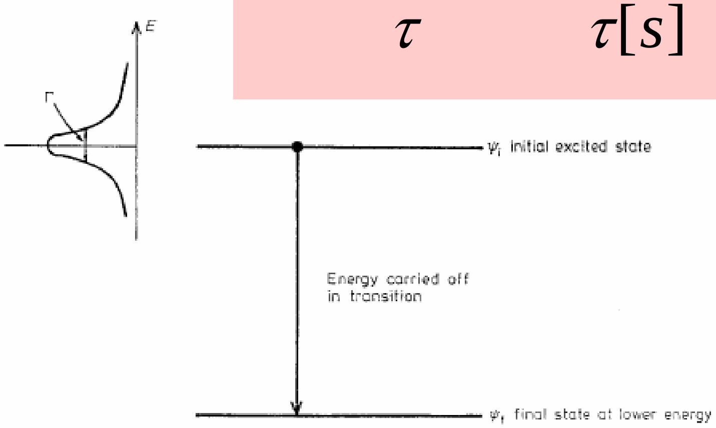


relation between τ, $T_{1/2}$ and λ

$$\tau = \frac{T_{1/2}}{\ln 2} = \frac{1}{\lambda}$$

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.58\times 10^{-16}}{\tau[s]} \quad \text{[eV]}$$

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



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

log ft values

$$\boxed{\log ft = \log f + \log t}$$

$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}}{BR_i}$$

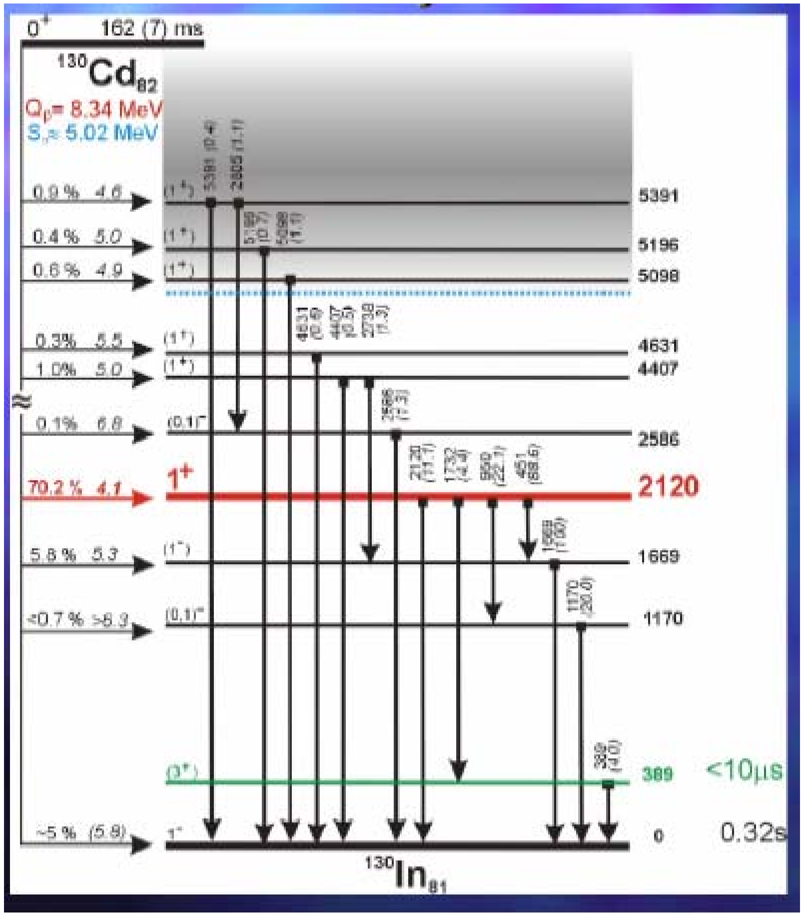
partial half-life of a given β– (β+,EC) decay branch

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

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

Decay Mode	Type	log *f*
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

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

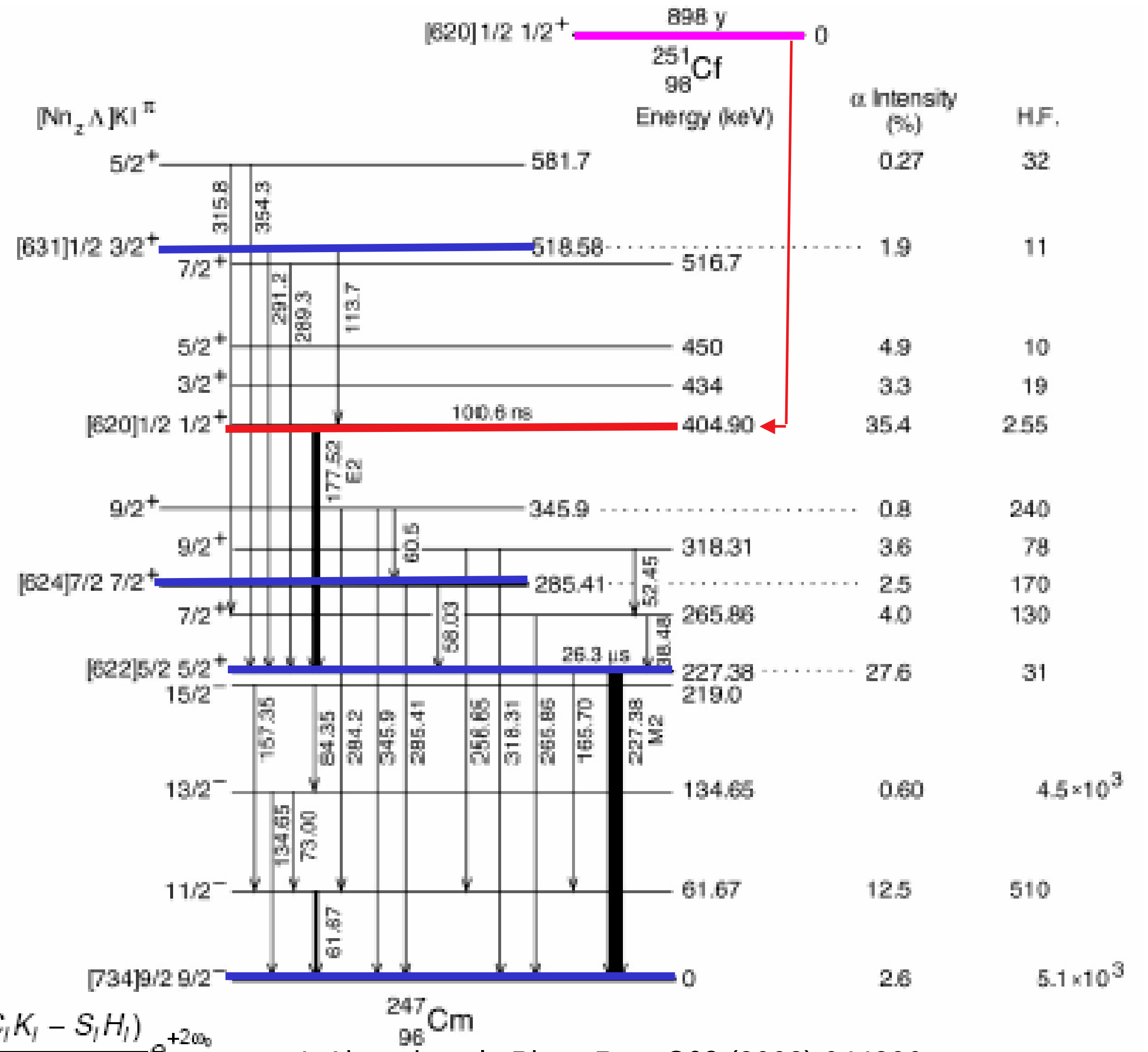
$$\pi_i \pi_f = (-1)^L$$

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



$$t_{1/2}^{\alpha} = \ln 2 \frac{r_0}{2v} \frac{\mu^2(H_l^2 + K_l^2) + \tan^2\alpha_0(C_l^2 + S_l^2) + 2\mu\tan\alpha_0(C_l K_l - S_l H_l)}{\mu^2 \tan\alpha_0 (H_l C_l + K_l S_l) Q_l} e^{+2\omega_0}$$

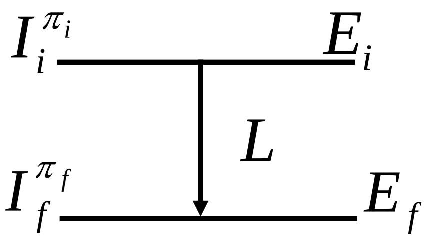
I. Ahmad et al., Phys. Rev. C68 (2003) 044306

γ–ray decay

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

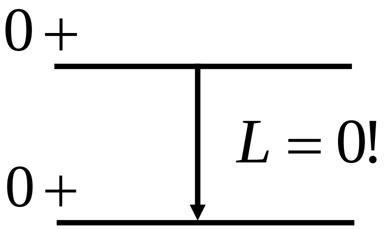
$$\Delta\pi(EL) = (-1)^L \qquad \Delta\pi(ML) = (-1)^{L+1}$$

electric multipole — magnetic multipole

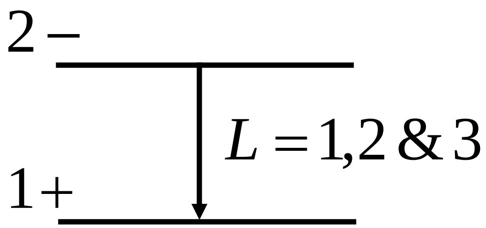


$$E_\gamma = E_i - E_f$$

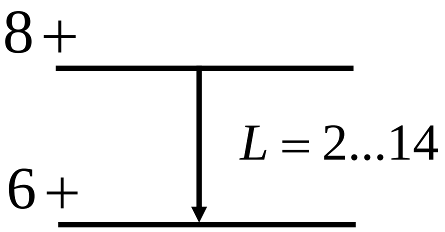
dipole	quadrupole	octupole	hexadecapole	
E1:L=1,yes	E2:L=2,no	E3:L=3,yes	E4:L=4,no	E5:L=5,yes
M1:L=1,no	M2:L=2,yes	M3:L=3,no	M4:L=4,yes	M5:L=5,no



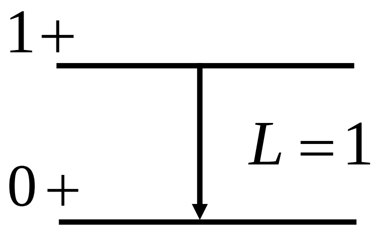
$E0$



$E1(M2, E3)$



$E2(M3, E4\ldots)$

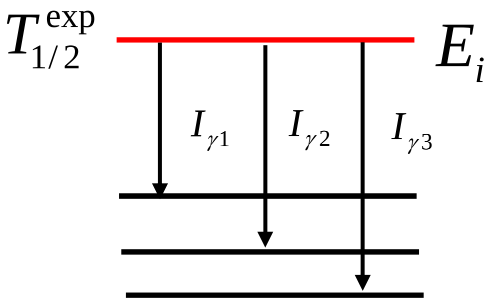


$M1$

Partial lifetime & Transition Probability

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

partial half-life



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

partial γ–ray Transition Probability

reduced Transition Probability

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

contains the nuclear structure information

Hindrance Factor in γ–ray decay

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

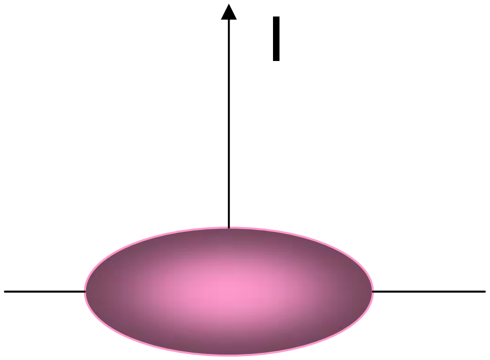
... usually an upper limit, but ...

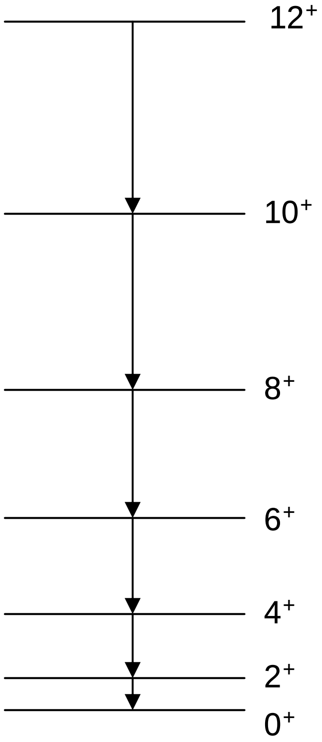
Hindrance Factor: Weisskopf (W): based on spherical shell model potential

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	$0.06446A^{2/3}$	$6.762A^{-2/3}E_\gamma^{-3}\times10^{-15}$	**M1**	1.7905	$2.202E_\gamma^{-3}\times10^{-14}$
E2	$0.0594A^{4/3}$	$9.523A^{-4/3}E_\gamma^{-5}\times10^{-9}$	**M2**	$1.6501A^{2/3}$	$3.100A^{-2/3}E_\gamma^{-5}\times10^{-8}$
E3	$0.0594A^{2}$	$2.044A^{-2}E_\gamma^{-7}\times10^{-2}$	**M3**	$1.6501A^{4/3}$	$6.655A^{-4/3}E_\gamma^{-7}\times10^{-2}$
E4	$0.06285A^{8/3}$	$6.499A^{-8/3}E_\gamma^{-9}\times10^{4}$	**M4**	$1.7458A^{2}$	$2.116A^{-2}E_\gamma^{-9}\times10^{5}$
E5	$0.06929A^{10/3}$	$2.893A^{-10/3}E_\gamma^{-11}\times10^{11}$	**M5**	$1.9247A^{8/3}$	$9.419A^{-8/3}E_\gamma^{-11}\times10^{11}$

Quadrupole Deformation





I=Jω

^{156}Dy

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

B(E2) ~ 200 W.U.

deformed nucleus

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

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

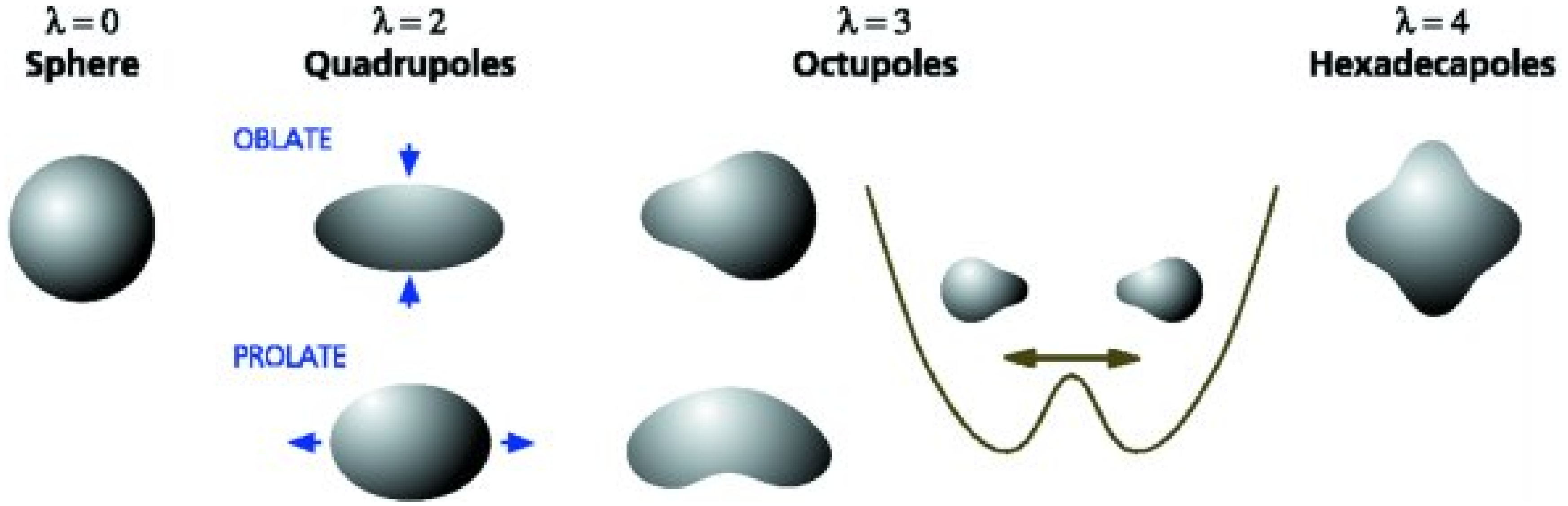
(from collective models)

