

2358-11

**Joint ICTP-IAEA Workshop on Nuclear Structure Decay Data: Theory and
Evaluation**

6 - 17 August 2012

Experimental Nuclear Physics: Part 2

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*Brookhaven National Lab.
USA*

Experimental Nuclear Physics: Part II

E.A. McCutchan

*National Nuclear Data Center
Brookhaven Nation Laboratory*



a passion for discovery

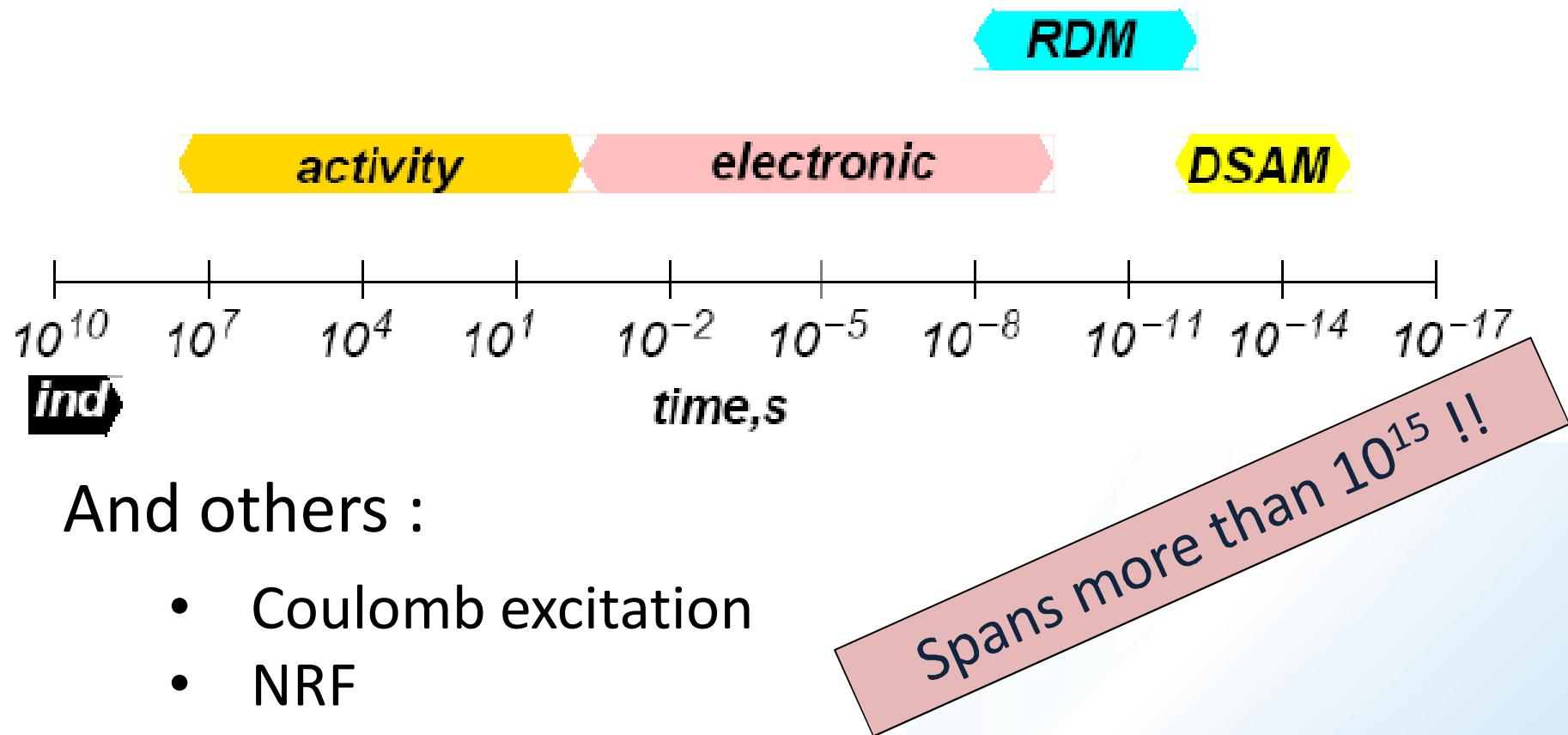


U.S. DEPARTMENT OF
ENERGY

Office of
Science

- Measuring Lifetimes
- Nitty gritty details of a lifetime experiment

A huge range to cover



And others :

- Coulomb excitation
- NRF
- Direct width measurements
- Inelastic electron scattering
- Mossbauer technique
- GRID

Why do we care??

Lifetime \rightarrow $B(E\lambda)$ or $B(M\lambda)$ \rightarrow Overlap of initial and final state wavefunctions

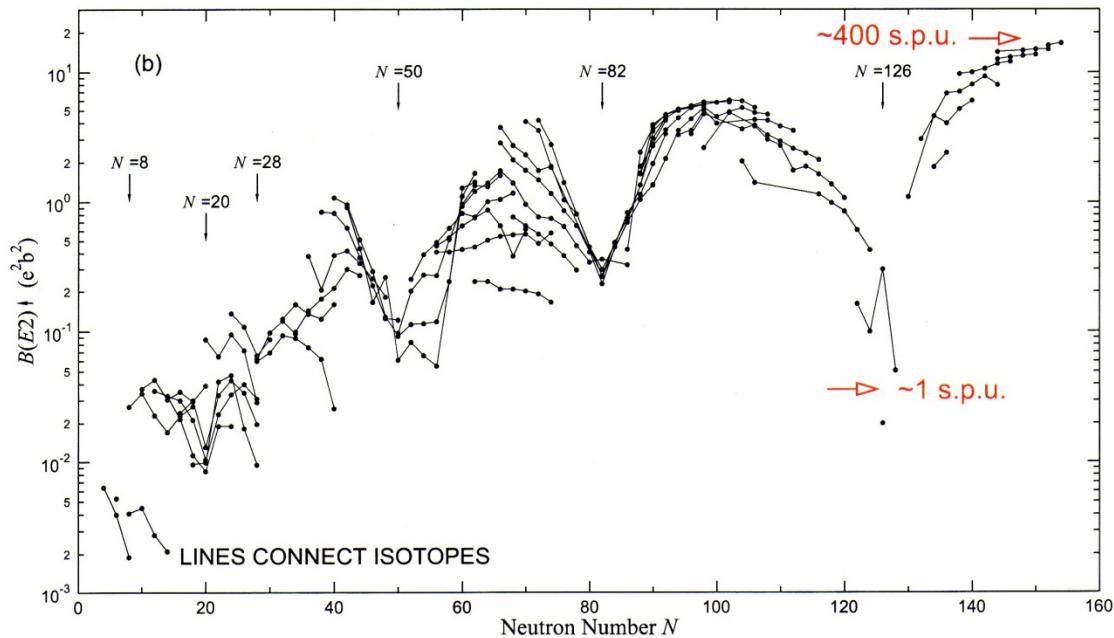
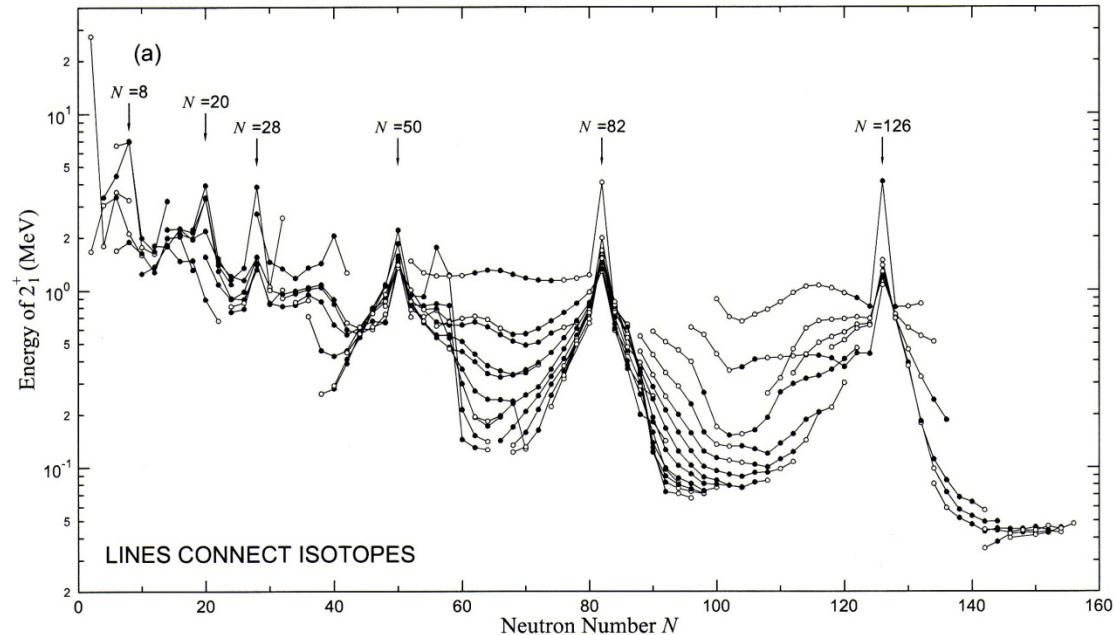
$$B(E2; J_i \rightarrow J_f) = \text{constant} \cdot \frac{1}{E_\gamma^5 \cdot \tau}$$

If $B(E2)$ is big, τ is small (i.e. fast = collective);

If $B(E2)$ is small, τ is big (i.e. slow = isomer)

Systematics of B(E2)s

S. Raman et al., Atomic Data & Nuclear Data Tables 78, 1



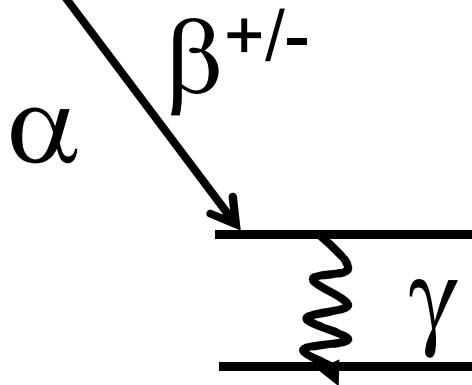
Measuring “long” lifetimes

Time range : seconds to years

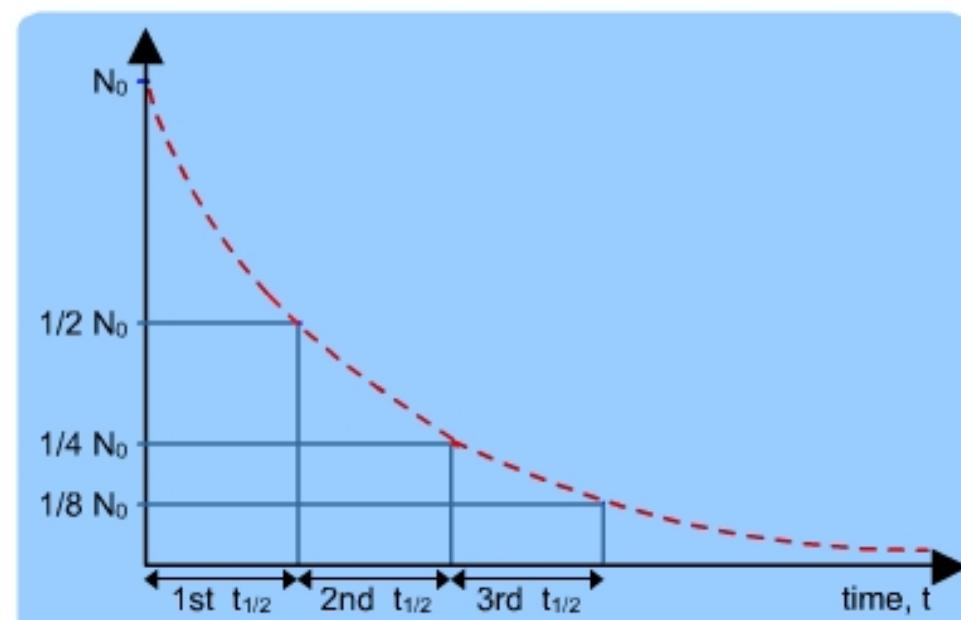
Observe the activity, A, as a function of time

$$A(t) = \lambda N_0 e^{-\lambda t}$$

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



Count β 's or α 's or
 γ 's following decay



Can reach incredible precision

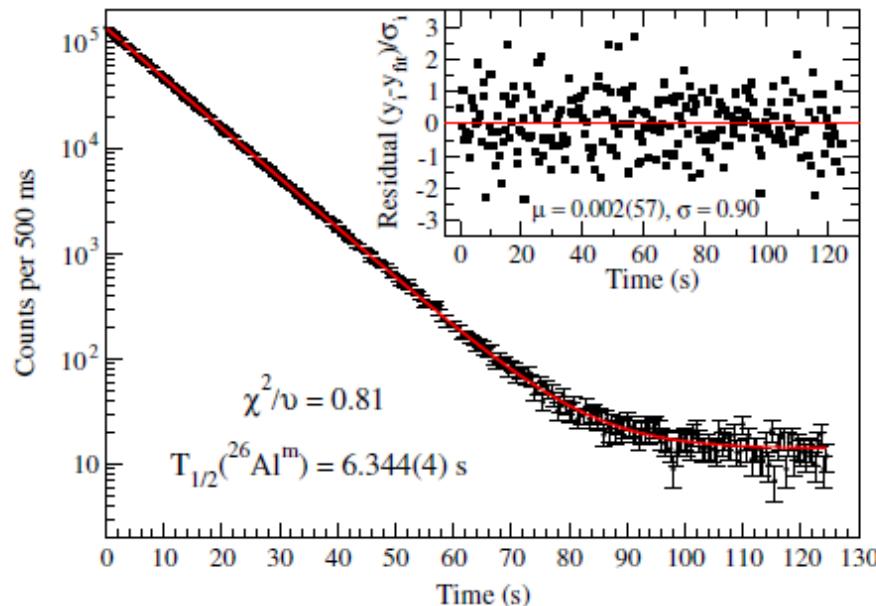
PRL 106, 032501 (2011)

PHYSICAL REVIEW LETTERS

week ending
21 JANUARY 2011

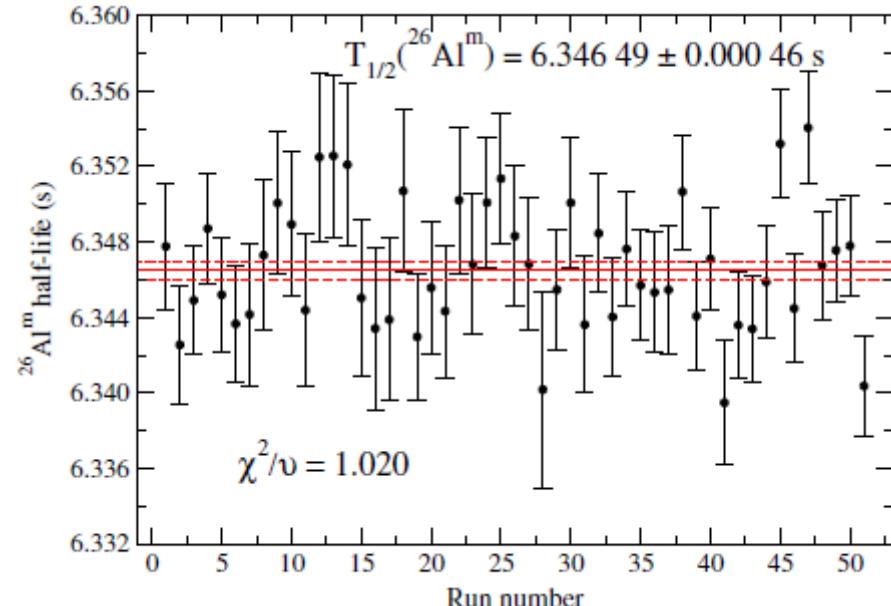
High-Precision Half-Life Measurement for the Superallowed β^+ Emitter $^{26}\text{Al}^m$

