Nuclear Level Lifetimes: The Long and Short of It

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8th Tastes of Nuclear Physics
UWC, 9-12 October 2018

Association for Research
at University Nuclear Accelerators

UK Accelerator Laboratory

- 7-MV single-ended Van de Graaff; rf ion source
- Gas targets: 0.5 to 10 MeV neutrons with ^{3}H(p,n) and ^{2}H(d,n); extended up to 25 MeV with ^{3}H(d,n); monoenergetic (ΔE_n < 100 keV) neutrons
- Nuclear spectroscopy with neutron time-of-flight and γ-ray (HPGe/BGO) detection
- Nuclear structure and reaction mechanisms
- Femtosecond nuclear level lifetimes
- Neutron detector development with collaborators
- Various applications of fast neutrons
- Research program supported by the NSF since accelerator installation in 1964; upgrade in 1990s
- A hands-on, student-run facility
- www.pa.uky.edu/accelerator/

Miscellaneous Facts and Highlights

- Research program funded continuously by NSF for over 55 years!!
- About 10 publications per year result from work performed at the UK accelerator.
- In recent years, the accelerator has operated 24/7 for greater than half of the days of the year.
- For external (non-UK) non-collaborators, beam time is sold (at a bargain rate).
- For collaborations led by external users, beam time is considered an in-kind contribution.
- About half of a technician's time is in support of the accelerator facility.

Nuclear Level Lifetimes: From 10^{34} years to 10^{-18} seconds

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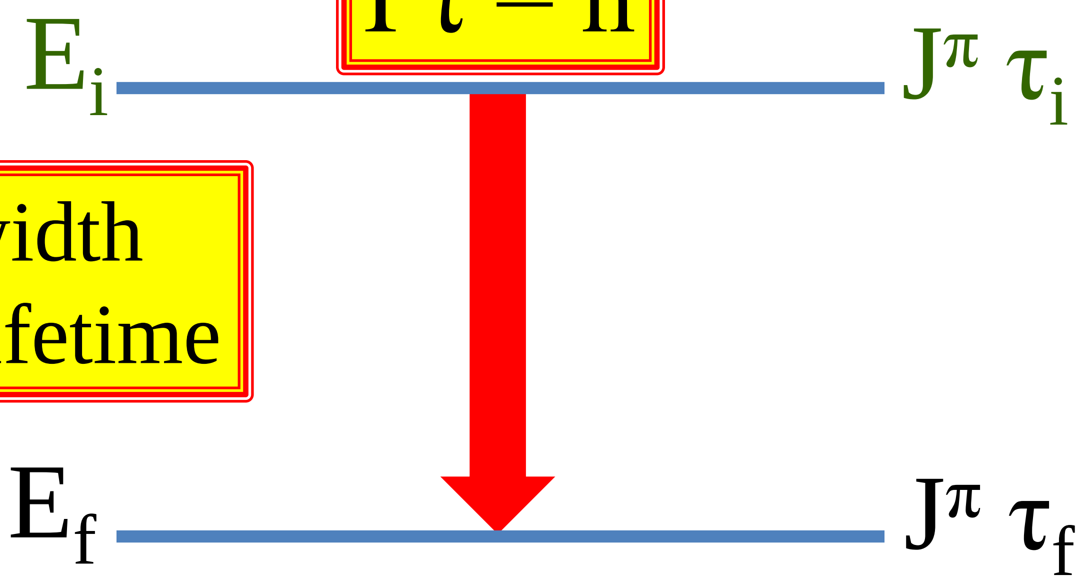
Lifetimes of Excited Nuclear States

Along with the energy, spin, and parity of an excited nuclear state, the lifetime is an important and characteristic property required for nuclear model descriptions.

$$\Gamma\tau = \hbar$$

Γ – level width
τ – level lifetime



Rates of Nuclear Decay

We will assume (correctly) that all radioactive decay is represented by **first-order kinetics**.

Rate of decay = $-\dfrac{dN}{dt} \propto \boldsymbol{N}$

Activity (A) = $-\dfrac{dN}{dt} = \lambda \boldsymbol{N}$

$$\int_{N_o}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$N = N_o e^{-\lambda t} \quad \text{or} \quad A = A_o e^{-\lambda t}$$

$$N = N_o e^{-\lambda t} \quad \text{or} \quad A = A_o e^{-\lambda t}$$

$$\ln \frac{N}{N_o} = -\lambda t \qquad \ln \frac{A}{A_o} = -\lambda t$$

At the half-life ($t_{½}$), $N = ½N_o$ or $A = ½A_o$

$$\ln \frac{½N_o}{N_o} = -\lambda t_{½}$$

Half-life $t_{½} = \frac{\ln 2}{\lambda}$

Mean life or lifetime $\tau = \frac{1}{\lambda}$

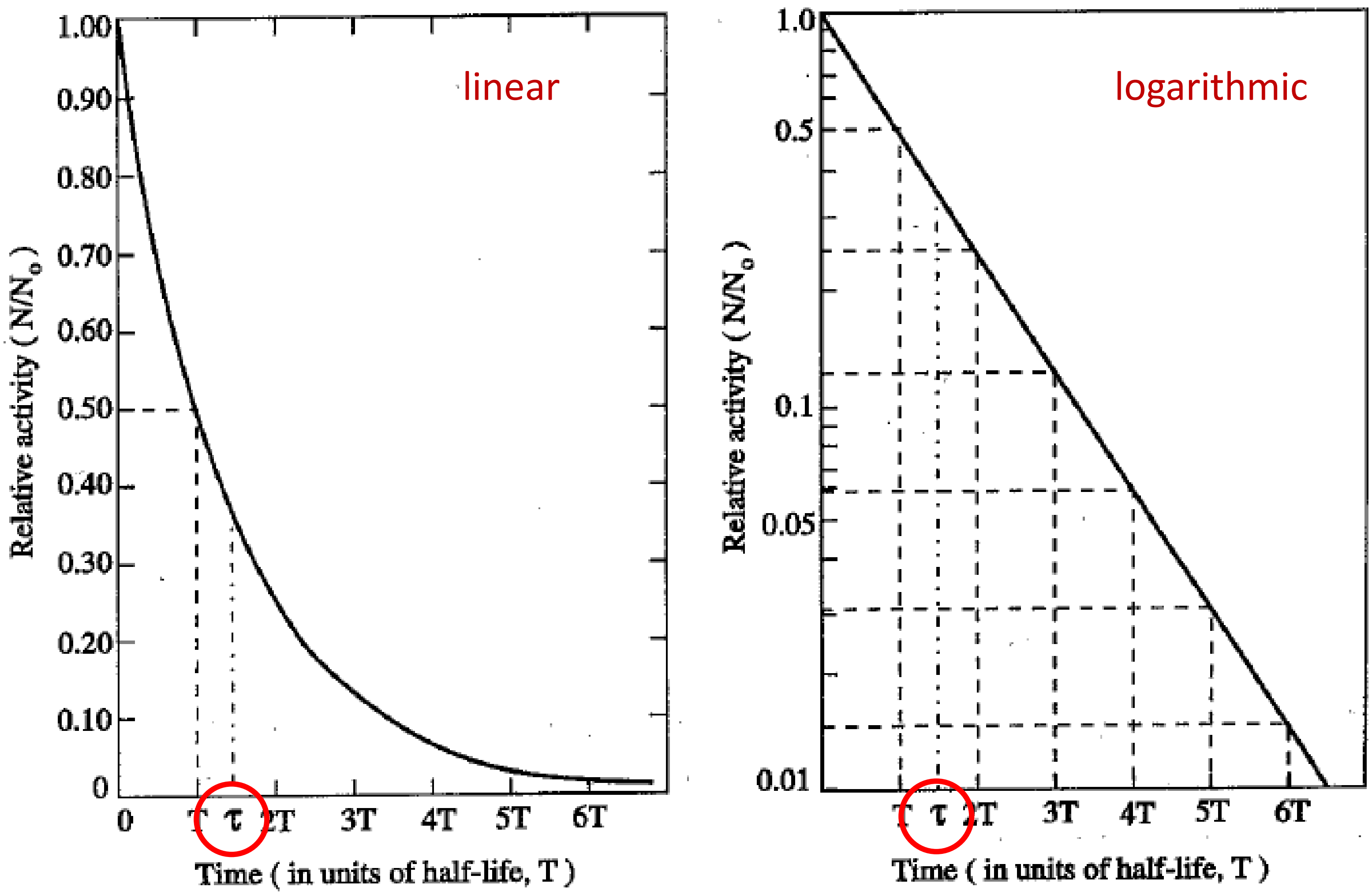
$$A = A_o e^{-\lambda t}$$

$$\ln A = \ln A_o - \lambda t$$

$$\boxed{\ln A = -\lambda t + \ln A_o}$$

The “simple” decay curve method is typically used for lifetimes of seconds to years.

Radioactive Decay



Electromagnetic Transition Rates

Reduced Eλ or Mλ transition rates are evaluated from the equation

$$B(\lambda; i \to f) := \frac{1}{2J_i + 1} |\langle J_f || \mathfrak{M}(\lambda) || J_i \rangle|^2 .$$

Transition rates are then expressed in terms of these reduced rates by

$$T(\lambda; i \to f) = \frac{8\pi}{\hbar} \frac{\lambda + 1}{\lambda[(2\lambda+1)!!]^2} k^{2\lambda+1} B(\lambda; i \to f),$$

where $k = E_\gamma / \hbar c$ and E_γ is the energy of the emitted gamma ray.

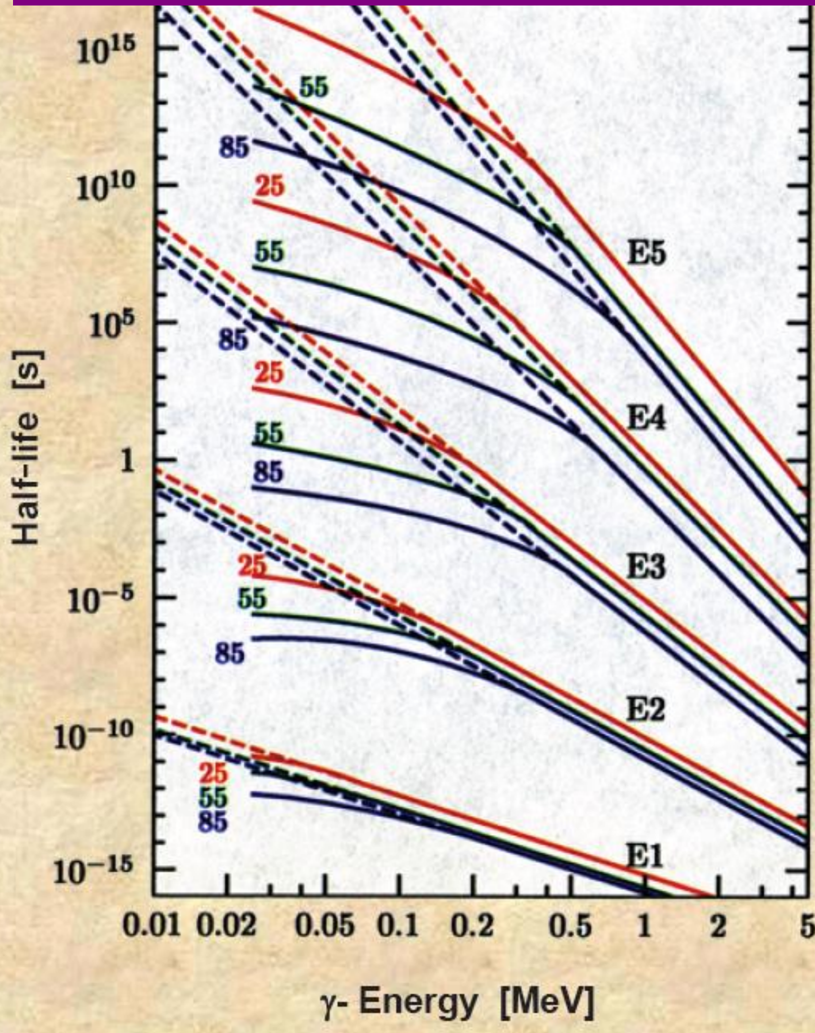
Reduced $B(\mathrm{E}\lambda)$ and $B(\mathrm{M}\lambda)$ transition rates are related to experimentally measurable quantities by

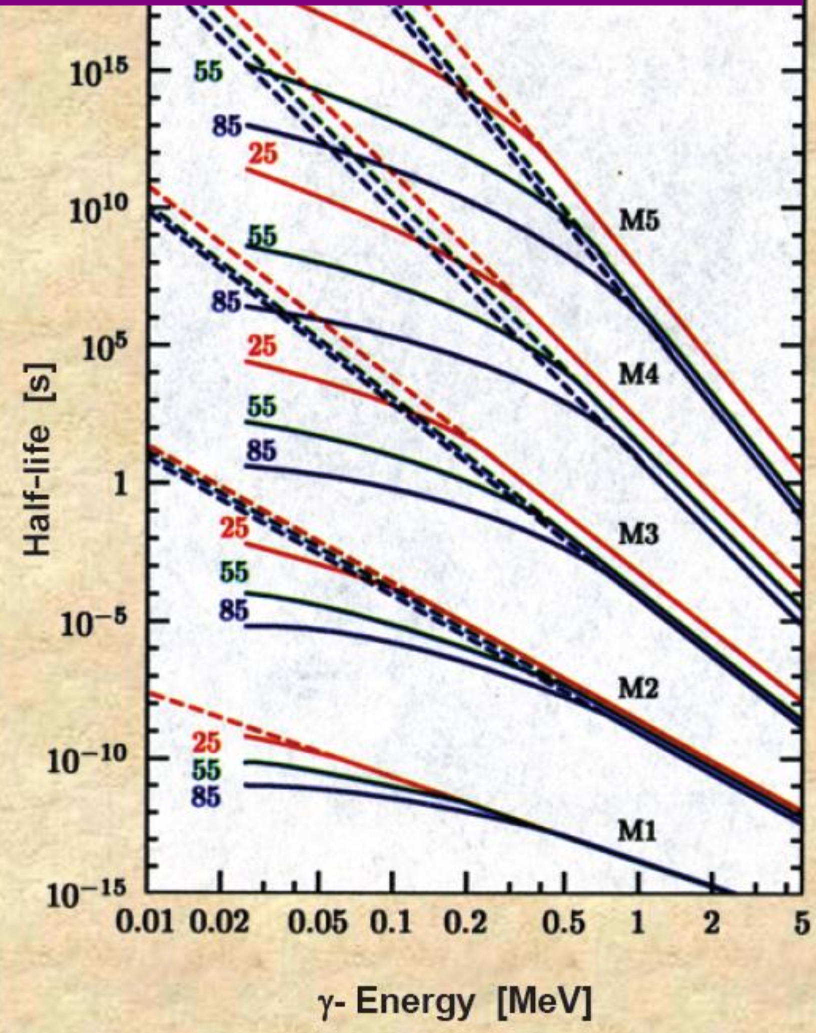
$$B(\mathrm{E}\lambda; i \to f) = \frac{\mathcal{F}_\lambda^{(\mathrm{E})}}{(E_\gamma)^{2\lambda+1} T^\gamma_{1/2}(\mathrm{E}\lambda) \ln 2} e^2 \cdot b^\lambda$$

$$B(\mathrm{M}\lambda; i \to f) = \frac{\mathcal{F}_\lambda^{(\mathrm{M})}}{(E_\gamma)^{2\lambda+1} T^\gamma_{1/2}(\mathrm{M}\lambda) \ln 2} e^2 . \mu_N^{\lambda-1},$$

