Experimental Nuclear Structure Part I

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Office of Science Laboratory
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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 – 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
“Techniques for Nuclear and Particle Physics Experiments”, W.R. Leo, 1987

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

~3000 Known Nuclei

~6000 nuclei are predicted to exist

~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
hyper-deformation
backbending
higher-K isomers
band termination
superdeformation
yrast line
magnetic rotation
identical bands
ΔI=4 bifurcation
Angular Momentum

core gap
nuclear superfluidity
reduced moments of inertia

I I+2

158Er

192Hg 194Hg

149Gd

Energy

ΔEγ

Even Even
Odd A

Energy Gap

Energy

Rigid body value

Protos Particles
Nuclear Reactions – very schematic!

- **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

**a multi-step process**
Reactions with Heavy Ions – Classical Picture

- **R, R_v, R_p** – half-density radii
- **b** – impact parameter

**“SOFT” GRAZING**
- INELASTIC SCATTERING
- DIRECT REACTIONS
- COMPOUND NUCLEUS
- \( b < R = R_p + R_t \)

**FUSION**
- DISTANT COLLISION

**“HARD” GRAZING**
- FRAGMENTATION
- DEEP INELASTIC REACTIONS

**DISTANT COLLISION**
- ELASTIC SCATTERING
- COULOMB EXCITATION

\( b > R \quad E < V_c \)
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.

\[ E_{cm} = \frac{M_t}{M_b + M_t} E_{lab} \]

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

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

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

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

\[ E_x = E_{cm} + Q - \text{K.E.} \]

Velocity of center-of-mass frame, which is \( \sim \) velocity of fused residues

\[ \beta_r^2 = 2 \frac{M_b c^2 E_{lab}}{[ (M_b + M_t)c^2]^2} \]
HI Fusion-Evaporation Reactions

\[ \sigma_R = \pi \hbar^2 \sum_{l=0}^{l_{max}} (2l + 1) T_l = \pi \hbar^2 (l_{max} + 1)^2 \]

\[ \hbar = \frac{\hbar}{\sqrt{2 \mu E_{CM}}} \]

\[ \mu = \frac{A_1 A_2}{A_1 + A_2} \]

\[ l_{max}^2 = \left( \frac{2 \mu R^2}{\hbar^2} \right) (E_{CM} - V_C) \]
Decay of the Compound Nucleus

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

- The excited residual nucleus cools off by emitting $\gamma$–rays. Their typical number is quite large, usually 30-40 and the average energy is $\sim 1-2$ MeV. So it is not a trivial task to detect all of them - the big advantage came with the large $\gamma$–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, ~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 cleanliness. In some cases (heavy nuclei) focal plane counters clean up the data for good sensitivity.
Some Channel Selection Detectors

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

USA

Argonne FMA

USA

Jyvaskyla RITU

Europe
Calculate Reaction Rates

**Reaction Yield:** \( Y = I_b \times N_t \times \sigma \) [nuclei/s]

- \( I_b = \frac{i}{\text{eq}} \); with \( i \) - electric current [A], \( q \) - charge state, \( e = 1.6 \times 10^{-19} \) [C]
- \( N_t = \frac{N_a}{A} \rho x \); with \( N_a \) = Avagadros #, \( A \) = mass, \( \rho \) = density [g/cm³] & \( x \) = thickness [cm] of the target
- \( \sigma \) - reaction cross section [cm²] .... note 1 [barn] is \( 10^{-24} \) [cm²]

**Accumulated data:** \( D = Y \times \text{Time} \times \text{Efficiency} \) [counts]

A typical “close to the line of stability” experiment may have:
- \( i=100 \) [nA], \( q=10 \), \( A=100 \), \( \rho x=10^{-3} \) [g/cm²] & \( \sigma=1 \) [barn] and Efficiency of 10% produces \( \sim 3.8 \times 10^4 \) [counts/sec], BUT

A typical “far from the line of stability” experiment may have:
- \( \sigma=100 \) [nb], so the accumulated data is \( \sim 14 \) [counts/hour];
- \( \sigma=10 \) [pb] gives \( \sim 2 \) 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

Diagram:

- $J^{\pi},K$ to $T_{1/2,es}$ to $E_x$ (excited state)
- $J^{\pi},K$ to $T_{1/2,gs}$ to $0$ (ground state)
- $\alpha, \beta^-, \beta^+, EC, p, fission, \gamma, ICC$
- $E_\gamma$
- Stable or, $\alpha, \beta^-, \beta^+, EC, p, cluster, fission$
**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:** \[ A = \frac{dN}{dt} = \lambda N \]