P. Finlay,^{1,*} S. Ettenauer,^{2,3} G. C. Ball,² J. R. Leslie,⁴ C. E. Svensson,¹ C. Andreoiu,⁵ R. A. E. Austin,⁶ D. Bandyopadhyay,² D. S. Cross,⁵ G. Demand,^{1,4} M. Djongolov,² P. E. Garrett,^{1,2} K. L. Green,¹ G. F. Grinyer,⁷ G. Hackman,² K. G. Leach,¹ C. J. Pearson,² A. A. Phillips,¹ C. S. Sumithrarachchi,¹ S. Triambak,^{1,2} and S. J. Williams²



$$T_{1/2} = 6.3465 (5) \text{ seconds}$$

Brookhaven Science Associates

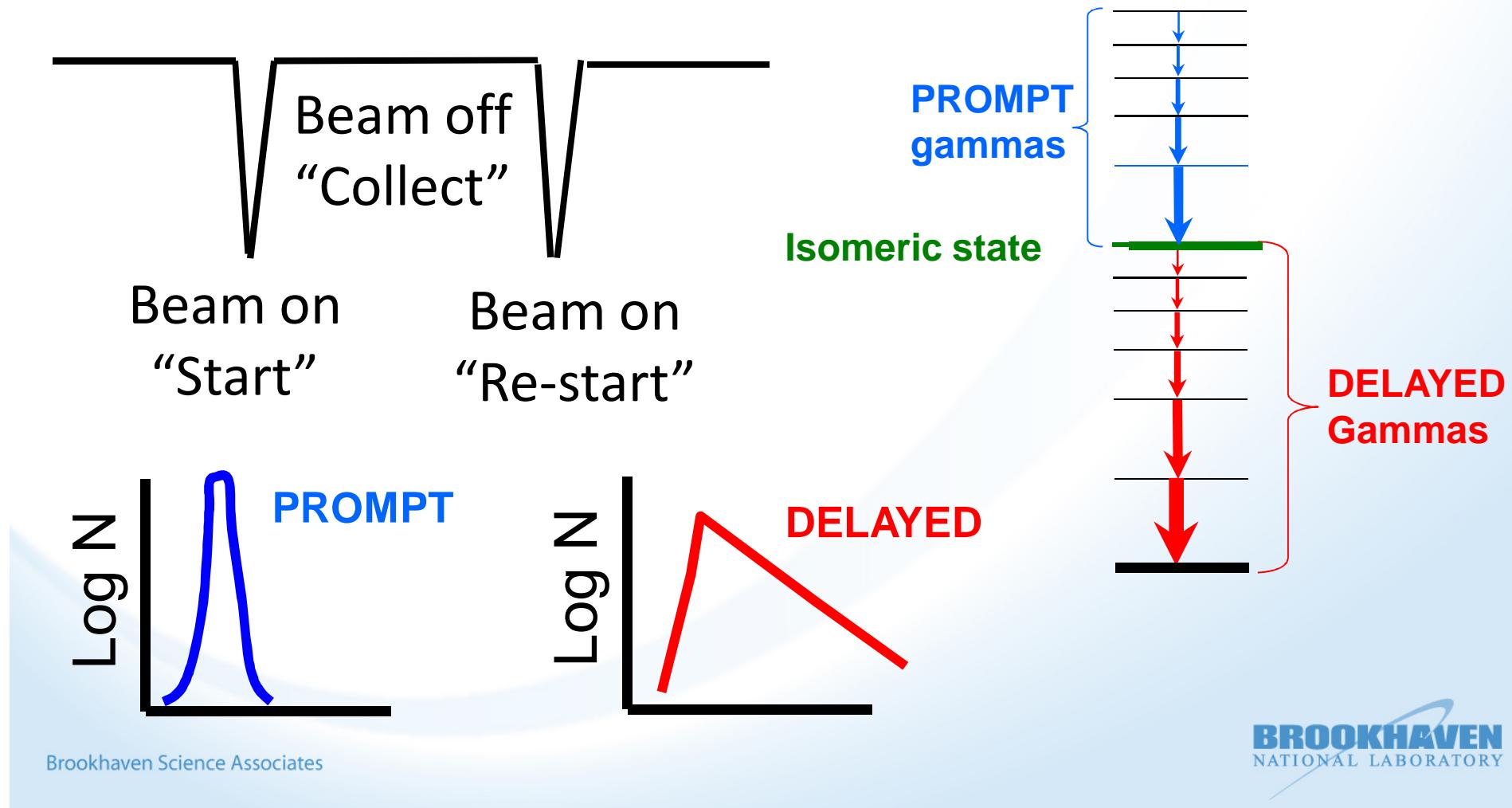


$$\Delta T_{1/2} \sim 0.012\%$$

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NATIONAL LABORATORY

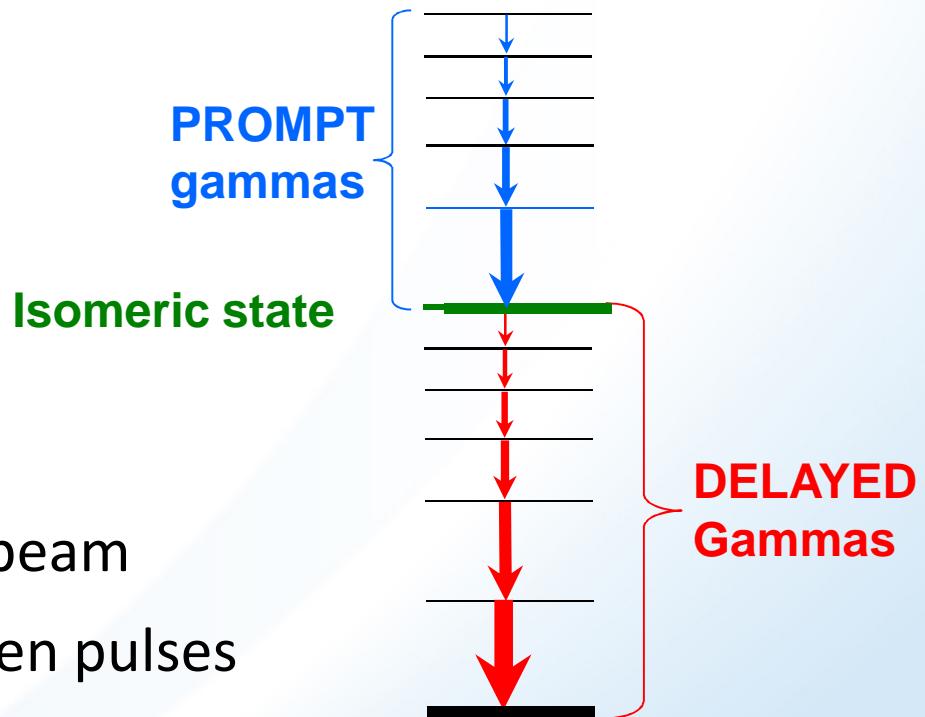
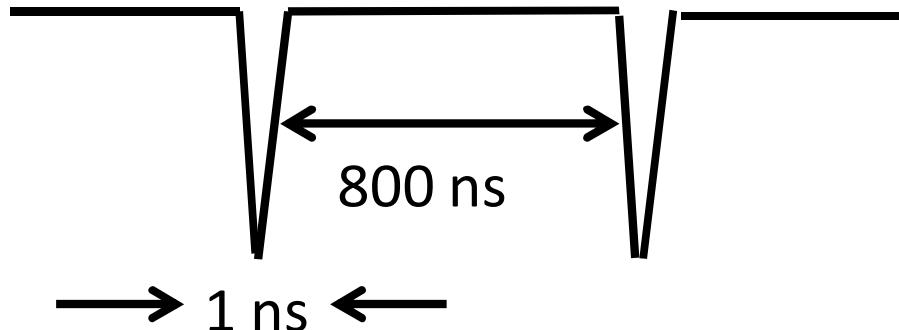
Electronic measurements

Time range : seconds to few ps



Electronic measurements

Time range : seconds to few ps



Shortest $T_{1/2}$: limited by width of beam

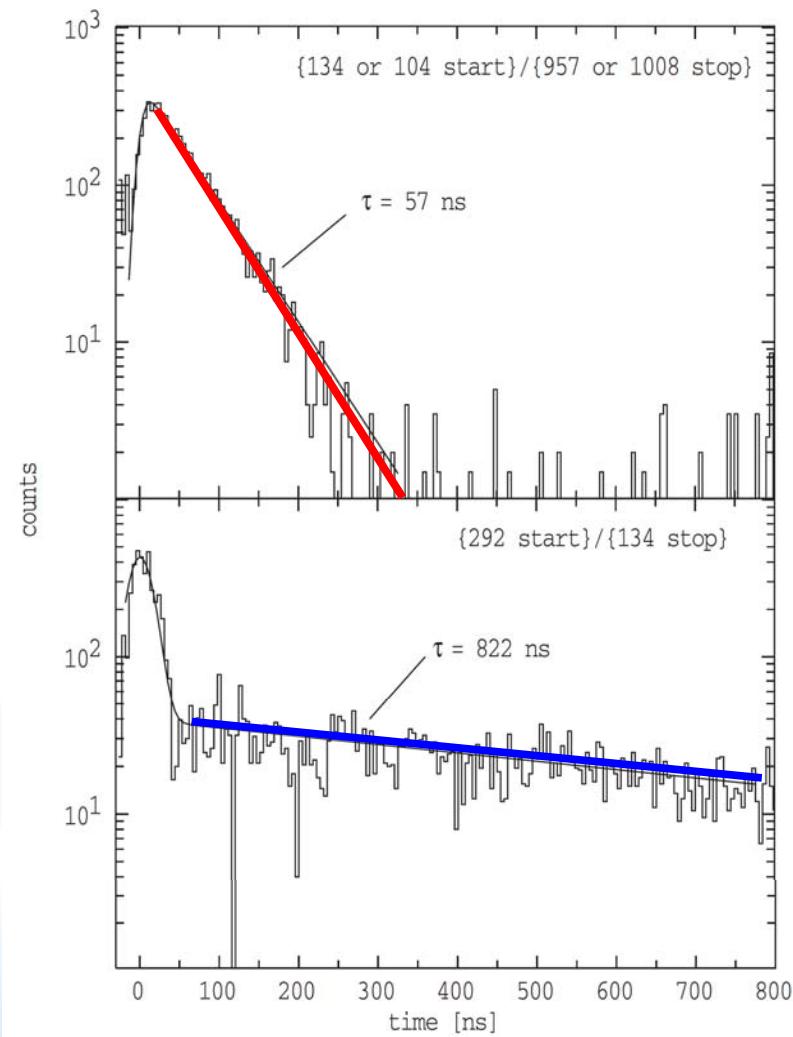
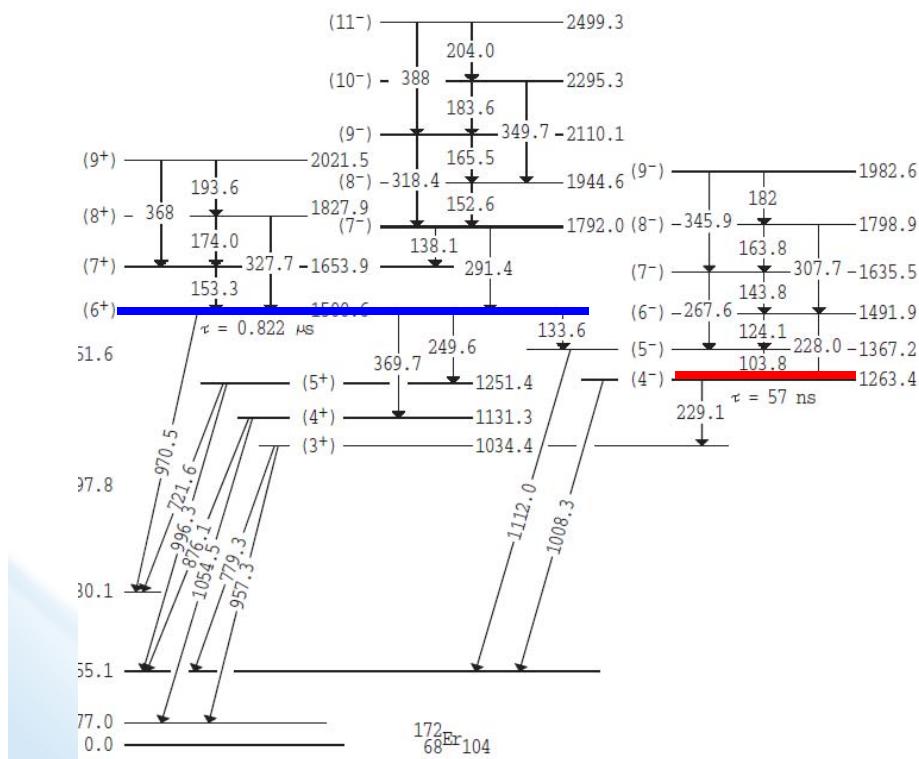
Longest $T_{1/2}$: limited by time between pulses

Singles : beam- γ -t

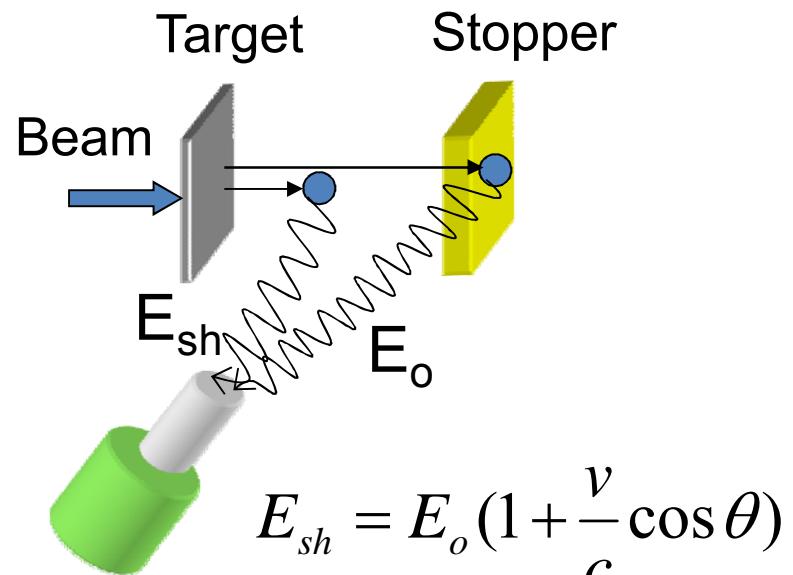
Coinc : beam- γ - γ -t

Two-quasiparticle structures and isomers in ^{168}Er , ^{170}Er , and ^{172}Er

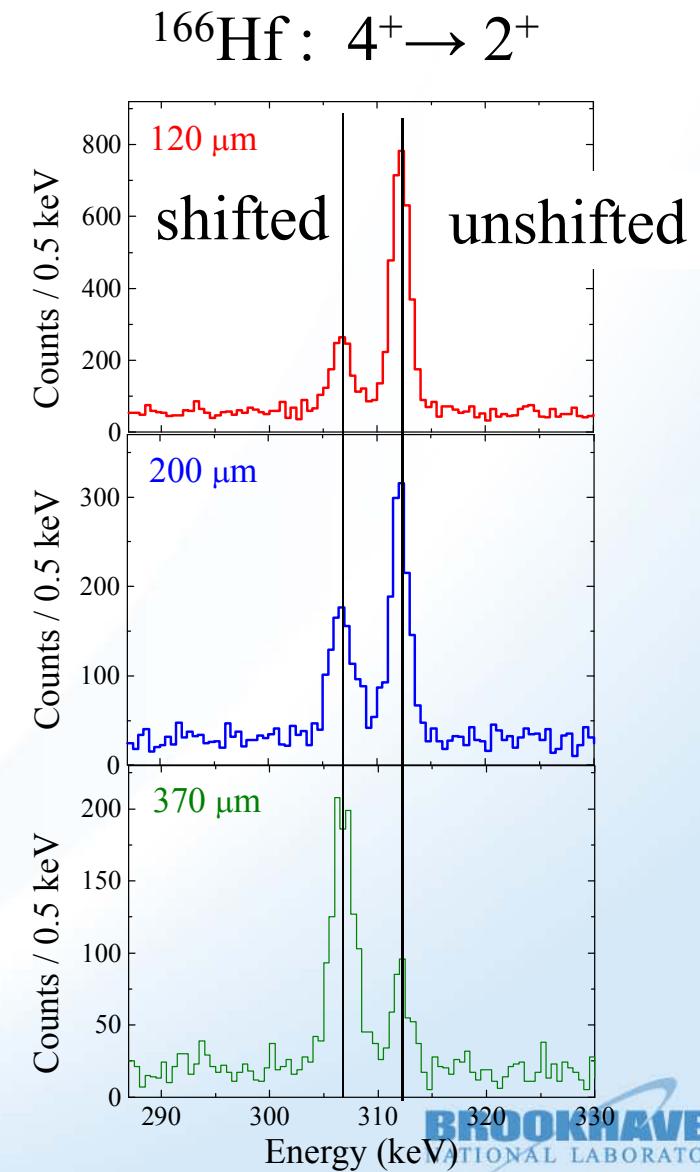
G. D. Dracoulis,^{1,*} G. J. Lane,¹ F. G. Kondev,² H. Watanabe,³ D. Seweryniak,⁴ S. Zhu,⁴ M. P. Carpenter,⁴ C. J. Chiara,^{2,†} R. V. F. Janssens,⁴ T. Lauritsen,⁴ C. J. Lister,⁴ E. A. McCutchan,⁴ and I. Stefanescu^{4,5}