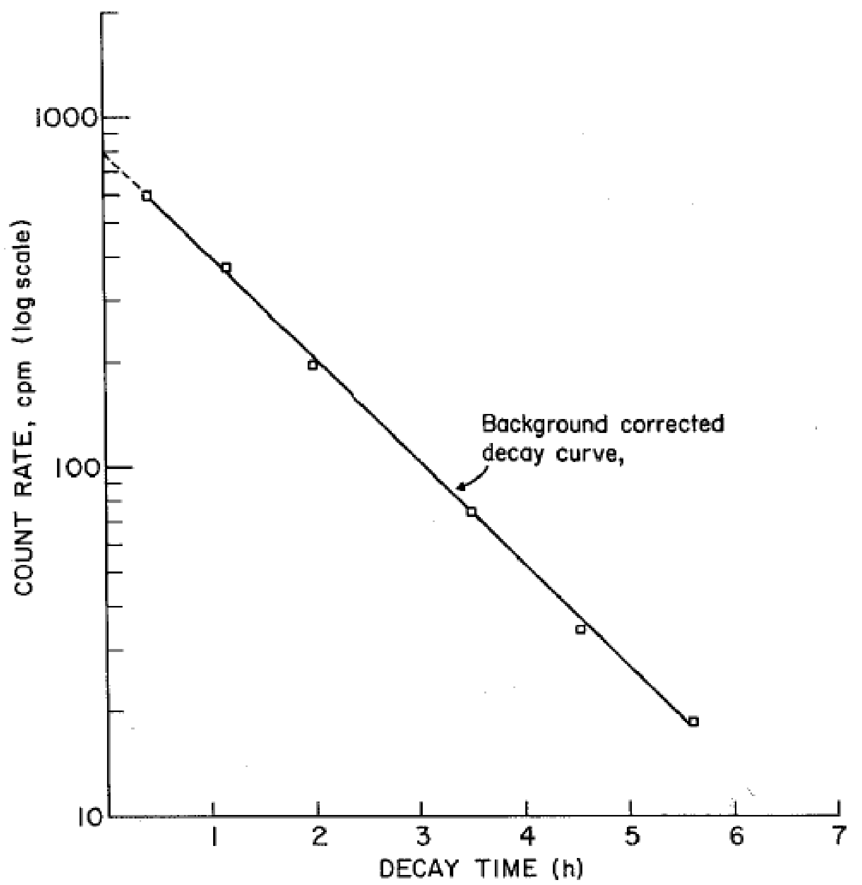
From Rowe and Wood

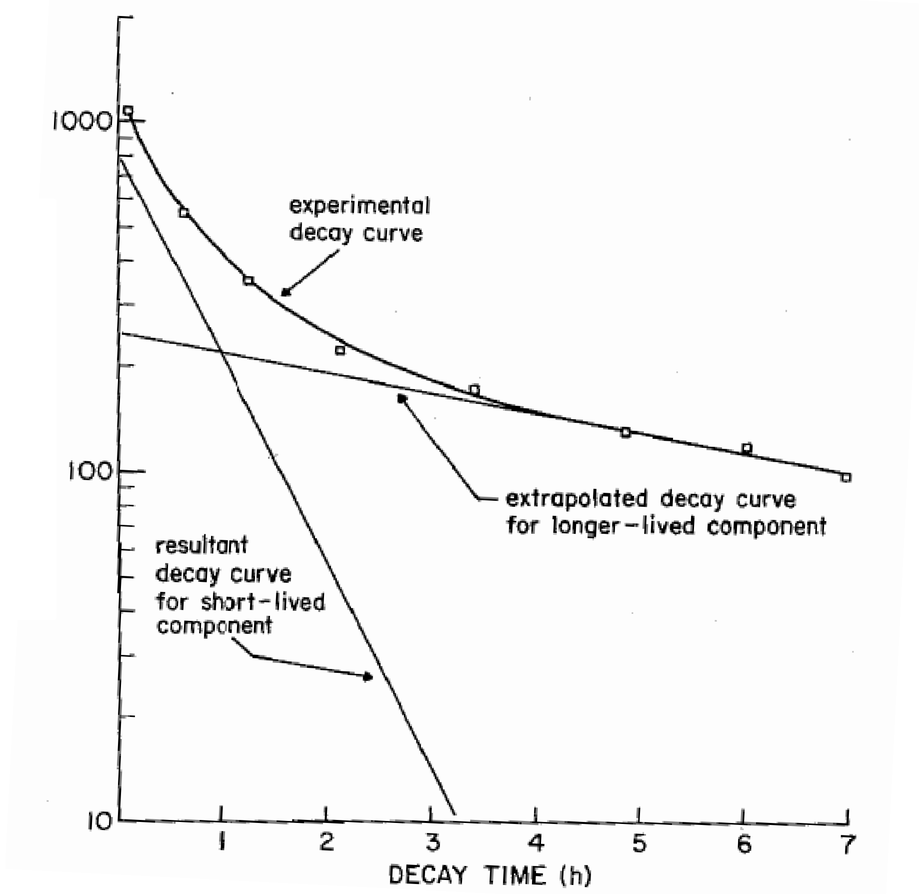
Half-lives decrease with the energy of the transition and increase with the multipolarily.