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

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

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

Octupole Deformation

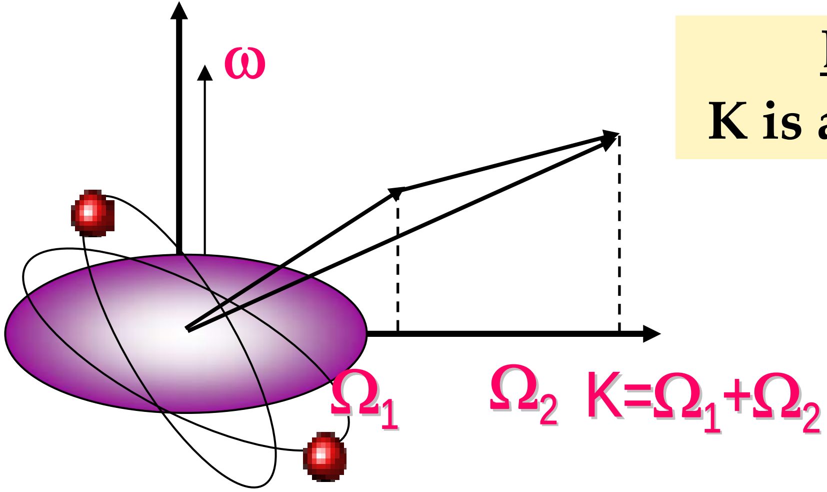


$$\tau_{E3}[s] = 0.012264 \times E_{3_1^-}^{-7} \times [B(E3)\uparrow]^{-1}$$

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

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

K-forbidden decay

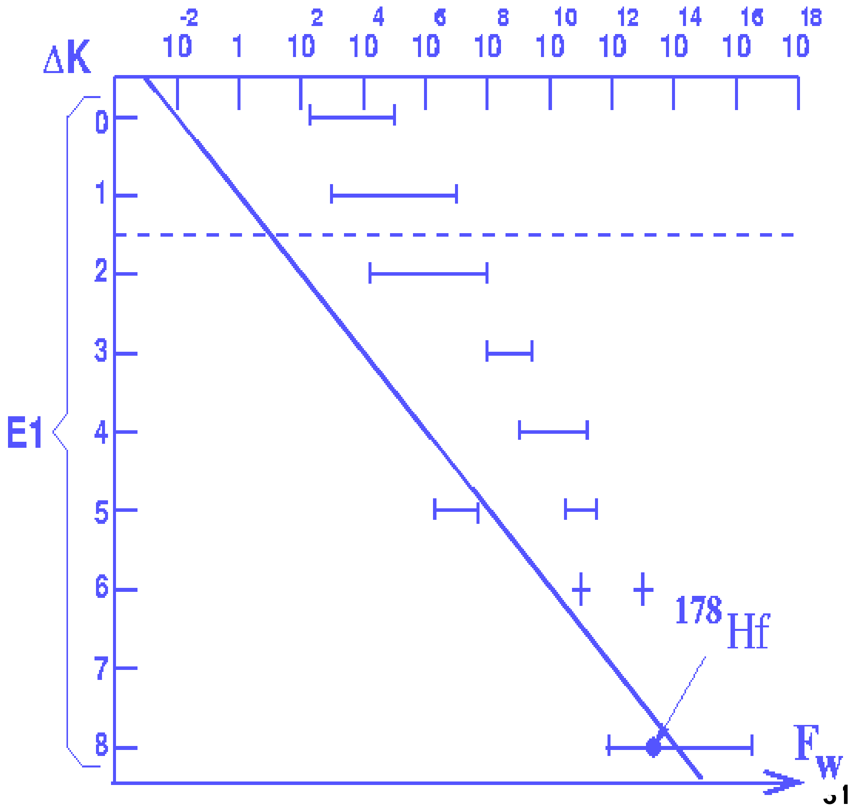


<u>Deformed, axially symmetric nuclei</u>

K is approximately a good quantum number

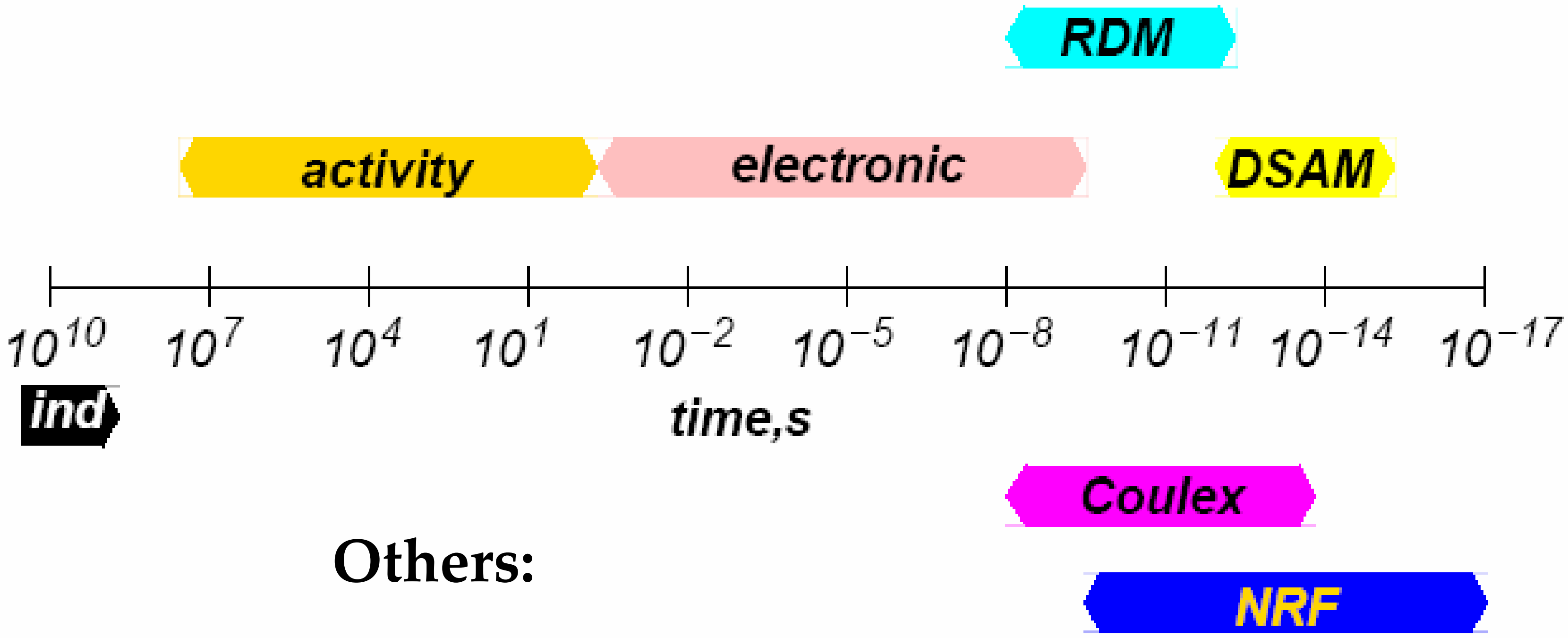
each state has not only

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} = 2v**
- **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



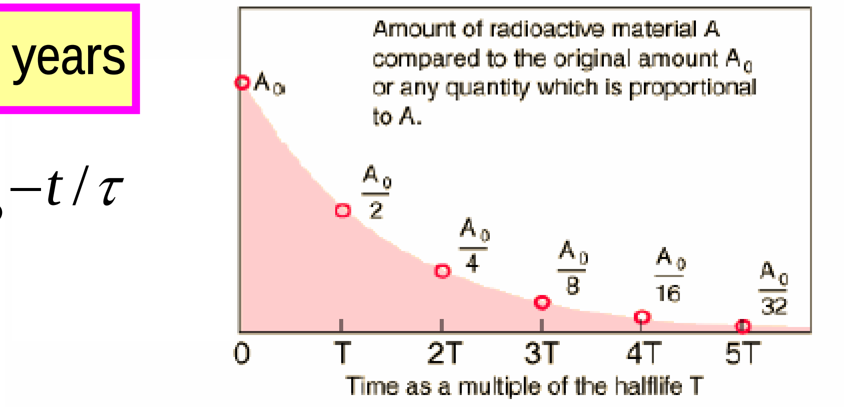
Others:

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

Activity measurements

Time Range: a few seconds up to several years

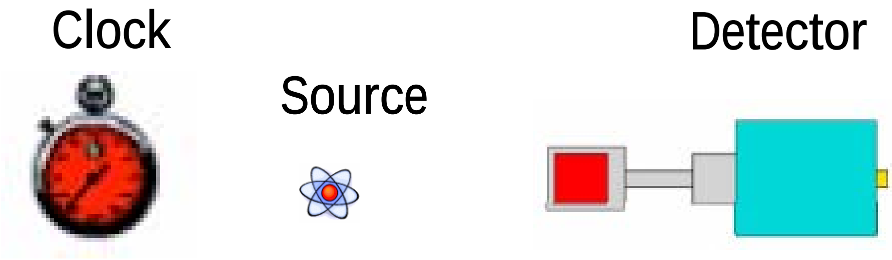
$$A = dN/dt = \lambda N = A_0 e^{-t/\tau}$$



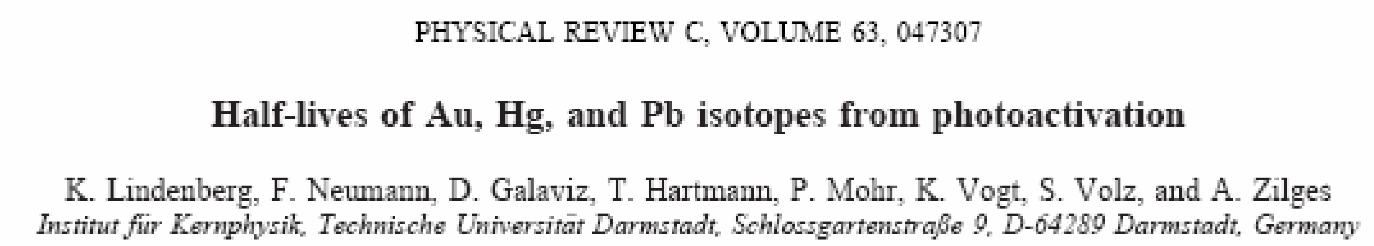
- Statistical uncertainties are usually small
- Systematic uncertainties (dead time, geometry, etc.) dominate

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



Activity Measurements: Example 1



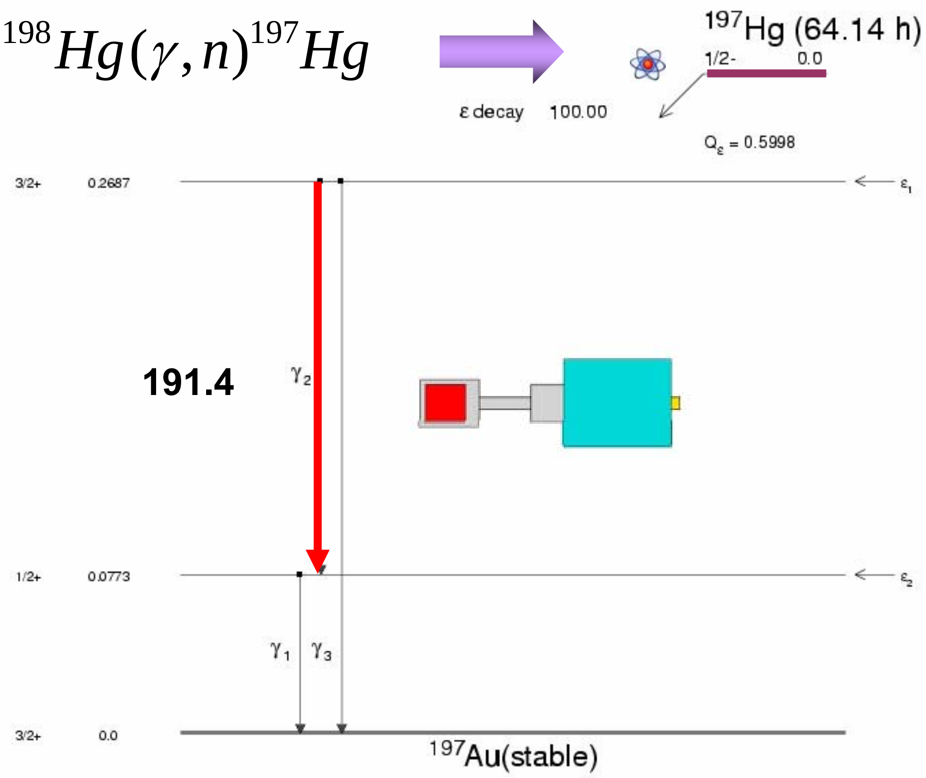
PHYSICAL REVIEW C, VOLUME 63, 047307

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

$^{198}Hg(\gamma,n)^{197}Hg$



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

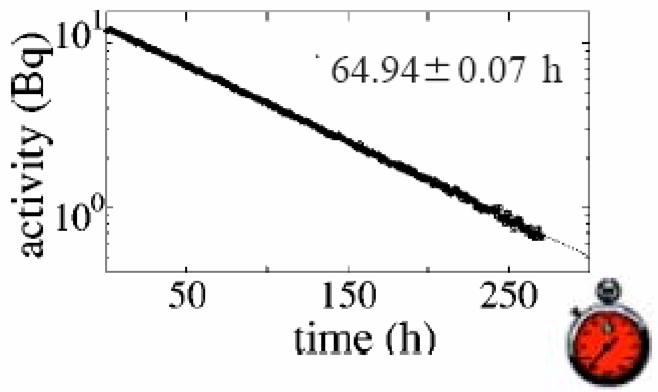
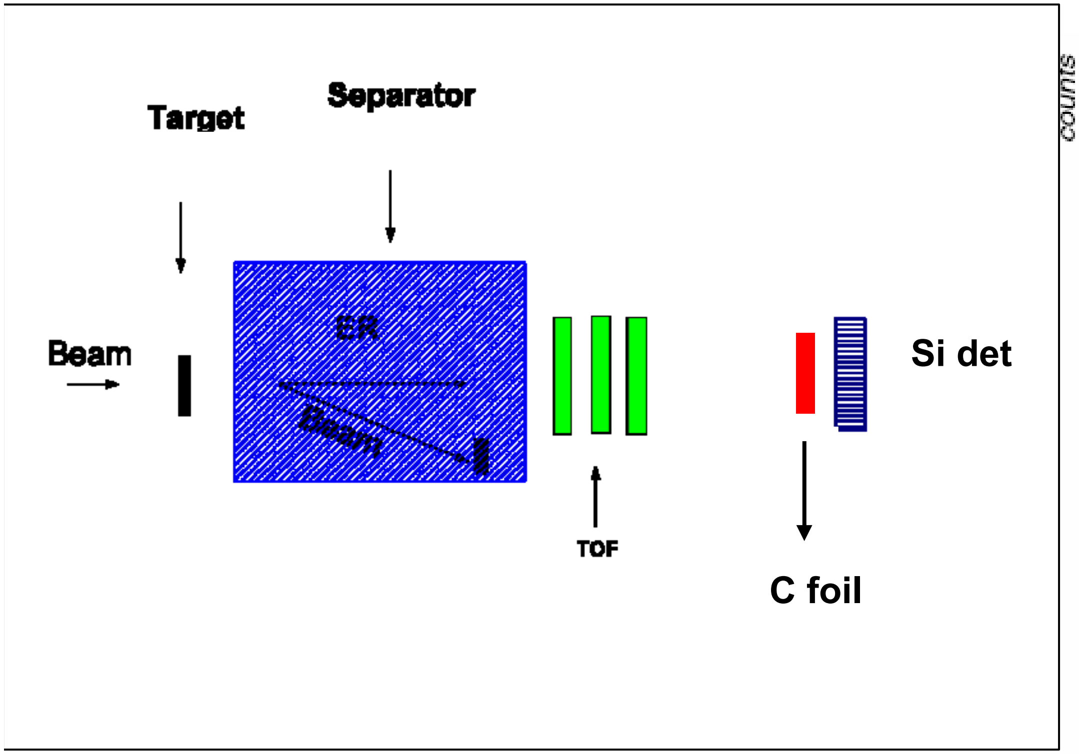
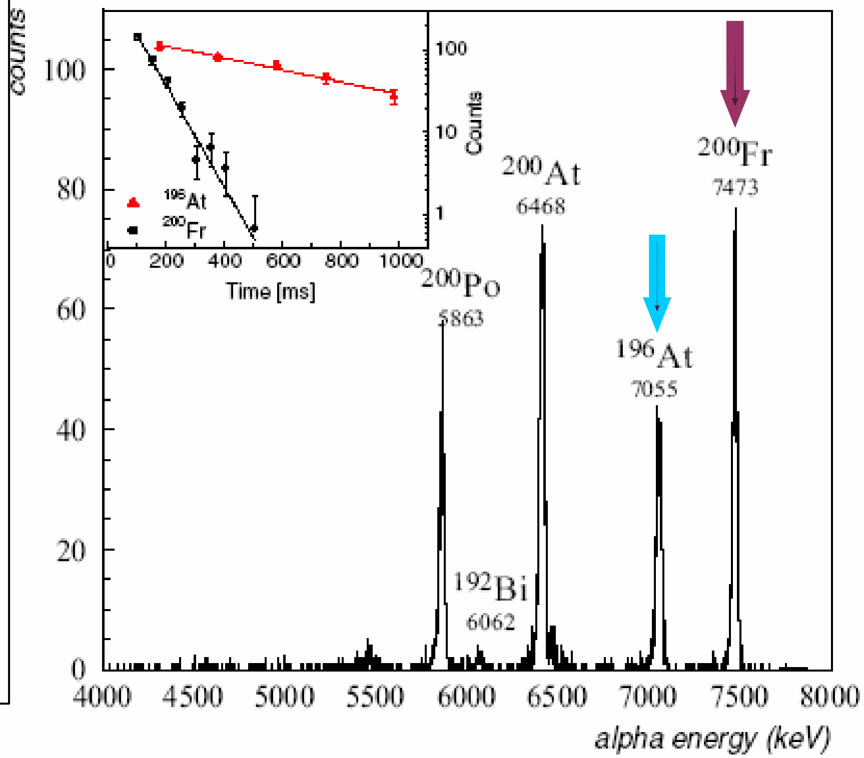


FIG. 3. Decay curve of ^{197}Hg at E_γ=191.4 keV.

