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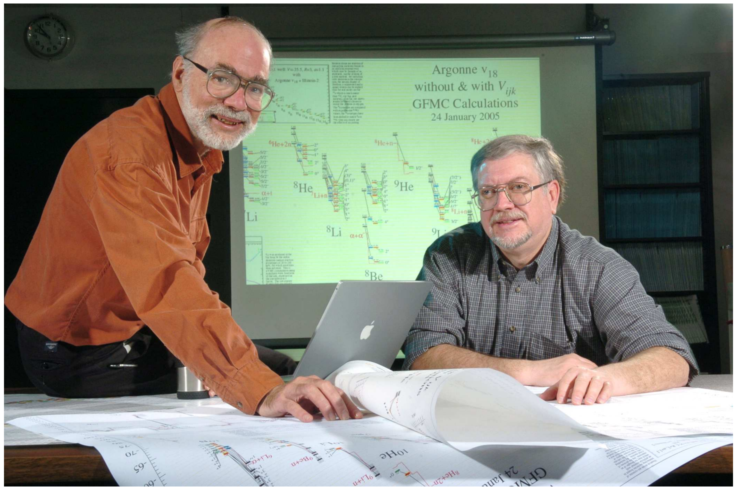
… for a brighter future

Tests of ab-initio shell models of light nuclei:

The special case of ^{10}Be

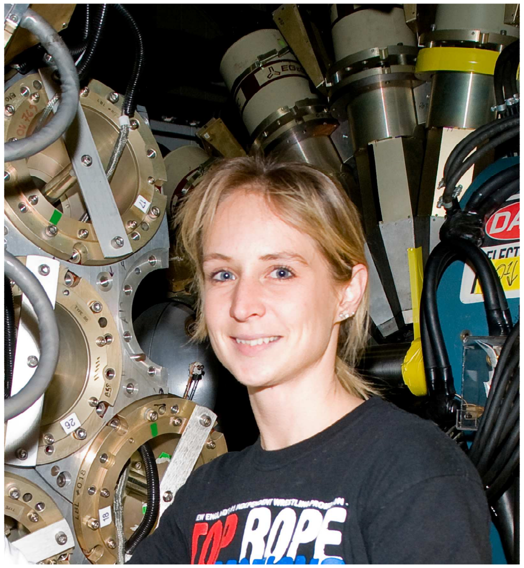


Steve Pieper

Bob Wiringa

C.J.(Kim) Lister
Lister@anl.gov

E.A. (Libby) McCutchan
McCutchan@phy.anl.gov



U.S. Department
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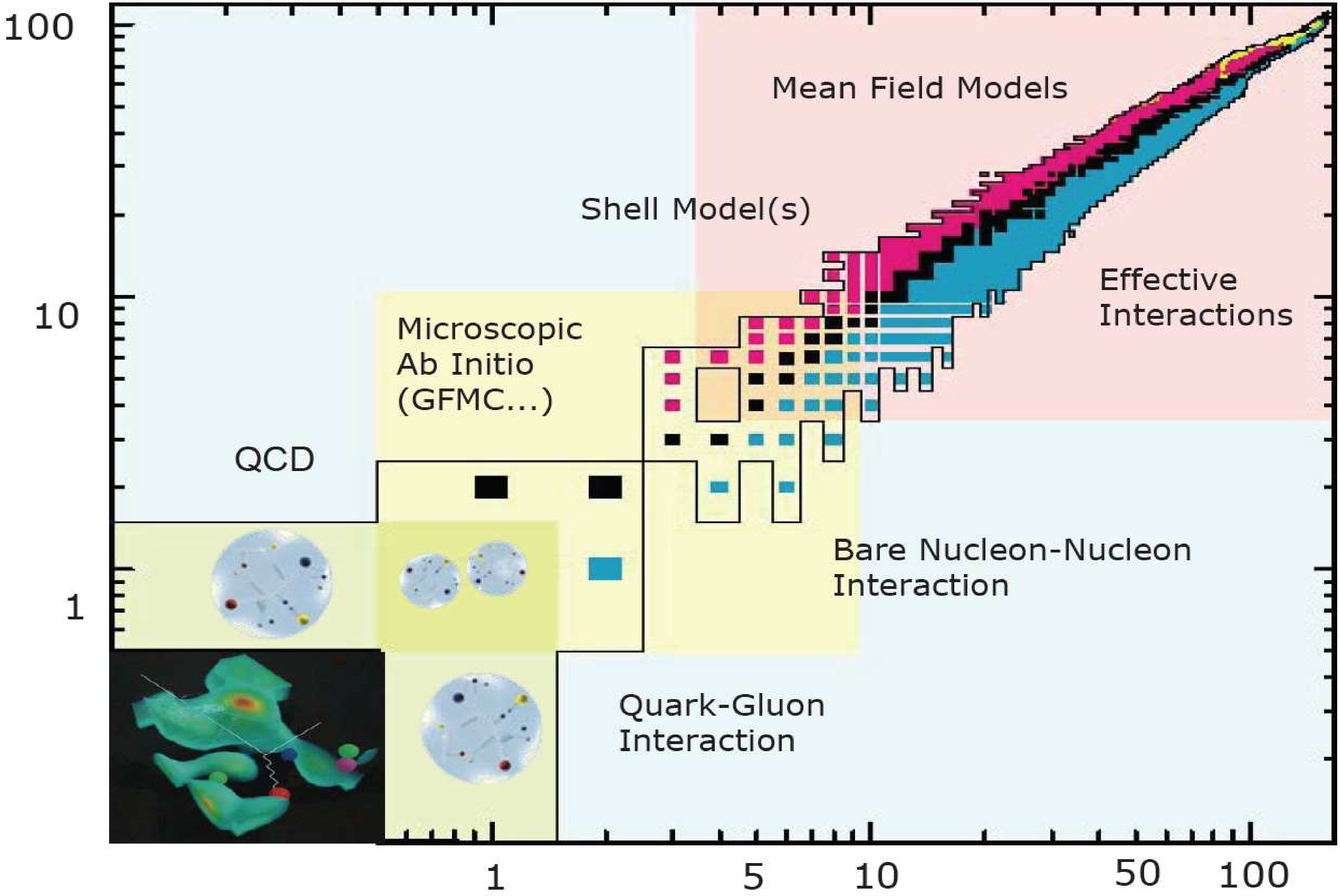
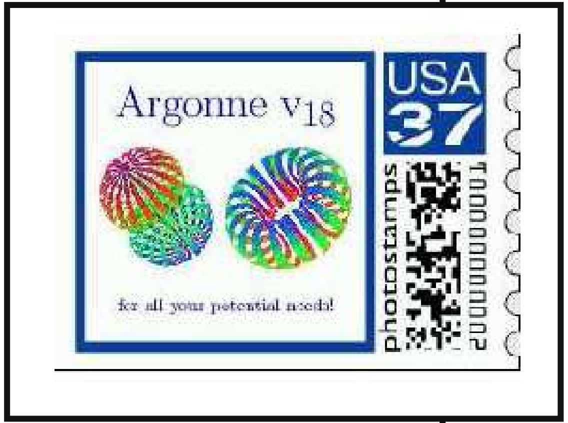
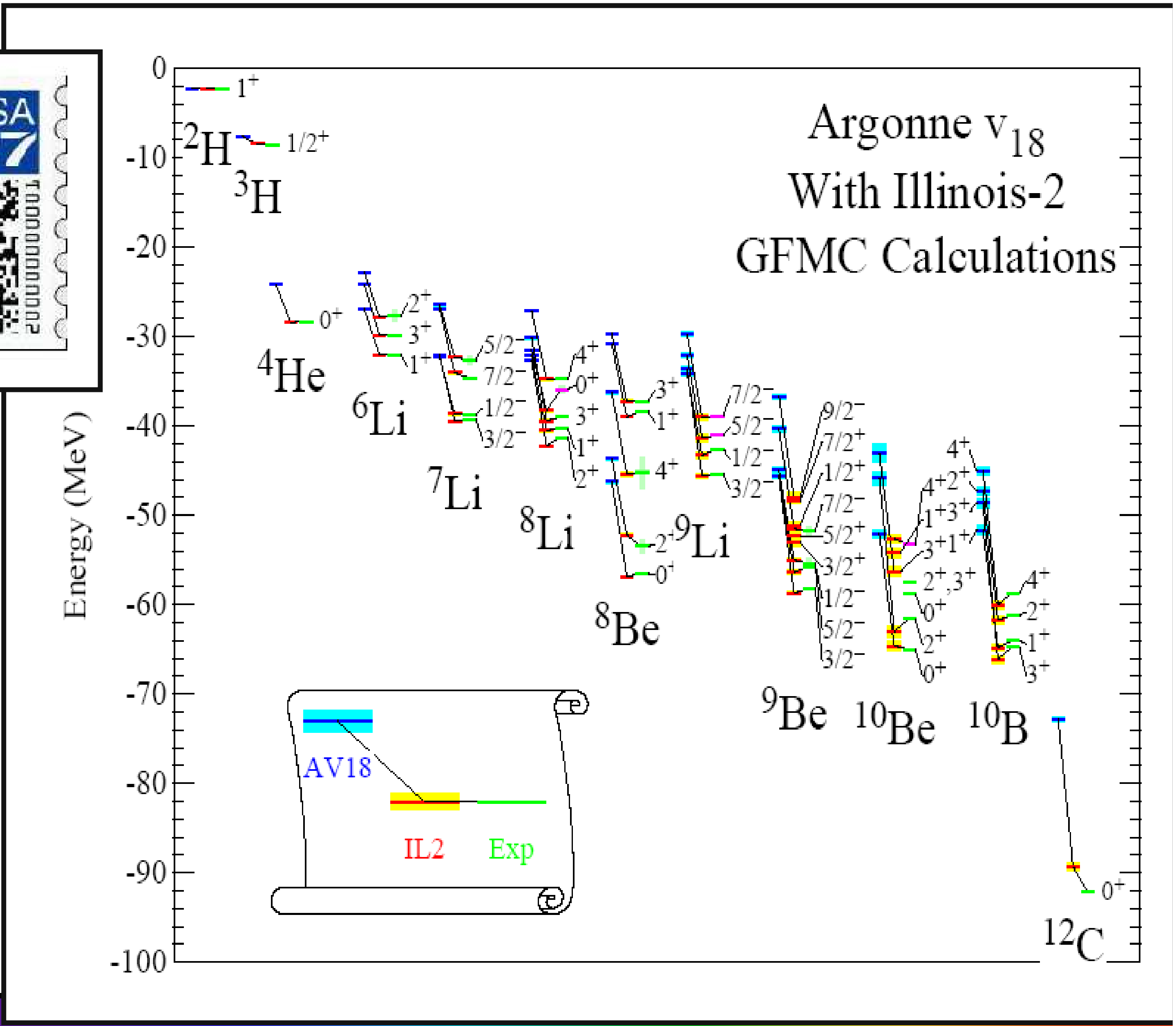
Our nuclear world