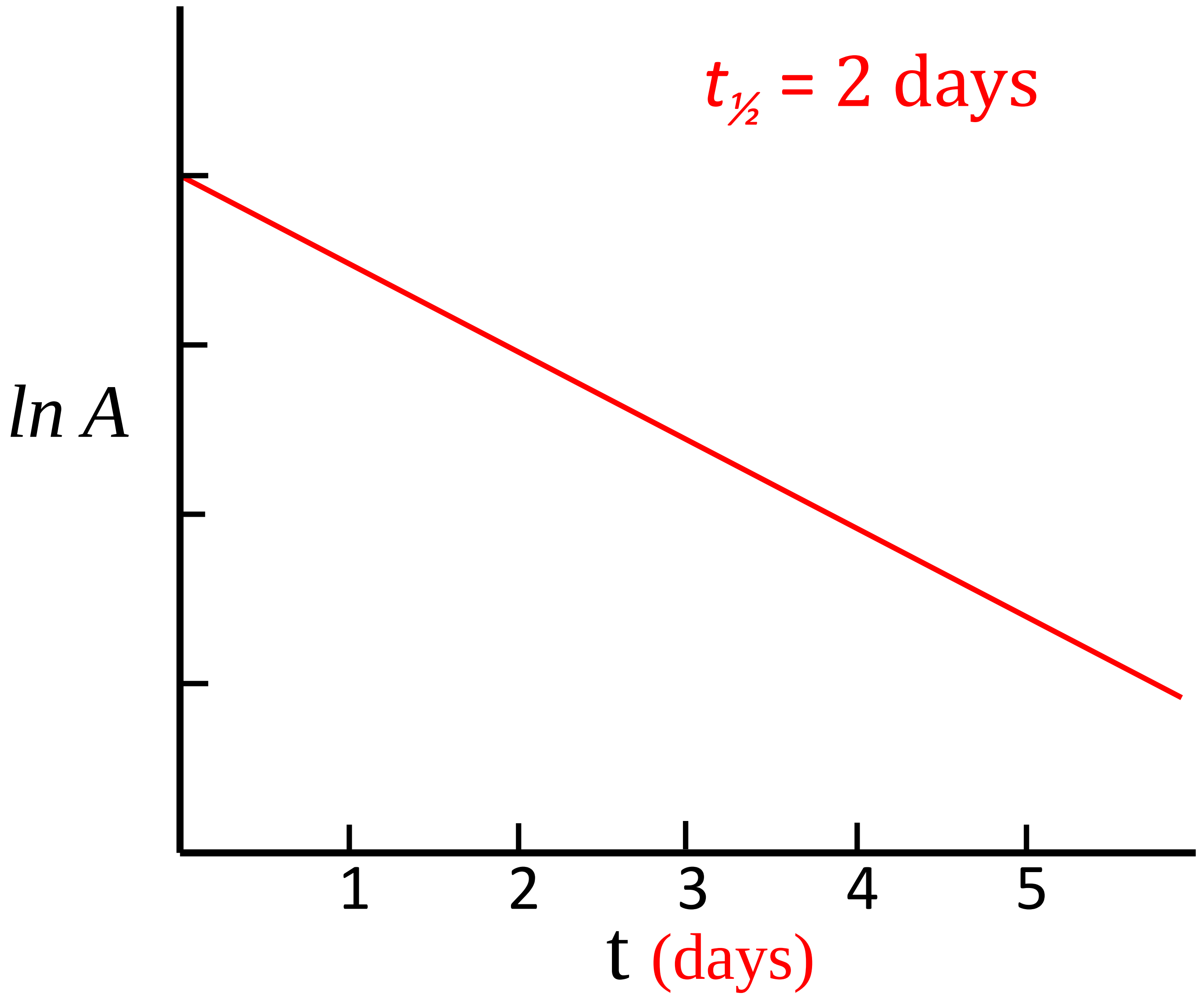




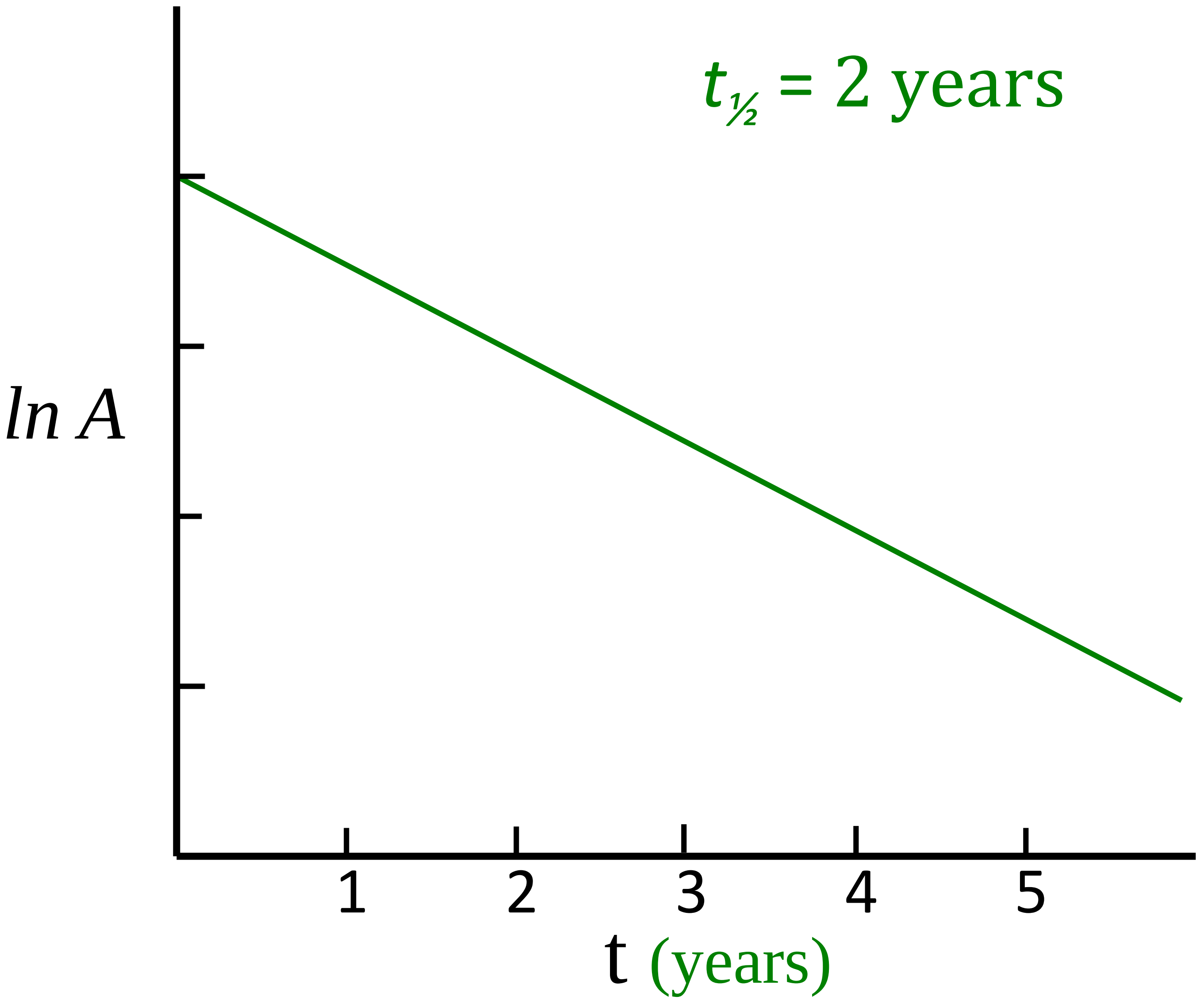
Decay Curve Analysis



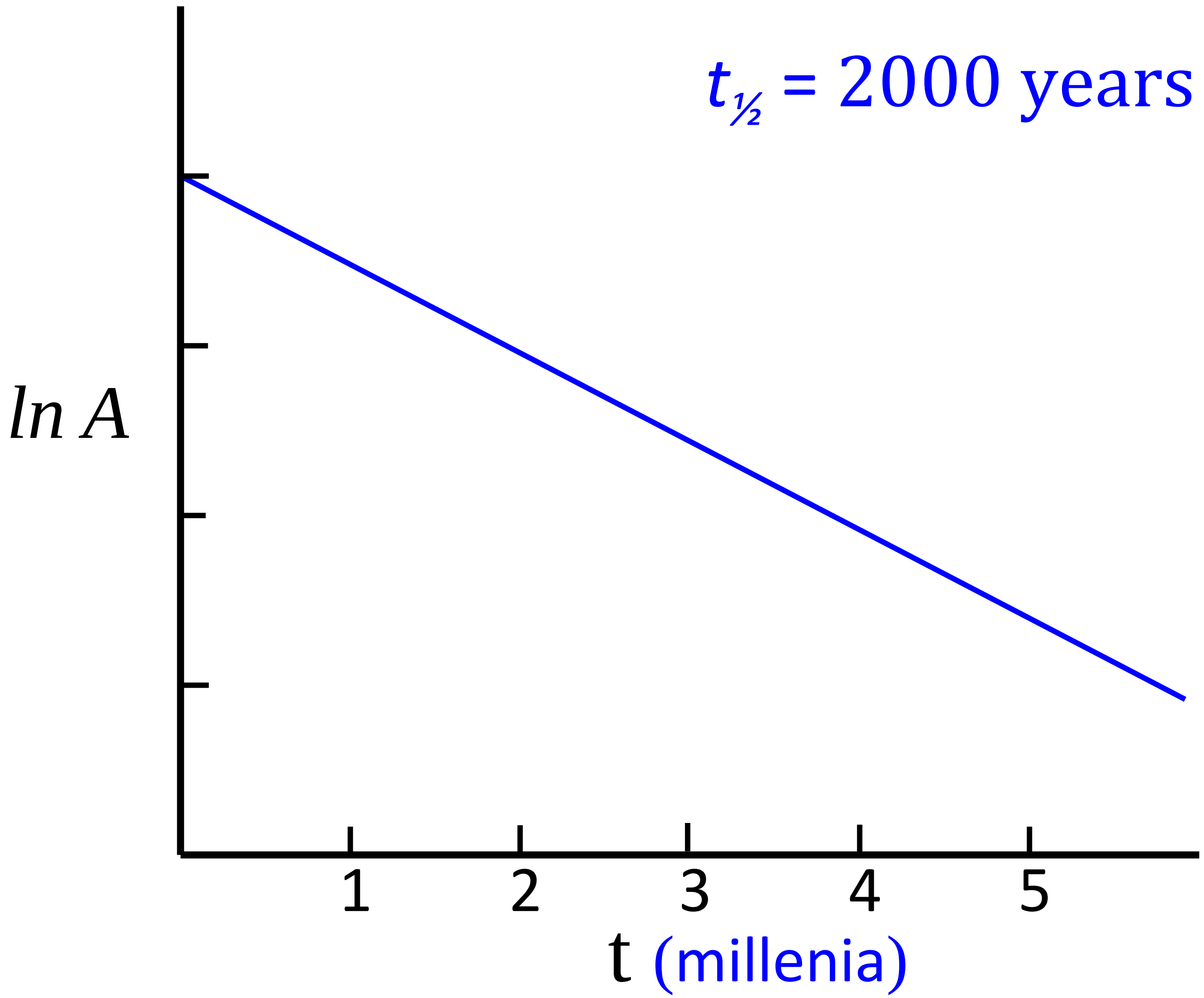




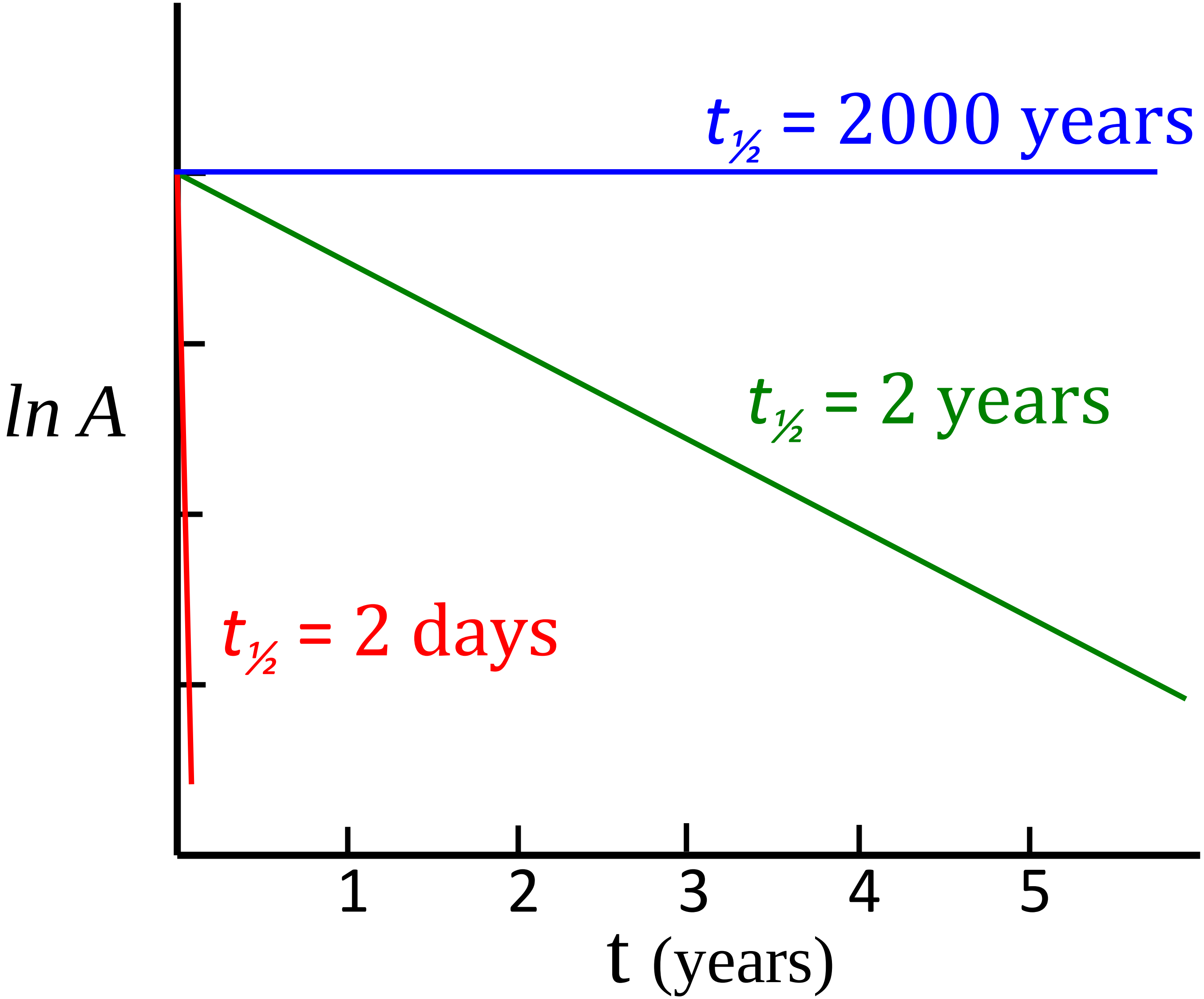
$$\ln A = -\lambda t + \ln A_o$$



$$\ln A = -\lambda t + \ln A_o$$



$$\ln A = -\lambda t + \ln A_o$$



$$\ln A = -\lambda t + \ln A_o$$

Specific Activity Method

specific activity (SA) – disintegrations per unit of time (minute) per gram of radioactive material, *i.e.*, A/g

$$A = \lambda N \quad \textit{where} \quad N = 6.022 \times 10^{23}(g/M)(IA)$$

$$A = (\ln 2/t_{1/2})(6.022 \times 10^{23})(g/M)(IA)$$

$$A/g = (\ln 2/t_{1/2})(6.022 \times 10^{23})(IA/M)$$

$$SA = (\ln 2/t_{1/2})(6.022 \times 10^{23})(IA/M)$$

$$t_{1/2} = (\ln 2 \times IA \times 6.022 \times 10^{23})/(M \times SA)$$

$$t_{1/2} = \frac{\ln 2 \times IA \times 6.022 \times 10^{23}}{M \times SA}$$

$$t_{1/2} = \frac{\ln 2 \times IA \times 6.022 \times 10^{23}}{M \times SA}$$

$$\tau = \frac{IA \times 6.022 \times 10^{23}}{M \times SA}$$

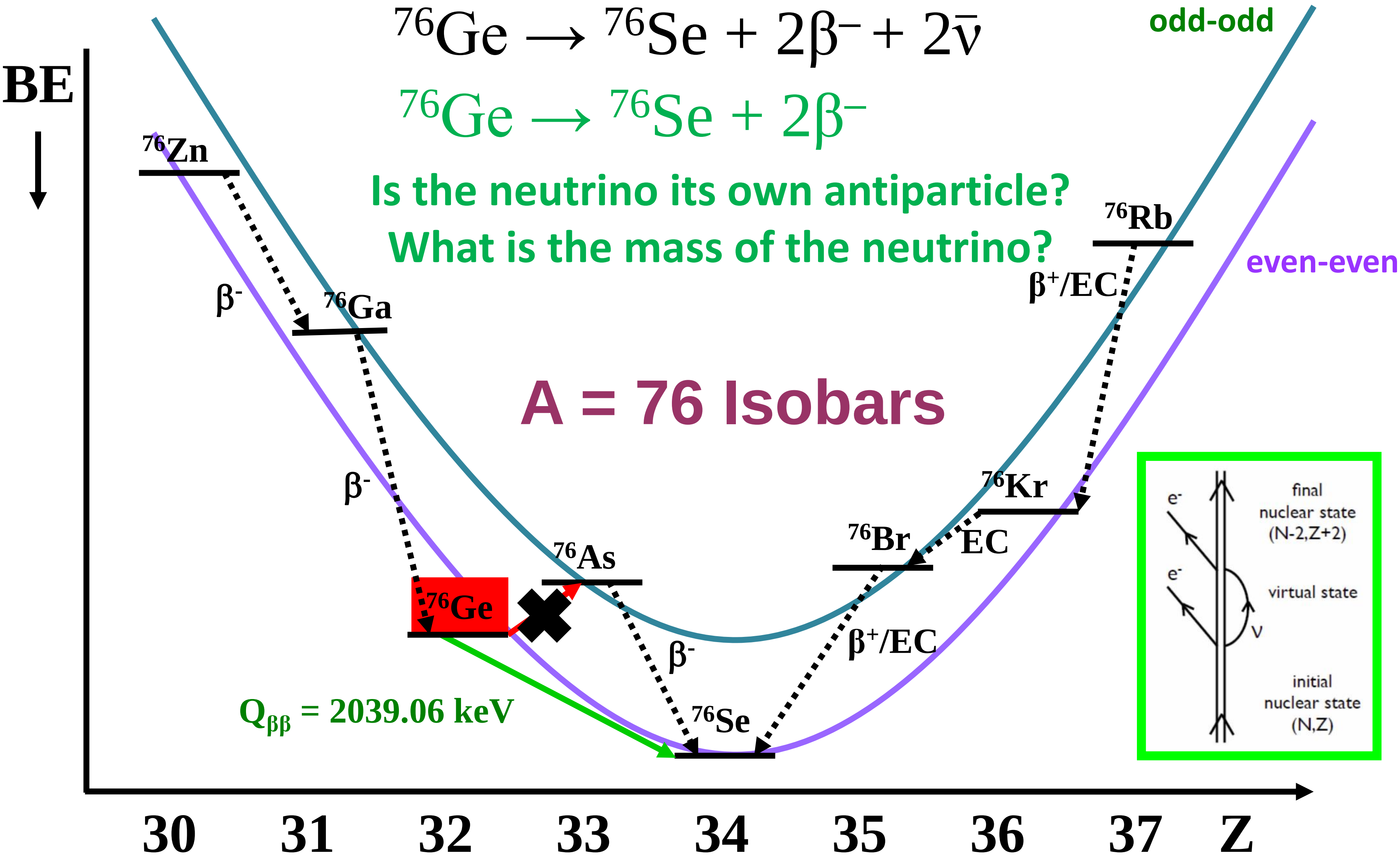
where IA – fractional isotopic abundance

M – molar mass (nuclidic mass in grams)

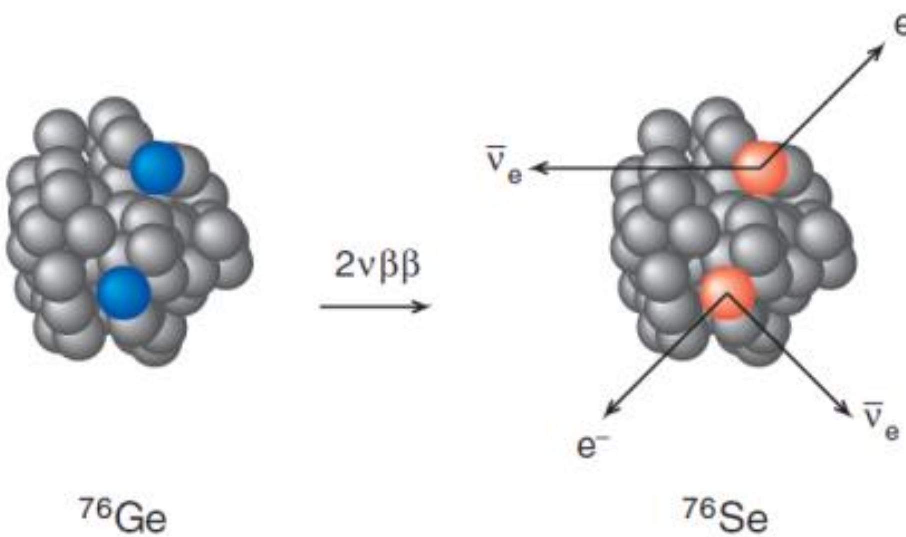
SA – specific activity (which requires knowledge of the mass and the absolute activity)

Obviously, the greater the specific activity, the shorter the half-life. This consideration, along with the mass of material (g) required in the measurement, sets limits on the applicability of the method.