Activity measurements: Example 2





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

on-line mass separation (ISOLDE)/CERN

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]

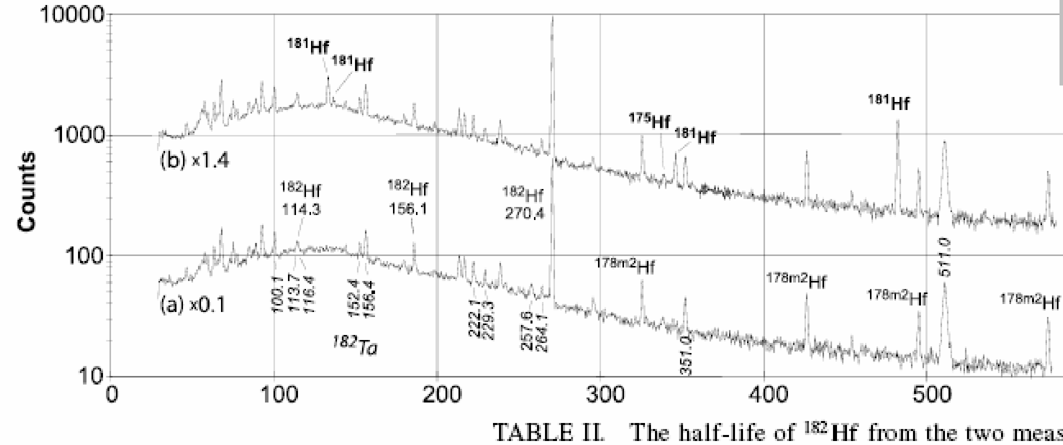
H. De Witte et al., EPJ A23 (2005) 243

Very long-lived cases – Example 1

Time Range: longer than 10^2 yr

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

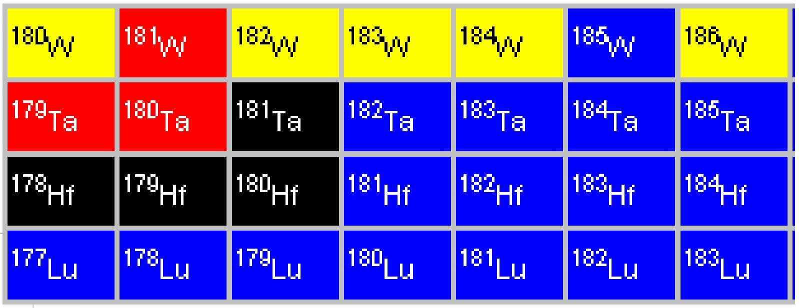
the number of atoms estimated by other means, e.g. mass spectrometry



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

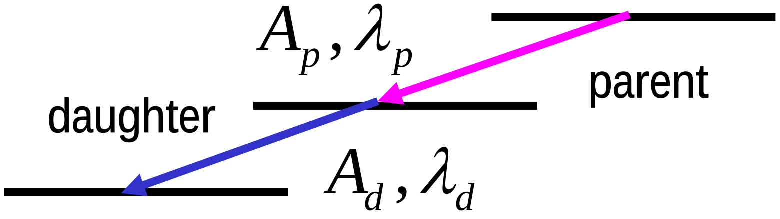
	Atomic abundance (%)						
Material	^{174}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{182}Hf
Helmer 1	≈ 0.0058	4.791	0.605	29.06	25.77	39.64	0.124
Helmer 2	≈ 0.00014	4.377	0.149	17.15	31.30	46.91	0.112
Natural	0.16	5.21	18.60	27.30	13.63	35.10	

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

Very long-lived cases – Example 2

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


A_p, λ_p

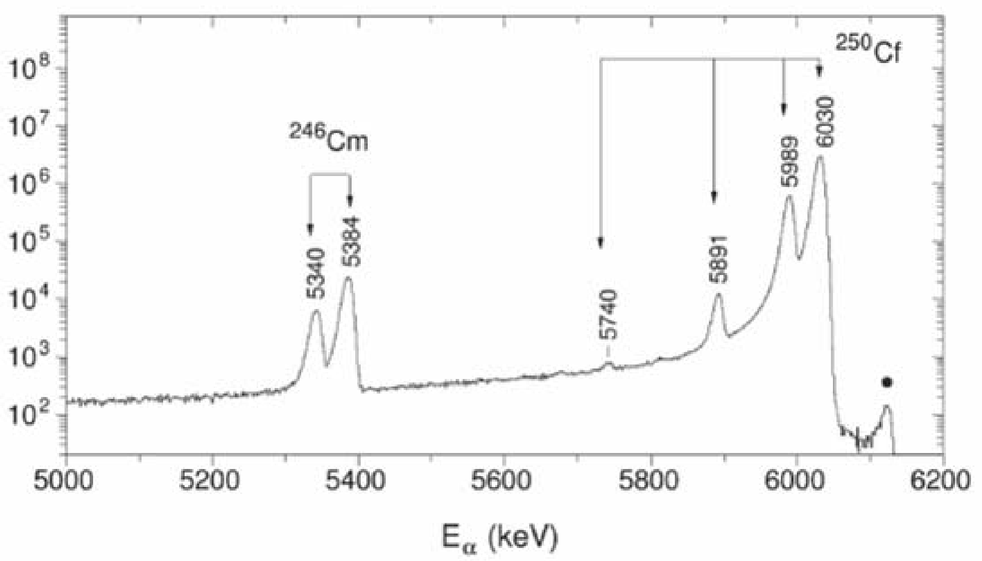
parent

daughter

A_d, λ_d

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

$$^{250}Cf \xrightarrow[13\ y]{\alpha} {}^{246}Cm \xrightarrow[4747\ y]{\alpha} {}^{242}Pu \xrightarrow[510^5\ y]{\alpha}$$



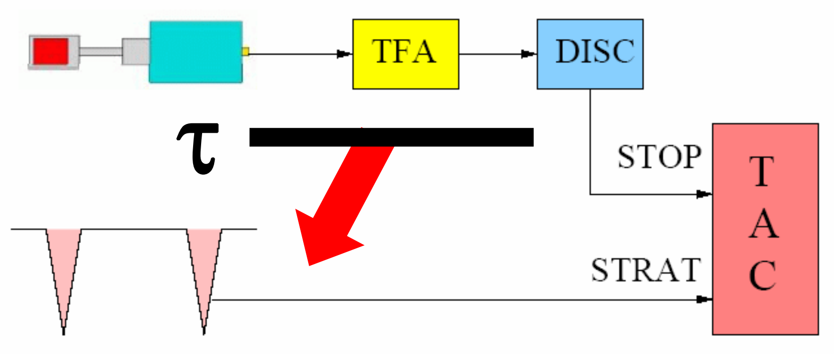
- mass-separated source
- alpha-decay counting technique

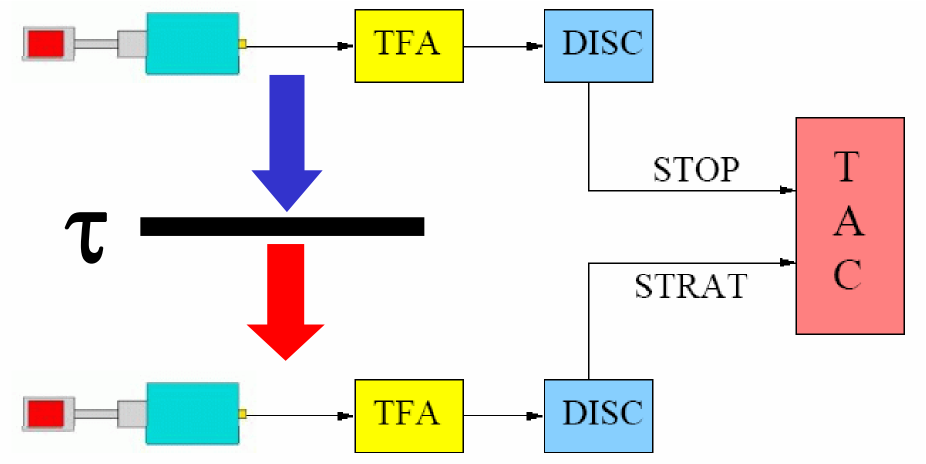
$T_{1/2}$ = 4747 (46) years / Compared to values ranging from $T_{1/2}$=2300 up to 6620 years

Electronic techniques

Time Range: tens of ps up to a few seconds

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





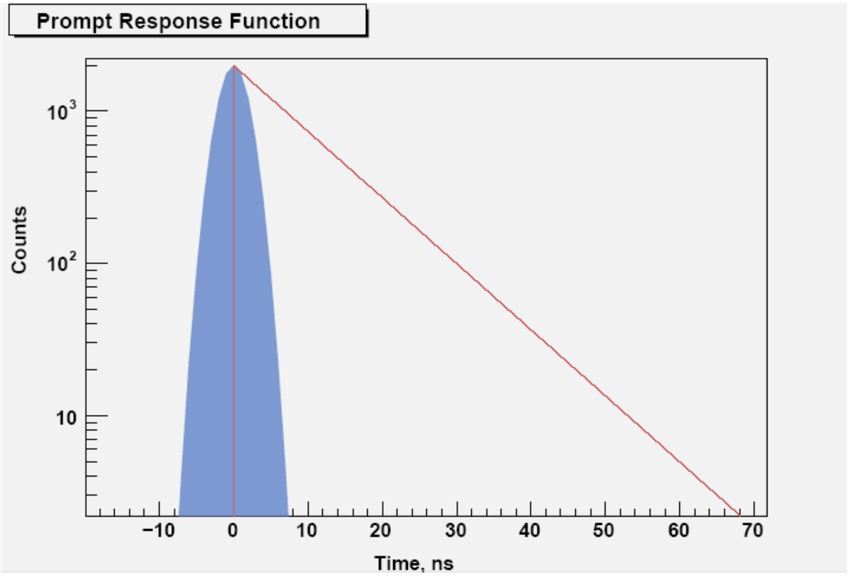
“singles” – E_γ-time, E_α-time

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

Difficulties at the boundaries: 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

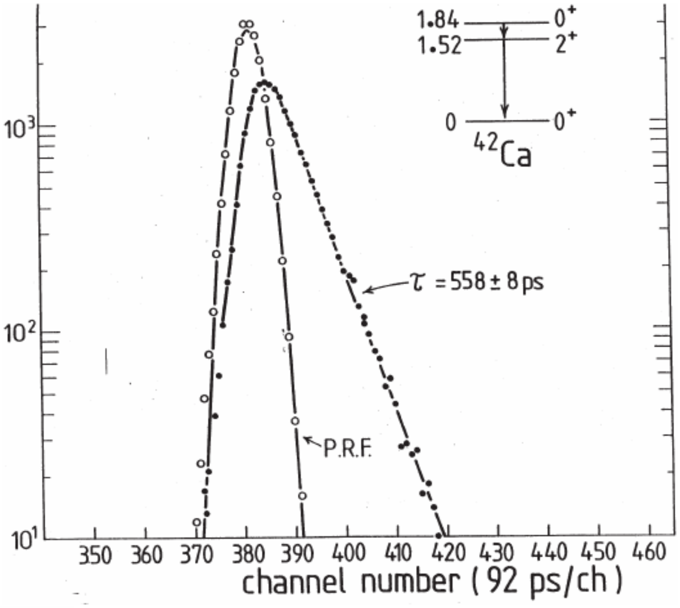
$$F(x,\lambda)=\int_{-\infty}^{\infty}\underline{f(t,\lambda)}\,\underline{P(x-t)}\,dt$$

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

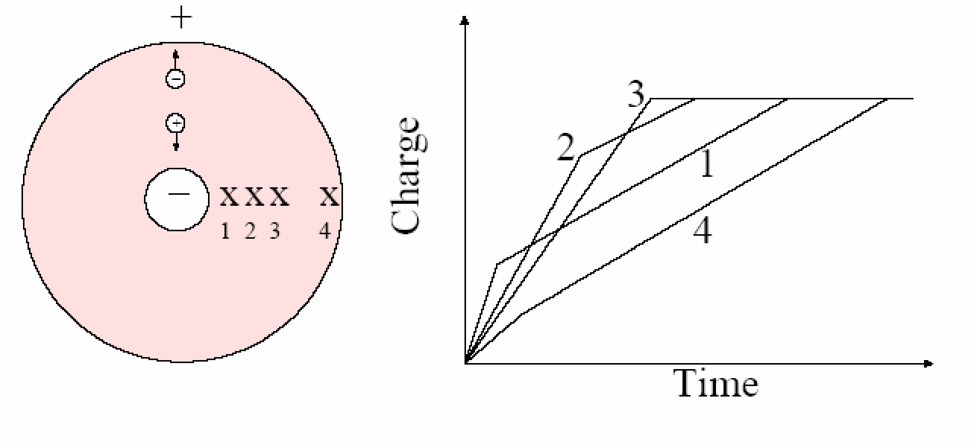
decay

PRF

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



a schematic illustration



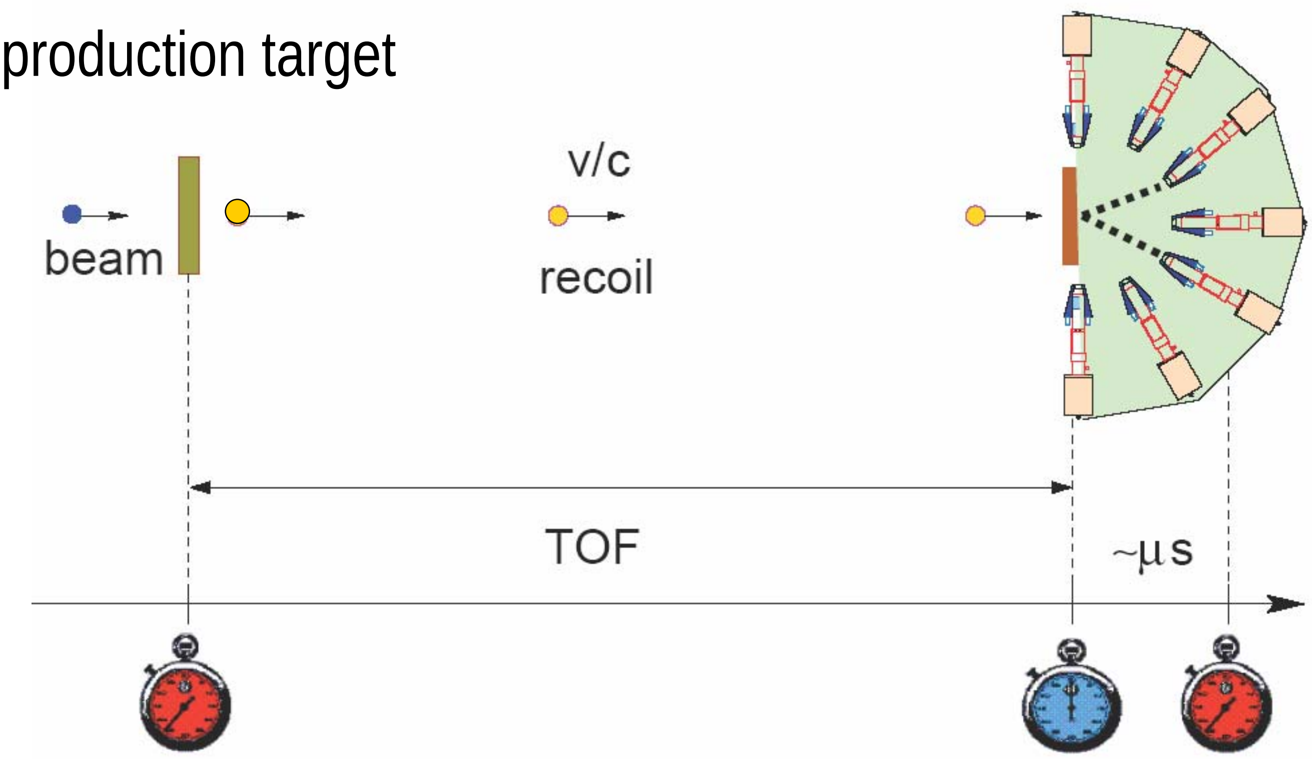
PRF depends on:

- 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

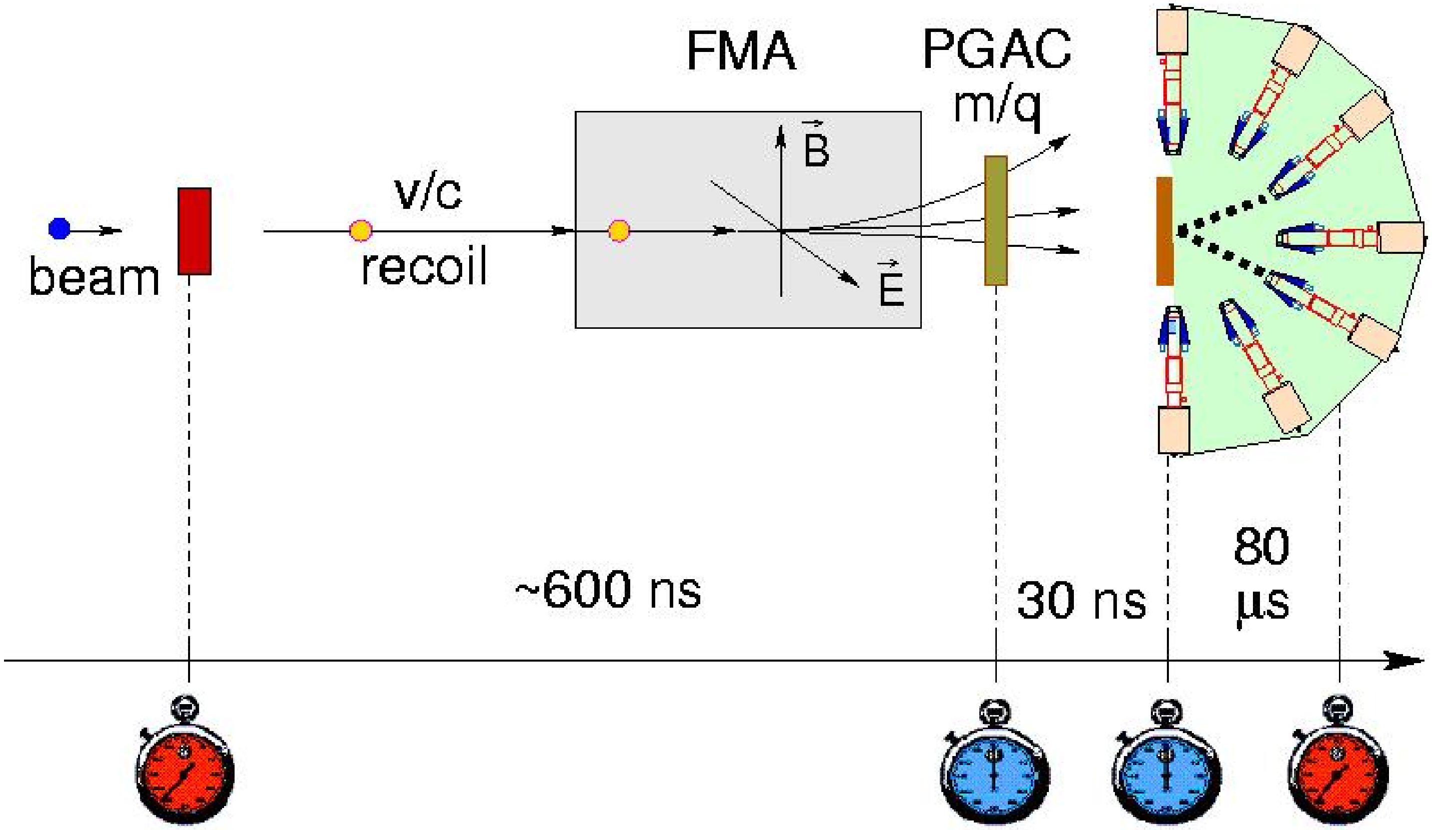
thin production target



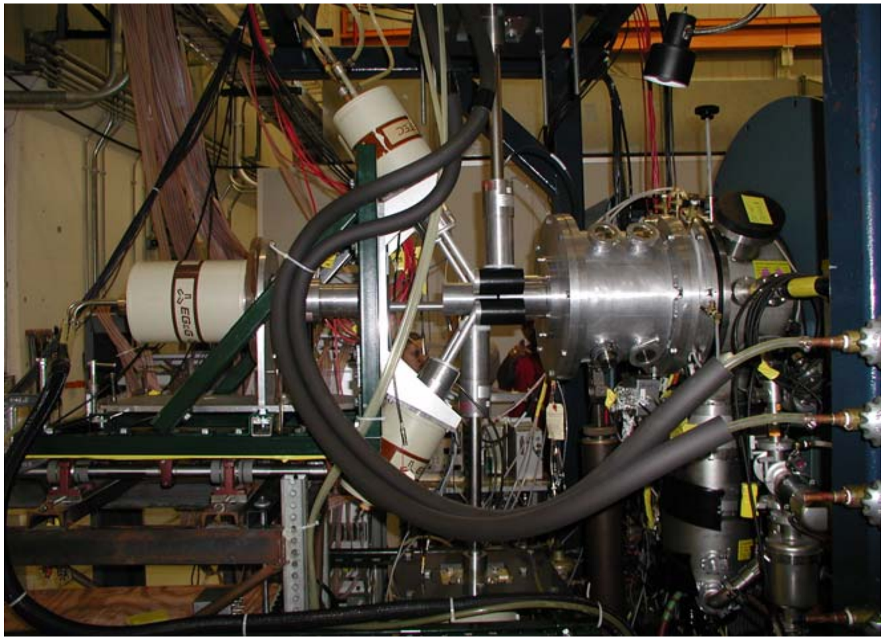
One example: ^{140}Dy experiment at ANL

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

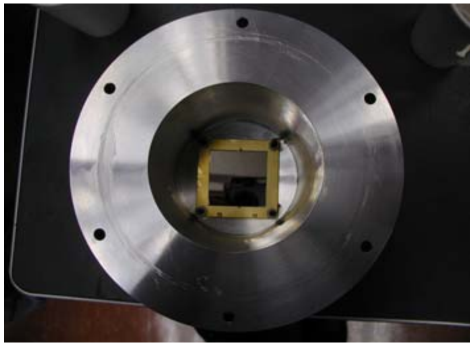
α2n channel, mass 140 only 5% from the total CS



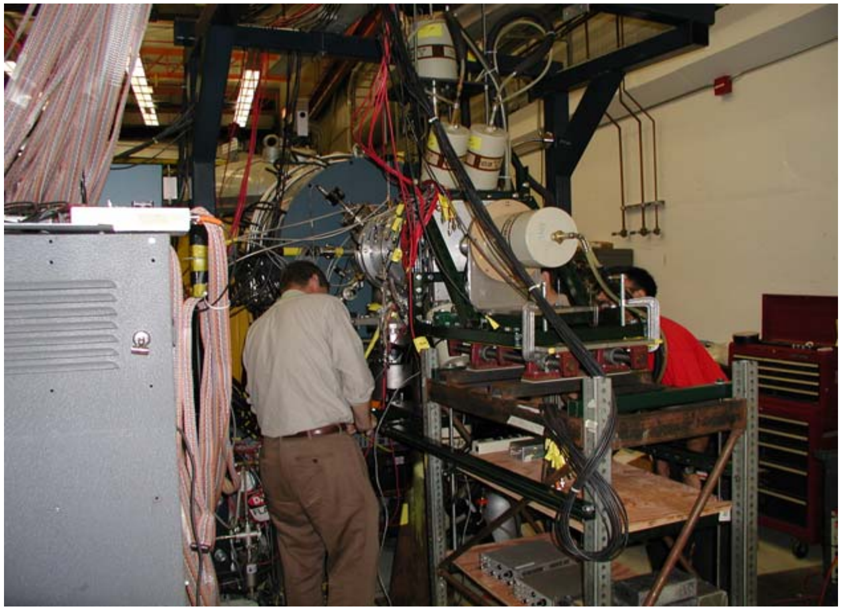
Some of the equipments used …



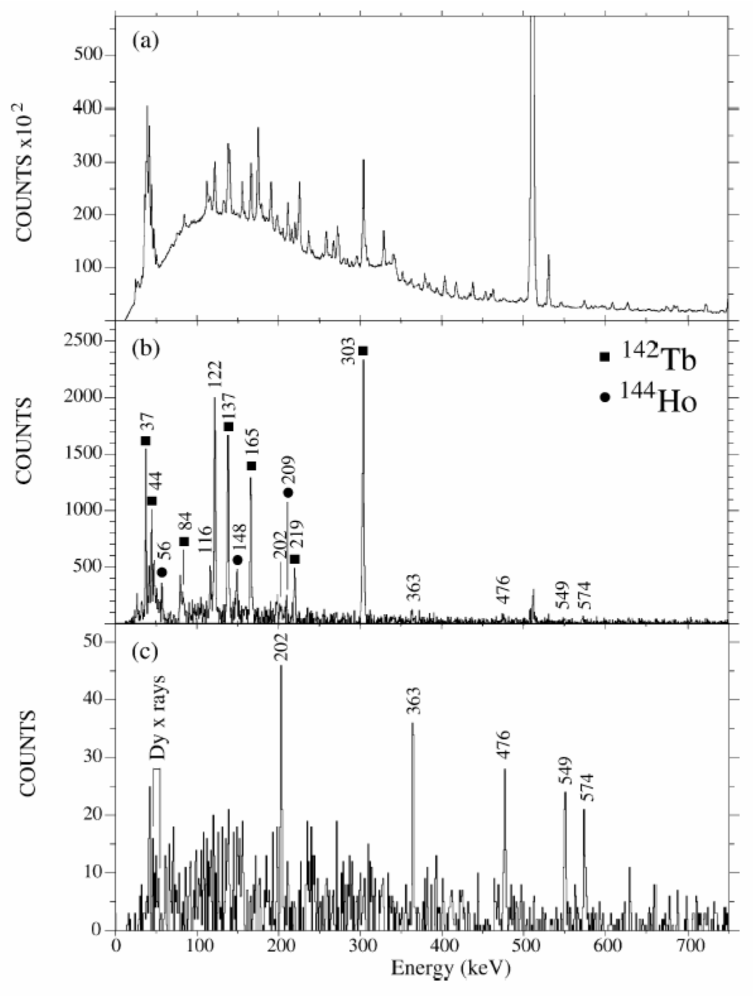
1 70% Gammasphere HpGe detector
4 25% Golf-club style HPGe detectors
2 LEPS detectors
1 2"x2" Large Area Si detector

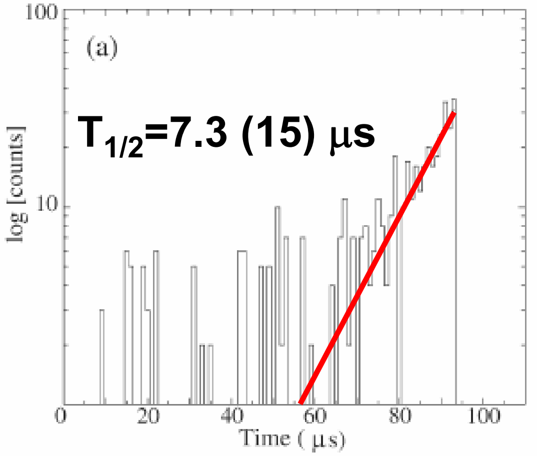


2"x2" Si Detector

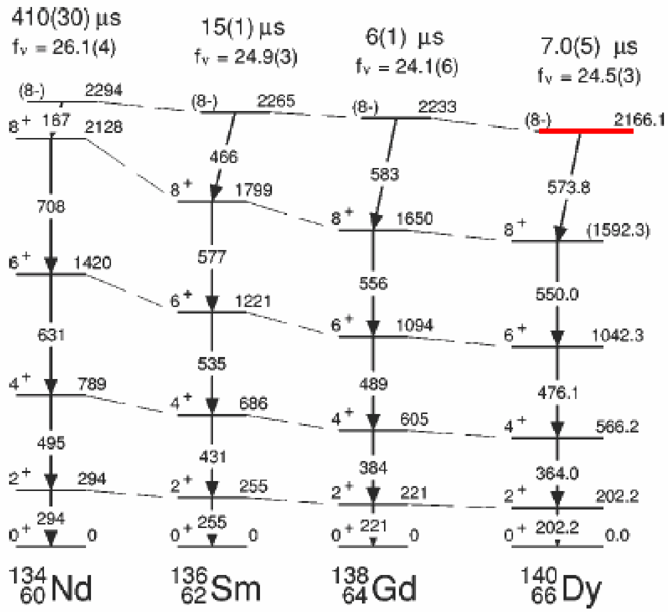


^{140}Dy: Experimental Results





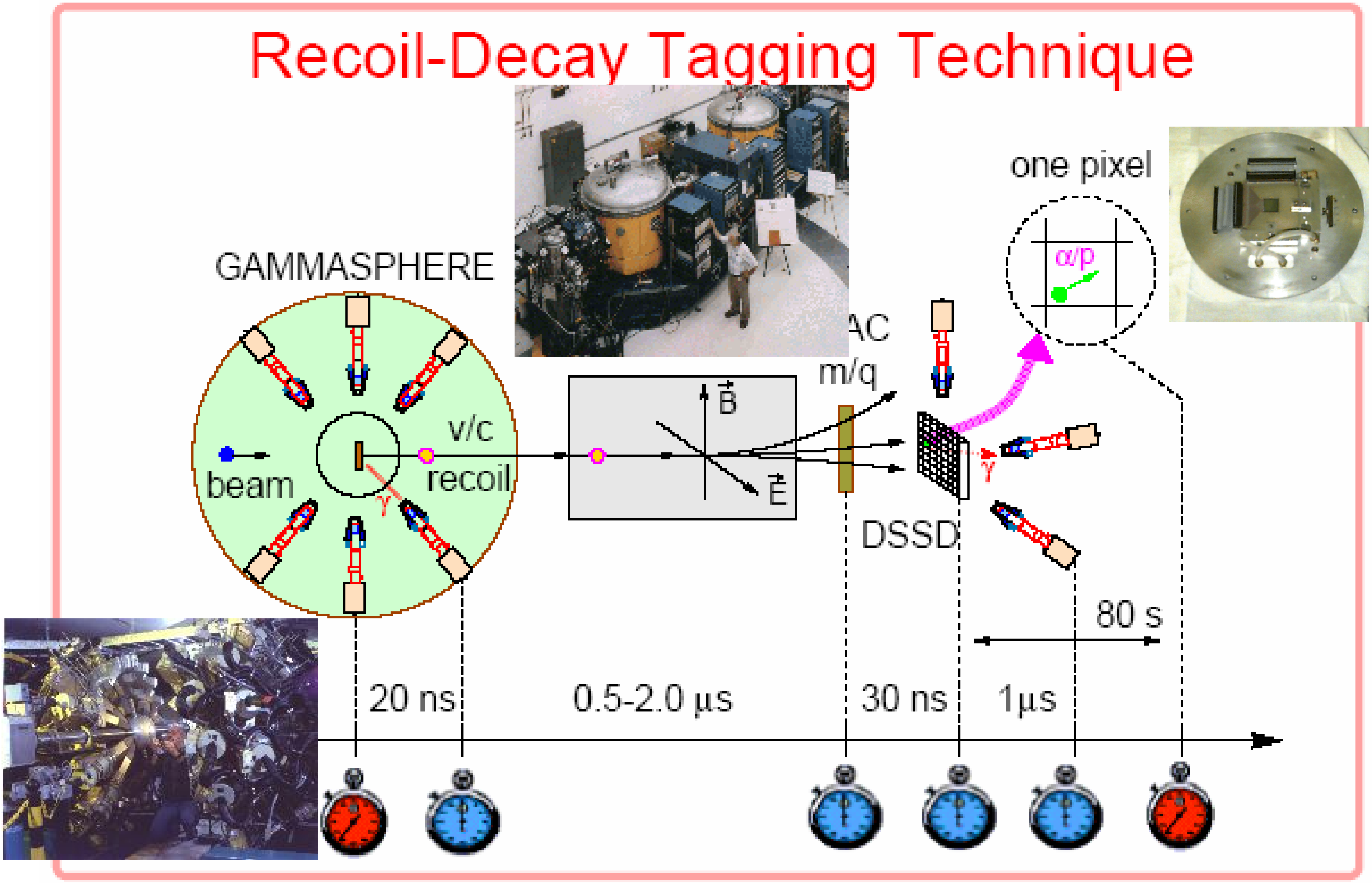
$T_{1/2}$=7.3 (15) μs



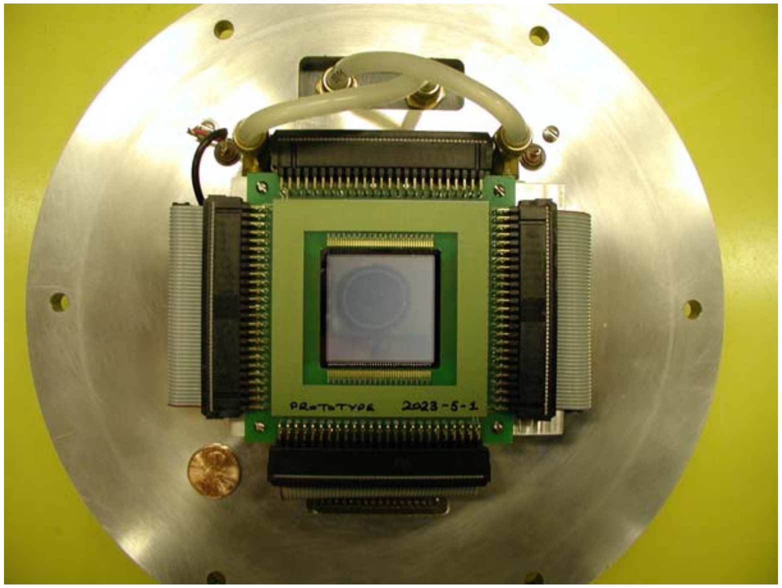
Similar results by the ORNL group, Krolas et al., PRC 65, 2002