Ab-initio Greens Functional Monte Carlo Calculations





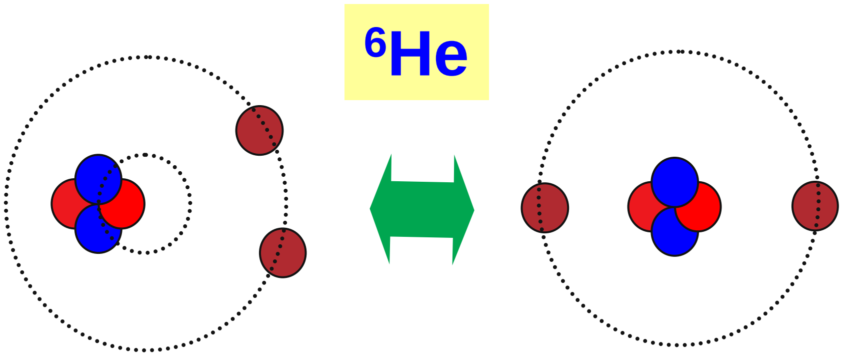
Pieper and Wiringa (ANL)

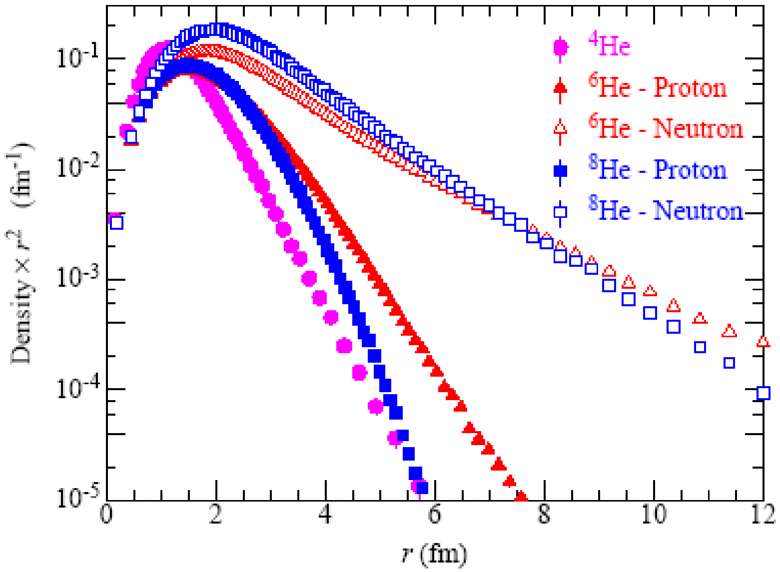
Described in

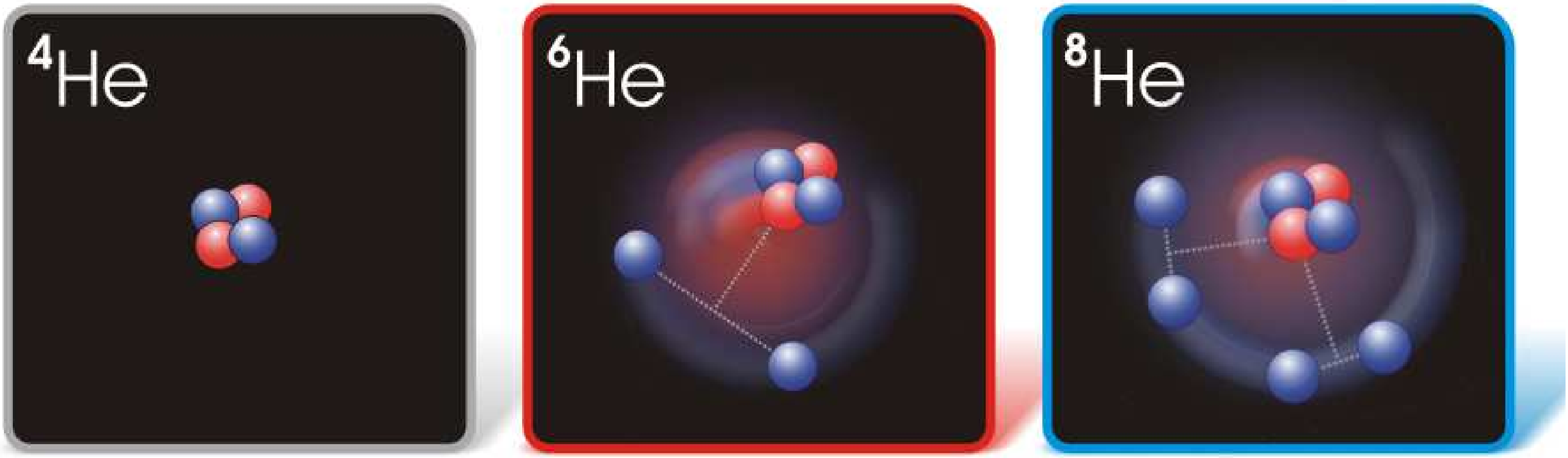
NP A751 516c (2005)