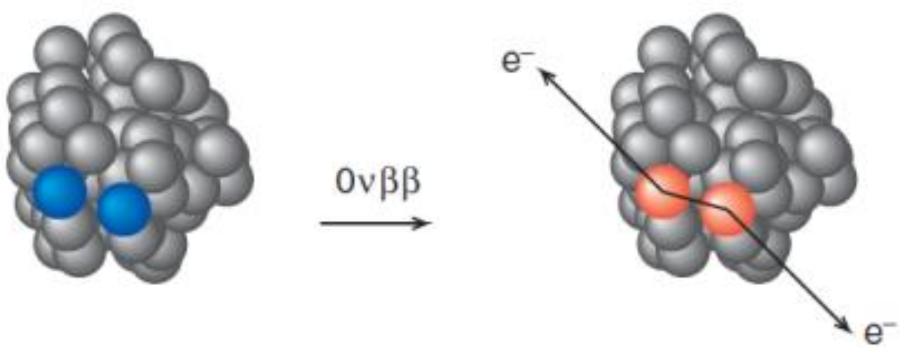
Mass Parabolas and Double-β Decay



Double-β Decay of ^{76}Ge

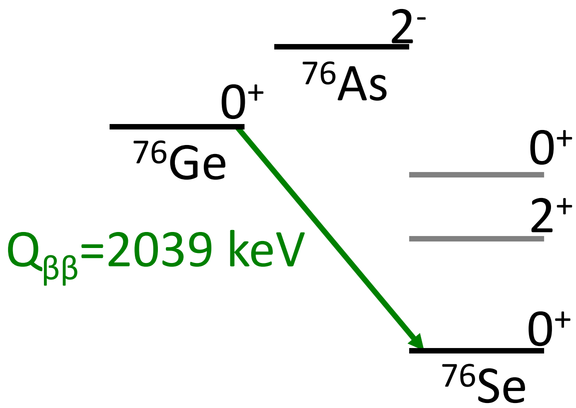


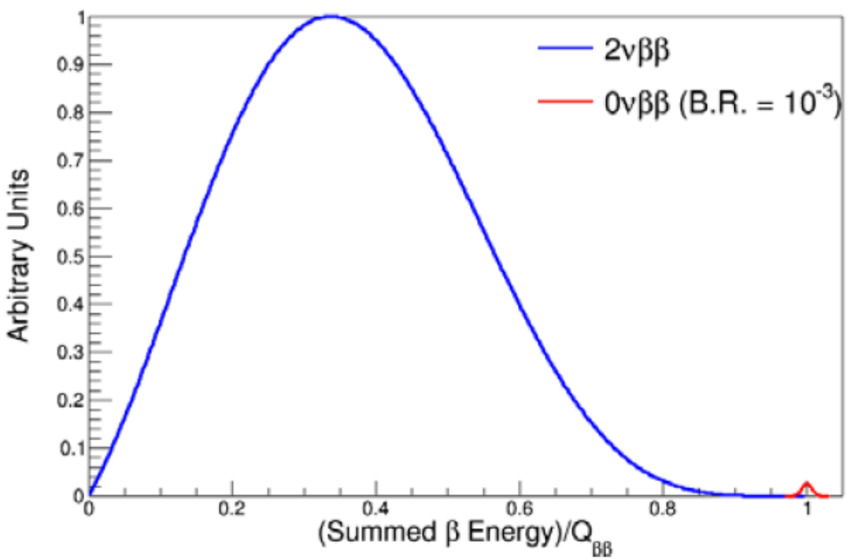
$Q_{\beta\beta}$ = 2039.06 keV

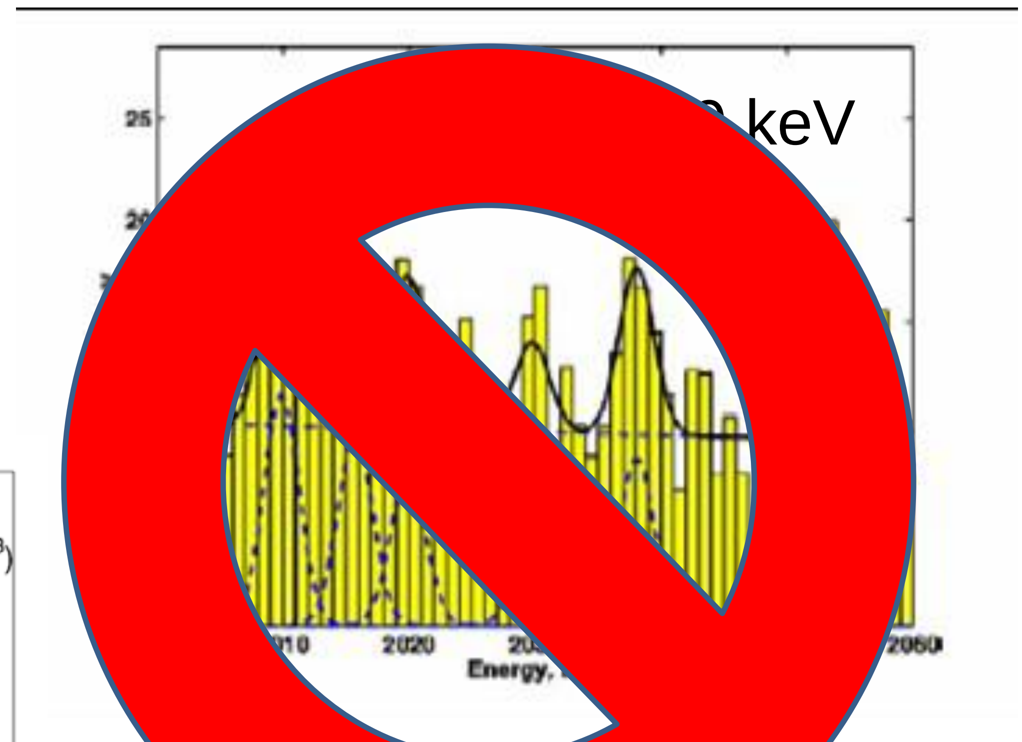


B. A. Brown, D. L. Fang, and M. Horoi, Phys. Rev. C **92**, 041301(R) (2015)

Experimental Signature of 0νββ







H.V. … rivoshina,
A. Dietz, … hys. Lett.
B586, 198 (2004)

Decay Rates of 2νββ and 0νββ

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 \langle m_{\beta\beta} \rangle^2$$

Phase space factor

Nuclear Matrix Element

Effective Majorana neutrino mass

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu}(Q_{\beta\beta}, Z)\left|M_{2\nu}\right|^2$$

$$T_{1/2}^{2\nu}(^{76}Ge) = 1.84 \times 10^{21} \; yr$$

M. Agostini et al. (GERDA), *J. Phys. G: Nucl. Part. Phys.* **40** 035110 (2013)

$$T_{1/2}^{0\nu}(^{76}Ge) > 8.0 \times 10^{25} yr$$

M. Agostini et al. (GERDA), PRL **120**, 132503 (2018)

Double-Beta Decay: Both Varieties

$^{76}Ge \rightarrow {}^{76}Se + 2\,\beta^{-} + 2\,\bar{\nu}$ $t_{½}$ = (1.84±0.10) x 10^{21} a

$^{76}Ge \rightarrow {}^{76}Se + 2\,\beta^{-}$ $t_{½}$ > 8.0 x 10^{25} a

$$(T_{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta},Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

What can be done to minimize the measurement time?

$$A = (ln2/t_{½})\ 6.022 \times 10^{23}\ (g/M)(IA)$$

Increase *IA*, *i.e.*, use enriched ^{76}Ge in the detector.

Increase g, *i.e.*, increase the mass of the detector.

Neutrinoless Double-β Decay Experiments

$^{76}Ge \rightarrow {}^{76}Se + 2\,\beta^-$ $\quad 8 \times 10^{25}\ a < t_{½} < 1 \times 10^{27}\ a$

Increase IA, *i.e.*, use enriched ^{76}Ge in the detector. **$€**
Increase g, *i.e.*, increase the mass of the detector. **$€**
Reduce backgrounds!!!

GERDA: 40 kg of 86% ^{76}Ge semiconductor, Gran Sasso
background $10^{-3} – 10^{-4}$ keV^{-1}a^{-1}kg^{-1}
http://wwwgerda.mppmu.mpg.de/

MAJORANA Demonstrator: 40 kg of 86% ^{76}Ge, SURF
background 10^{-3} keV^{-1}a^{-1}kg^{-1}
http://www.npl.washington.edu/majorana/

Current Searches for ^{76}Ge 0νββ

MAJORANA DEMONSTRATOR

30 kg 86% ^{76}Ge + 10 kg ^{nat}Ge
SURF, SD, USA

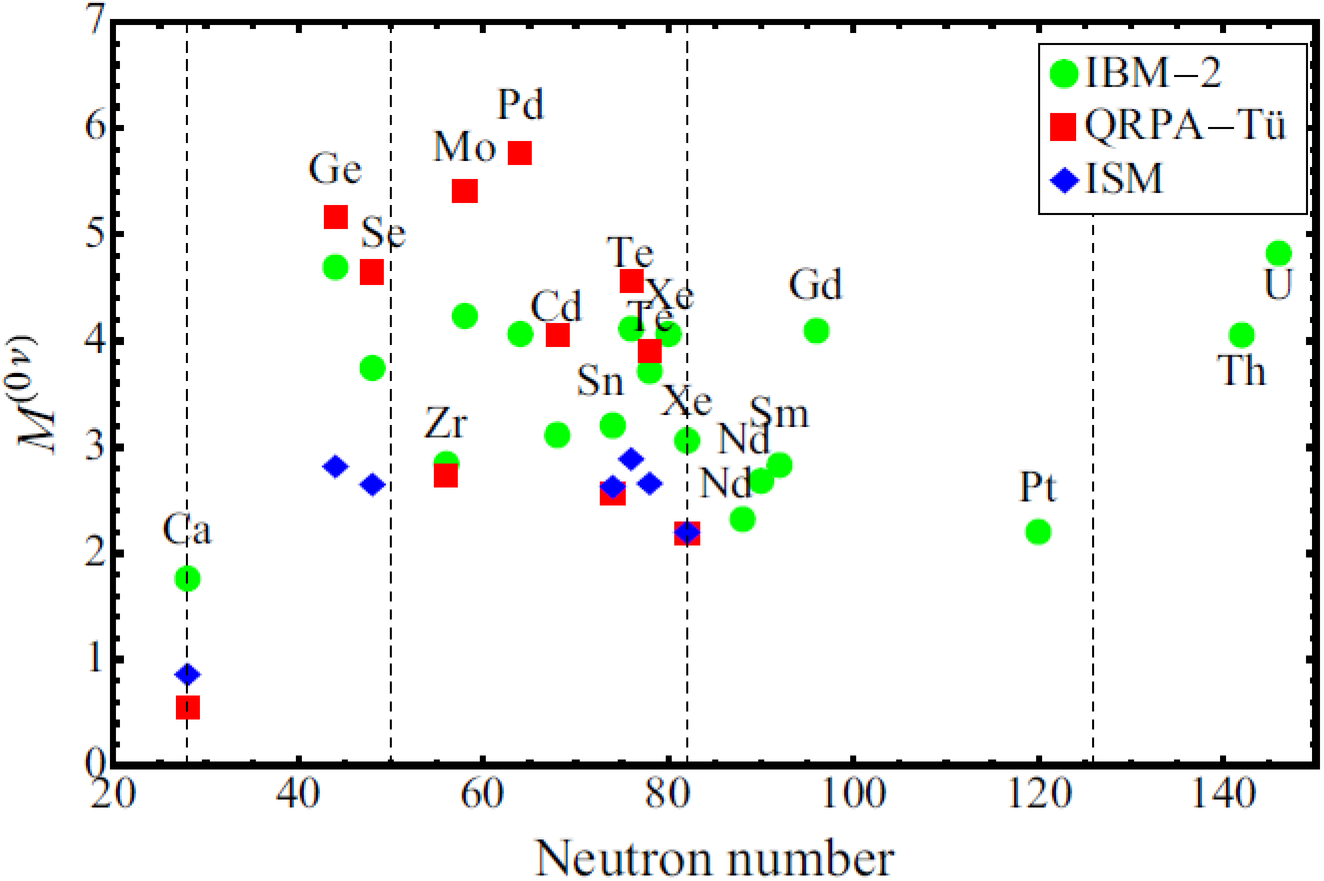
http://neutrino.lbl.gov/majorana.htm

GERDA

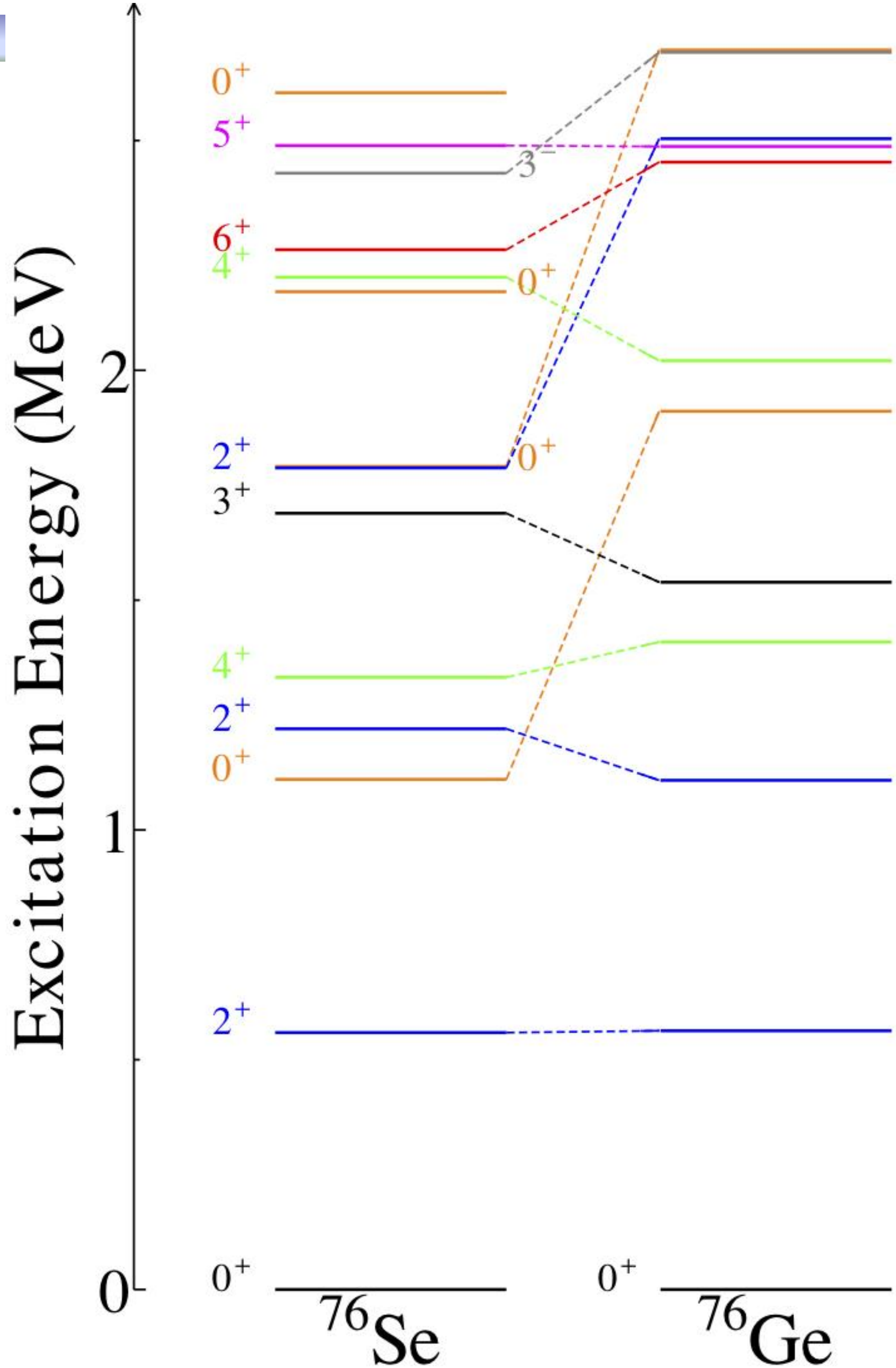
40 kg 86% ^{76}Ge
Gran Sasso, Italy

http://www.mpi-hd.mpg.de/gerda/

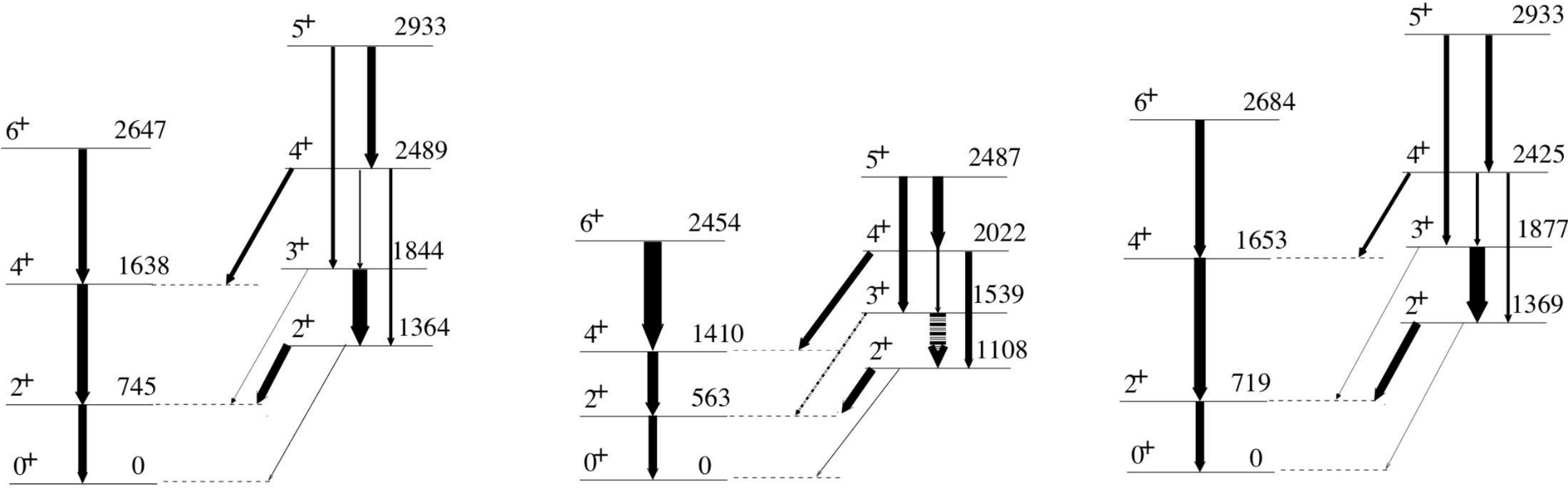
Comparison of calculated nuclear matrix elements for 0νββ candidates