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

Recoil-decay tagging

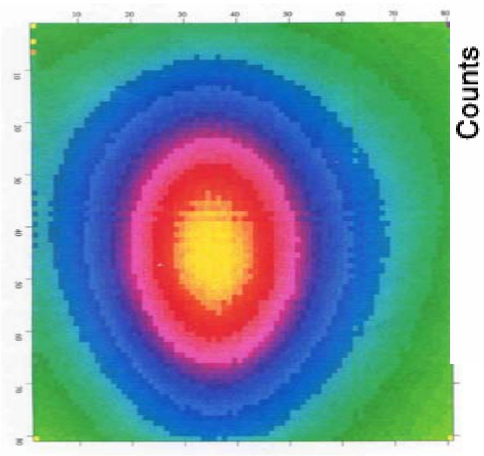

Recoil-Decay Tagging Technique

The Heart of RDT: the DSSD

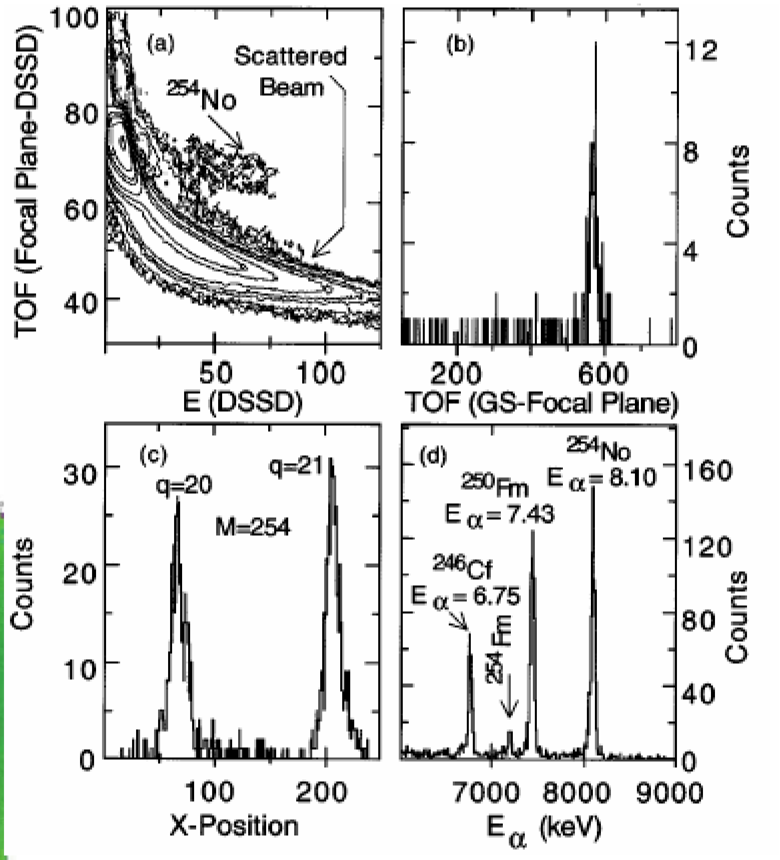


80 x 80 detector 300 µm strips, Each with high, low, and delay line amplifiers, for implant, decay, and fast-decay recognition.