RMS Radii of ^{6,8}He

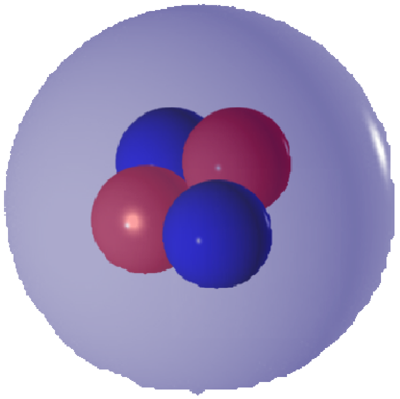
P.Mueller et. al (ANL)







Transfer Reactions



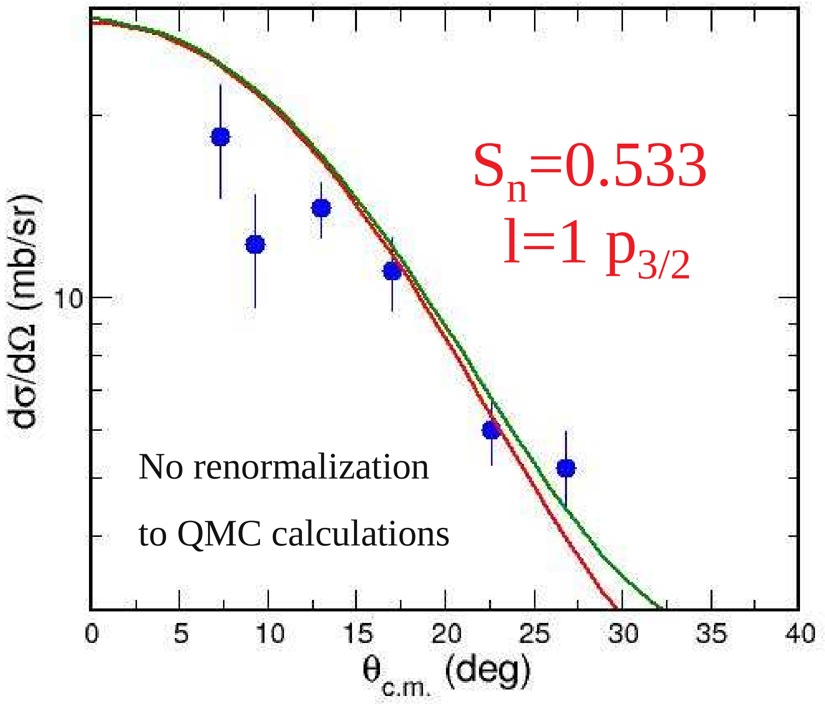
ANL-UWM Collaboration

A. H. Wuosmaa et. al. PRL94 082592 and PRC72 061301(R) 2005

Example: $^{6}He(d,p)^{7}He$

Issues: How reliable are calculations of unbound states?

Is there a low lying state below 1MeV?