J. Barea, J. Kotila, and F. Iachello, Phys. Rev. 91, 034304 (2015).


Excitation Energy (MeV)
0
1
2
0+
5+
3−
6+
4+
0+
2+
0+
3+
4+
2+
0+
2+
0+
0+
76Se
76Ge

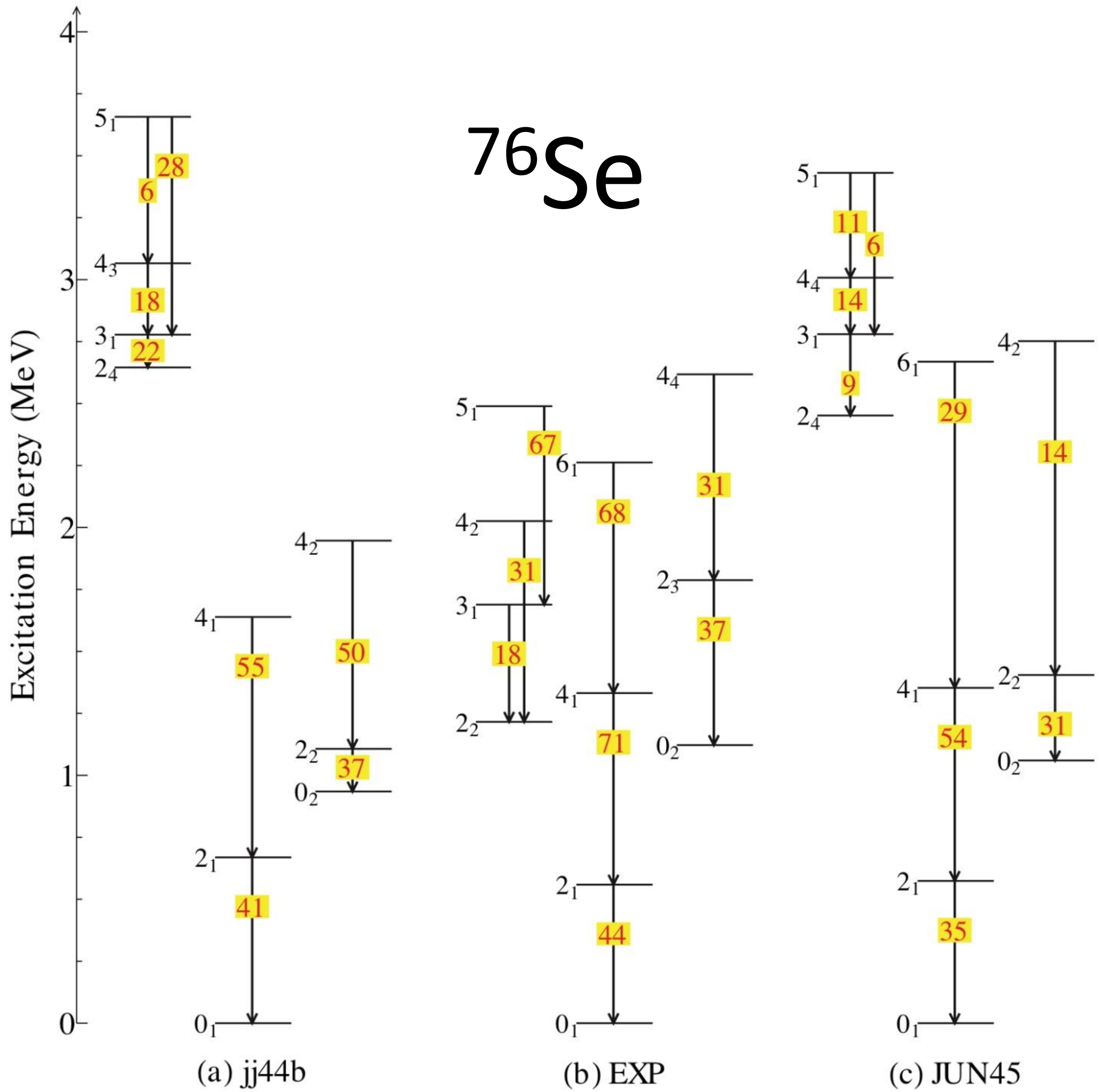
S. Mukhopadhyay *et al*., Phys. Rev. C **95**, 014327 (2017)



(a) JUN45 (b) Experiment (c) jj44b

^{76}Ge

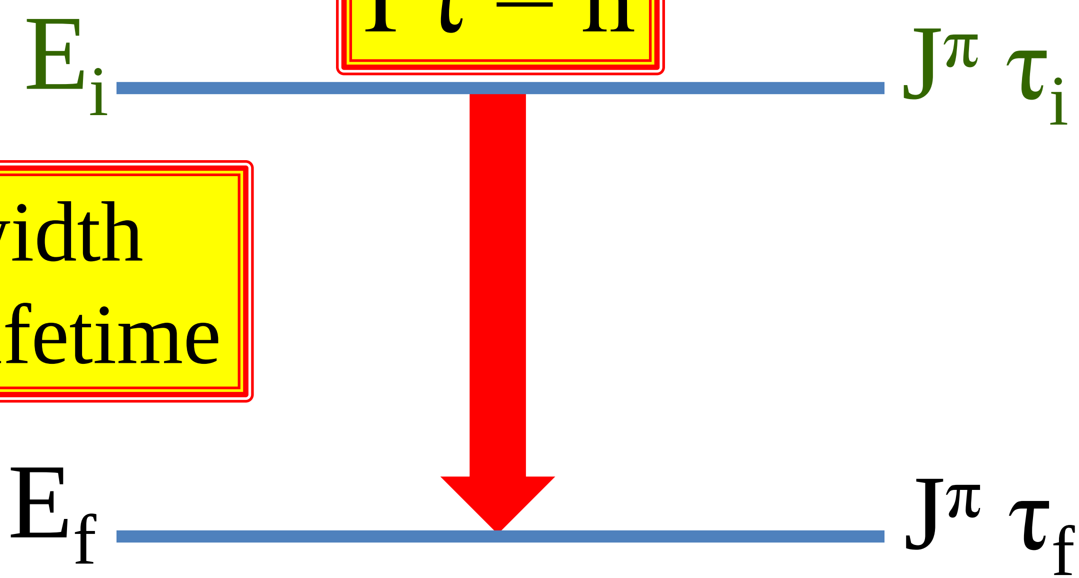
S. Mukhopadhyay *et al.*, Phys. Rev. C, submitted



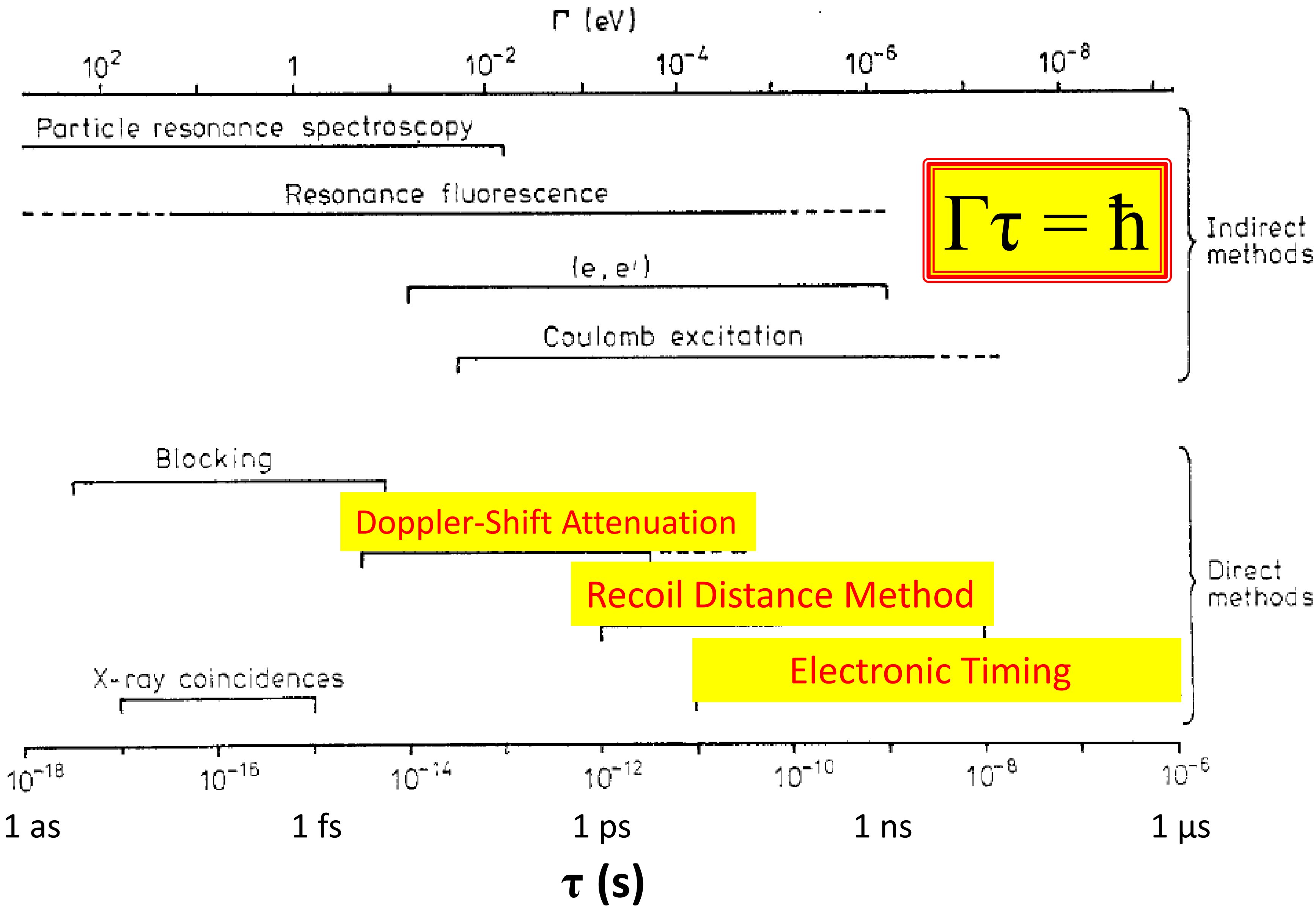
Lifetimes of Excited Nuclear States

The lifetime of an excited nuclear state (level) is, along with its energy, spin and parity, an important and characteristic property required for nuclear model descriptions.