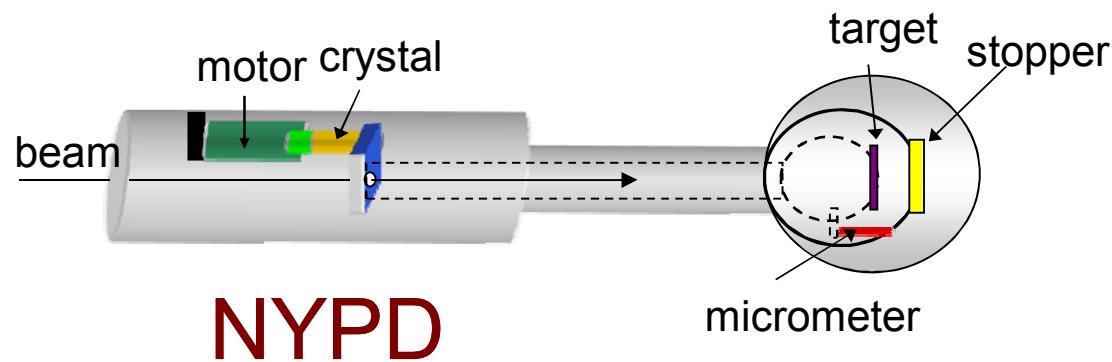
Recoil Distance Doppler Shift Method (RDM)



- ♦ Lifetimes of ~ 1 to 1000 ps

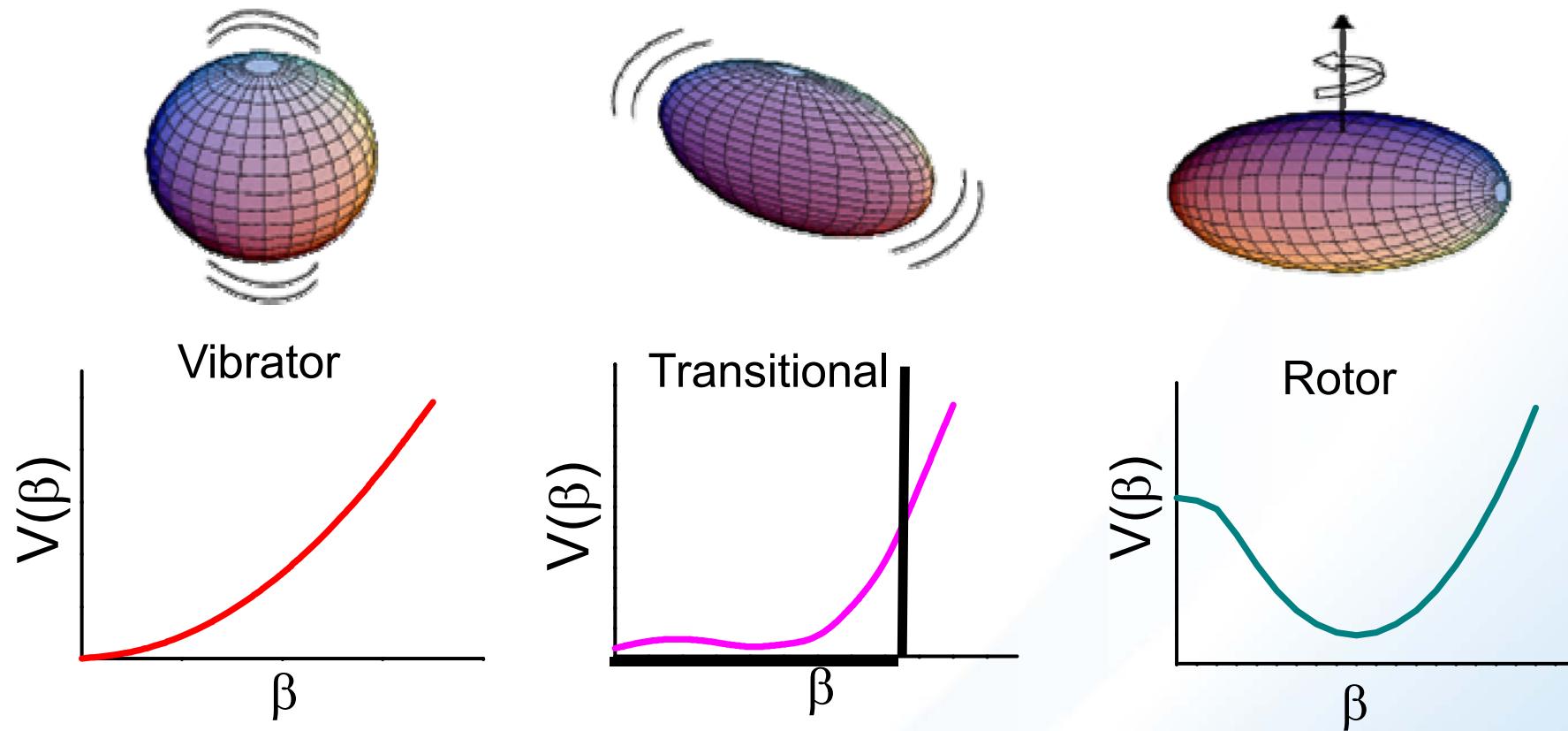


New Yale Plunger Device



- Developed by A. Dewald for RDDS method
- Piezo electric motor & crystal to move foils
- Capacitive feedback loop maintains distances to
 - 0.2 μm @ 1-10 μm
 - 3% @ 100 – 500 μm

A model for phase transitions

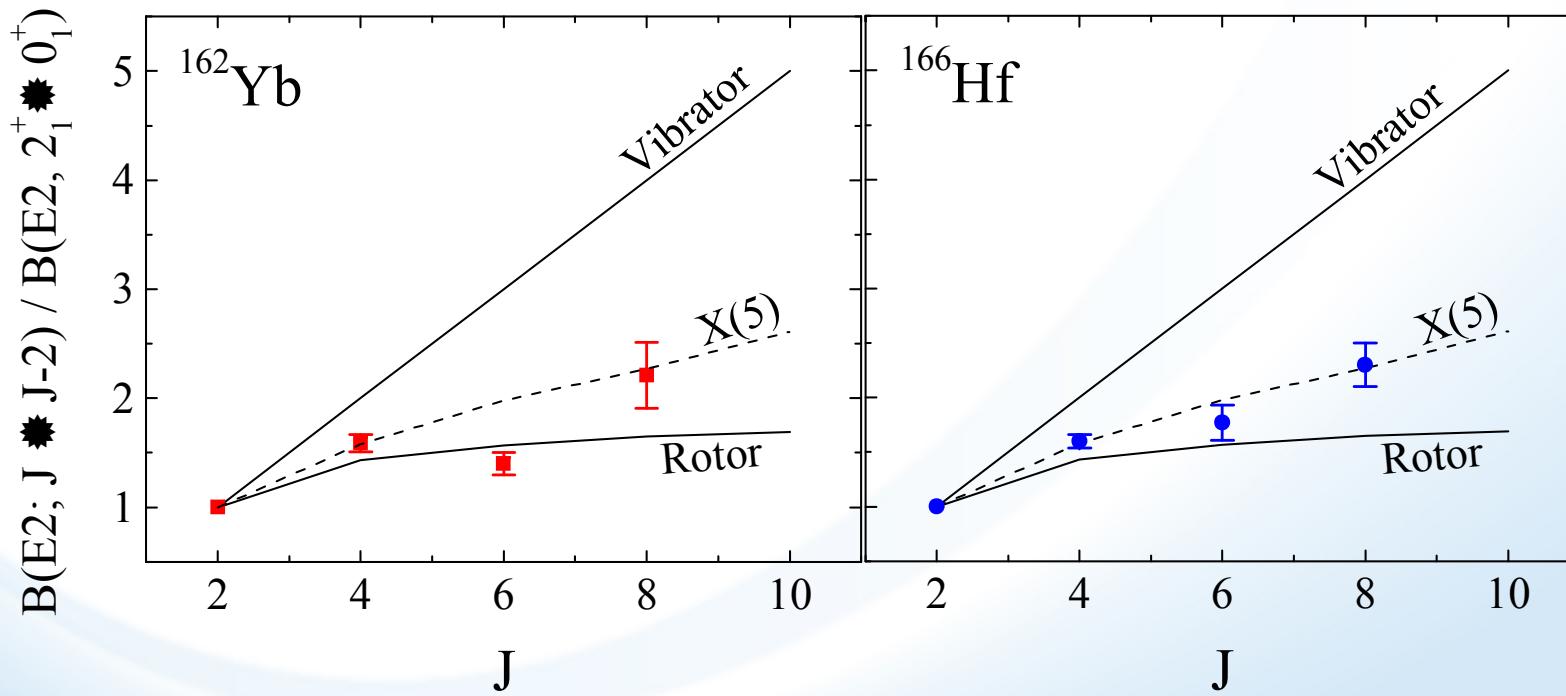


Critical Point
New analytical solution
 $X(5)$

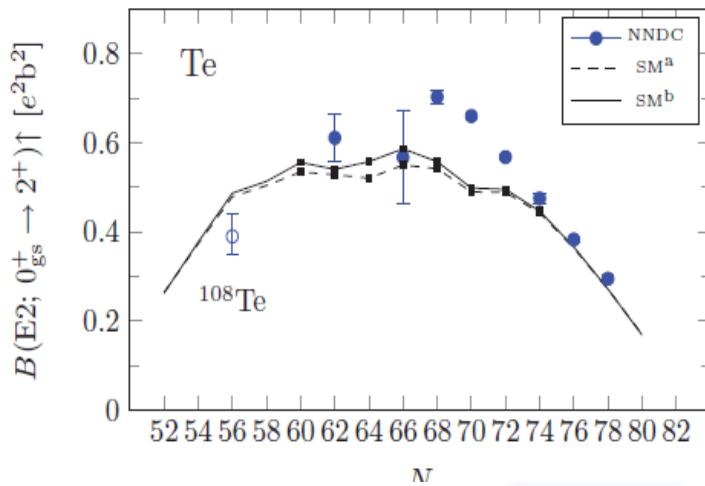
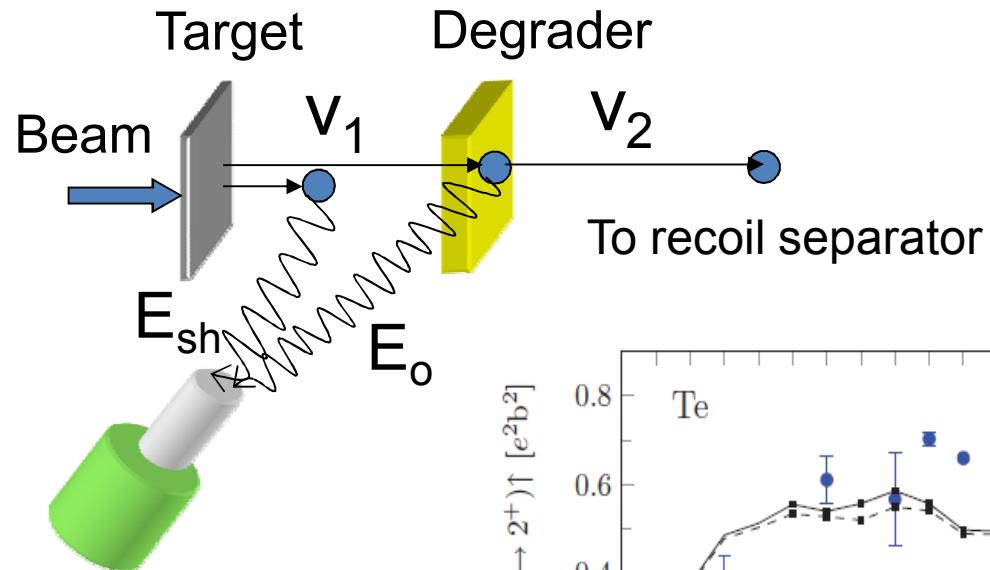
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000); 87, 052502 (2001).

Lifetimes in ^{162}Yb and ^{166}Hf

- Yrast level lifetimes for 4^+ , 6^+ , and 8^+ states
- Most values consistent with previous measurements
- Significant reduction in uncertainty



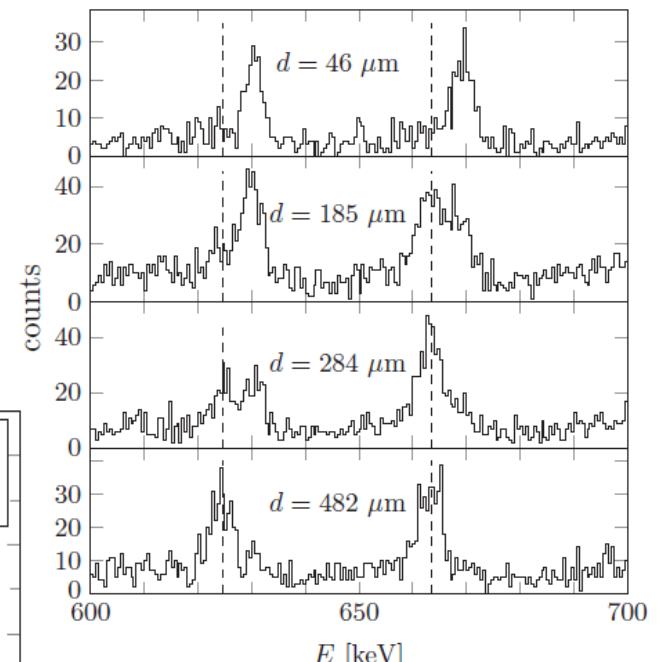
A variation on RDM



PHYSICAL REVIEW C 84, 041306(R) (2011)