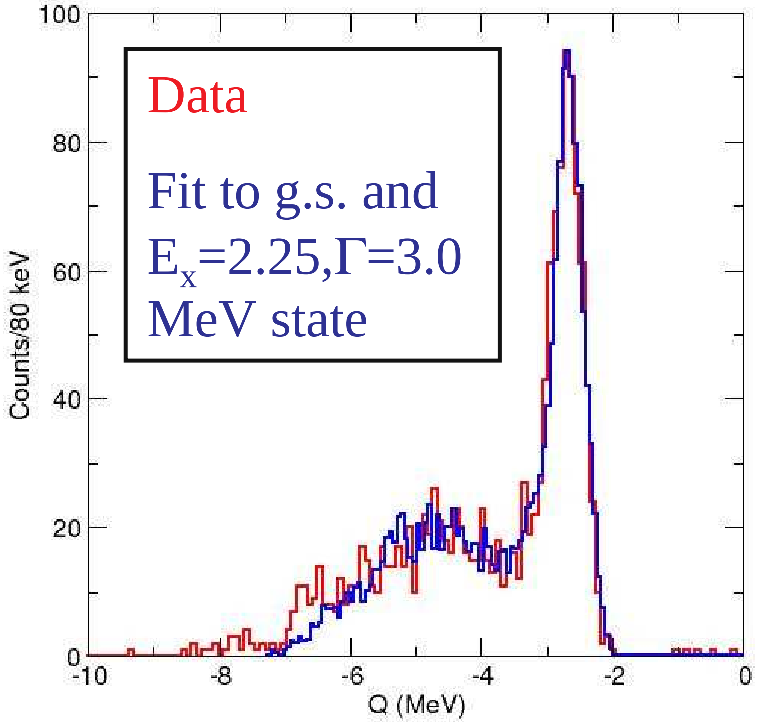


$S_n=0.533$

$l=1\ p_{3/2}$

No renormalization

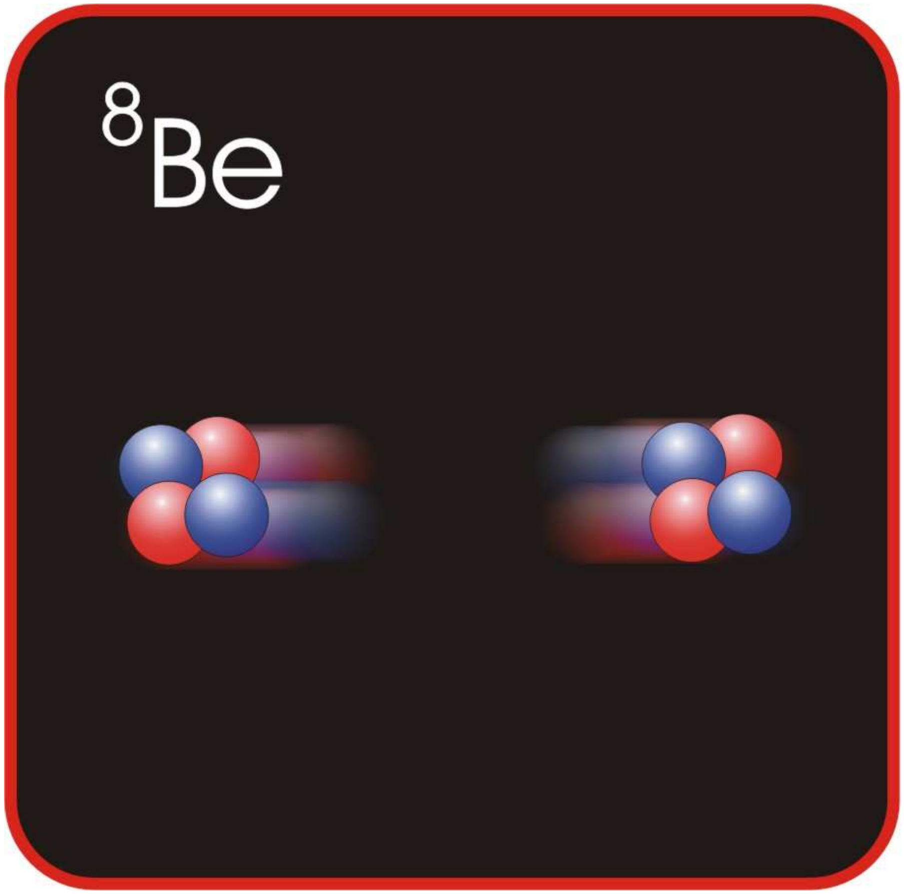
to QMC calculations

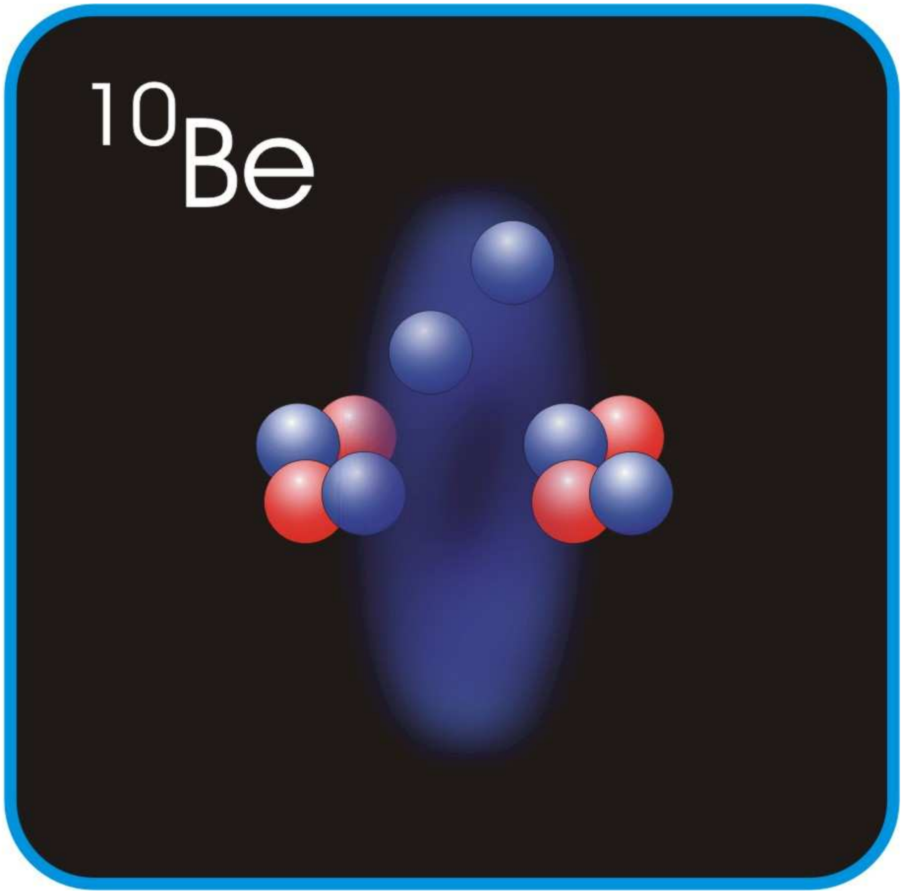


Data

Fit to g.s. and $E_x=2.25, \Gamma=3.0$ MeV state

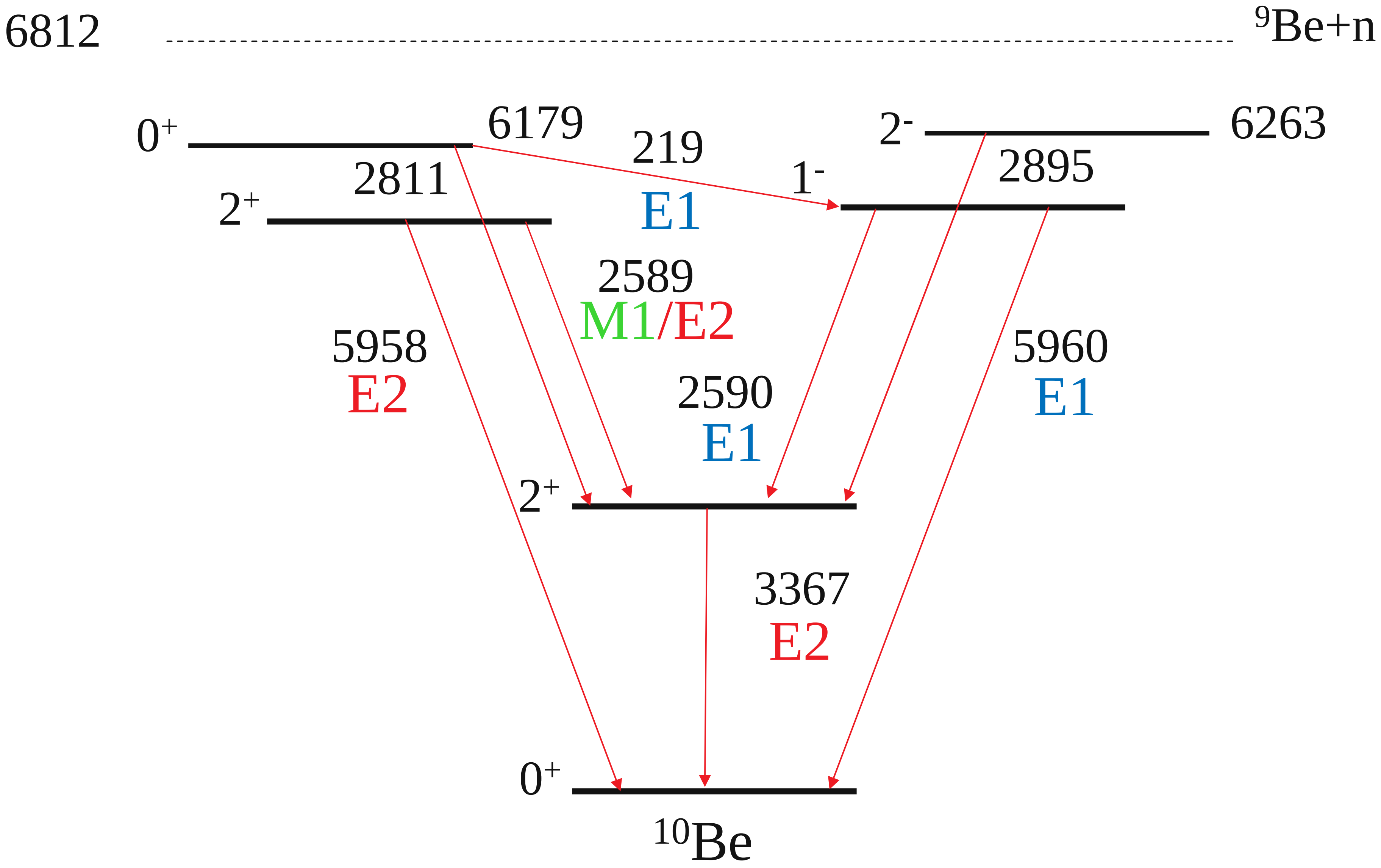
The Special case of ^{10}Be



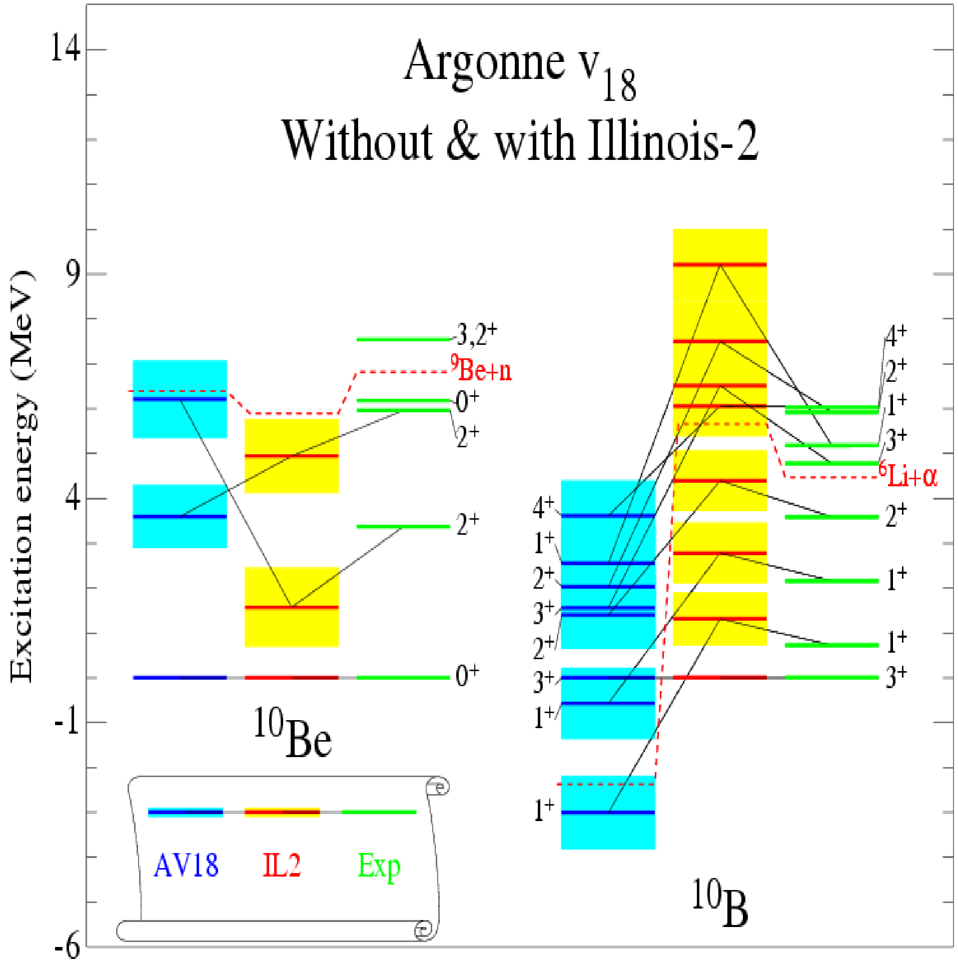


Key Issues: Microscopically, how do the neutrons really form a potential to bind the nucleus? Is it the same for all states?