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

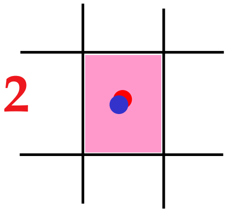


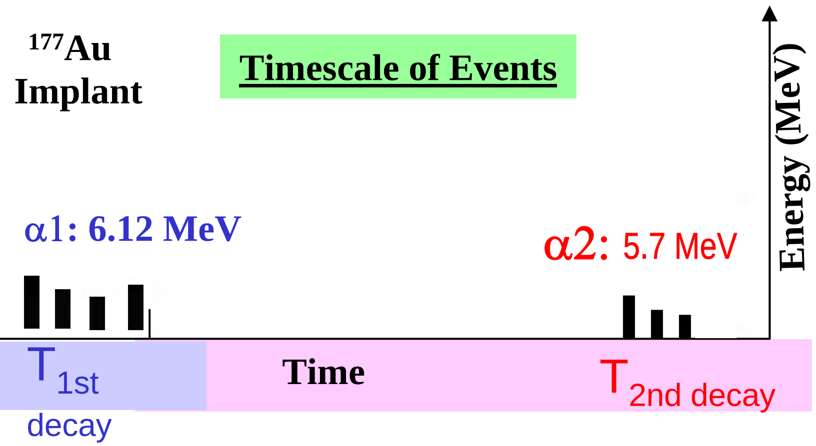
$^{208}Pb(^{48}Ca,2n)^{254}No$

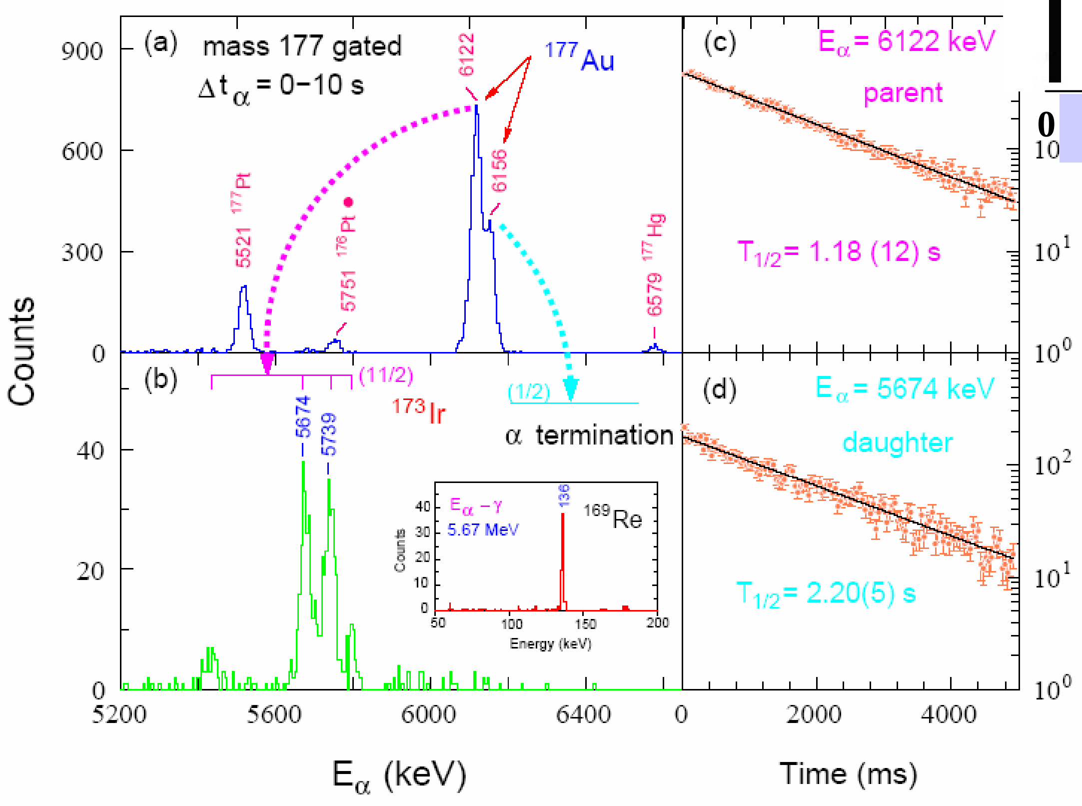


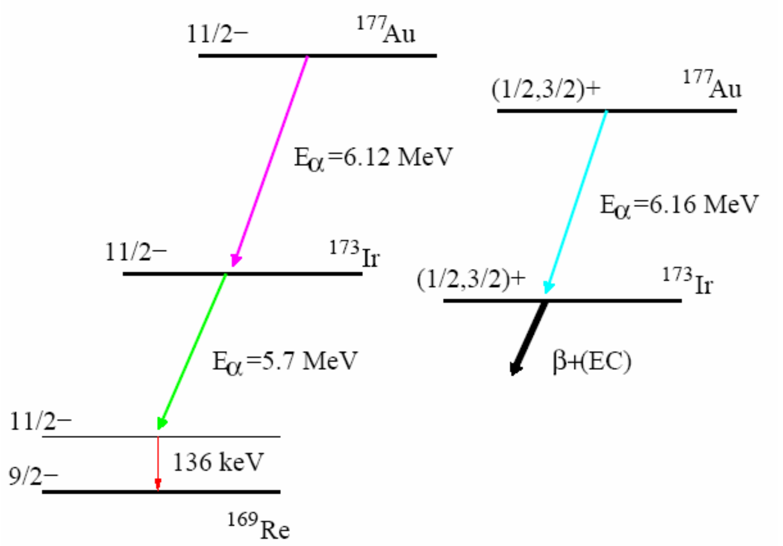
α–α (parent-daughter) correlations

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



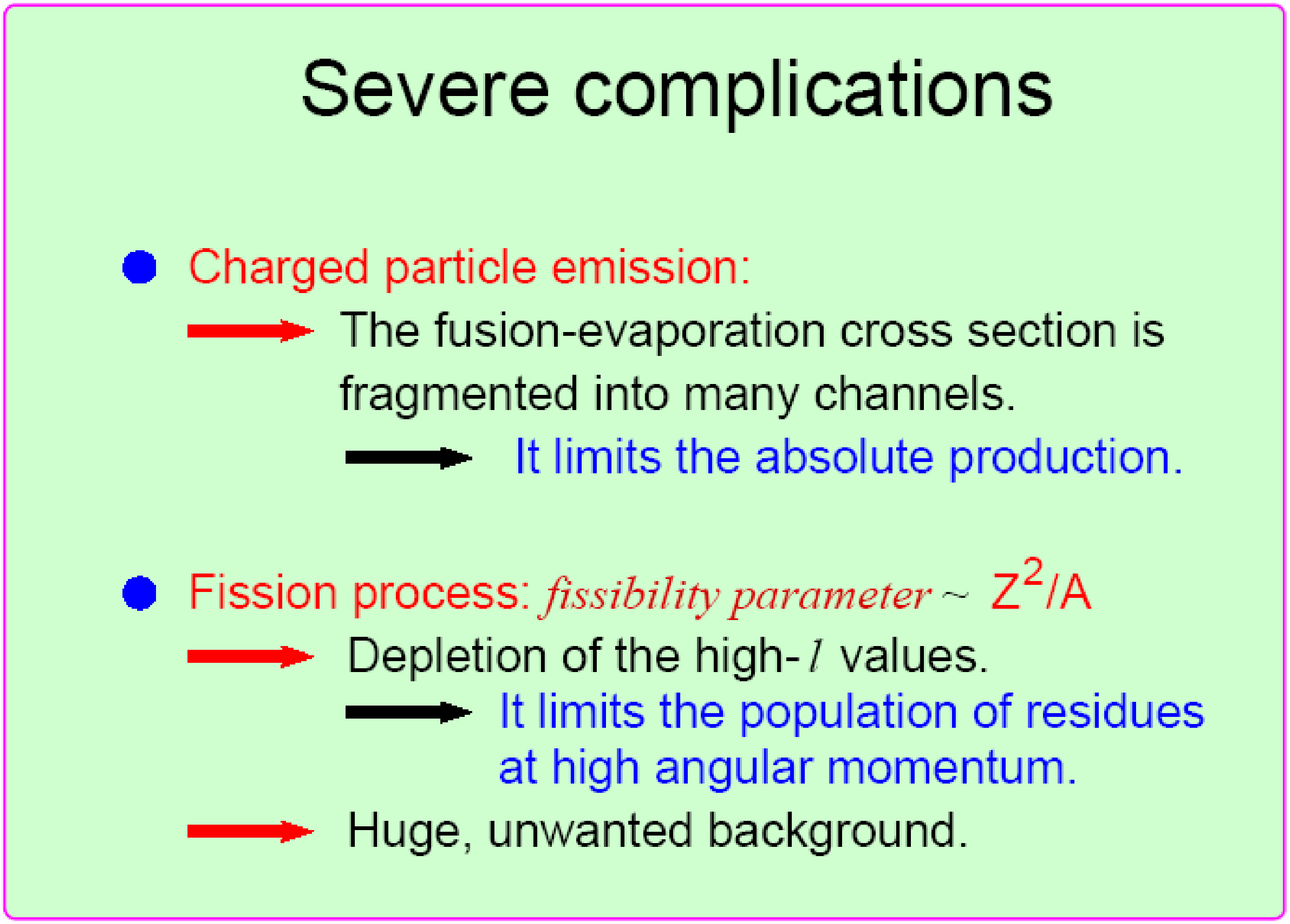






F.G. Kondev et al. Phys. Lett. B528 (2002) 221

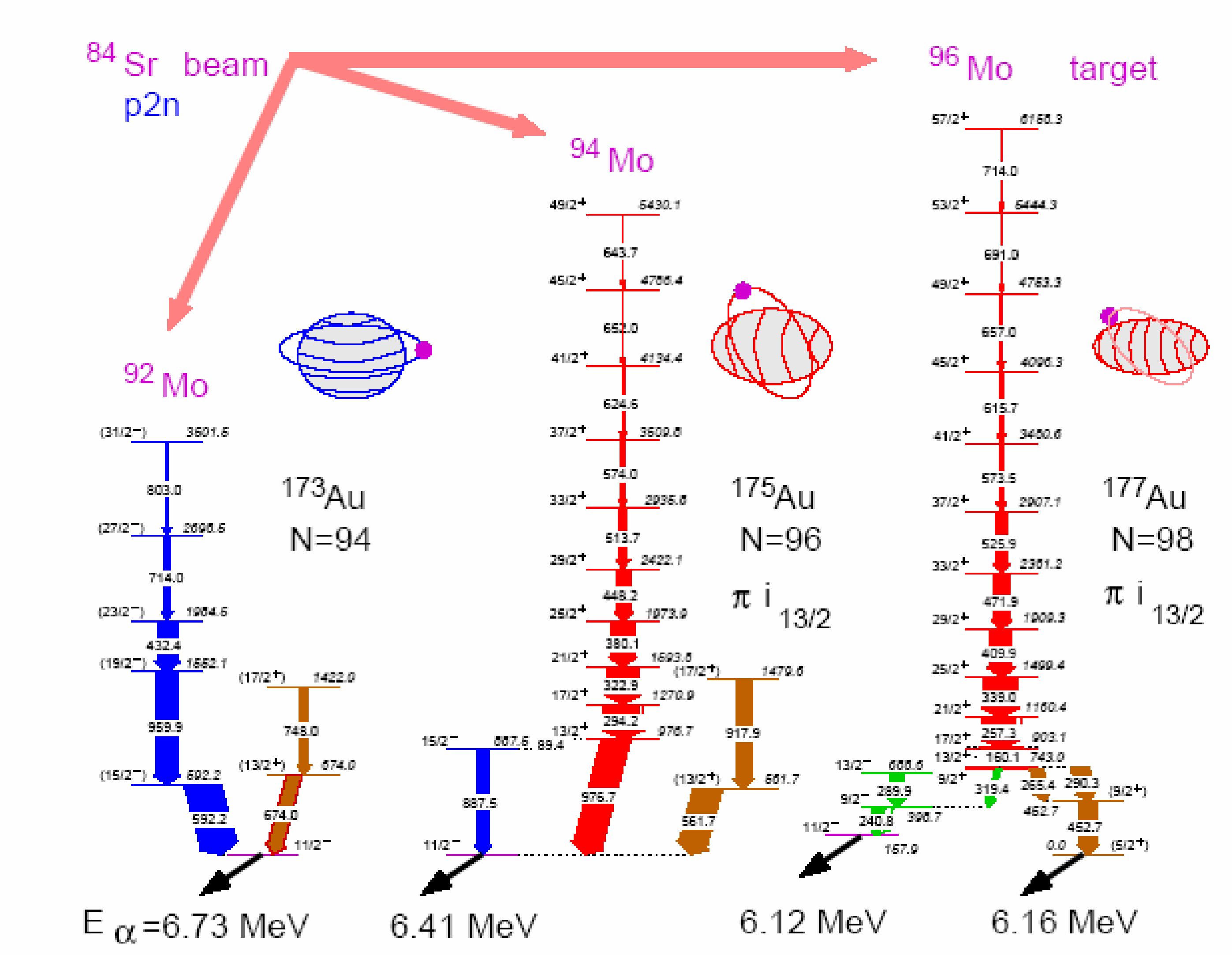
Neutron deficient nuclei



Severe complications

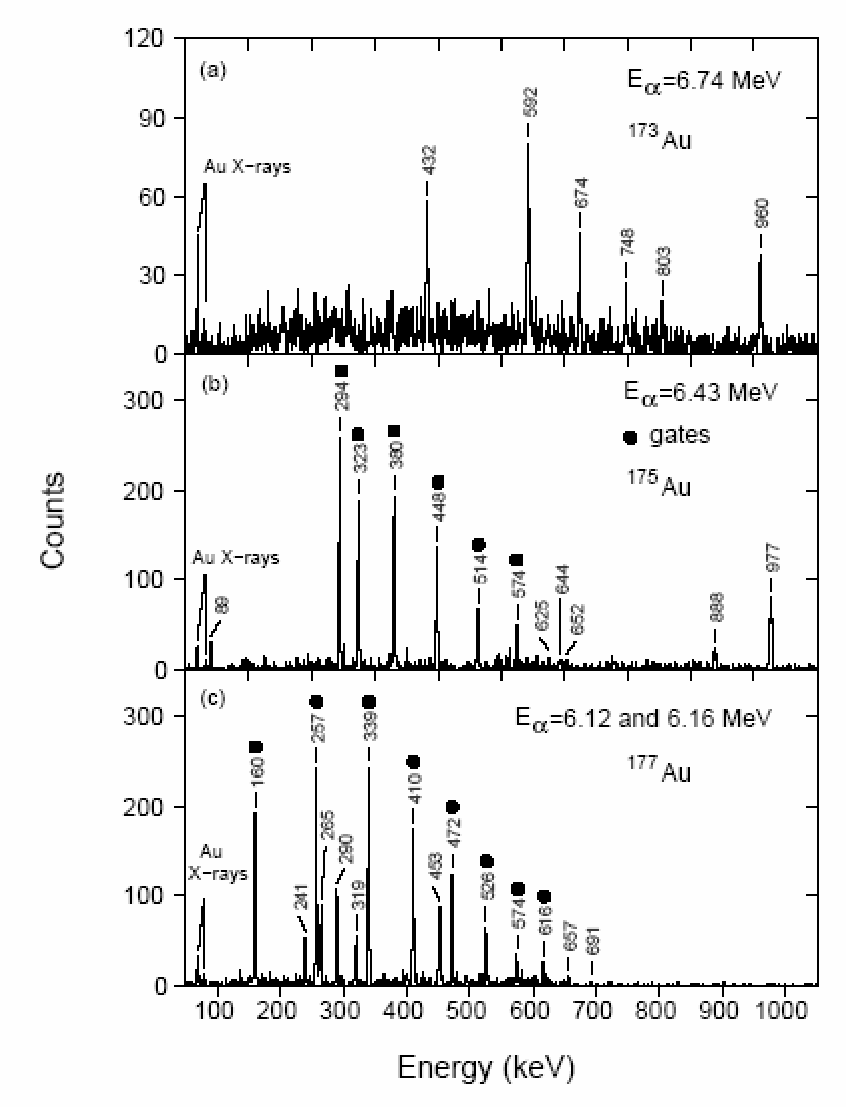
- Charged particle emission:
  - The fusion-evaporation cross section is fragmented into many channels.
    - It limits the absolute production.
- Fission process: *fissibility parameter ~* Z^2/A
  - Depletion of the high-l values.
    - It limits the population of residues at high angular momentum.
  - Huge, unwanted background.

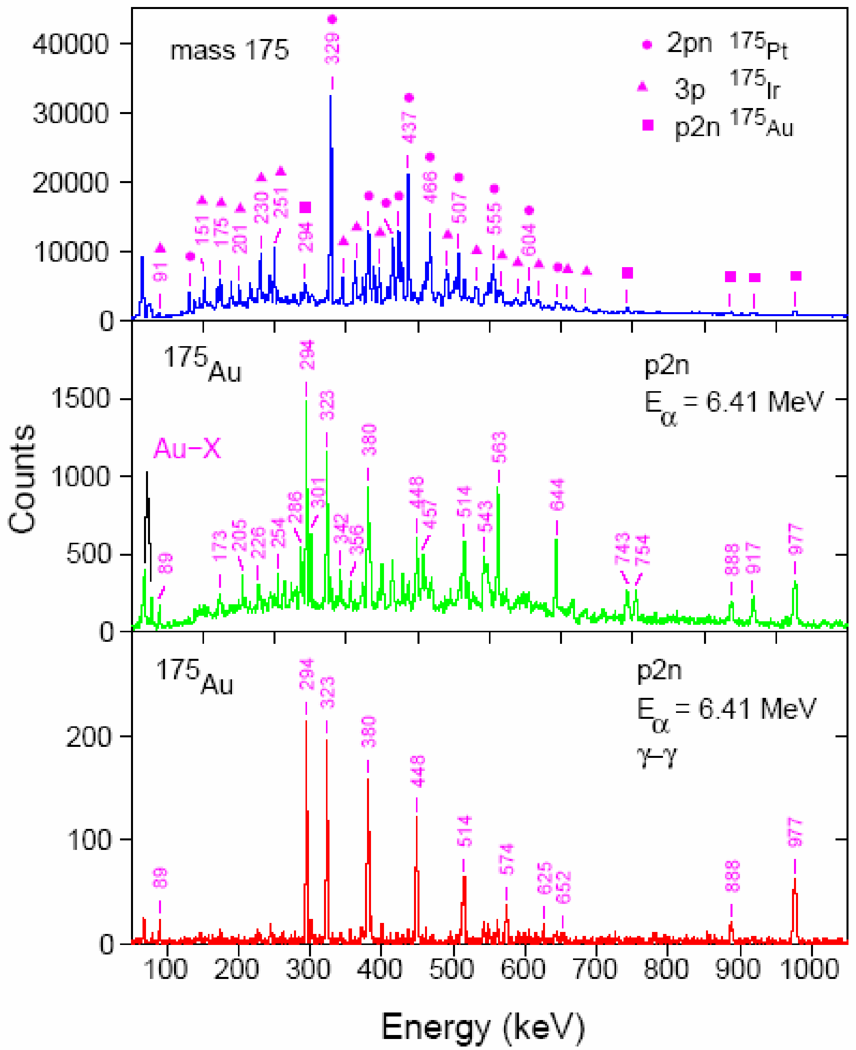
Odd-Z Au (Z=79) isotopes



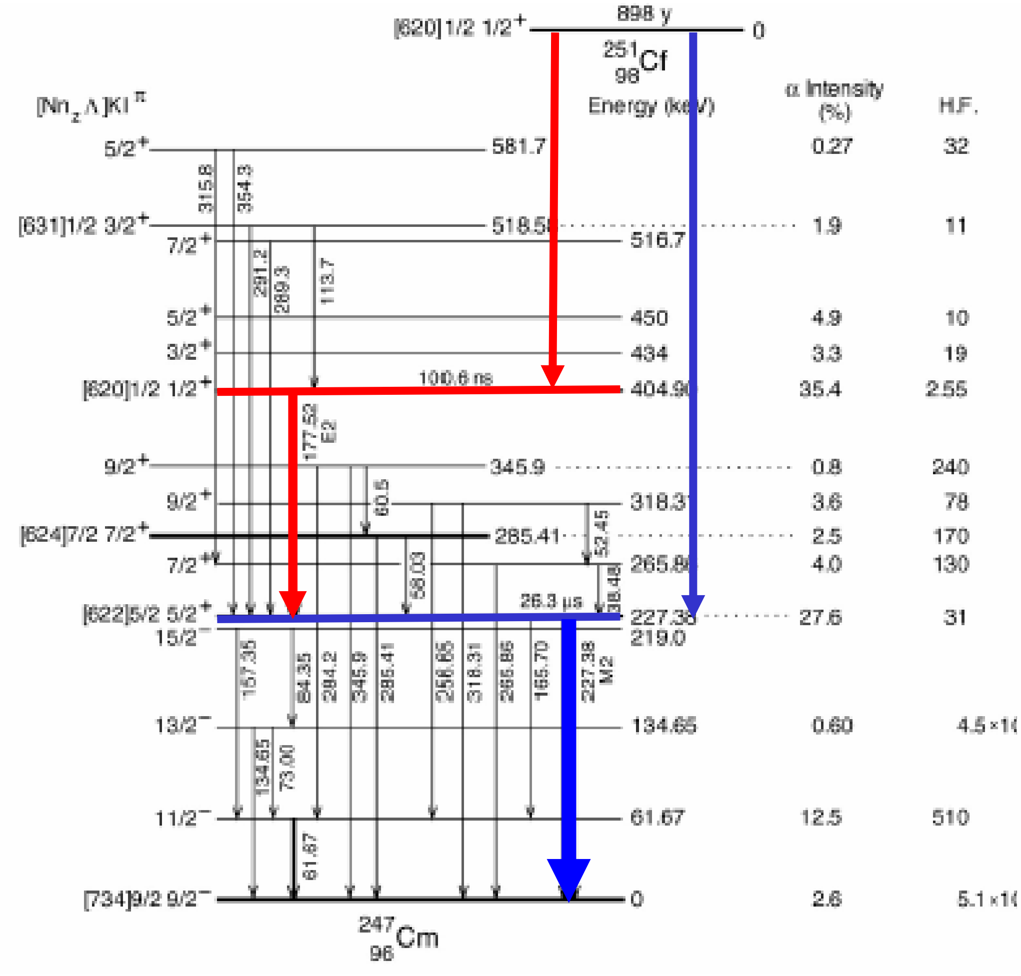
F.G. Kondev et al. Phys. Lett. B528 (2002) 221

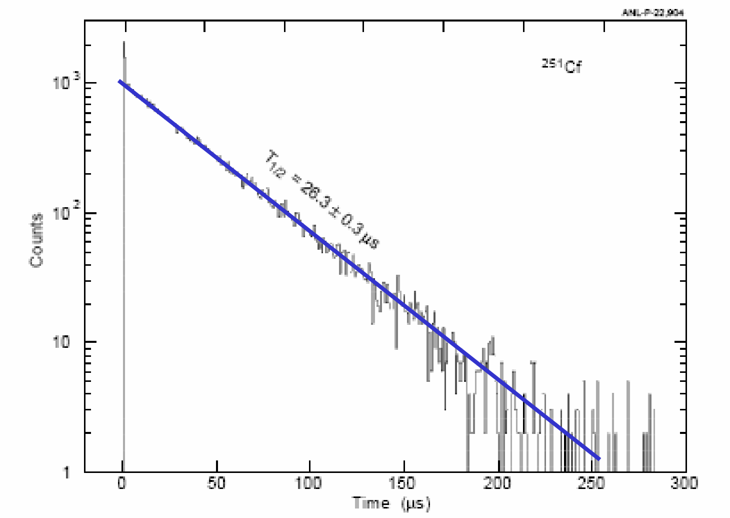
Odd-Z Au (Z=79) isotopes –sample spectra

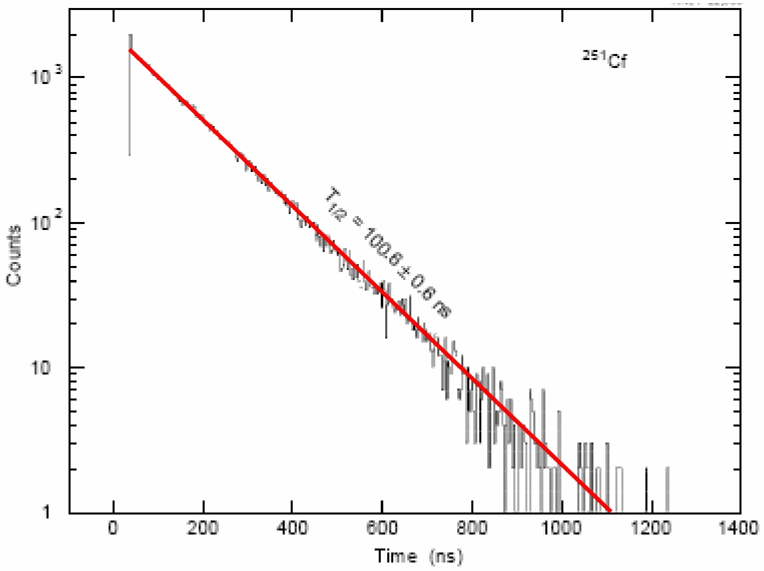




α–γ correlations



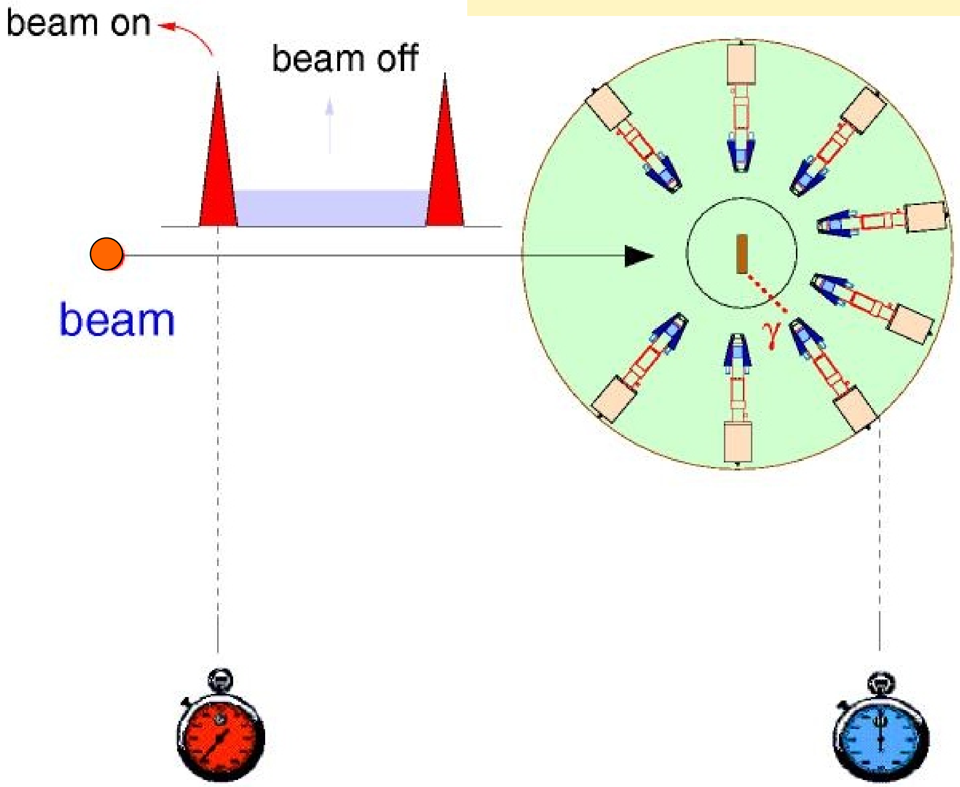




I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

Pulsed beam technique

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

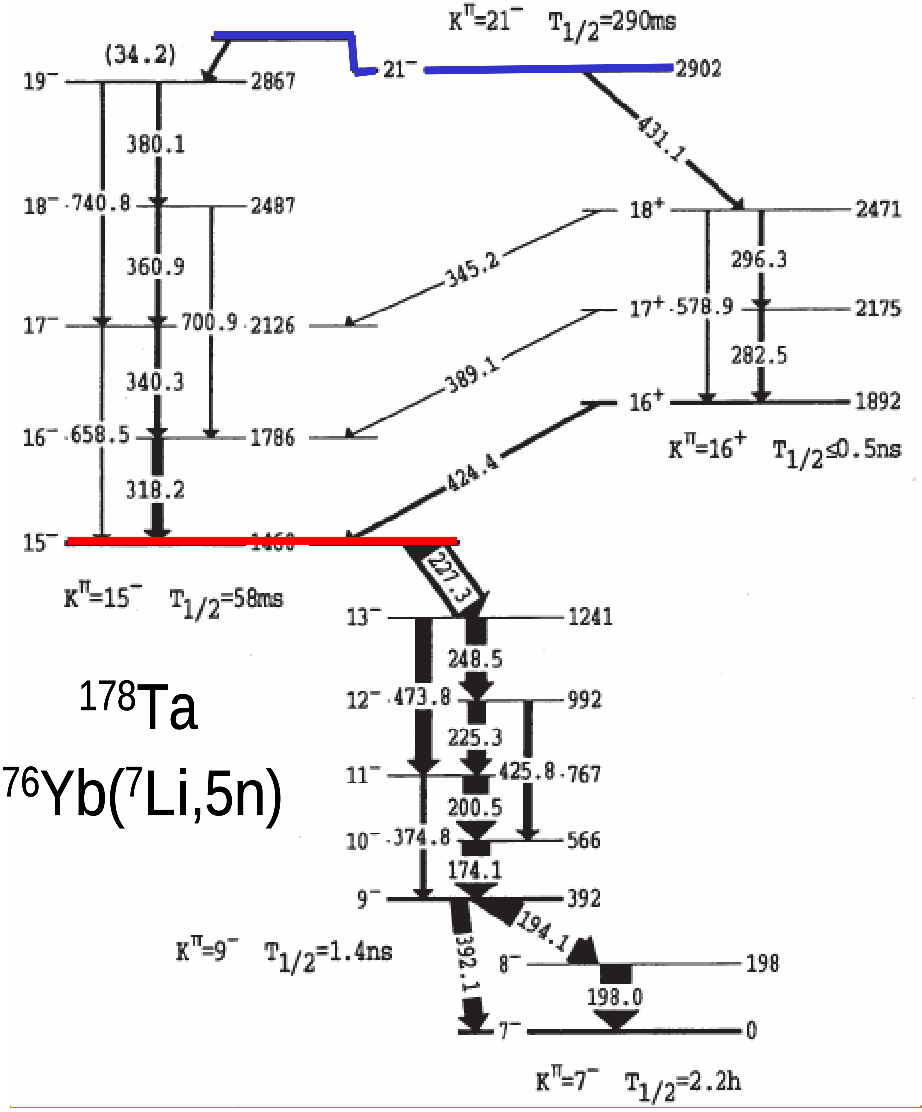


- **Less effective, but …**
  - ✓ **well defined "clock"**
  - ✓ **sensitive to in-beam and decay events**