$$\Gamma\tau = \hbar$$



Γ – level width
τ – level lifetime



P. J. Nolan and J. F. Sharpey-Schafer, *Rep. Prog. Phys.* **42,** 1 (1979).

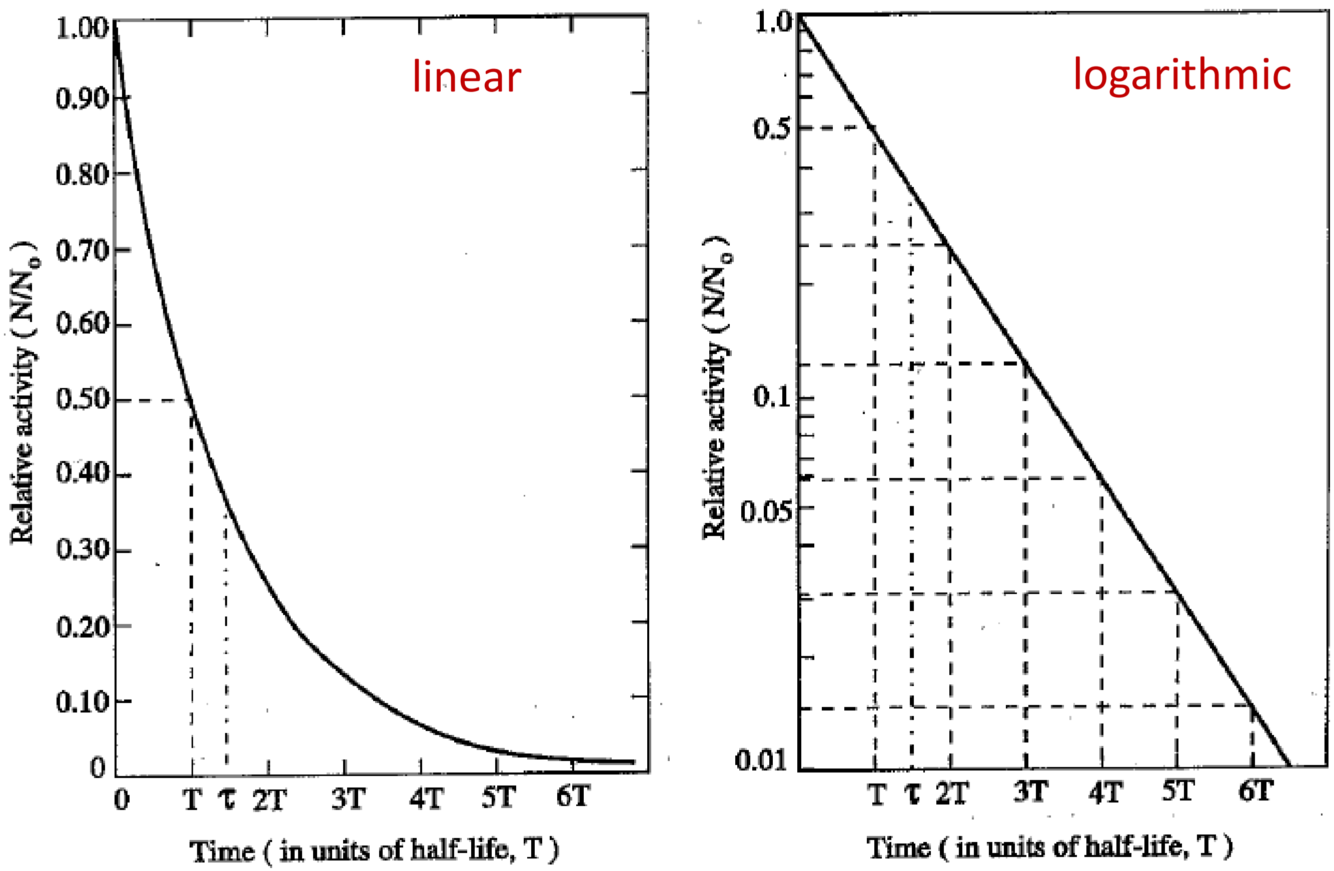
$$A = A_o e^{-\lambda t}$$

$$ln\ A = ln\ A_o - \lambda t$$

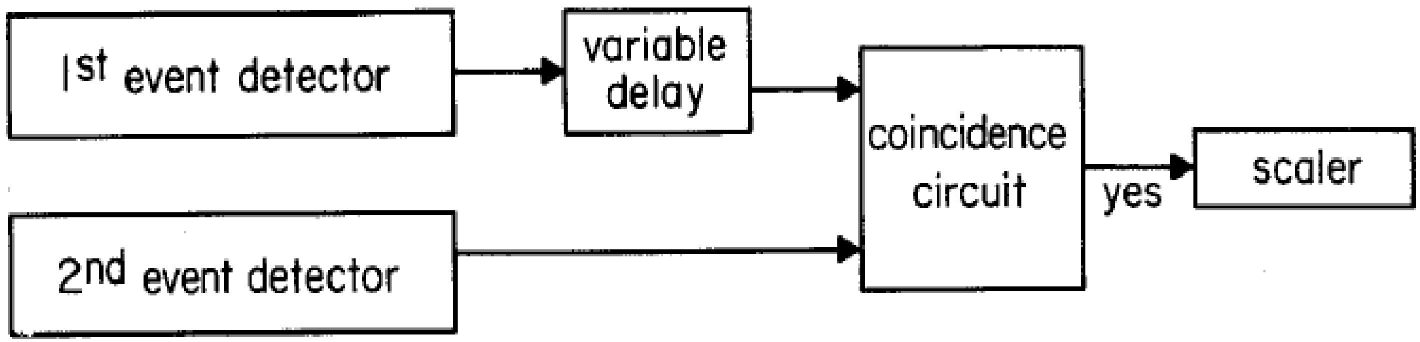
$$ln\ A = -\lambda t + ln\ A_o$$

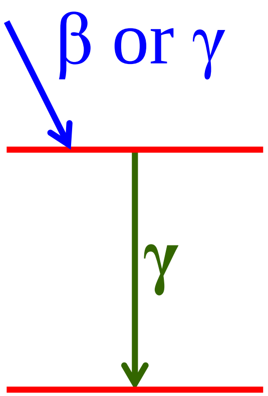
The "simple" decay curve method ~~is typically used for lifetimes of seconds to years.~~ can be used for shorter lifetimes if …

So, we have looked at the longest lifetimes. What about those that are shorter than we normally determine with the simple decay curve method?



Delayed Coincidences—An Electronic Timing Method





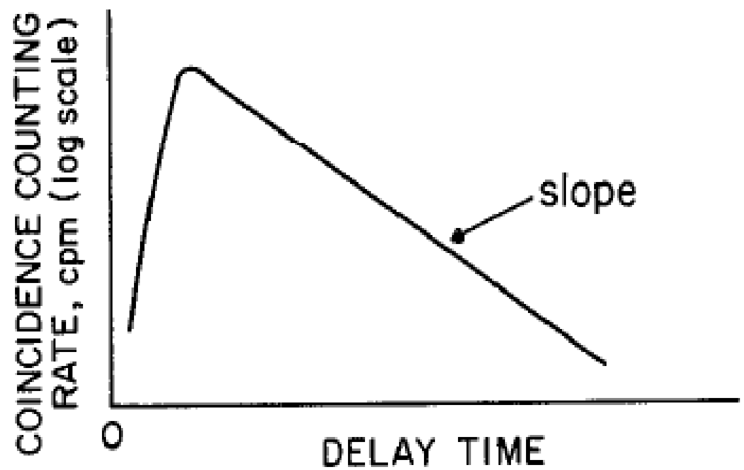
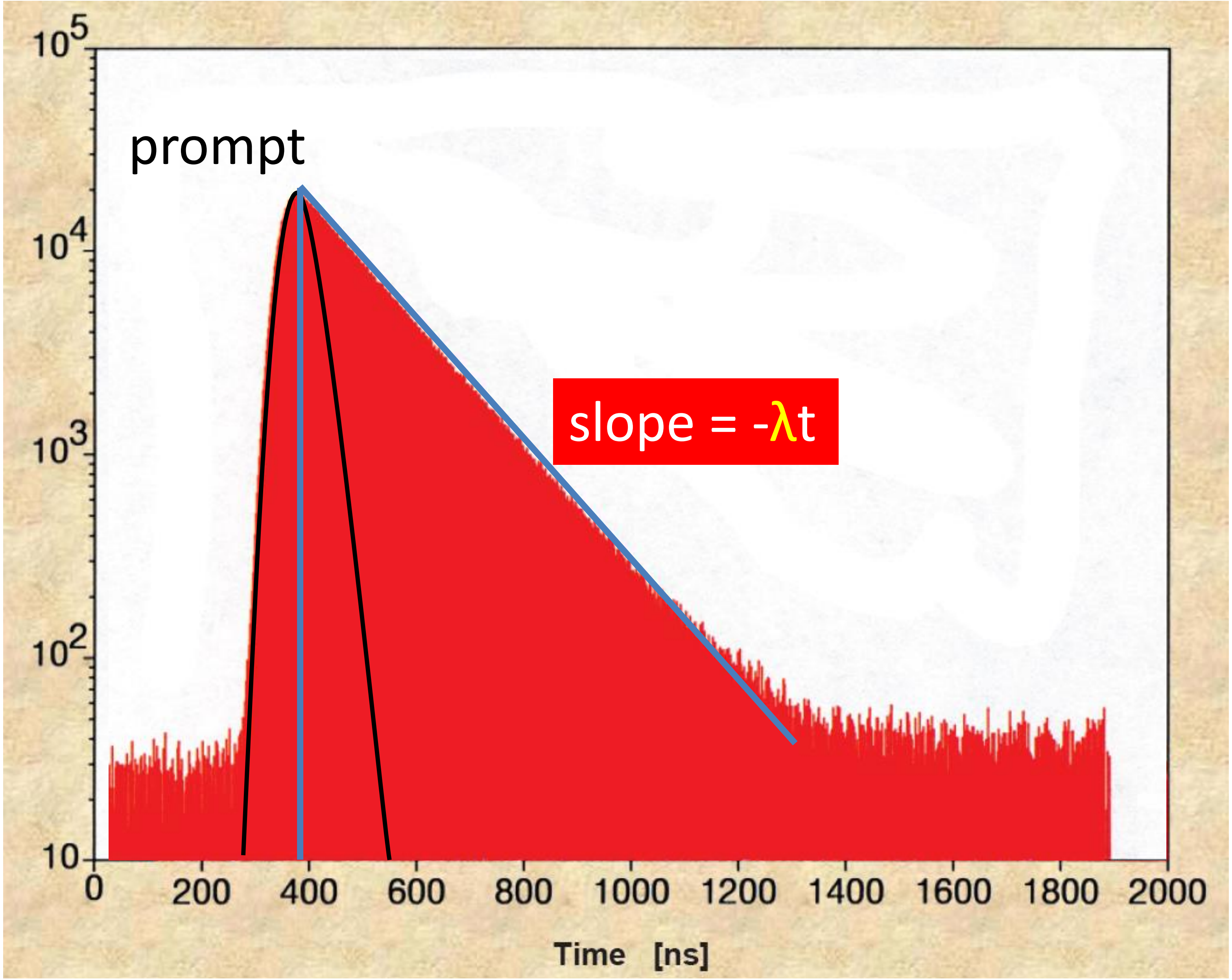


Figure 5.8. Block diagram representation of the method of determining short half-lives by the method of delayed coincidences.

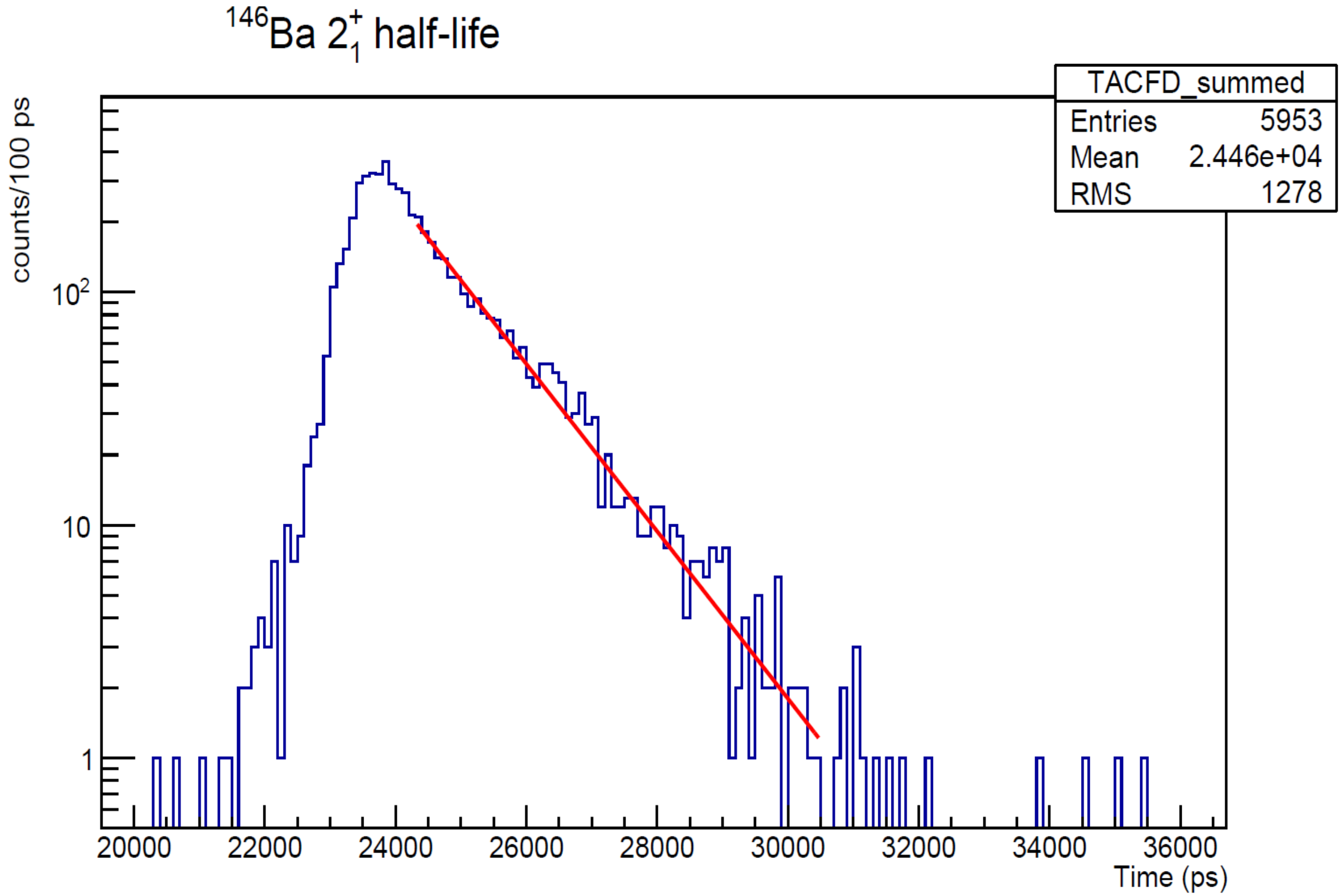


prompt
slope = -λt
10^5
10^4
10^3
10^2
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time [ns]

Recent experiment (Aug. 19–21): ^{146}Cs β decay to ^{146}Ba

$t_{½}$ =840±20 ps (NNDC: 860±30 ps)

- Commission the $LaBr_3$ detectors
- GRIFFIN configuration
  - 12 HPGE detectors
  - 10 plastic scintillator paddles for β tagging
  - 1 very-fast plastic scintillator for fast timing
  - 4 $LaBr_3$ detectors for fast timing
  - 68 DESCANT detectors for neutrons



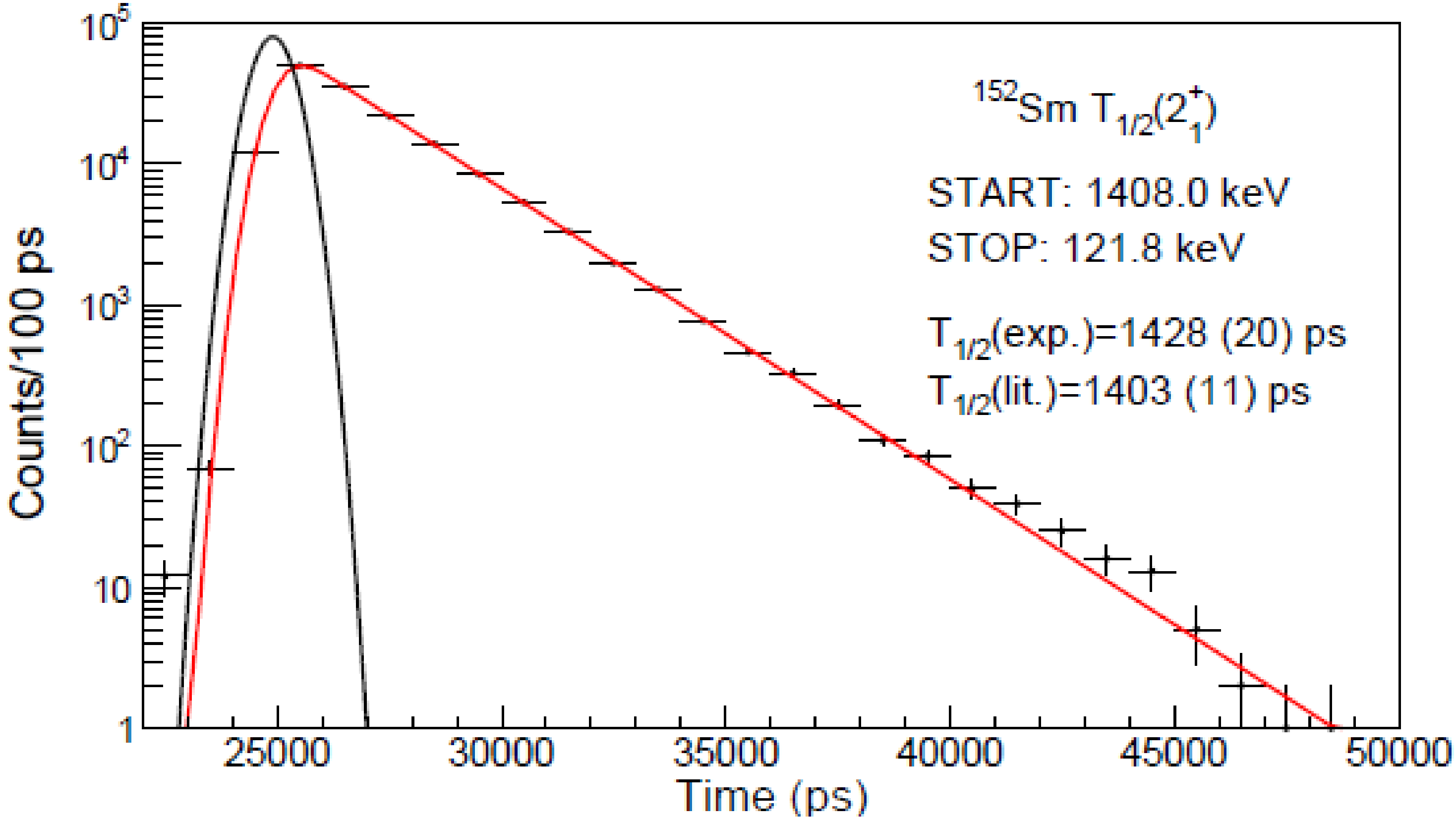


Figure 25: Example of the convolution fit method for ^{152}Eu source data collected with the $LaBr_3$(Ce) in the GRIFFIN array to measure the lifetime of the 2^+_1 state in ^{152}Sm.