The Bound States of ^{10}Be



A=10 nuclei provide a sensitive test of GFMC



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

Very sensitive to the effects of 3-body correlations.

^{10}Be Data Compilation

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

GFMC Theory

$$B(E2;2_1^+ \rightarrow 0_1^+) = 7.89(30)e^2\,fm^4$$

Q ≤ 0

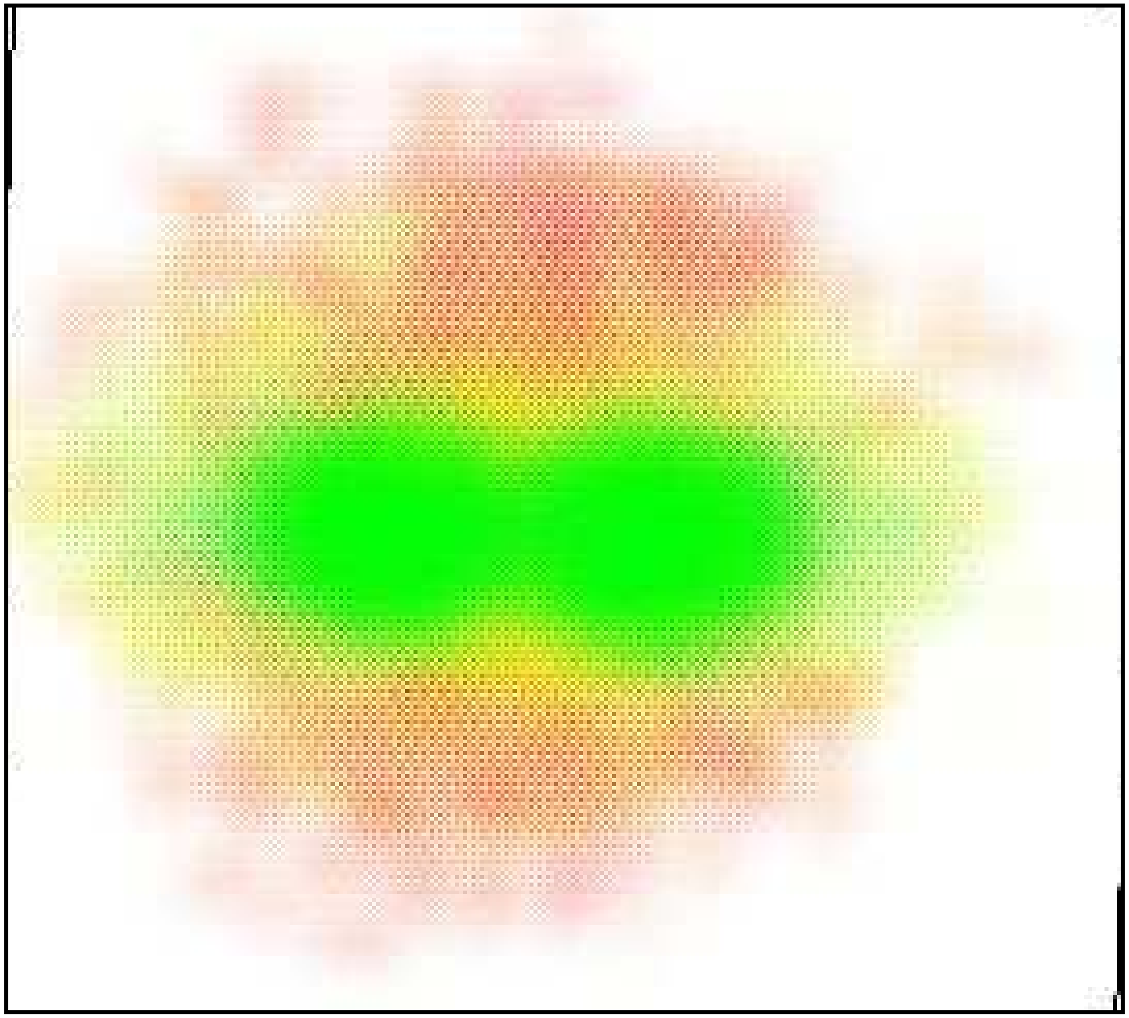
$$B(E2;2_2^+ \rightarrow 0_1^+) = 2.08(26)e^2\,fm^4$$