✓ Activity of 1 mole of material \((6.02 \times 10^{23} \text{ atoms})\) with \( T_{1/2}=10^9 \text{ y} \) \((\lambda=2.2 \times 10^{-17} \text{ s}^{-1})\) is \(~0.4 \text{ mCi} (1 \text{ Ci}=3.7 \times 10^{10} \text{ dps})\) (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 \( T_{1/2}>1.5 \times 10^{25} \text{ yr.} \)
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) N
✓ Weak Decay (β⁺, β⁻ and EC)
✓ α decay
✓ More complex cluster emission
✓ Fission

( Mostly because of energy conservation)
Mean Lifetime

\[ f_{\text{decay}}(t) = \frac{A e^{-\lambda t}}{\int_0^\infty A e^{-\lambda t} \, dt} = \lambda e^{-\lambda t} \]

Probability for decay of a nuclear state (normalized distribution function); \( \lambda \) – 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 - \( \tau \)) 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 $\lambda$:

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

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

$$\Gamma \propto |\langle \psi_1 | M | \psi_2 \rangle|^2$$

Determine the matrix element describing the mode of decay between the initial and final state.
log ft values

\[ \log ft = \log f + \log t \]

\[ t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}}{BR_i} \quad \text{partial half-life of a given } \beta^- \ (\beta^+, \text{EC}) \text{ decay branch} \]

\[ f \equiv f_\beta \equiv f_n, \ n = 0, 1, 2... \]

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

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Type</th>
<th>( \log f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta^- )</td>
<td>allowed</td>
<td>( \log f_0^- )</td>
</tr>
<tr>
<td>( \beta^- )</td>
<td>1st-forb</td>
<td>( \log f_0^- + \log(f_1^- / f_0^-) )</td>
</tr>
<tr>
<td>EC+( \beta^+ )</td>
<td>allowed</td>
<td>( \log(f_0^{EC} + f_0^+) )</td>
</tr>
</tbody>
</table>

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

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

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

$\frac{r_0}{2\nu} = \ln2 \frac{\mu^2(H_i^2 + K_i^2) + \tan^2\alpha_0(C_i^2 + S_i^2) + 2\mu\tan\alpha_0(C_iK_i - S_iH_i)}{\mu^2\tan\alpha_0(H_iC_i + K_iS_i)Q_i} e^{2\omega_0}$

**γ–ray decay**

\[
| I_i - I_f | \leq L \leq | I_i + I_f |
\]

\[
\Delta \pi(EL) = (-1)^L \quad \Delta \pi(ML) = (-1)^{L+1}
\]

<table>
<thead>
<tr>
<th>electric multipole</th>
<th>magnetic multipole</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>dipole</th>
<th>quadrupole</th>
<th>octupole</th>
<th>hexadecapole</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1:L=1, yes</td>
<td>E2:L=2, no</td>
<td>E3:L=3, yes</td>
<td>E4:L=4, no</td>
</tr>
<tr>
<td>M1:L=1, no</td>
<td>M2:L=2, yes</td>
<td>M3:L=3, no</td>
<td>M4:L=4, yes</td>
</tr>
</tbody>
</table>

\[
I_i^{\pi_i} \quad E_i \\
I_f^{\pi_f} \quad L \quad E_f
\]

\[
E_{\gamma} = E_i - E_f
\]

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>$E_{1}(M2, E3)$</th>
<th>$E_{2}(M3, E4...)$</th>
<th>$M1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 0!$</td>
<td>$L = 1, 2 &amp; 3$</td>
<td>$L = 2...14$</td>
<td>$L = 1$</td>
</tr>
</tbody>
</table>
Partial lifetime & Transition Probability

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

partial half-life

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

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

partial $\gamma$–ray Transition Probability

\[ B(XL : I_i \rightarrow I_f) \]

contains the nuclear structure information

\[ E_i \]

reduced Transition Probability

\[ T_{1/2}^\text{exp} \]

\[ I_{\gamma_1} \]

\[ I_{\gamma_2} \]

\[ I_{\gamma_3} \]
Hindrance Factor in $\gamma$–ray decay

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

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

**Nilsson (N):** based on deformed Nilsson model potential

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

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

\[ B(E2) = \frac{8.16 \times 10^{13}}{E_\gamma \text{[keV]} \tau_\gamma \text{[ps]}} \left[ e^2 b^2 \right] \]

\[ B(E2; KI_i \rightarrow KI_f) = \frac{5}{16\pi} Q_0^2 \left\langle I, K 20 | I_f, K \right\rangle^2 \]

(from collective models)