- "singles": γ–time
- coincidence: γ–γ–time

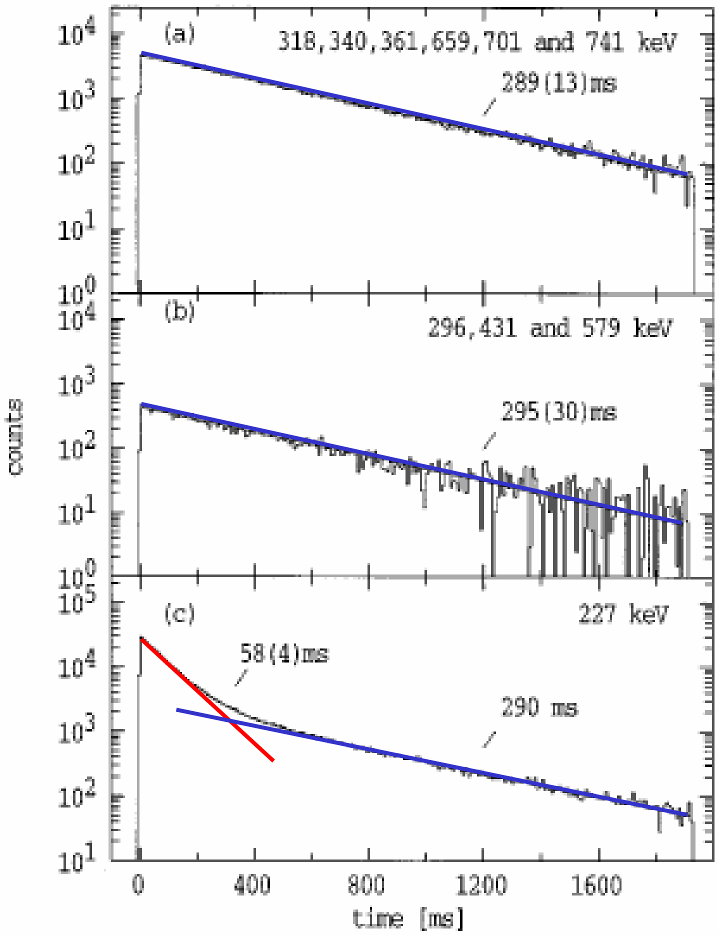
the longest lifetime that can be measured is limited by the time interval between the beam pulses

Pulsed beam: γ–time



^{178}Ta

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



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

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

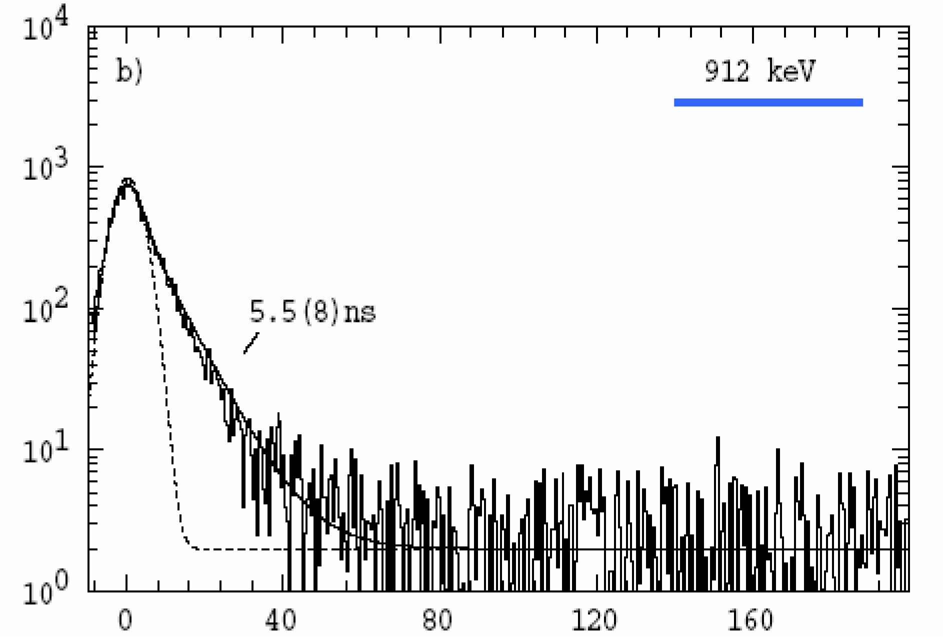
Pulsed beam: γ–time (short-lived)

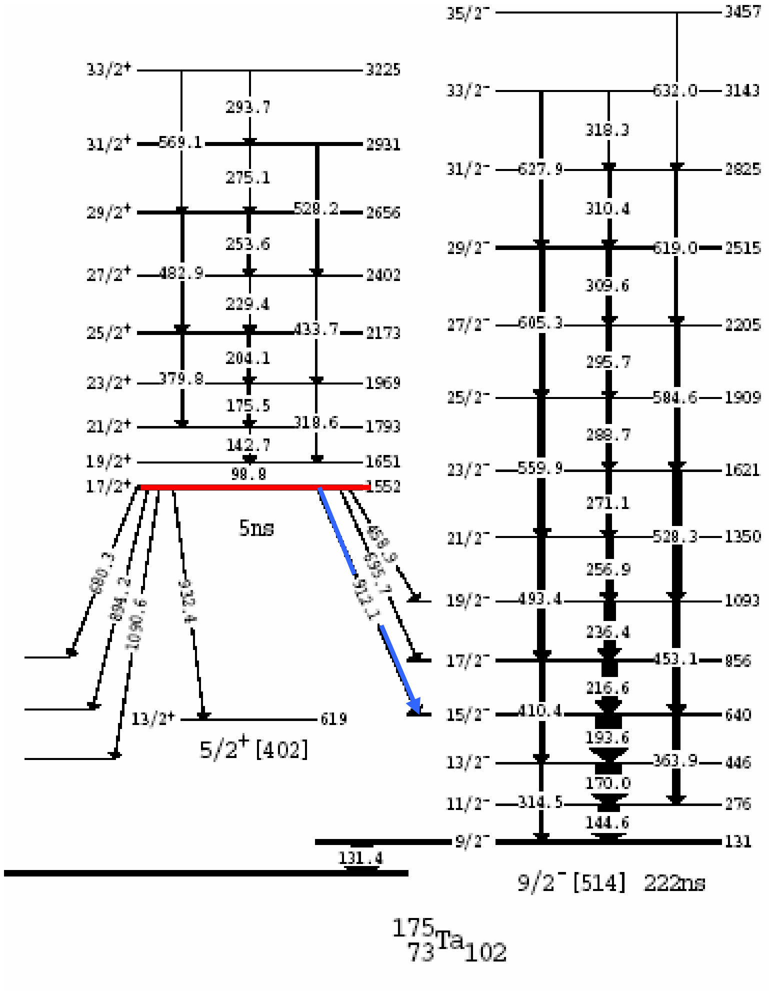
The importance of PRF

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

^{175}Ta

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

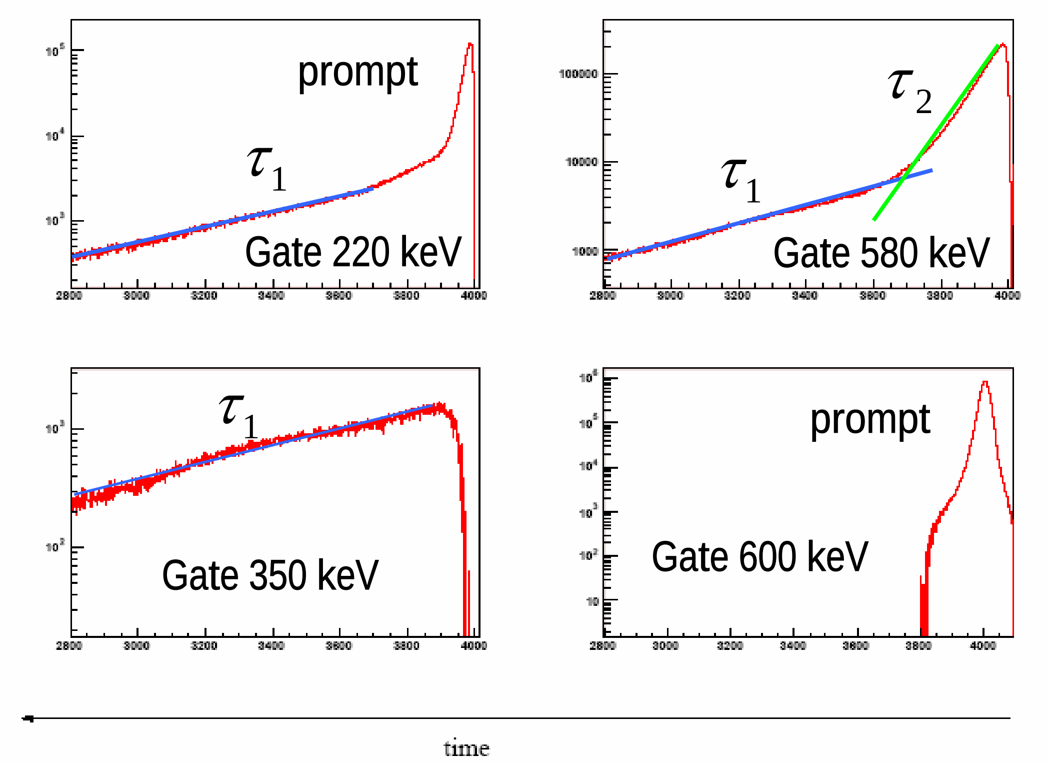


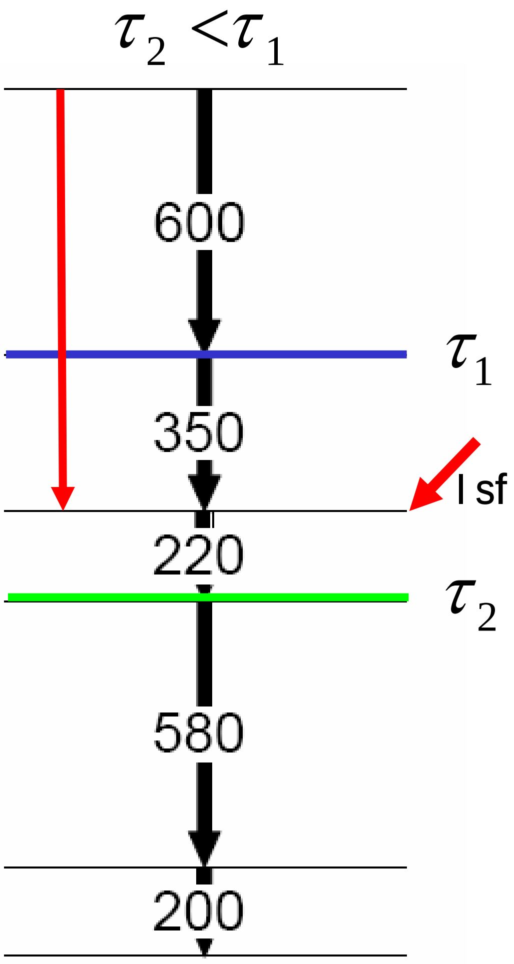


F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

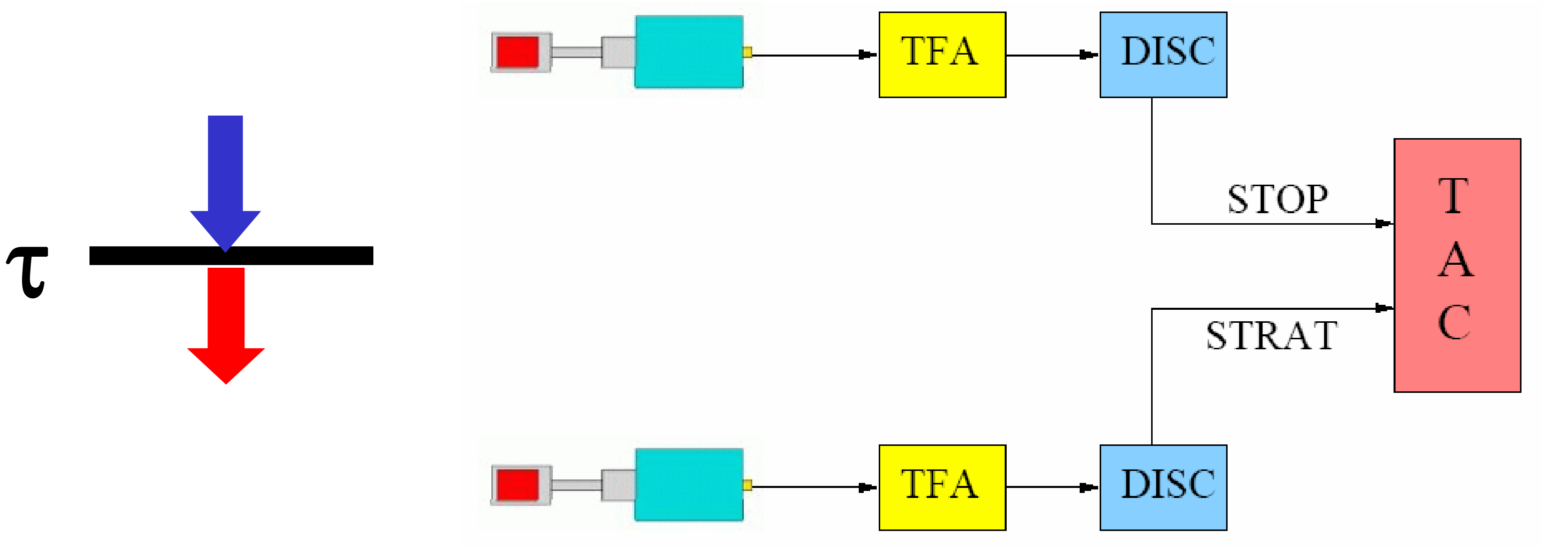
Limitations: Pulsed beam γ–time

- 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





Pulsed beam: γ–γ–time technique



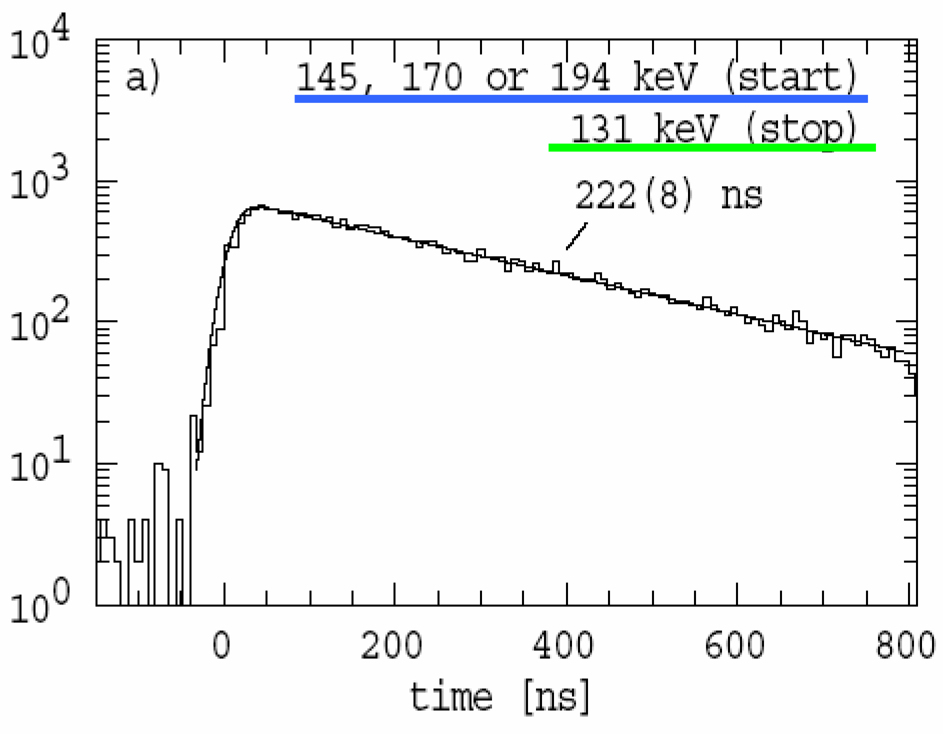
“coincidence” – $E_{\gamma 1}$-$E_{\gamma 2}$-Δt ; $E_{\alpha 1}$-$E_{\gamma 1}$-Δt