$$B(E2;2_2^+ \rightarrow 2_1^+) = 6.9(10)e^2\,fm^4$$

Q ≥ 0

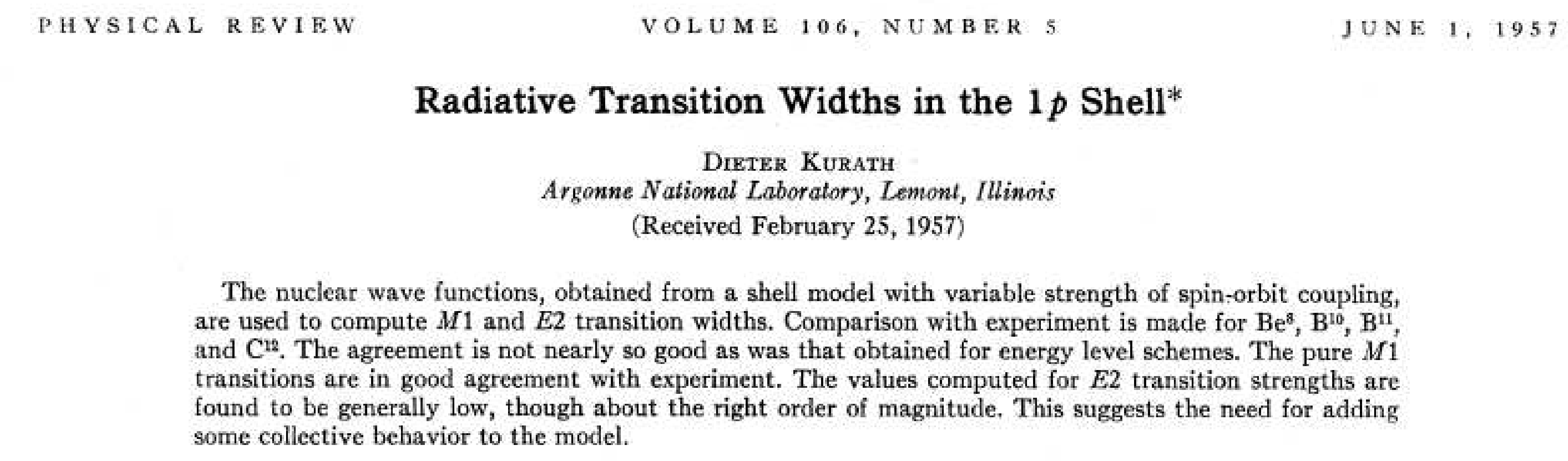
$$\boxed{R = \frac{B(E2:2_1 \rightarrow 0_1)}{B(E2:2_2 \rightarrow 0_1)} = 3.8}$$

The Ab-Initio projection of T=0 and T=1 density



Ken Nollett (ANL) and Brent Graner (UC)
visulization of ^{10}Be J=2_1 state (2008)

The Traditional Shell Model (1956+++)



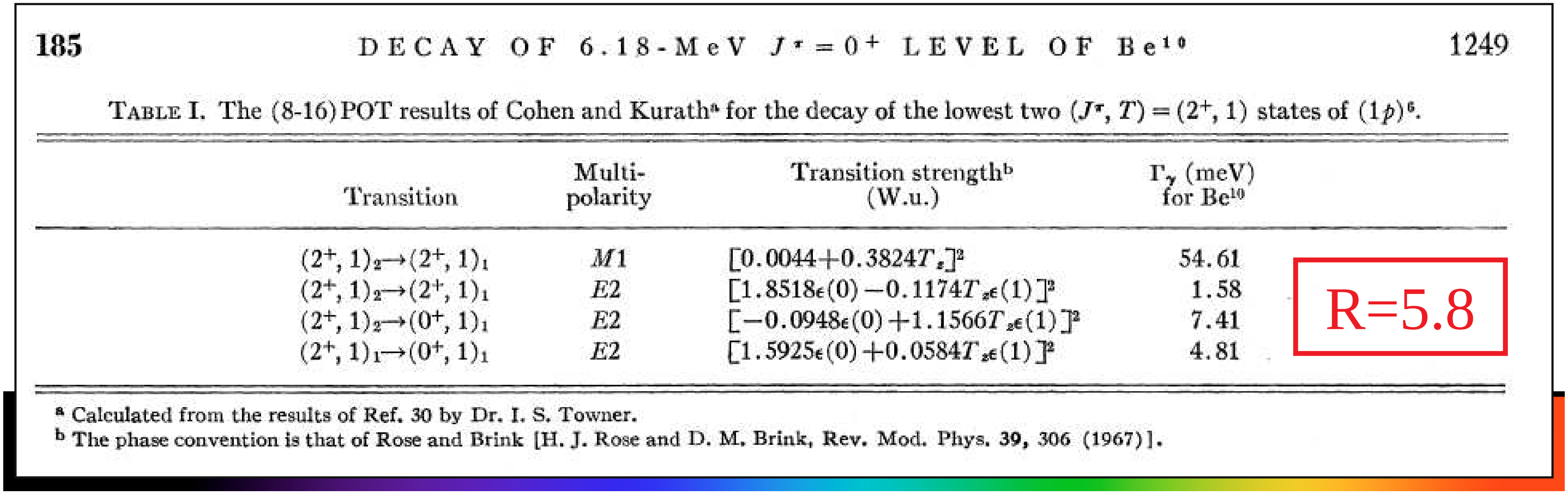
PHYSICAL REVIEW VOLUME 106, NUMBER 5 JUNE 1, 1957

Radiative Transition Widths in the 1*p* Shell*

DIETER KURATH
Argonne National Laboratory, Lemont, Illinois
(Received February 25, 1957)

The nuclear wave functions, obtained from a shell model with variable strength of spin-orbit coupling, are used to compute *M*1 and *E*2 transition widths. Comparison with experiment is made for Be^8, B^{10}, B^{11}, and C^{12}. The agreement is not nearly so good as was that obtained for energy level schemes. The pure *M*1 transitions are in good agreement with experiment. The values computed for *E*2 transition strengths are found to be generally low, though about the right order of magnitude. This suggests the need for adding some collective behavior to the model.

Kurath, Cohen and Kurath, Millener and Kurath, Millener and Warburton



185 DECAY OF 6.18-MeV $J^\pi = 0^+$ LEVEL OF Be^{10} 1249

TABLE I. The (8-16)POT results of Cohen and Kurath[a] for the decay of the lowest two $(J^\pi, T) = (2^+, 1)$ states of $(1p)^6$.

Transition	Multi-polarity	Transition strength[b] (W.u.)	Γ_γ (meV) for Be^{10}
$(2^+, 1)_2 \rightarrow (2^+, 1)_1$	*M*1	$[0.0044+0.3824T_z]^2$	54.61
$(2^+, 1)_2 \rightarrow (2^+, 1)_1$	*E*2	$[1.8518\epsilon(0)-0.1174T_{z\epsilon}(1)]^2$	1.58
$(2^+, 1)_2 \rightarrow (0^+, 1)_1$	*E*2	$[-0.0948\epsilon(0)+1.1566T_{z\epsilon}(1)]^2$	7.41
$(2^+, 1)_1 \rightarrow (0^+, 1)_1$	*E*2	$[1.5925\epsilon(0)+0.0584T_{z\epsilon}(1)]^2$	4.81

[a] Calculated from the results of Ref. 30 by Dr. I. S. Towner.
[b] The phase convention is that of Rose and Brink [H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967)].