Delayed Coincidence Method

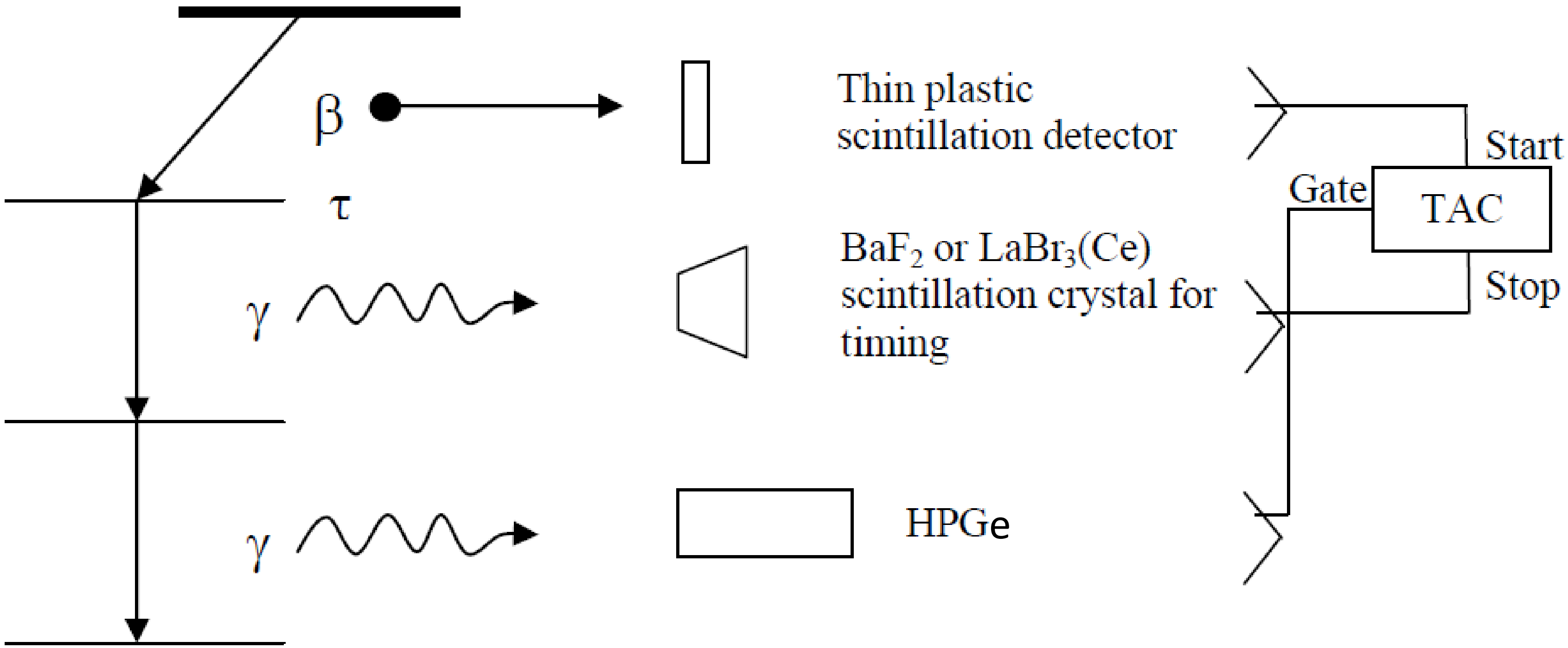


Fig. 1. The principle of the fast timing method for measuring the lifetime of the excited state labeled with "τ". The HPGe detector is used for its energy resolution in order to isolate the gamma cascade.

M. Moszyński and H. Mach, NIM 277, 407 (1989).

Delayed Coincidence Method

- The delayed coincidence method is applicable for lifetimes from about 10^{-4} s to 10^{-11} s.
- As the lifetimes become shorter, the centroid shift of the time distribution is measured, rather than a slope.
- Measurements of the shortest lifetimes require detectors with fast response, *e.g.*,
  - BaF_2 or $LaBr_3$(Ce) for γ rays
  - plastic scintillators for β particles

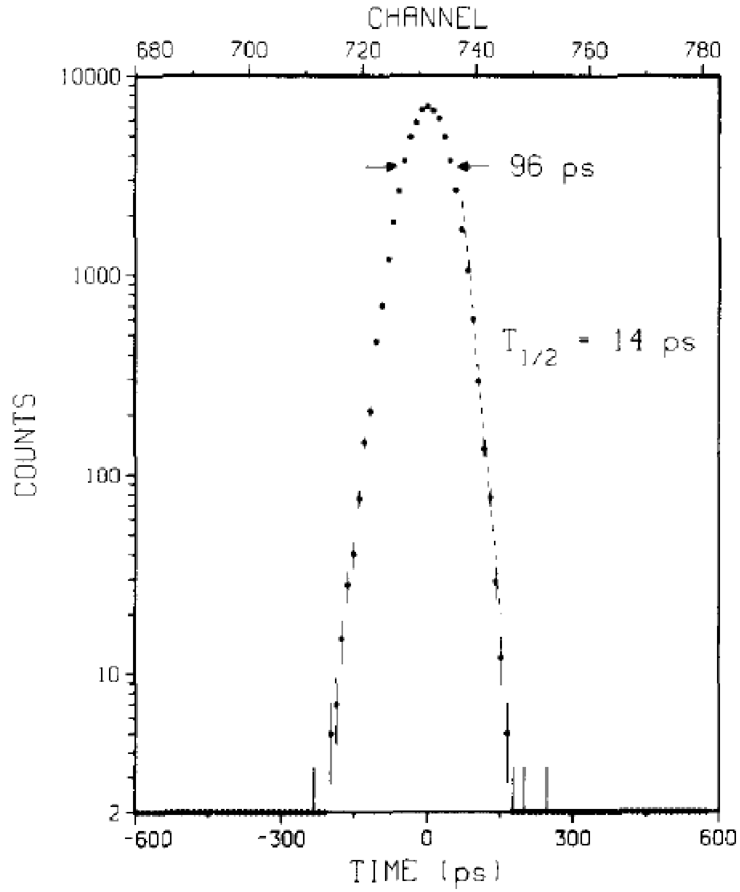


Fig. 1. Prompt β−γ time spectrum measured with a ^{24}Na source. It is characterized by the FWHM resolution of 96 ps and an apparent slope of $T_{1/2} = 14$ ps. In the start β-detector a 40% energy window, centered at about 600 keV, was accepted, while in the stop BaF_2 crystal a full energy peak at 1.37 MeV was selected.

M. Moszyński and H. Mach, NIM 277, 407 (1989).

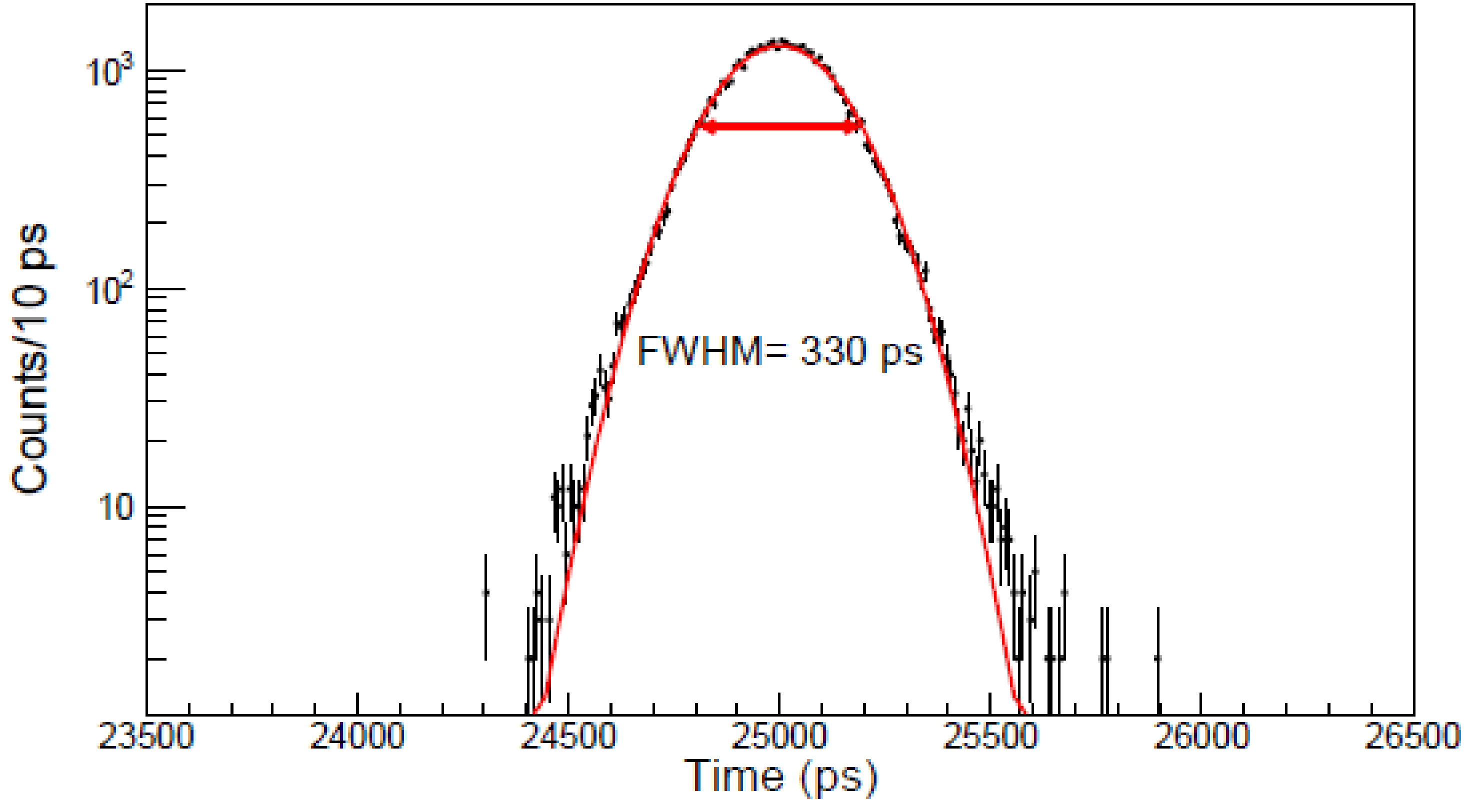


Figure 27: Timing resolution of the full 8-detector $LaBr_3(Ce)$ array in GRIFFIN measured with a ^{60}Co source.