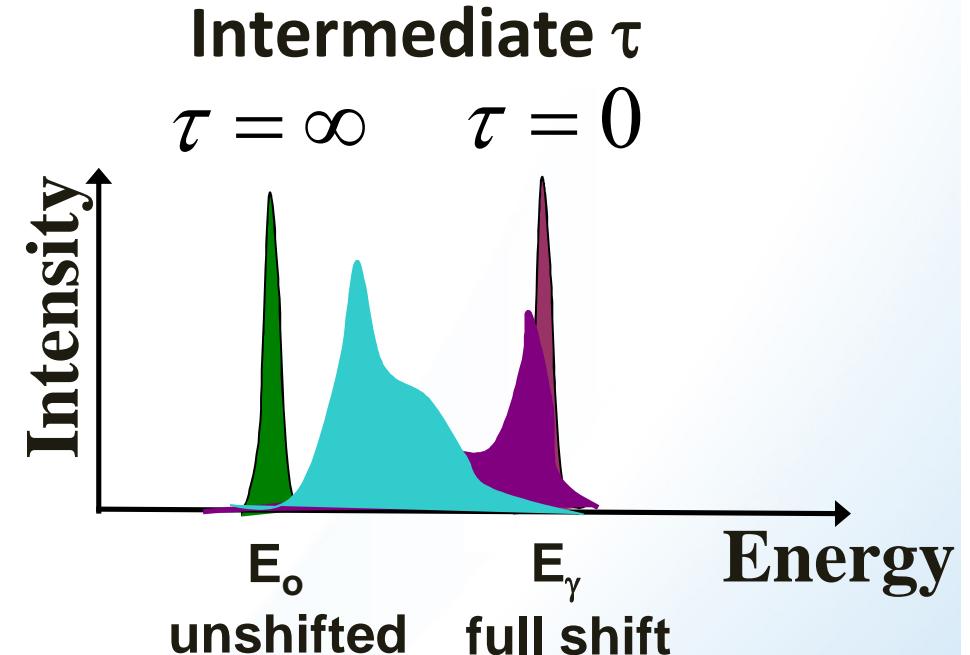
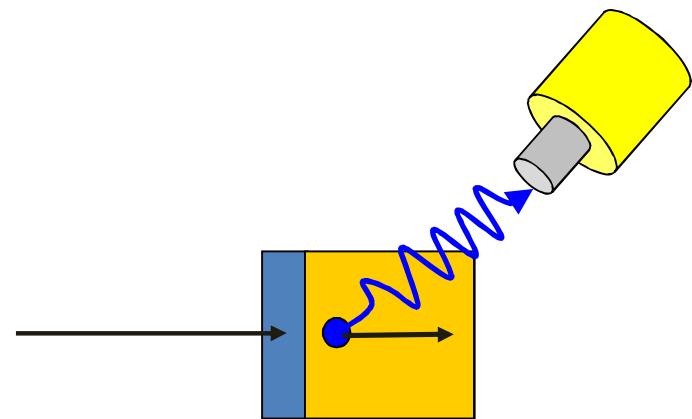
Lifetime measurement of the first excited 2^+ state in ^{108}Te

T. Bäck,^{1,*} C. Qi,¹ F. Ghazi Moradi,¹ B. Cederwall,¹ A. Johnson,¹ R. Liotta,¹ R. Wyss,¹ H. Al-Azri,² D. Bloor,² T. Brock,² R. Wadsworth,² T. Grahn,³ P. T. Greenlees,³ K. Hauschild,^{3,†} A. Herzan,³ U. Jacobsson,³ P. M. Jones,³ R. Julin,³ S. Juutinen,³ S. Ketelhut,³ M. Leino,³ A. Lopez-Martens,^{3,†} P. Nieminen,³ P. Peura,³ P. Rahkila,³ S. Rinta-Antila,³ P. Ruotsalainen,³ M. Sandzelius,³ J. Sarén,³ C. Scholey,³ J. Sorri,³ J. Uusitalo,³ S. Go,⁴ E. Ideguchi,⁴ D. M. Cullen,⁵ M. G. Procter,⁵ T. Braunroth,⁶ A. Dewald,⁶ C. Fransen,⁶ M. Hackstein,⁶ J. Litzinger,⁶ and W. Rother⁶



Doppler Shift Attenuation Method (DSAM)

$$E_\gamma = E_o \left[1 + \frac{v}{c} \cos(\theta) \right]$$



- Thin target with thick backing to slow/stop recoils
- Line-shape depends on nuclear lifetime
- Short lifetime: Full shift
- Long lifetime: No shift

Musical medley of ^{10}Be measurements

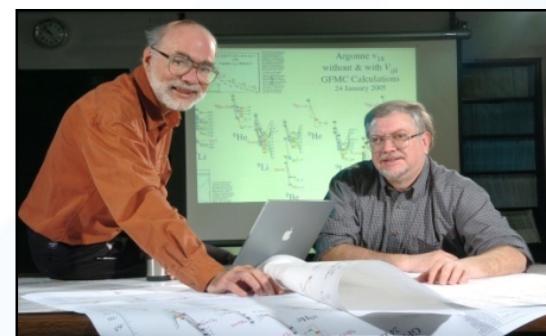
- Physics questions we want to address
- How to improve over existing measurements
 - Technological advances
 - Re-thinking the technique
- Experimental results
- What we've learned

1 Question in nuclear physics

What are the forces between protons and neutrons that bind nuclei??

Up till about 10 years ago, we had no idea

UNTIL...

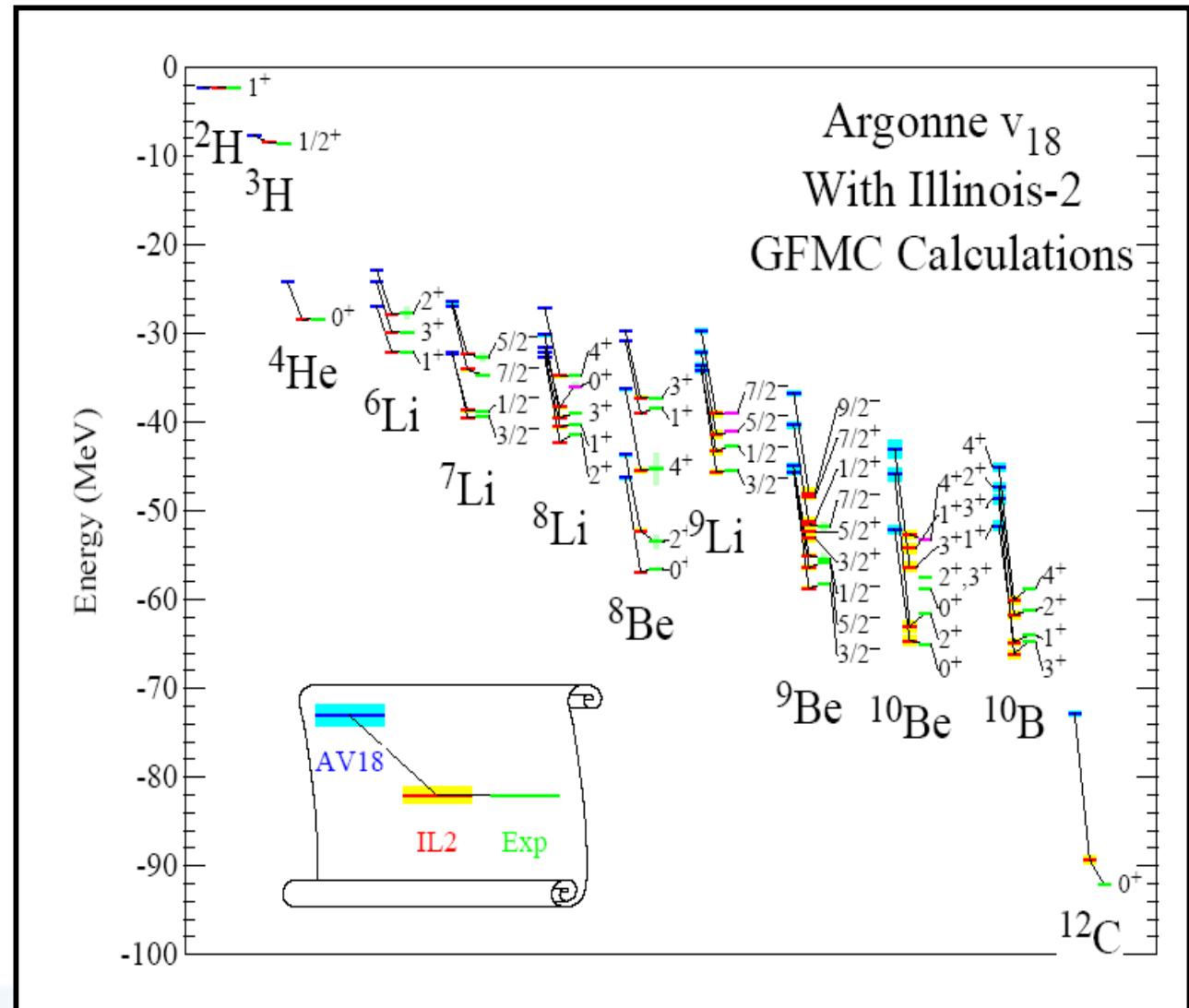


Pieper and Wiringa
(ANL)

Ab-initio Greens Functional Monte Carlo Calculations



Pieper and
Wiringa (ANL)



Described in NPA751, 516c (2005)

NN Potential

A number on the market: Argonne V18, CD Bonn, Nijmegen ...

Argonne v18 two-body potential:

$$H = \sum_i K_i + \sum_{i < j} v_{ij}^{\gamma} + v_{ij}^{\pi} + v_{ij}^R$$

EM **1- π** **short range**

18 Operators
~40 Parameters
Fit to ~4300 NN Scattering data

Don't mess with it

Problem :
Binding energies of most light nuclei too small

R.B. Wiringa *et al.*, Phys. Rev. C **51**, 38 (1995).

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$$v^{\text{EM}}(pp) = V_{C1}(pp) + V_{C2} + V_{DF} + V_{VP} + V_{MM}(pp) .$$

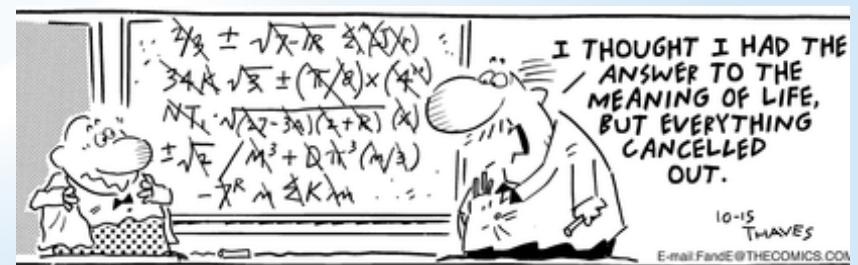
$$V_{C1}(pp) = \alpha' \frac{F_C(r)}{r} ,$$

$$V_{C2} = -\frac{\alpha}{2M_p^2} \left[(\nabla^2 + k^2) \frac{F_C(r)}{r} + \frac{F_C(r)}{r} (\nabla^2 + k^2) \right] \approx -\frac{\alpha\alpha'}{M_p} \left[\frac{F_C(r)}{r} \right]^2 ,$$

$$V_{DF} = -\frac{\alpha}{4M_p^2} F_\delta(r) ,$$

$$V_{VP} = \frac{2\alpha\alpha'}{3\pi} \frac{F_C(r)}{r} \int_1^\infty dx e^{-2m_e rx} \left[1 + \frac{1}{2x^2} \right] \frac{(x^2 - 1)^{1/2}}{x^2} ,$$

$$V_{MM}(pp) = -\frac{\alpha}{4M_p^2} \mu_p^2 \left[\frac{2}{3} F_\delta(r) \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + \frac{F_t(r)}{r^3} S_{ij} \right] - \frac{\alpha}{2M_p^2} (4\mu_p - 1) \frac{F_{ls}(r)}{r^3} \mathbf{L} \cdot \mathbf{S} .$$



Three body forces

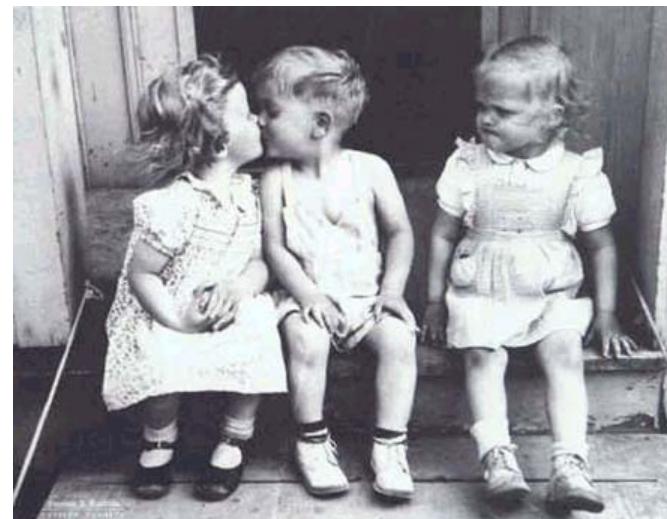
From Wikipedia:

A **three-body force** is a [force](#) that does not exist in a system of two objects but appears in a three-body system.

Very Basic Example

Object = People

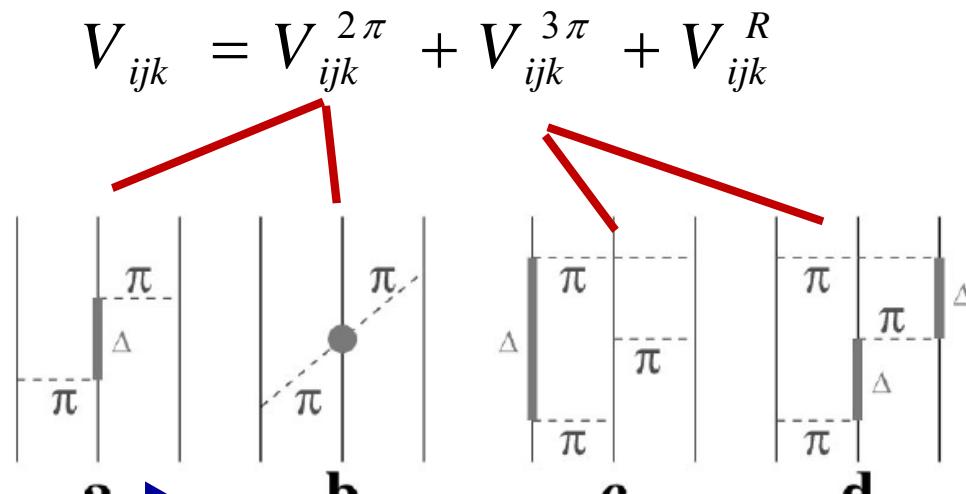
Force = Emotions



3-body force = Jealousy

Three body forces in nuclei

Extra interactions in nuclear matter when nucleons are packed close together



Fujita-
Miyazawa
Dominant Term

Urbana Potentials:

$$a + V^R$$

Illinios Potentials:

$$a + b + c + d + V^R$$

Coupling constants from fitting
binding energies of light nuclei
~4 parameters

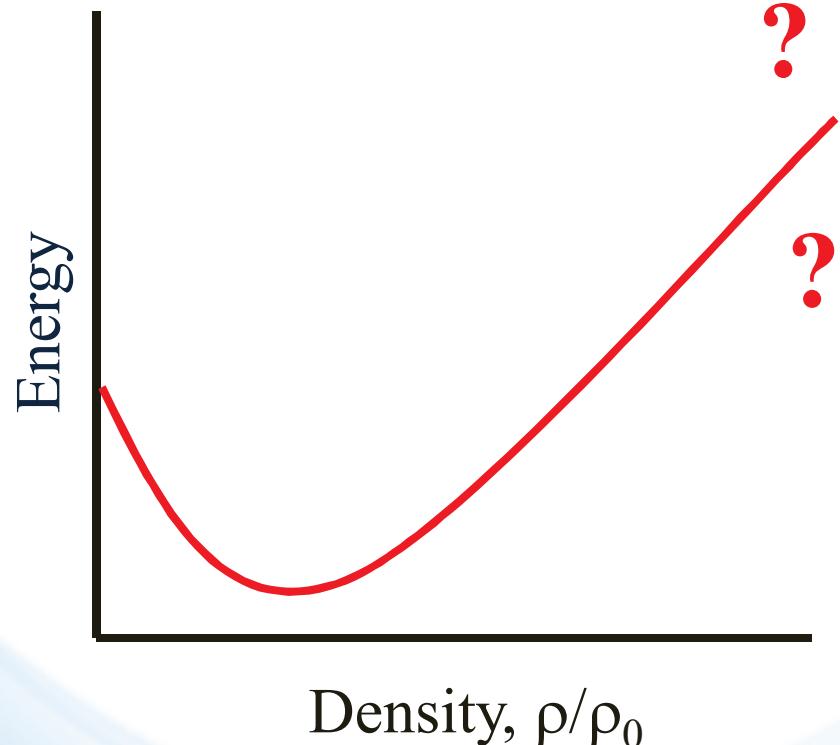
Work in progress

Neutron Stars



Can we figure out what's going on inside ?