R=5.8

Previously measured DSAM $J=2_1$ lifetime in ^{10}Be

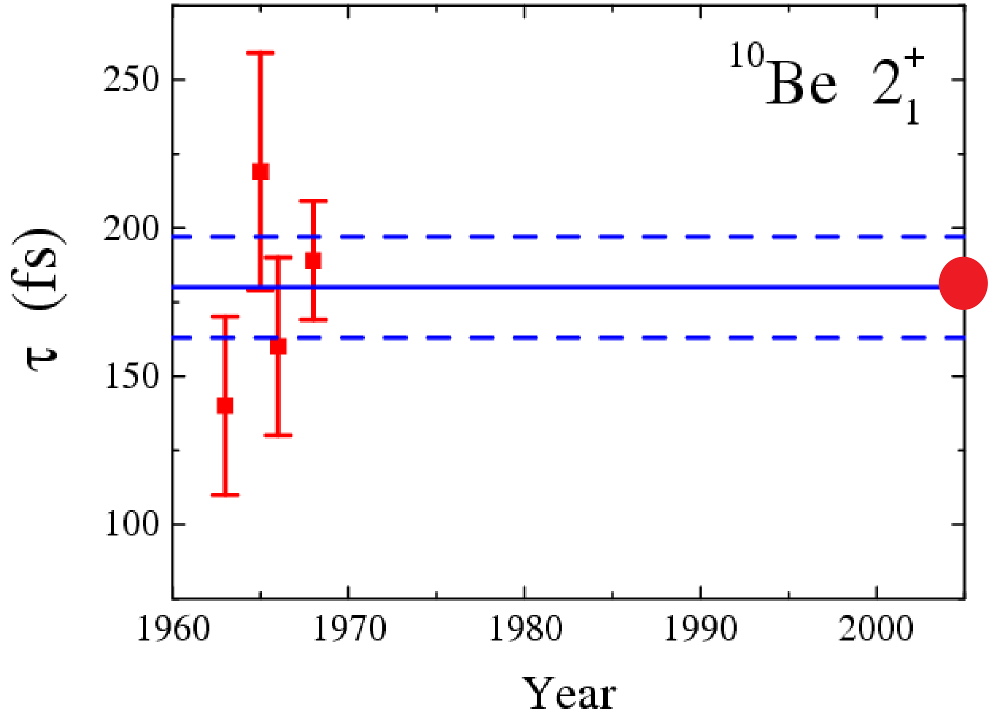
Systematic problems of:-

- Initial recoil velocity ill-defined
- Stopping powers poorly known
- Very slow recoils
- State feeding poorly known
- Detector angle poorly defined

At the time these measurements WERE cutting edge and providec discriminating tests of the (new) intermediate-coupling shell model (Kurath et al 1958) .

But now we need better!

Evaluated τ = 180(18) fs
All DSAM measurements



E.K. Warburton *et al.*, Phys. Rev. **129**, 2180 (1963).

G.C. Morrison *et al.*, - unpublished (1965).

E.K. Warburton *et al.*, Phys. Rev. **148**, 1072 (1966).

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

^{10}Be : A popular nucleus

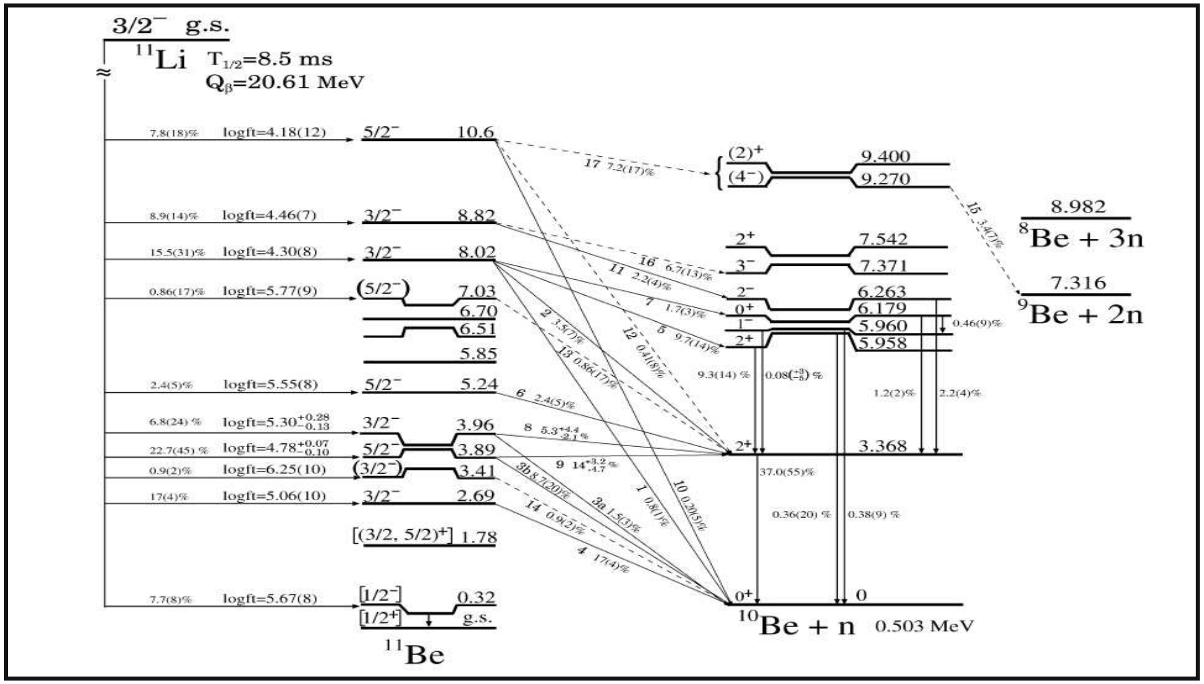
Author	Calc.	$B(E2;2_1^+ \rightarrow 0_1^+)$ (e^{2}fm^4)	$B(E2;2_2^+ \rightarrow 0_1^+)$ (e^{2}fm^4)	Ratio
Okabe	MO	11.26	0.44	25.6
Caurier	NCSM	6.58	0.13	49.5
Itagaki	TMO	11.8	0.70	16.9
Navratil	NCSM	5.4	0.17	32.7
Arai	MCM	4.8	0.10	48.0
Wiringa	GFMC	7.89(30)	2.08(26)	3.8
EXPT		10.5(1.0)	??	??

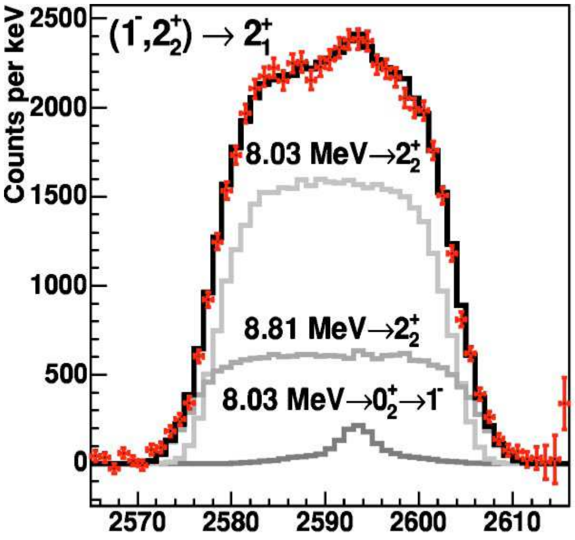
MO : Molecular orbit model, N. Itagaki and S. Okabe, Phys. Rev. C **61**, 044306 (2000).
NCSM : No-core shell model, E. Caurier *et al.*, Phys. Rev. C **66**, 024314 (2002).
TMO : Triaxial Molecular Orbital, N. Itagaki *et al.*, Phys. Rev. C **65**, 044302 (2002).
MCM : Microscopic cluster model, K. Arai, Phys. Rev. C **69**, 014309 (2004).
GFMC : Greens Functional Monte Carlo, R. Wiringa and S. Pierper *et al.*, Private Communication.