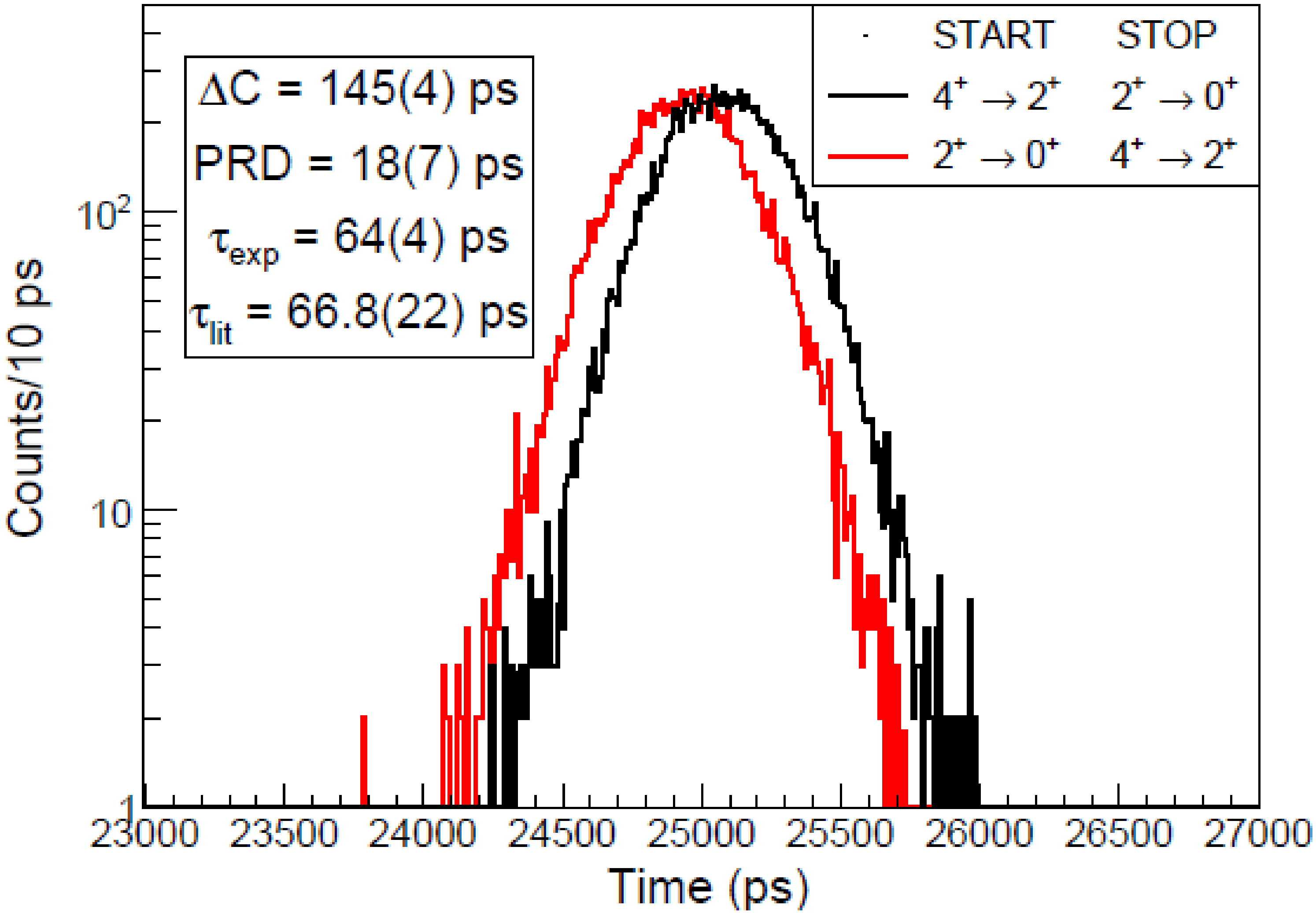
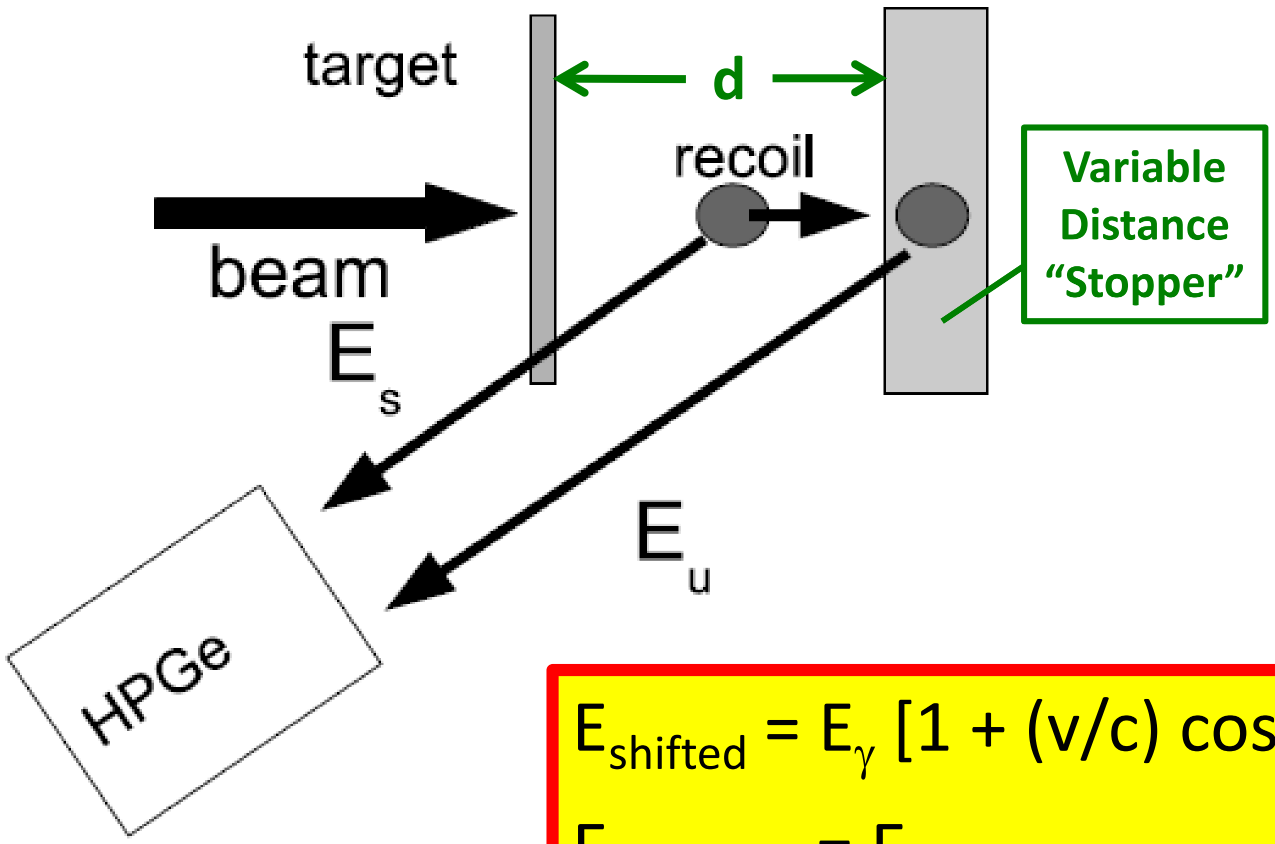


Figure 26: Mean lifetime of the 2_1^+ state in ^{200}Hg measured using the centroid difference method. See text for details.

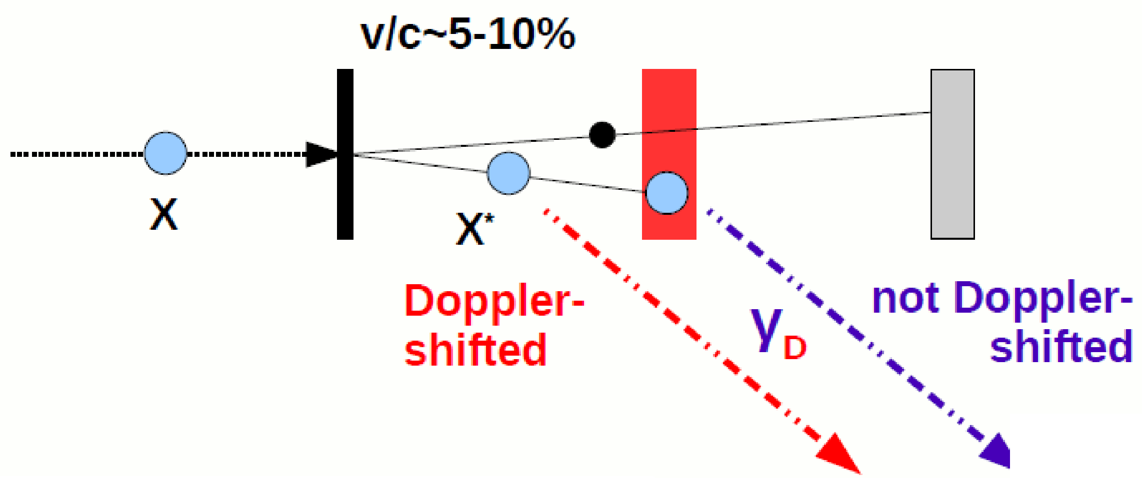
Recoil Distance Doppler-Shift Method (RDDS, RDM, or "Plunger")



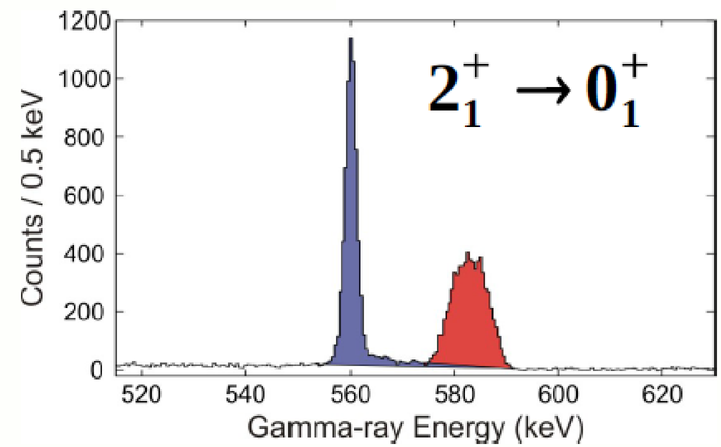
$$E_{shifted} = E_{\gamma} [1 + (v/c) \cos \theta]$$

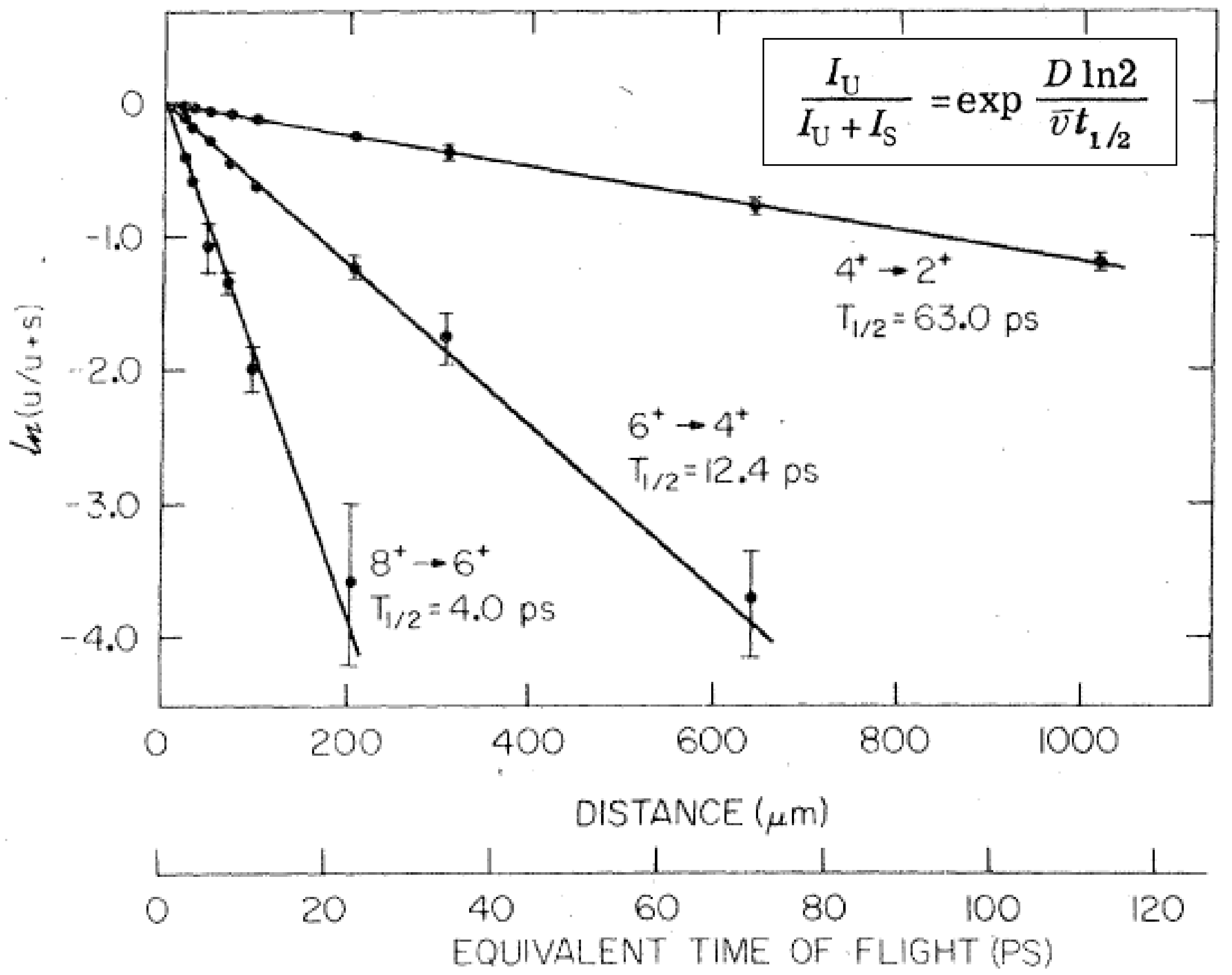
$$E_{unshifted} = E_{\gamma}$$

Recoil Distance Doppler-Shift Method (RDDS, RDM, or “Plunger”)



High recoil velocity!





S. W. Yates *et al.*, Phys. Rev. C **17**, 634 (1978).

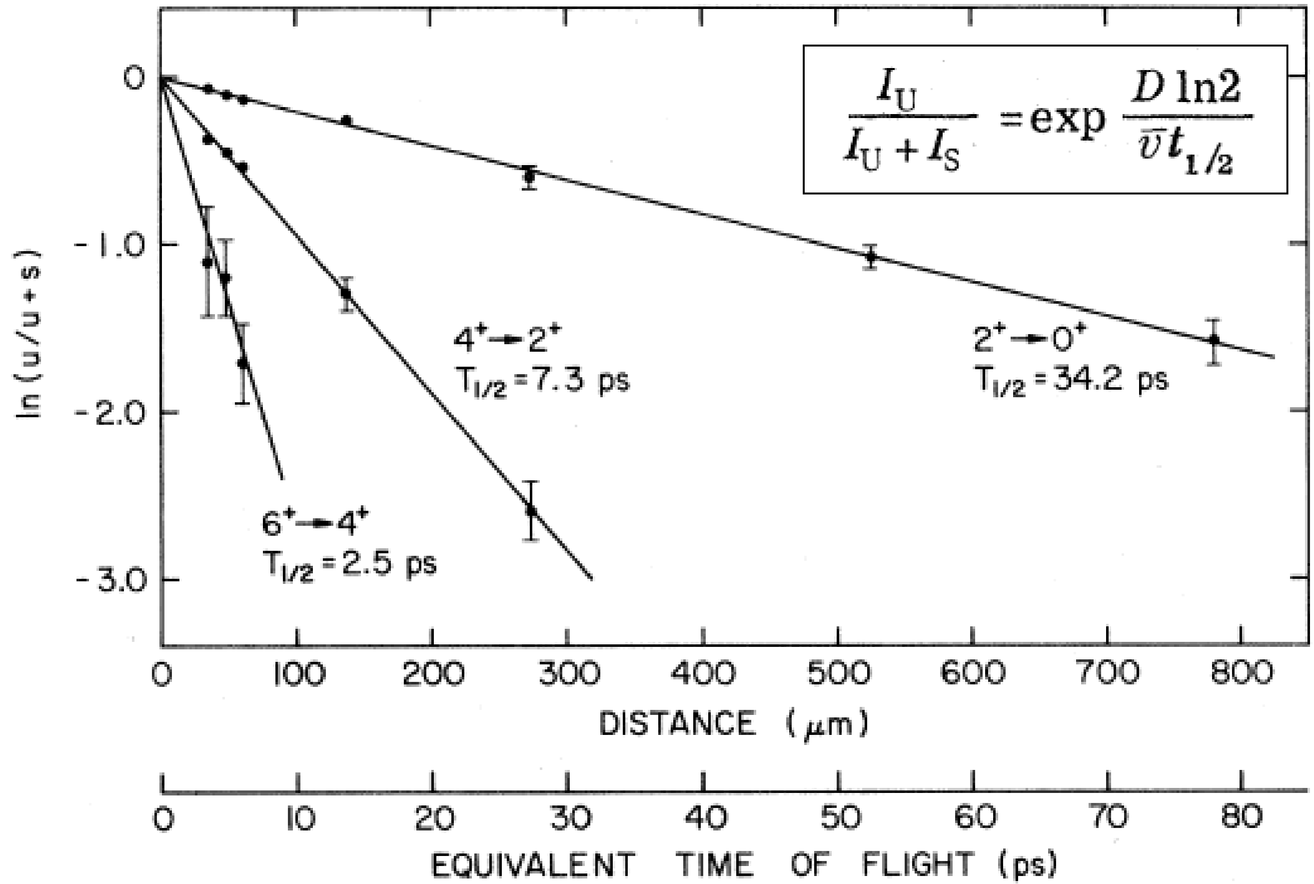


FIG. 2. Plots of ratios of unshifted to the sum of unshifted-plus-shifted γ ray intensities as a function of target-stopper separation for ground-band members of ^{152}Gd excited in the present experiments.

N. R. Johnson *et al.*, Phys. Rev. C **26**, 1004 (1982).