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

\[ \tau_\gamma \text{[ps]} = (1.58 \pm 0.28) \times 10^{14} E_{2_i}^{-4} \text{[keV]} Z^{-2} A^{2/3} \]

\[ \beta_2 = \frac{466 \pm 41}{A \times \sqrt{E_{2_i} \text{[keV]}}} \]

\[ I = J \omega \]

\[ E_i = \frac{\hbar^2}{2J} I(I+1) \]

\[ B(E2) \sim 200 \text{ W.U.} \]
Octupole Deformation

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

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

\[ \beta_3 = \frac{4\pi}{ZR^3} \sqrt{\frac{B(E3) \uparrow}{e^2}} \]
K-forbidden decay

- The solid line shows the dependence of $F_W$ on $\Delta K$ for some E1 transitions according to an empirical rule: $\log F_W = 2(|\Delta K| - \lambda) = 2\nu$
- 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

Deformed, axially symmetric nuclei

$K$ is approximately a good quantum number

each state has not only $J^\pi$ but also $K$
Experimental techniques

Others:

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

**Time Range:** a few seconds up to several years

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

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

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

Tag on specific signature radiations ($\alpha$, $\beta$, ce or $\gamma$) in a “singles” mode

```
Clock
Source
Detector
```

Amount of radioactive material $A$ compared to the original amount $A_0$ or any quantity which is proportional to $A$. 

Time as a multiple of the half-life $T$.
Activity Measurements: Example 1

More than 270 spectra were measured
Followed 4 x T\(_{1/2}\)

FIG. 3. Decay curve of \(^{197}\text{Hg}\) at \(E_\gamma = 191.4\) keV.
Activity measurements: Example 2

1 GeV pulsed proton beam on 51 g/cm² ThCx target on-line mass separation (ISOLDE)/CERN

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy (keV)</th>
<th>$T_{1/2}$ (ms)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{200}$Fr</td>
<td>7473(12)</td>
<td>49(4)</td>
<td>this work</td>
</tr>
<tr>
<td>7500(30)</td>
<td>570+270 -140 ms</td>
<td>[4]</td>
<td></td>
</tr>
<tr>
<td>7468(9)</td>
<td>19+13 -6 ms</td>
<td>[5]</td>
<td></td>
</tr>
</tbody>
</table>
Very long-lived cases – Example 1

**Time Range:** longer than $10^2$ yr

$$A = \lambda N$$

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

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

**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. Helmer6

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{174}$Hf (%)</th>
<th>$^{176}$Hf (%)</th>
<th>$^{177}$Hf (%)</th>
<th>$^{178}$Hf (%)</th>
<th>$^{179}$Hf (%)</th>
<th>$^{180}$Hf (%)</th>
<th>$^{181}$Hf (%)</th>
<th>$^{182}$Hf (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>0.16</td>
<td>5.21</td>
<td>18.60</td>
<td>27.30</td>
<td>31.30</td>
<td>46.91</td>
<td>0.112</td>
<td>0.0112</td>
</tr>
<tr>
<td>Helmer 1</td>
<td>0.0058</td>
<td>4.791</td>
<td>0.605</td>
<td>29.06</td>
<td>25.77</td>
<td>39.64</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>Helmer 2</td>
<td>0.00014</td>
<td>4.377</td>
<td>0.149</td>
<td>17.15</td>
<td>31.30</td>
<td>46.91</td>
<td>0.112</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Method</th>
<th>Half-life ($\times 10^6$ yr)</th>
<th>Uncorrelated uncertainty ($\times 10^6$ yr)</th>
<th>Total uncertainty ($\times 10^6$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helmer 1</td>
<td>Neutron activation + activity measurement</td>
<td>9.034</td>
<td>$\pm 0.241$</td>
<td>$\pm 0.251$</td>
</tr>
<tr>
<td>Helmer 2</td>
<td>Isotope dilution + activity measurement</td>
<td>8.896</td>
<td>$\pm 0.057$</td>
<td>$\pm 0.089$</td>
</tr>
<tr>
<td></td>
<td>Weighted mean</td>
<td>8.904</td>
<td>$\pm 0.056$</td>
<td>$\pm 0.088$</td>
</tr>
</tbody>
</table>
Very long-lived cases – Example 2

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

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

mass-separated source
alpha-decay counting technique

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

Time Range: tens of ps up to a few seconds

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

“singles” – $E_{\gamma}$-time, $E_{\alpha}$-time

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

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

<table>
<thead>
<tr>
<th>Detector</th>
<th>FWHM, ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>plastic scintillators</td>
<td>~100</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>~100</td>
</tr>
<tr>
<td>Si</td>
<td>~200</td>
</tr>
<tr>
<td>Na(I)</td>
<td>~500</td>
</tr>
<tr>
<td>Ge</td>
<td>0.6-9 ns</td>
</tr>
</tbody>
</table>
Prompt Response Function: Ge detectors