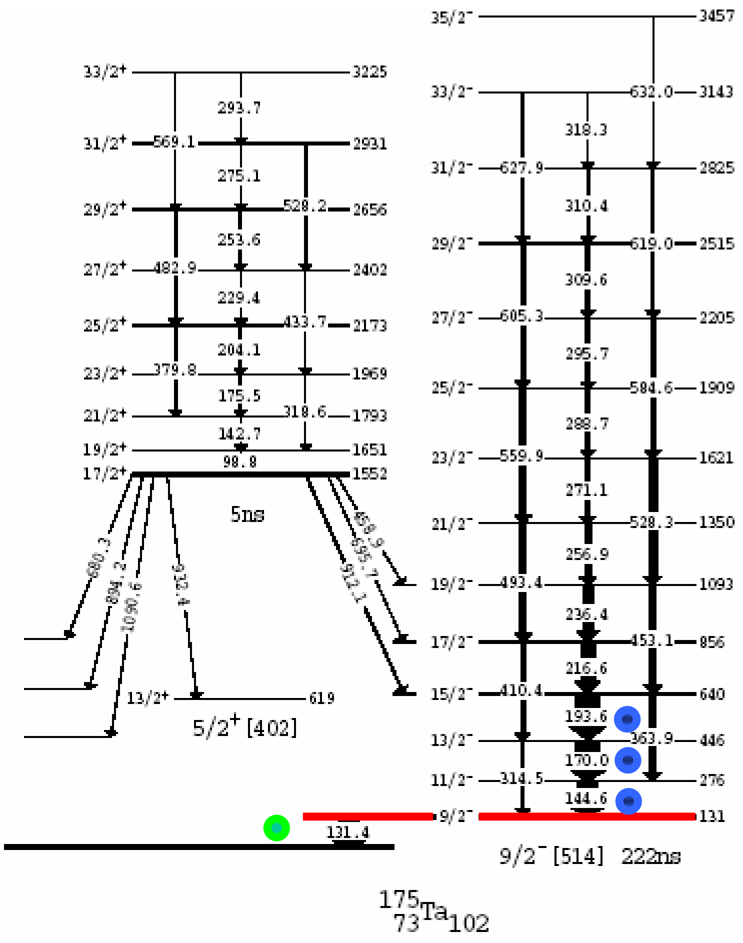
$E_{\alpha 1}$-$E_{\alpha 2}$-Δt

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

^{175}Ta

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





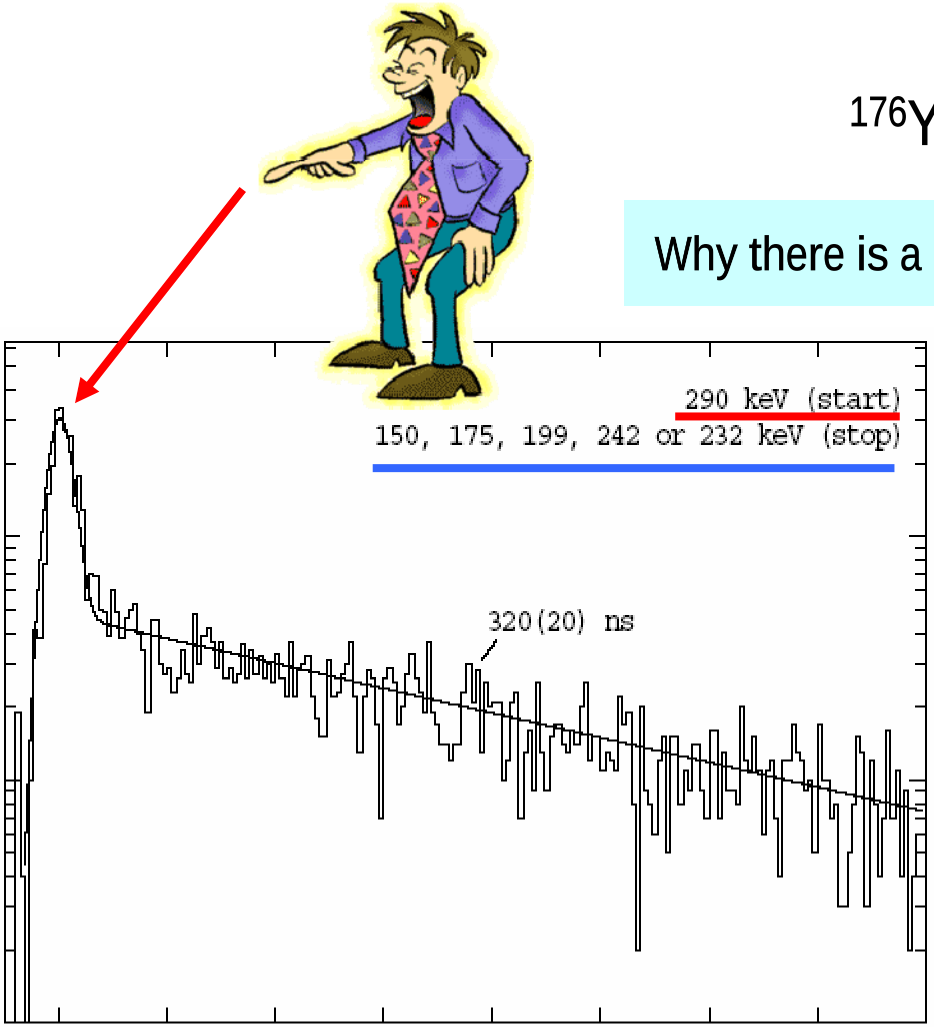
F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

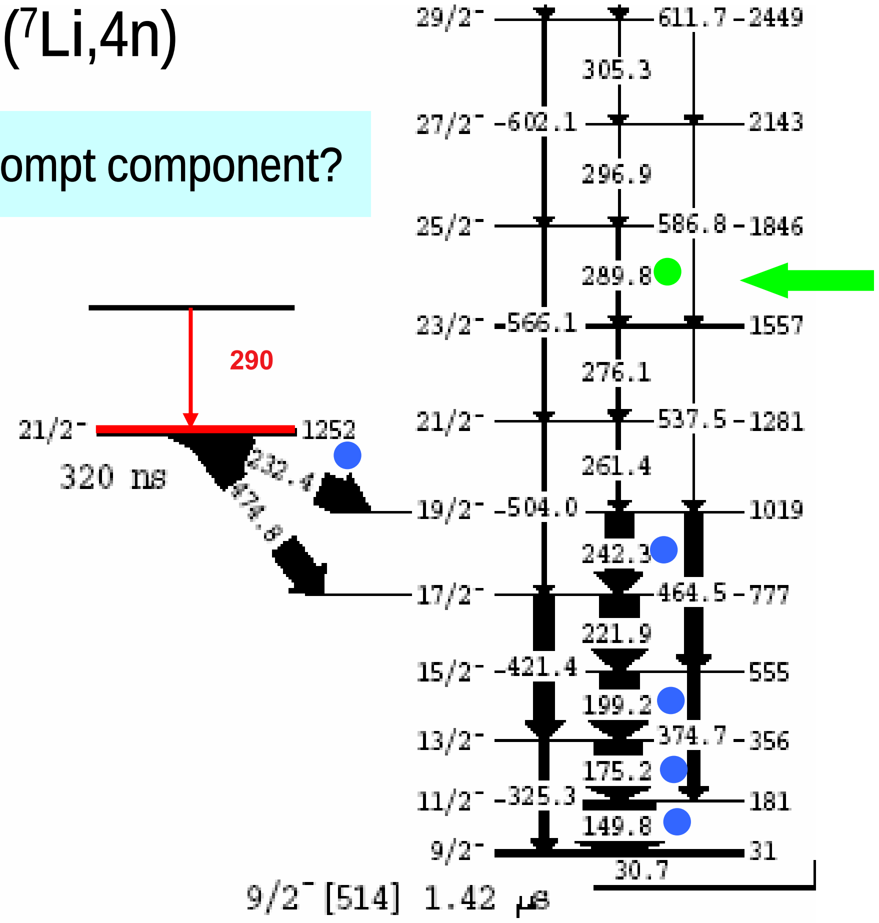
γ–γ–time: decay of the 21/2- isomer in ^{179}Ta

^{179}Ta

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

Why there is a prompt component?





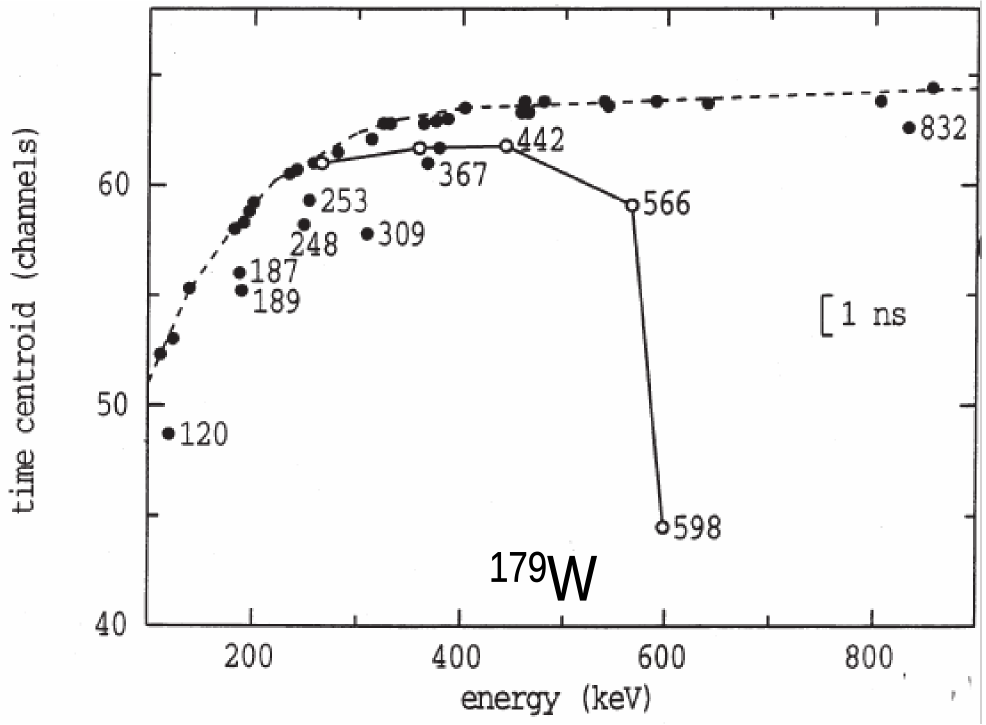
F.G. Kondev et al. Nucl. Phys. A617 (1997) 91

Centroid-shift technique: γ–time

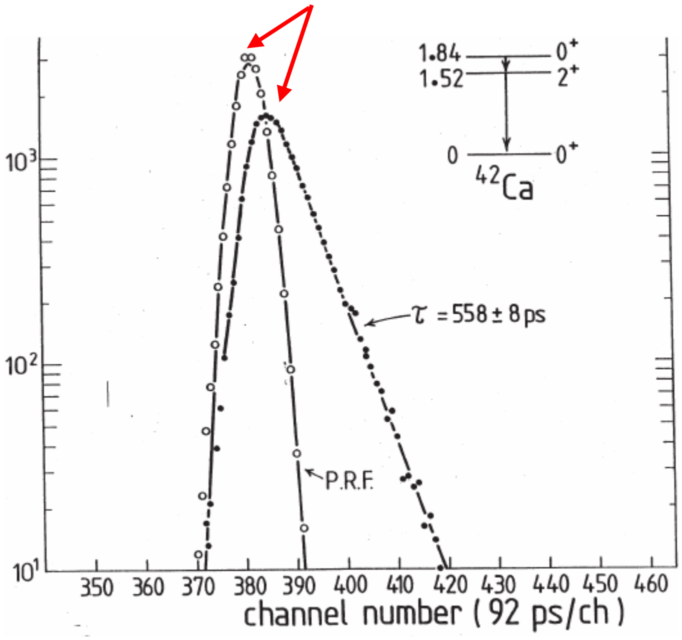
Time Range: near PRF

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

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

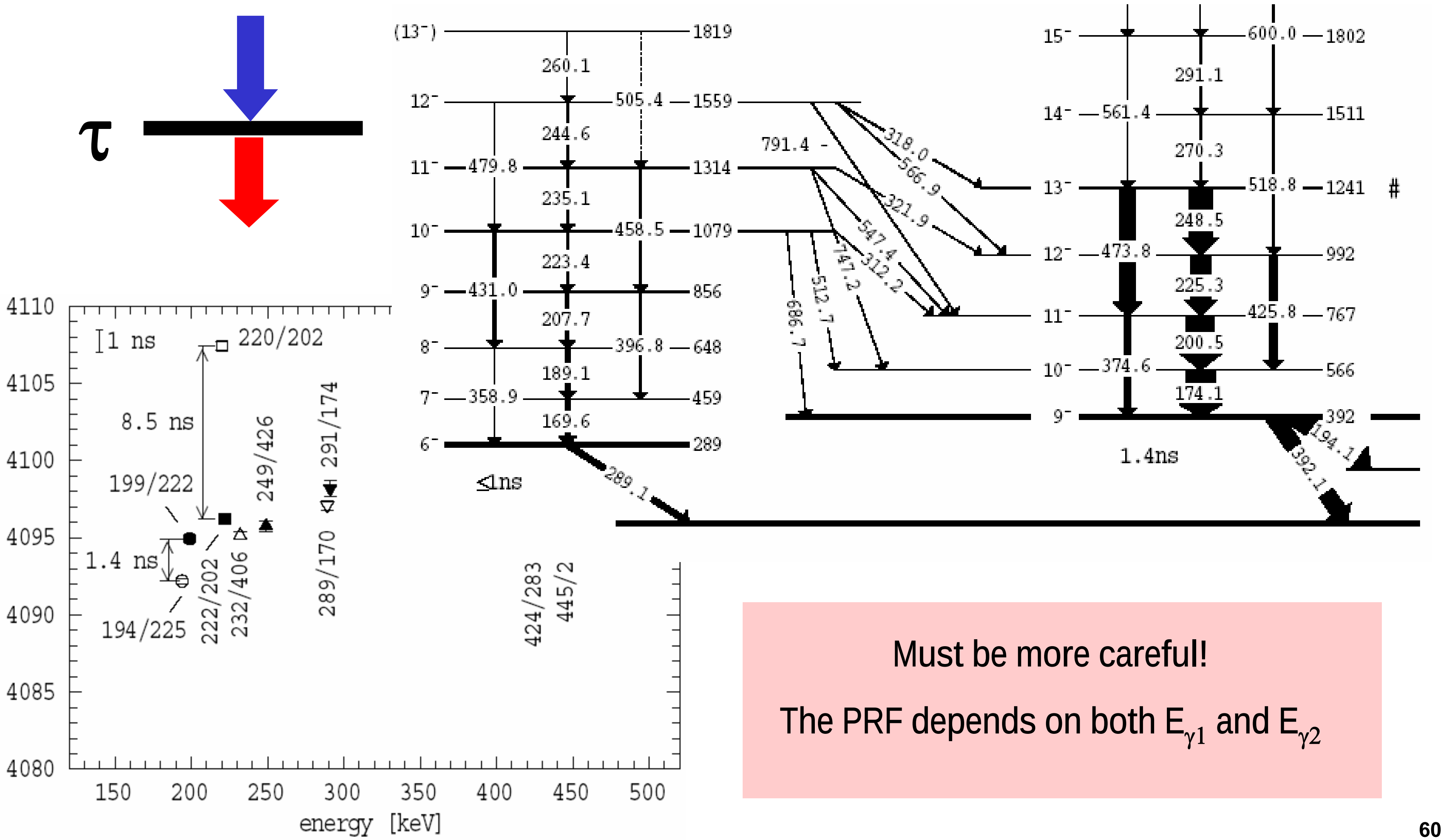


6 ch x 92 ps = 552 ps



P.M. Walker et al. Nucl. Phys. A (1996)

Centroid-shift technique: γ–γ–time



Must be more careful!

The PRF depends on both $E_{\gamma1}$ and $E_{\gamma2}$

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

Coulomb excitations

Time Range: up to hundreds of ps

Observables

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

$$E < V_{cb}$$

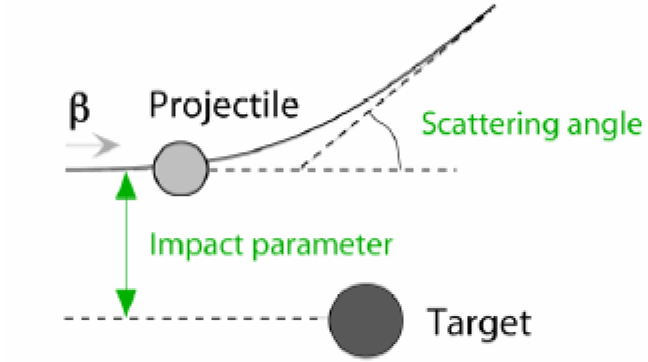
$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} >> 1$$

^{19}F(1 MeV) on ^{238}U η~1.6

^{40}Ar(152 MeV) on ^{238}U η~130

Experimental results

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



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

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

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

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

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

SeGA

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