- Need to know the “Nuclear Equation of State”
- How much energy does it cost to squeeze nuclear matter



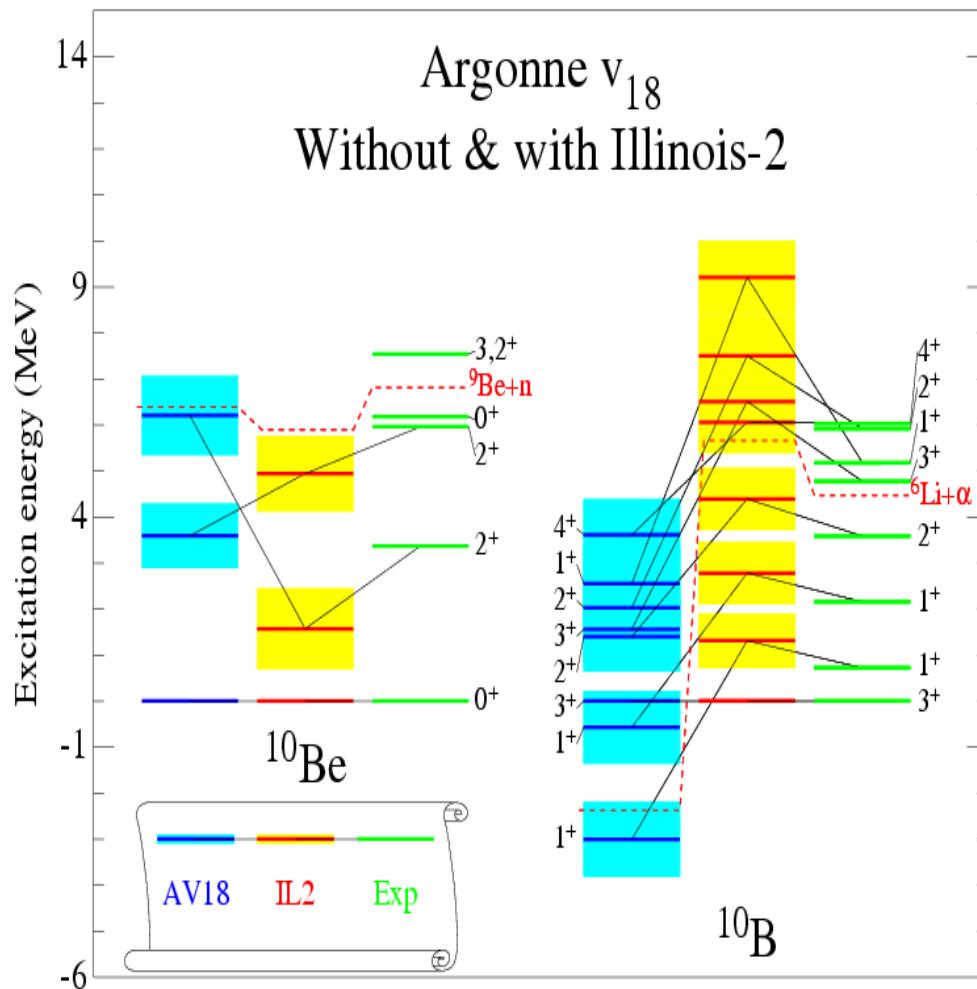
This density dependence is
CRITICALLY dependent on the
THREE-BODY forces, as the more
you crush....

then closer then nucleons get and
the more chance of 3-body
interactions.

AND

We can only learn about the 3-body
forces by studying nuclei on earth.

A=10 nuclei provide a sensitive test of GFMC



Can lifetime measurements probe the effects of 3-body forces?

S.C. Pieper, K. Varga and R.B. Wiringa, Phys. Rev. C **66**, 044310 (2002).

B(E2)'s: The rate of emitting gamma rays

The problem is.....the radiation comes out **VERY** fast.

Units of time:

1ms 10^{-3} s

1μs 10^{-6} s

1ns 10^{-9} s

1ps 10^{-12} s

1fs 10^{-15} s ^{10}Be lifetimes are 10-200fs

$$B(E2) \sim \frac{1}{\tau}$$

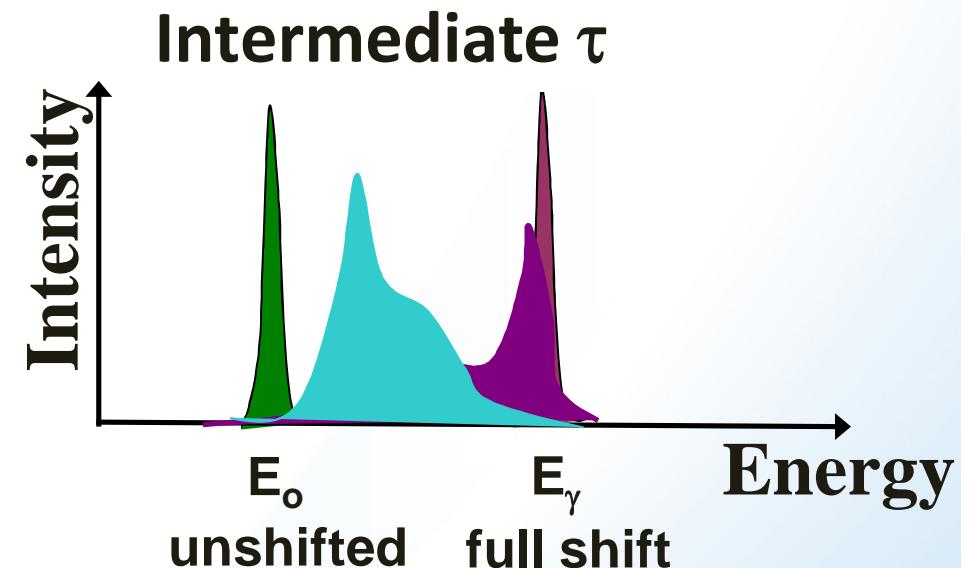
How can you measure femtosecond-type lifetimes?

No clock runs evenly remotely that fast.

THE ONLY MECHANISM THE NUCLEAR TRAIN
WRECK!!!

Doppler Shift Attenuation Method (DSAM)

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



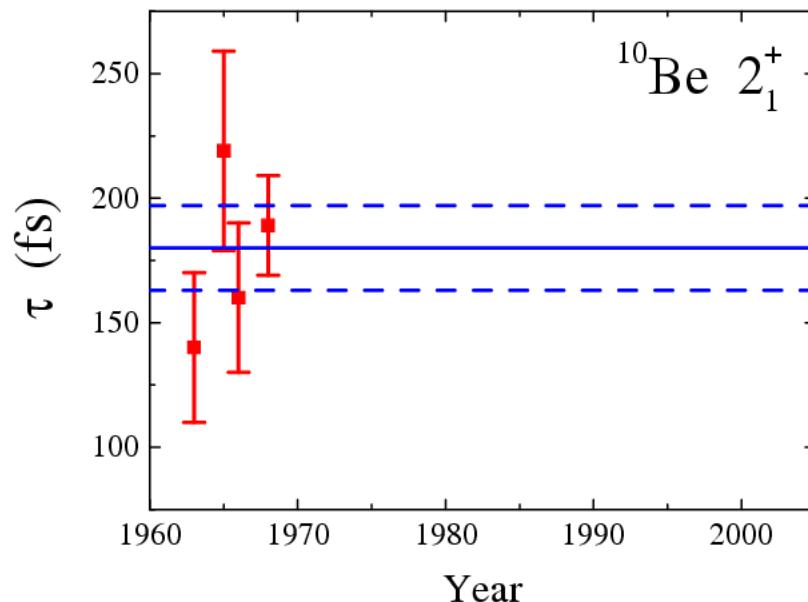
- Thin target with thick backing to slow/stop recoils
- Line-shape depends on nuclear lifetime
- Short lifetime: Full shift
- Long lifetime: No shift

Previously measured lifetimes in ^{10}Be

All DSAM measurements



Evaluated $\tau = 180 (17)$ fs



- E.K. Warburton *et al.*, Phys. Rev. 129, 2180 (1963).
G.C. Morrison *et al.*, - unpublished.
E.K. Warburton *et al.*, Phys. Rev. 148, 1072 (1966).
T.R. Fisher *et al.*, Phys. Rev. 176, 1130 (1968).

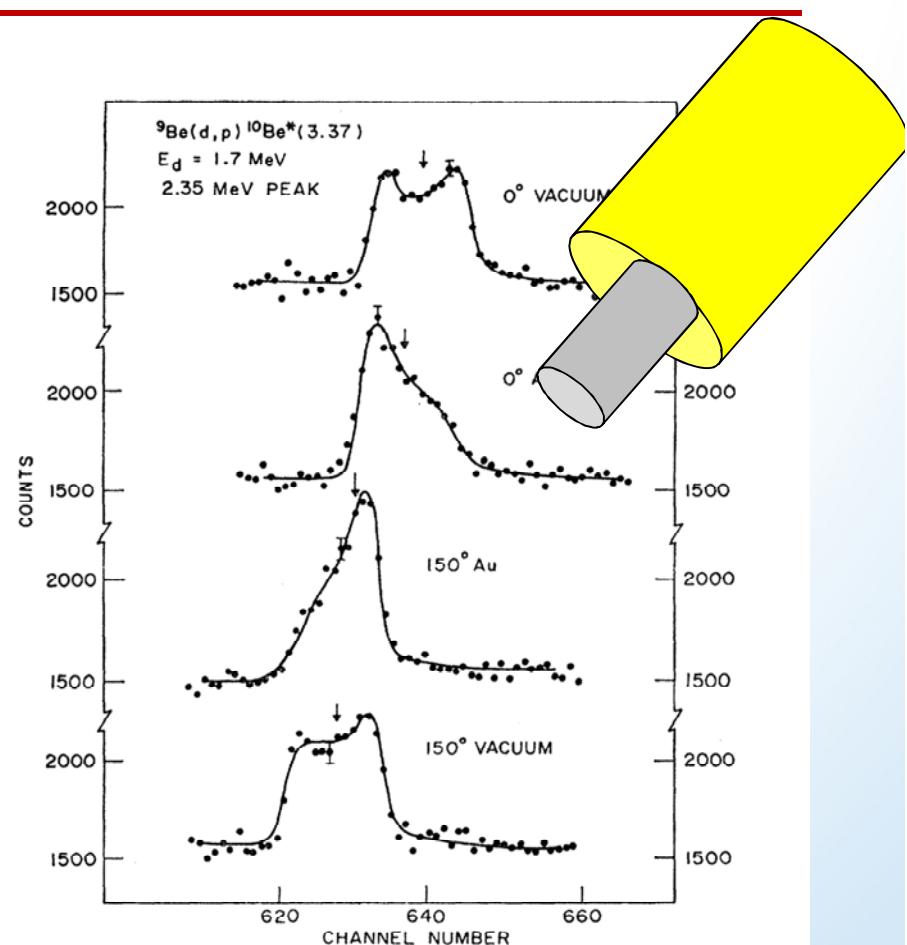
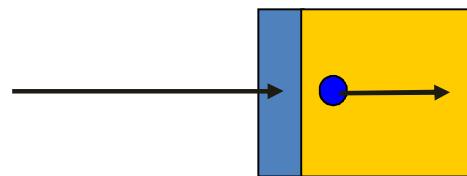


FIG. 3. Sequence of spectra for the two-escape peak of the 3.37-MeV γ ray from the reaction $^9\text{Be}(d, p)^{10}\text{Be}^*(3.37)$. The curves are computer fits to the data. The arrows indicate the centroids of the lines.

T.R. Fisher *et al.*, Phys. Rev. 176, 1130 (1968).

Key component : Stopping powers

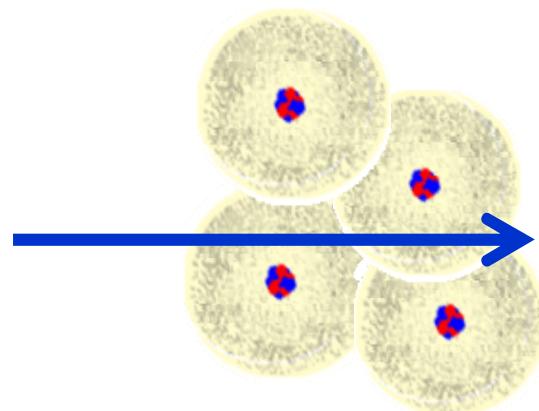


Huge deceleration !!

$$a = -10^{18} \text{ g} !!!$$

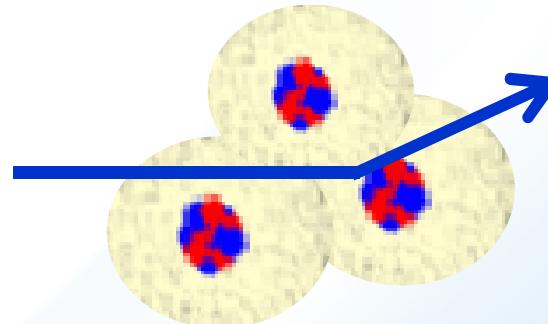
At high velocities:

Electronic stopping



At low velocities:

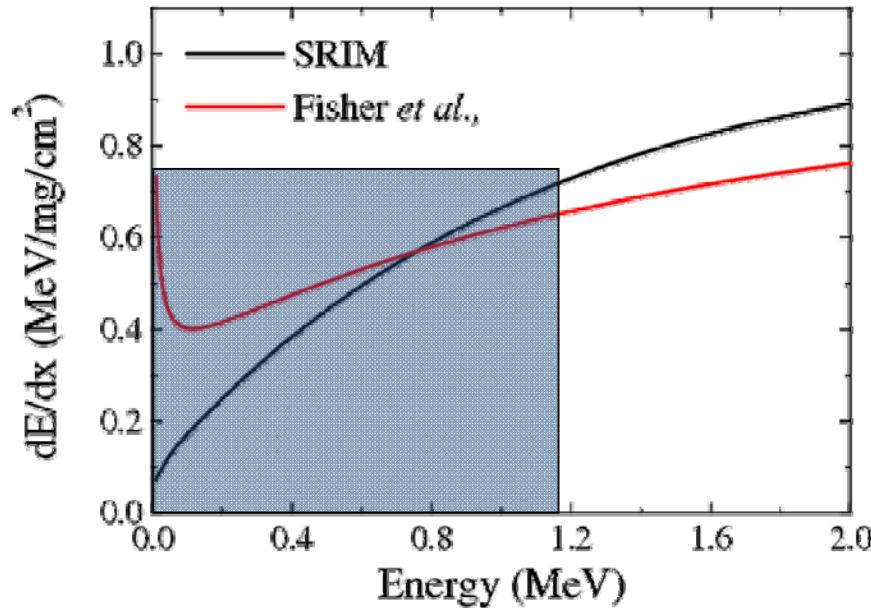
Electronic stopping
Nuclear stopping



- Ions see mainly a cloud of electrons
- Scattering is small
- Pure Coulomb, easy to calculate

- Scattering off of target nuclei
- Large deviations from trajectory
- Not well understood