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

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

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 $\gamma$-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

$\alpha$2n 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
$^{140}\text{Dy}: \text{Experimental Results}$

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

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
\( \alpha-\alpha \) (parent-daughter) correlations

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

\[ \alpha_1: 6.12 \text{ MeV} \]
\[ \alpha_2: 5.7 \text{ MeV} \]

**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:** \( fissibility \text{ parameter } \sim \frac{Z^2}{A} \)
  - 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

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

Pulsed beam technique

beam on
beam off

beam

“singles”: \( \gamma \)-time

coincidence: \( \gamma \)-\( \gamma \)-time

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

the longest lifetime that can be measured is limited by the time interval between the beam pulses
Pulsed beam: $\gamma$–time

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

Pulsed beam: $\gamma$–time (short-lived)

The importance of PRF

In $\gamma$–time measurements PRF depends on $E_\gamma$ for a single transition

$^{175}\text{Ta}$

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

**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

![Diagram showing τ₁ and τ₂](image)

 τ₂ < τ₁

Gate 220 keV

Gate 580 keV

Gate 350 keV

Gate 600 keV

I sf

τ₁

τ₂

600

350

220

580

200
Pulsed beam: $\gamma-\gamma$–time technique

"coincidence" – $E_{\gamma_1}-E_{\gamma_2}-\Delta t$; $E_{\alpha_1}-E_{\gamma_1}-\Delta t$

$E_{\alpha_1}-E_{\alpha_2}-\Delta t$
$\gamma-\gamma$ time: decay of the 9/2- isomer in $^{175}$Ta

$^{175}$Ta

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

\(\gamma-\gamma\)-time: decay of the 21/2- isomer in \(^{179}\text{Ta}\)

\[^{179}\text{Ta}\]

\[^{176}\text{Yb}(^7\text{Li},4\text{n})\]

Why there is a prompt component?

**Centroid-shift technique: \( \gamma \)-time**

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

\[
M_r(F(t)) = \int_{-\infty}^{\infty} t' F(t) dt
\]

\[
\tau = M_1(F(t)) - M_1(P(t))
\]

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

Time Range: near PRF

\[6 \text{ ch} \times 92 \text{ ps} = 552 \text{ ps}\]

Centroid-shift technique: $\gamma$–$\gamma$–time

Must be more careful!
The PRF depends on both $E_{\gamma 1}$ and $E_{\gamma 2}$

Coulomb excitations

**Time Range:** up to hundreds of ps

\[ E < V_{cb} \]

\[ \eta = \frac{Z_1 Z_2 e^2}{\hbar \nu} \gg 1 \]

\( ^{19}\text{F}(1 \text{ MeV}) \text{ on } ^{238}\text{U} \eta \approx 1.6 \)

\( ^{40}\text{Ar}(152 \text{ MeV}) \text{ on } ^{238}\text{U} \eta \approx 130 \)

Observables
- Number of gamma rays detected \( (N_\gamma) \)
- Number of beam particles detected \( (N_{\text{beam}}) \)
- Energy of de-excitation gamma ray \( (E_\gamma) \)

Experimental results
- Coulomb excitation cross section \( (\sigma) \)
- Reduced transition probability \( B(E2, \uparrow \rightarrow \downarrow) \)
- Energy of excited state

\[ \sigma_{0 \rightarrow 2} \approx \left( \frac{Z_{\text{target}} e^2}{\hbar c} \right)^2 \frac{\pi}{e^2 b_{\text{min}}^2} B(E 2.0^+ \rightarrow 2^+) \]

Intermediate energy Coulomb excitations

| Primary beam: | $^{76}$Ge @ 130 MeV/nucl. |
| Secondary beam: | $^{54}$Ti @ 88 MeV/nucl. |
| $\beta = 0.406$ |
| $^{197}$Au target thickness: 257.67 mg/cm² |
| $\Theta_{\text{max}} = 3.20^\circ$ (CM) |
| Number of $^{54}$Ti particles detected: 91.665E6 |

SeGA (Segmented Germanium Array)—Eighteen 32-fold segmented HP germanium detectors

Measured for $^{54}$Ti
- $E_\gamma = 1497(4)$ keV
- $\sigma(\theta<\Theta_{\text{max}}) = 83(15)$ mb
- $B(E2,) = 357(63)$ e²fm⁴

$\tau = 1.5(3) \text{ ps}$