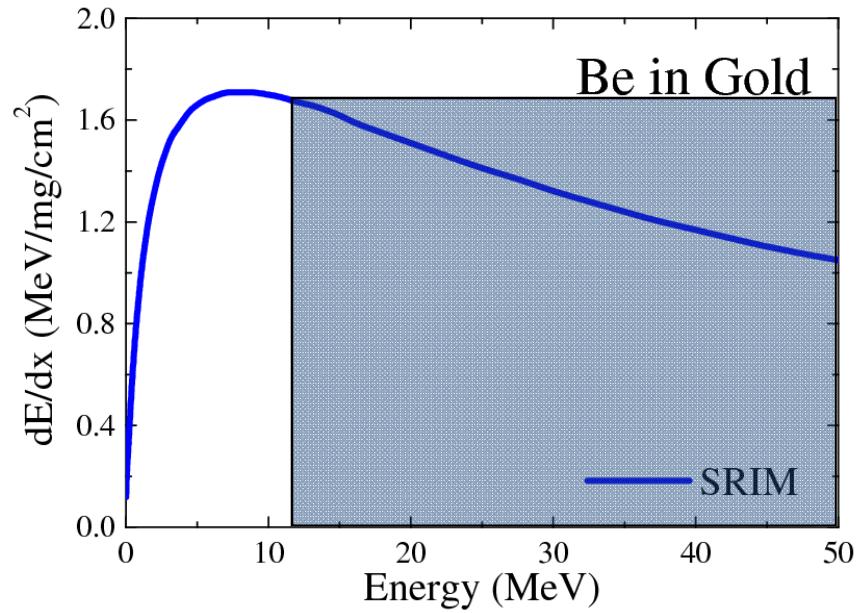
Stopping powers



Reaction



$$E_{\text{Li}} = 10 \text{ MeV}$$

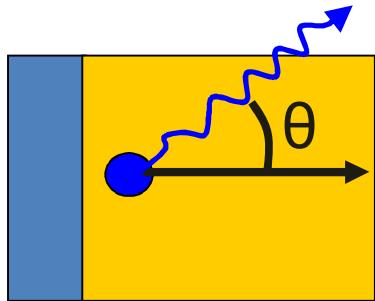


Large positive Q value

${}^{10}\text{Be}$ (g.s) ~ 18 MeV

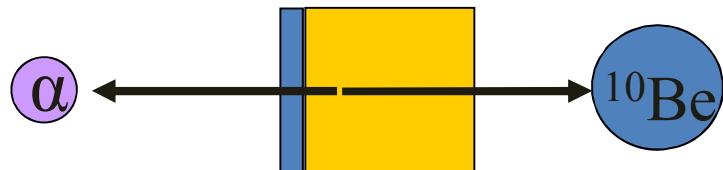
high velocity recoils

Key component :Recoil velocity vector

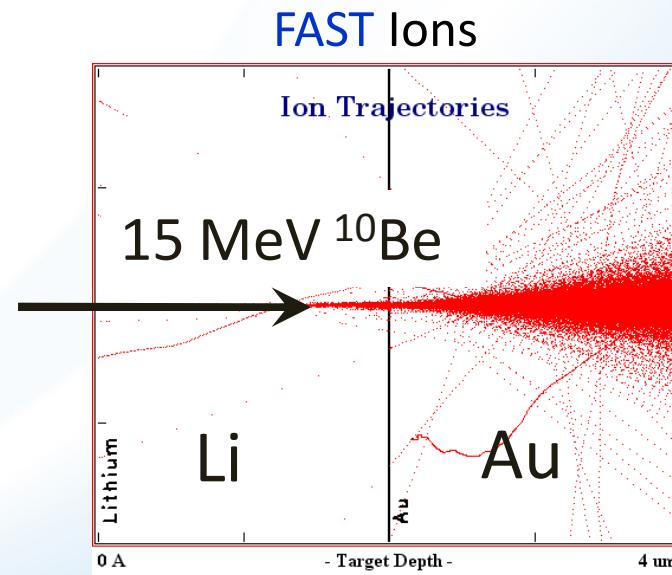
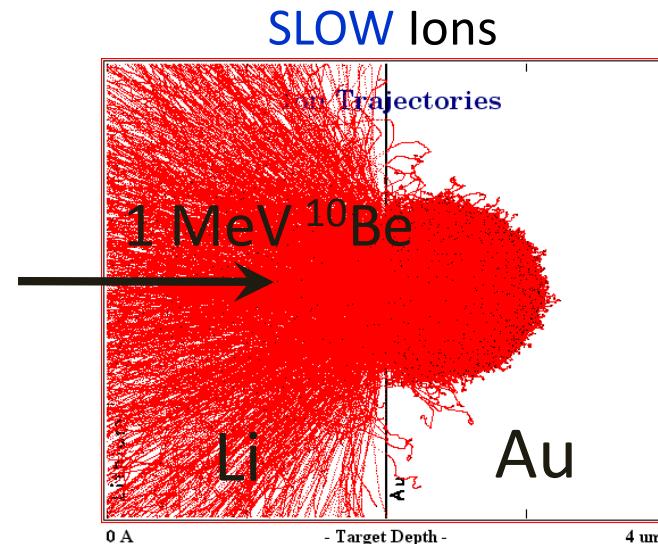


$$E_\gamma = E_o \left[1 + \frac{v}{c} \cos(\theta) \right]$$

Need to know θ

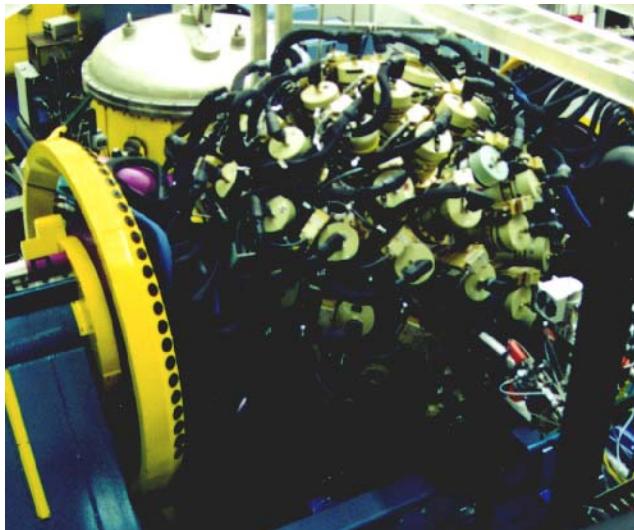


Unique selection
of recoil velocity



Gamma ray and recoil detection

Gammasphere



100 Germanium detectors
Almost 4π coverage



Brookhaven Science Associates

Fragment Mass Analyzer (FMA)



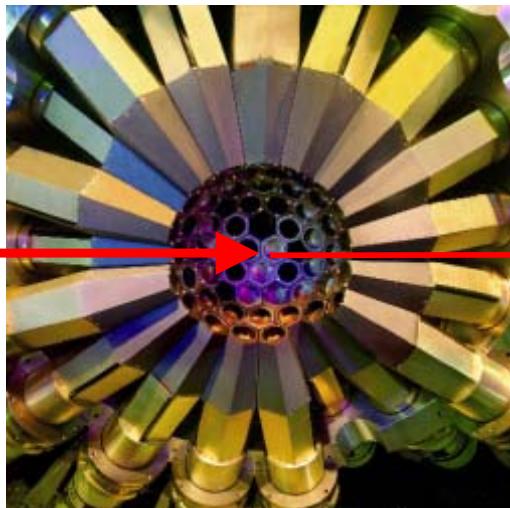
- Vacuum recoil separator
- 2 Electric & 1 Magnetic Dipole
- Selects based on A/Q
- Rejects beam on 10^{-10} level

Gammasphere + FMA : The ideal tools

2-body kinematics



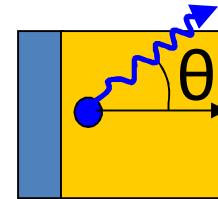
High recoil velocity



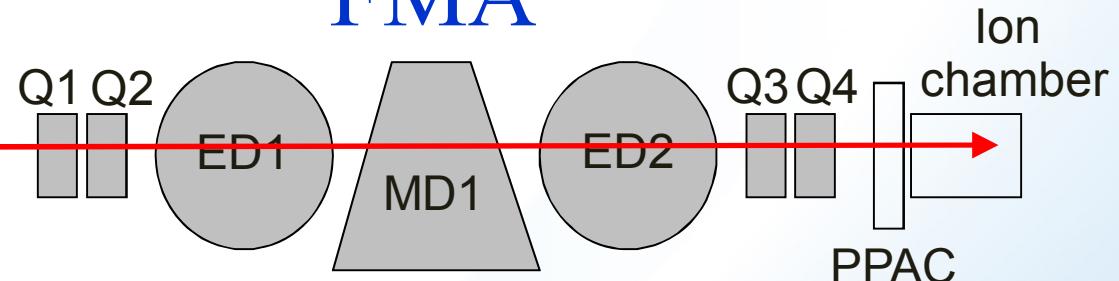
High efficiency

Large number of angles

Well defined recoil- γ angle



FMA

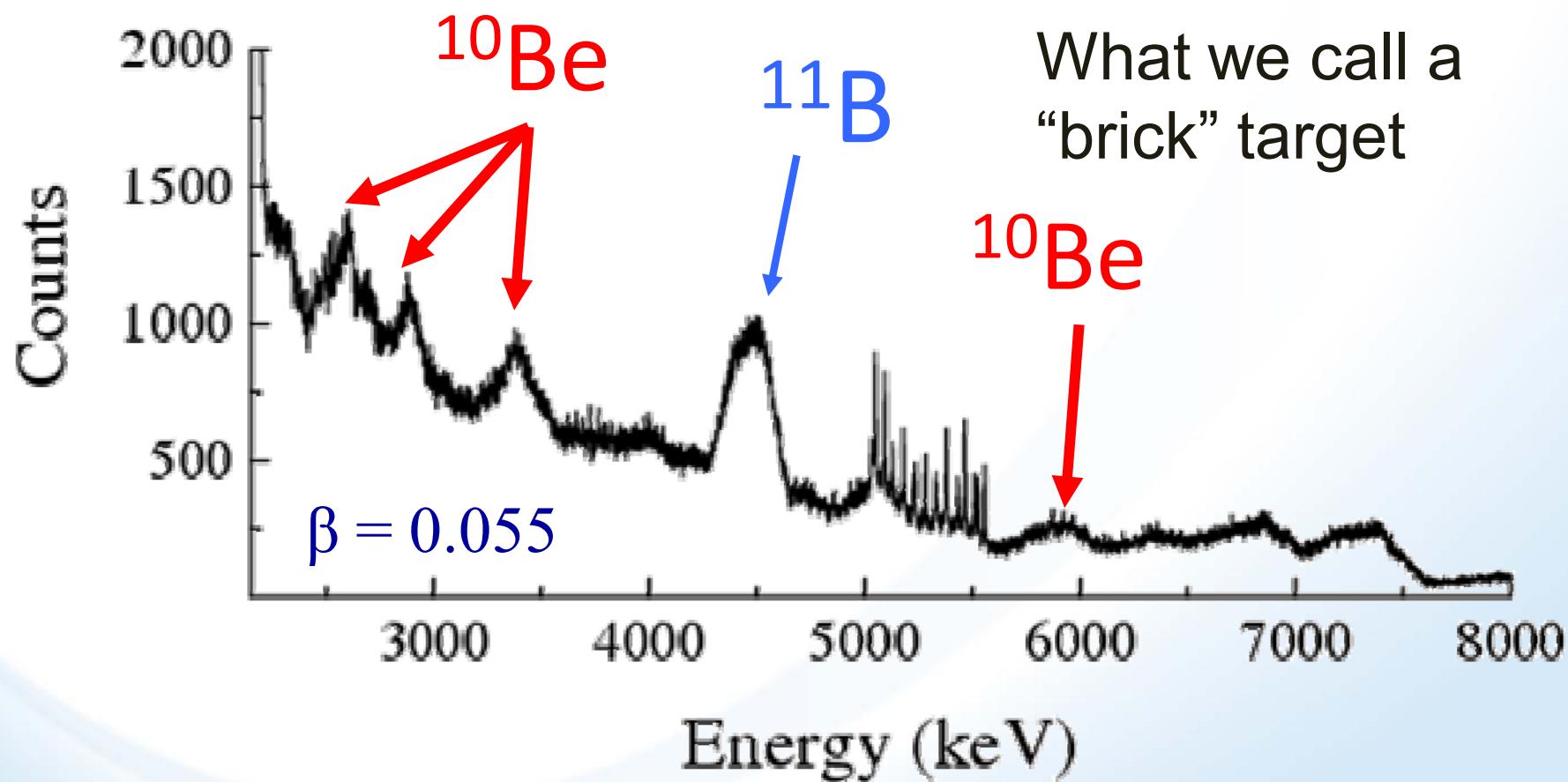


$$^{10}\text{Be}^*(3.3) = 16.5 \text{ MeV}$$

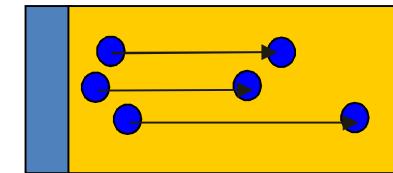
$$^{10}\text{Be}^*(5.9) = 15.0 \text{ MeV}$$

Control of state population

The old way...



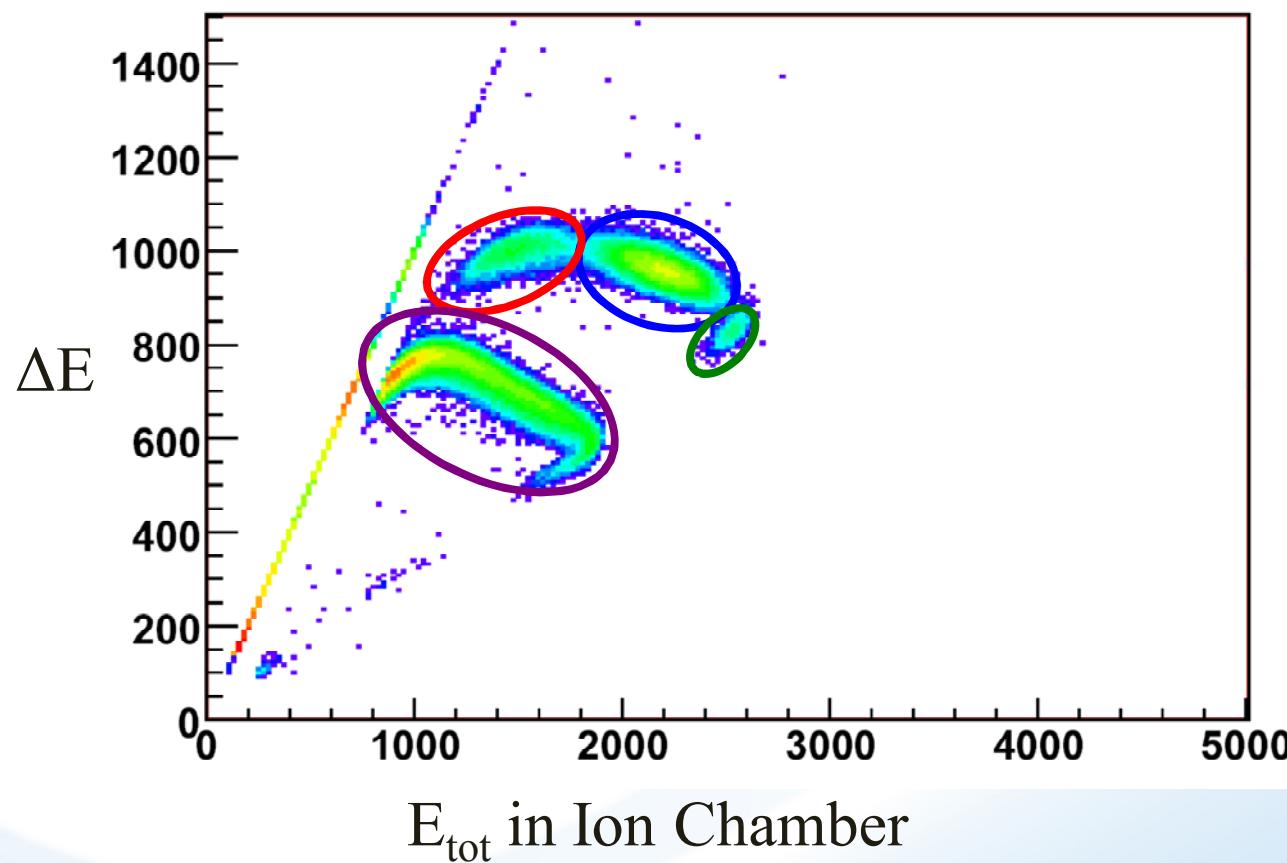
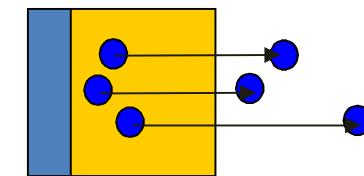
Backing stops all recoils



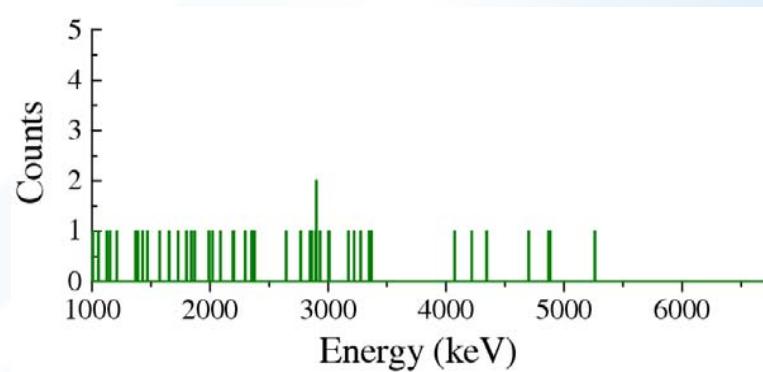
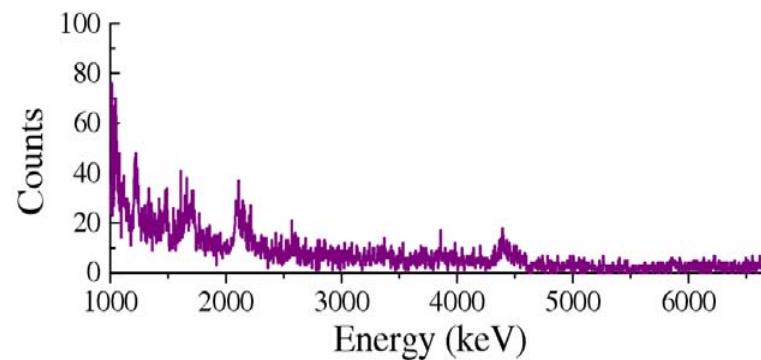
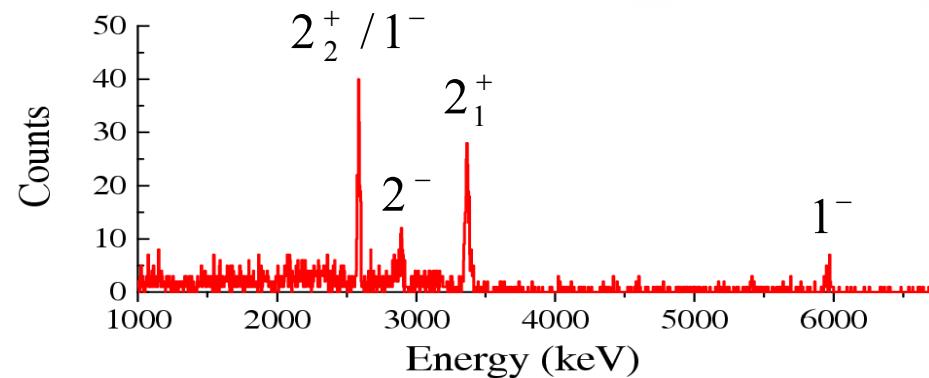
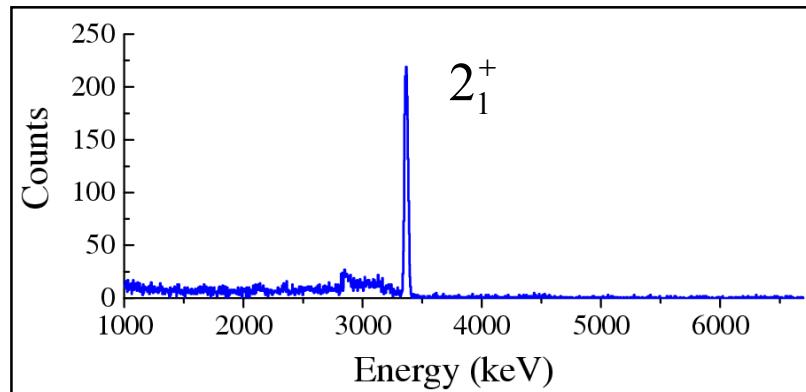
What we call a
“brick” target

And the new way...

3 mg/cm² Cu backing



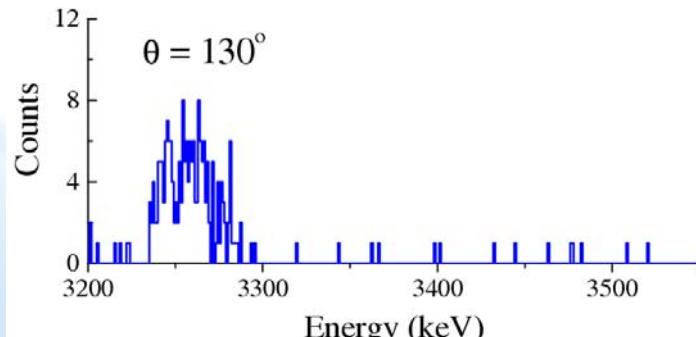
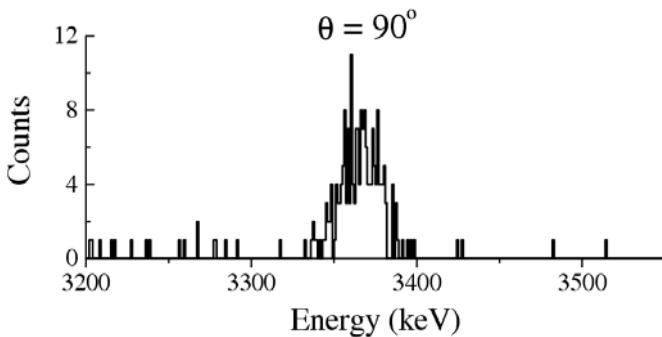
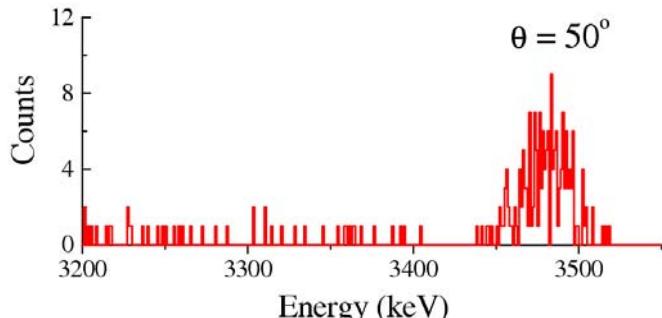
And the new way...



Centroid Shift Analysis

16 Angle Rings in Gammasphere

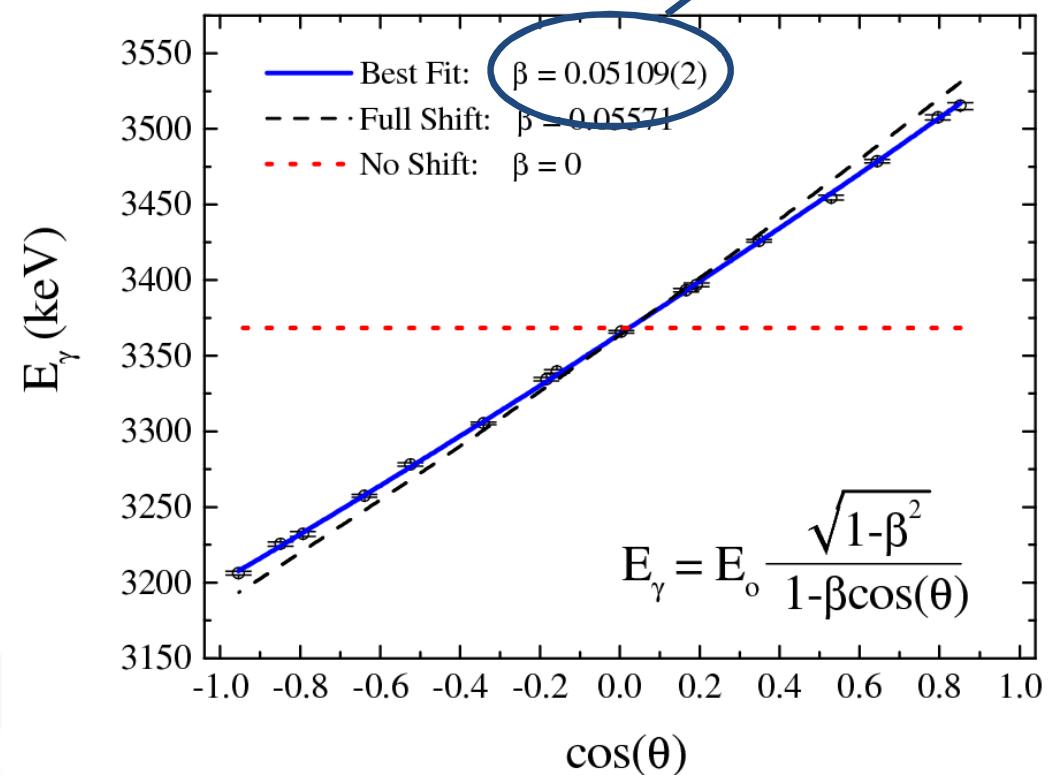
Determine peak centroid in each ring



Fit with:

$$E_\gamma = E_o \left(\frac{\sqrt{1-\beta^2}}{1-\beta \cos \theta} \right)$$

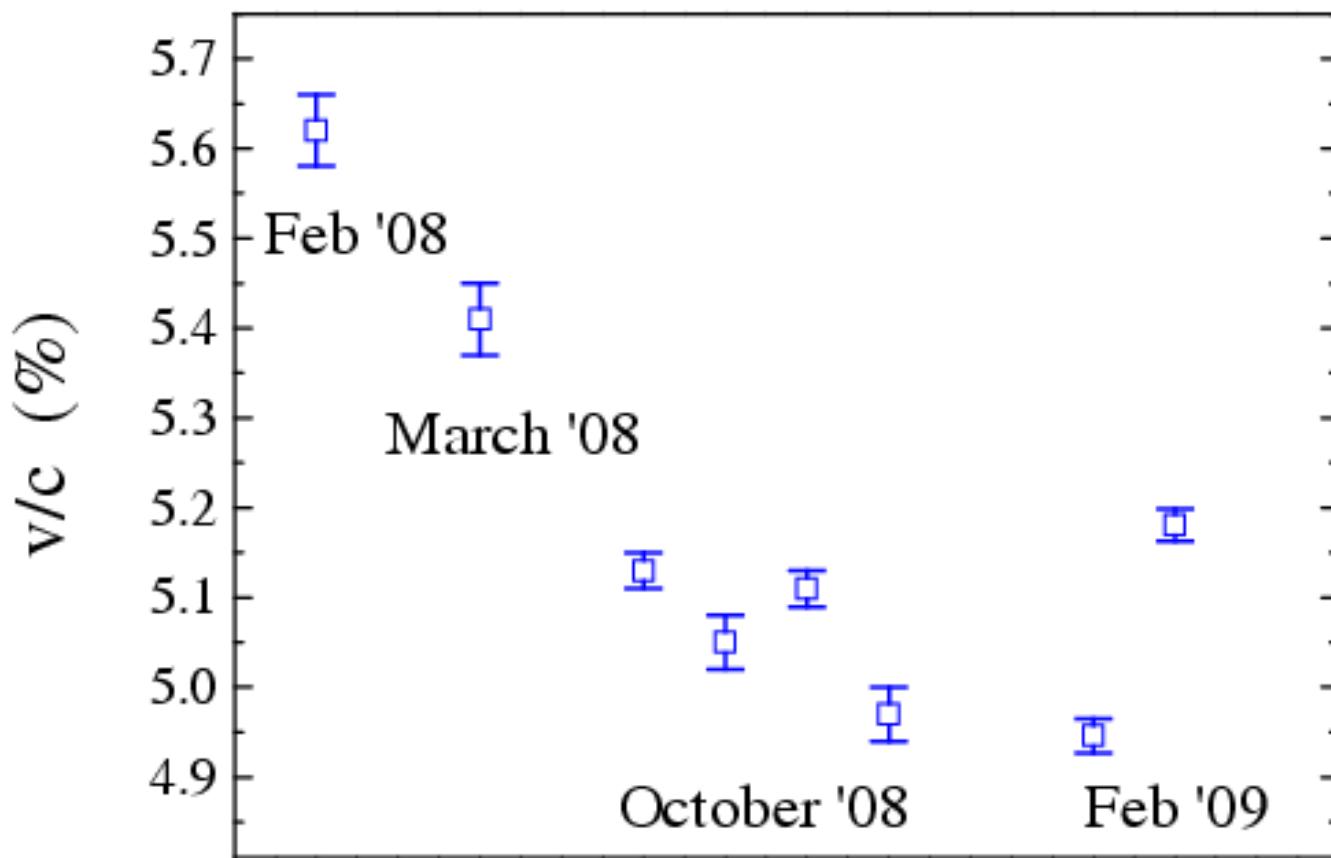
<1% in β



Results for 3369keV J=2 state

Targets of ${}^7\text{Li}$ and ${}^7\text{LiF}$

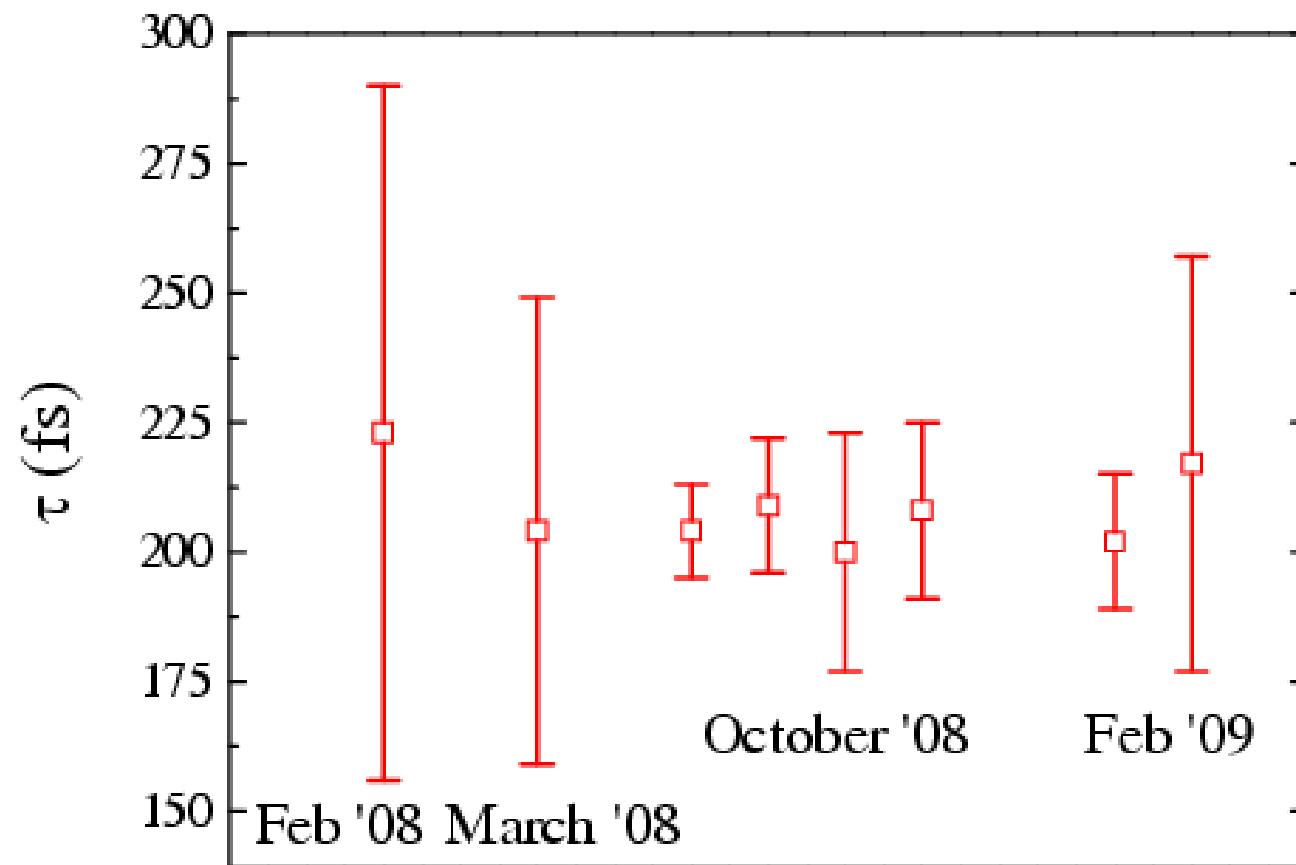
Backings of Gold and Cu



Results for 3369keV J=2 state

Targets of ${}^7\text{Li}$ and ${}^7\text{LiF}$

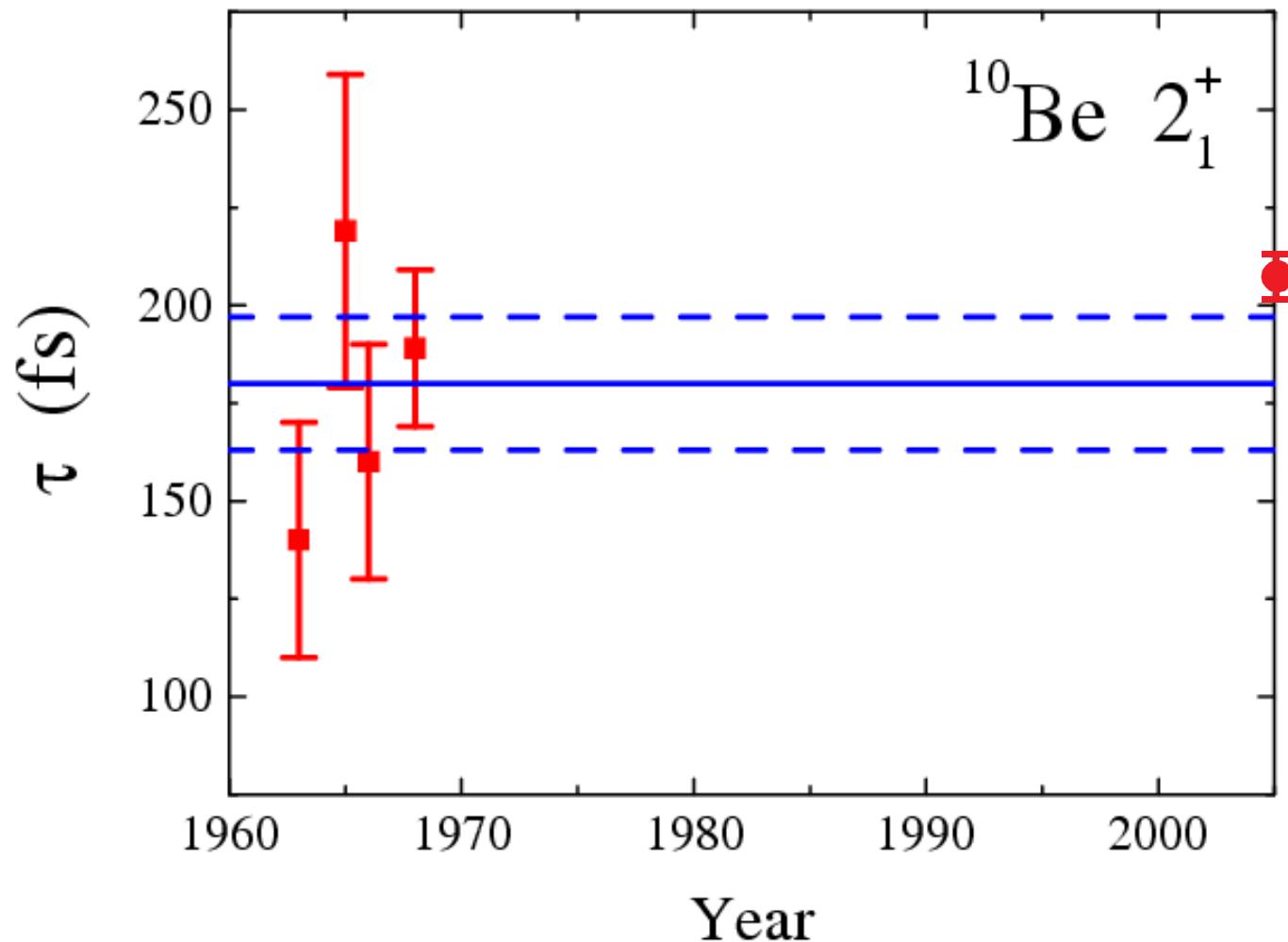
Backings of Gold and Cu



Results for 3369keV J=2 state

Targets of ${}^7\text{Li}$ and ${}^7\text{LiF}$

Backings of Gold and Cu



2⁺ states in ¹⁰Be

First 2⁺ state

NNDC transition strength

$$B(E2; 2_1^+ \rightarrow 0_1^+) = 10.5(10) e^2 fm^4$$

Revised transition strength

$$B(E2; 2_1^+ \rightarrow 0_1^+) = 9.2(3) e^2 fm^4$$

Ab-initio transition strength

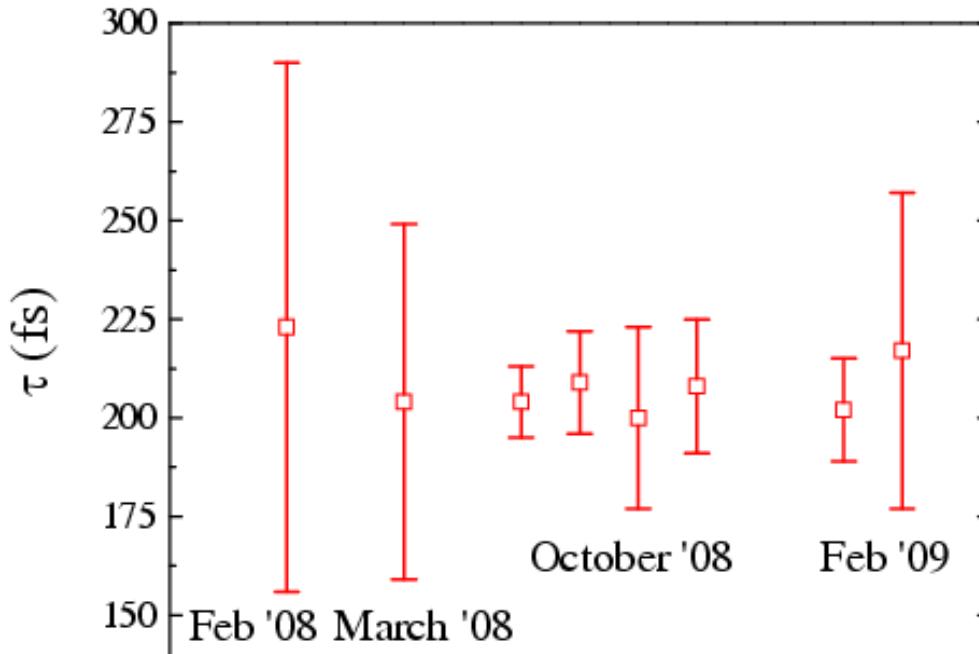
$$B(E2; 2_1^+ \rightarrow 0_1^+) = 8.8(2) e^2 fm^4$$

Second 2⁺ state

$$\tau = 59(10) fs$$

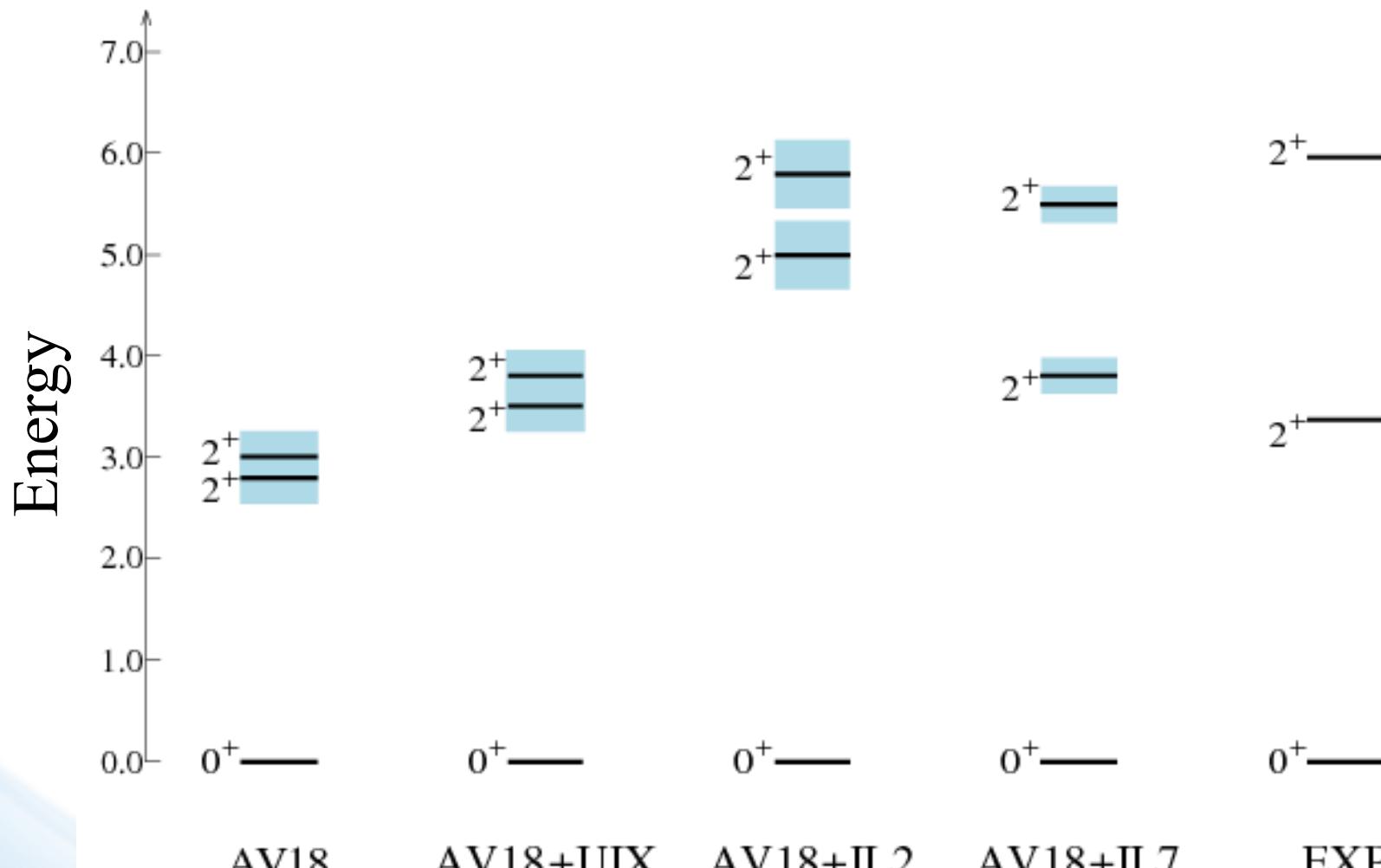
$$B(E2; 2_2^+ \rightarrow 0_1^+) = 0.11(2) e^2 fm^4$$

$$\tau = 205(\pm 5)_{stat} (\pm 7)_{sys} fs$$

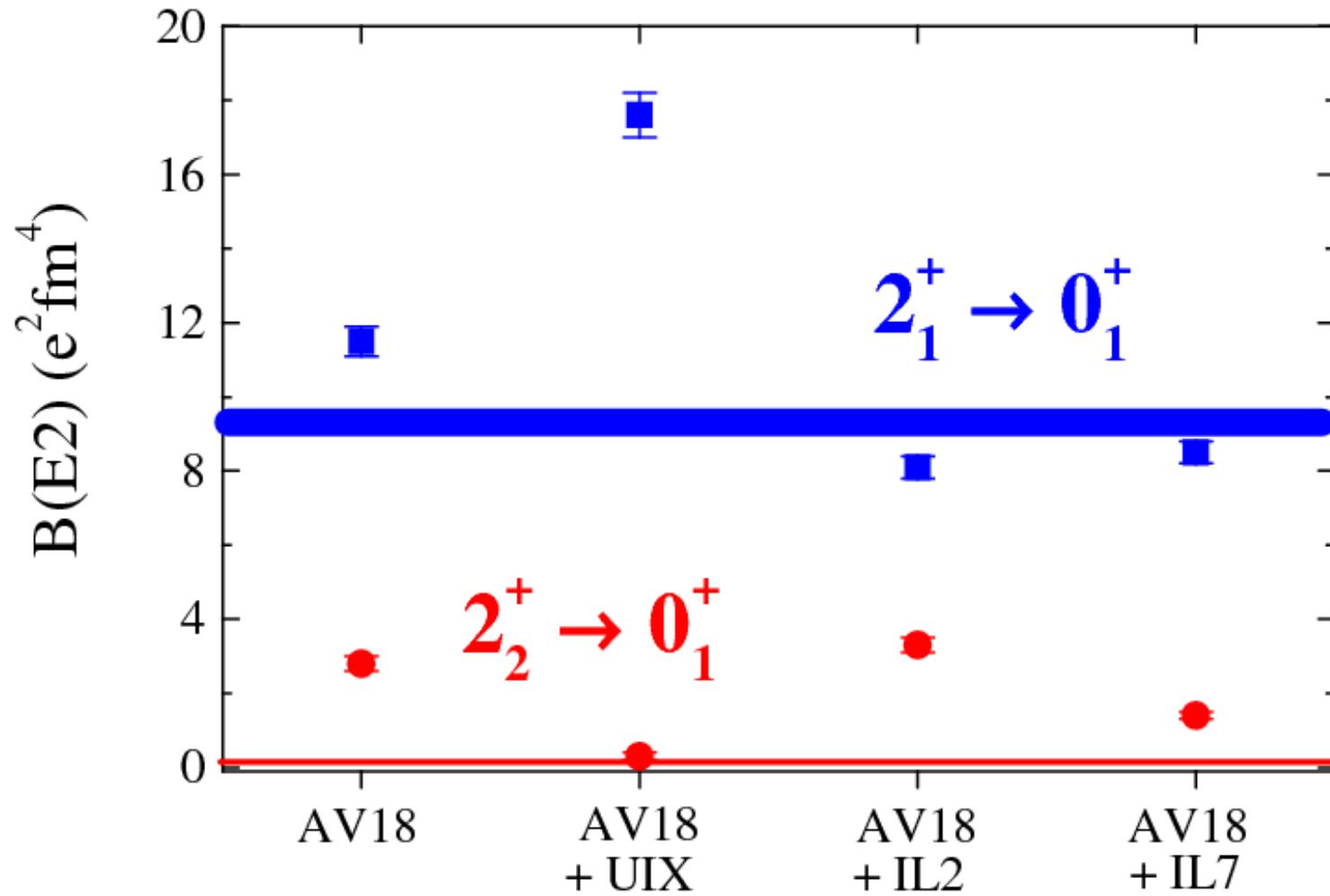


$$B(E2) \sim \frac{1}{\tau}$$

Comparison of different potentials



Comparison of different potentials



Conclusions

In Experiment

- Precise measurement of the first 2^+ state lifetime in ^{10}Be .
- Reliable <5% DSAM **IS** possible.

In Theory

- We have a powerful tool for investigating nuclear structure.
- Three body forces play a critical role: in determining total binding energy **AND** in the fine details of the wavefunctions.
- Electromagnetic transition rates **ARE** very discriminating!