^{11}Li β-delayed 1-n emission

Line shape depends on

- Energies and intensities of all neutron branches feeding the level
- Lifetime of the level
- Angular correlation between gamma ray and neutron

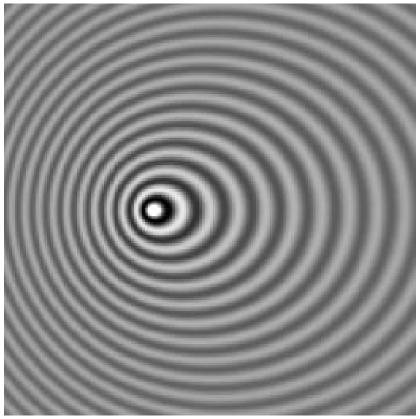




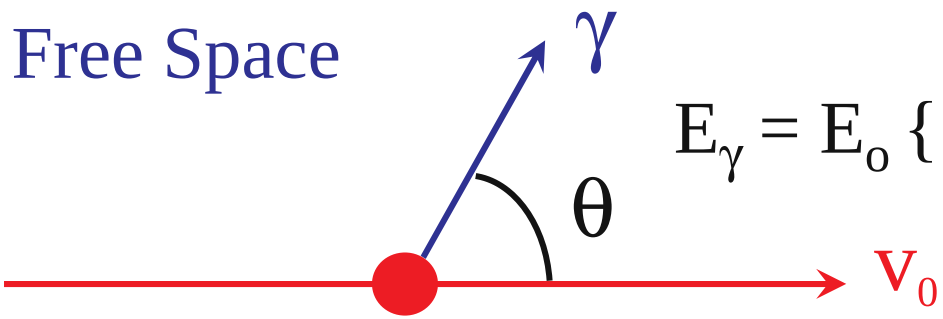
Y. Hirayama *et. al*. Phys Lets **B611** 239 (2005)…..polarized β-decay at ISAC/TRIUMF (high stats)

F. Sarazin *et al*., Phys. Rev. C **70**, 031302(R) (2004)….β-decay at ISAC / TRIUMF

The Doppler Shift Attenuation Method

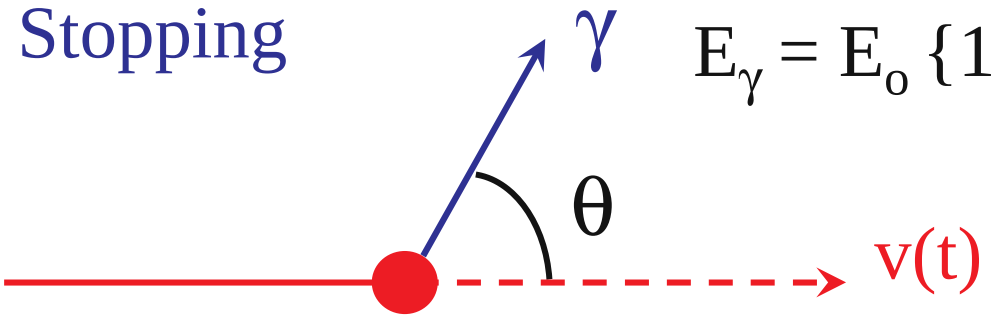


Free Space

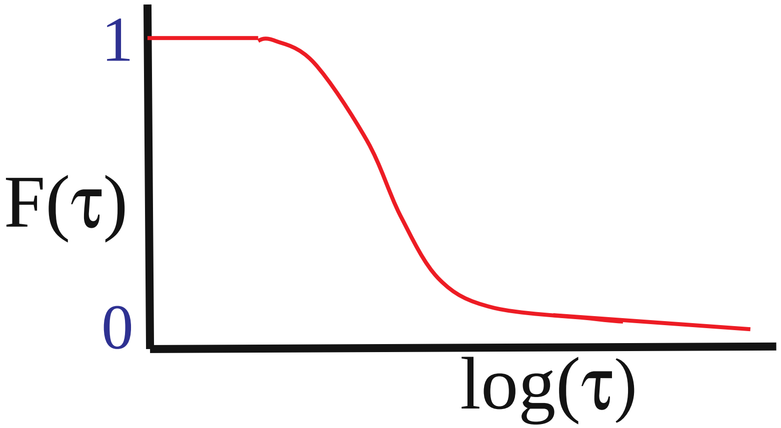


$$E_\gamma = E_o\,\{1 + (v_0/c)\mathrm{Cos}\theta\}$$

Stopping

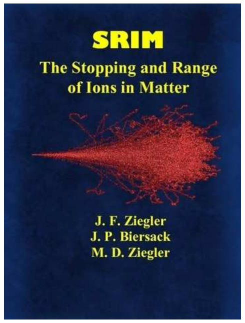


$$E_\gamma = E_o\,\{1 + F(t)\mathrm{Cos}\theta\}$$



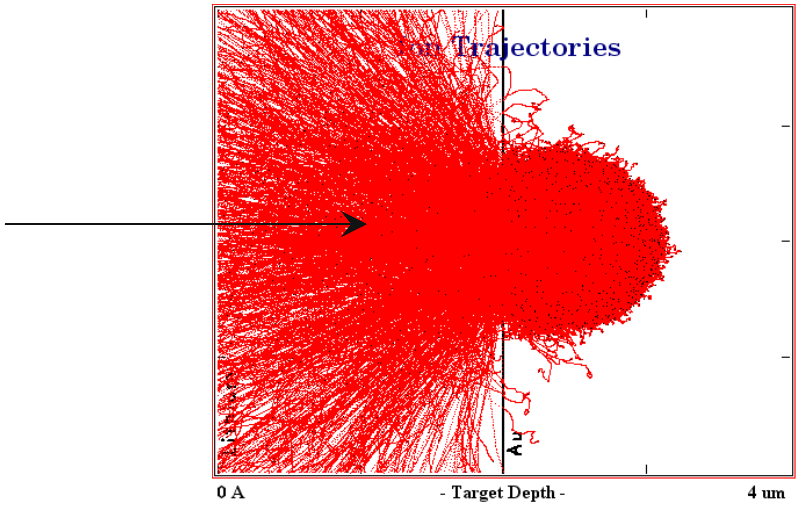
Actually, recoils are sufficiently swift (v/c ~6%) that 2nd order relativistic is correction needed

What SRIM shows us

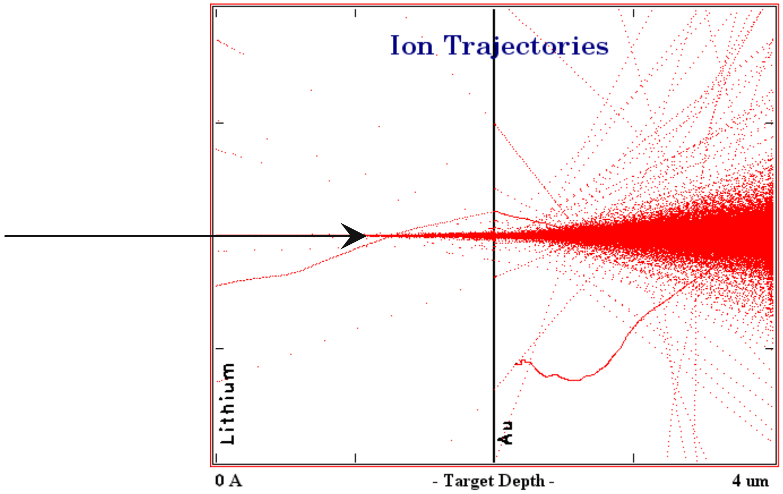


SRIM
The Stopping and Range
of Ions in Matter

J. F. Ziegler
J. P. Biersack
M. D. Ziegler



SLOW Ions…. 1 MeV ^{10}Be in 100µg/cm^2 Li on 6mg/cm^2 Au



FAST Ions…. 15 MeV ^{10}Be in 100µg/cm^2 Li on 6mg/cm^2 Au

(99.99% electronic stopping)

J.F. Ziegler, J.P. Biersack and M.D. Ziegler http://www.srim.org

DSAM*

E.A. McCutchan et. al. (ANL)

DSAM done properly:-

2-body kinematics

High recoil velocity

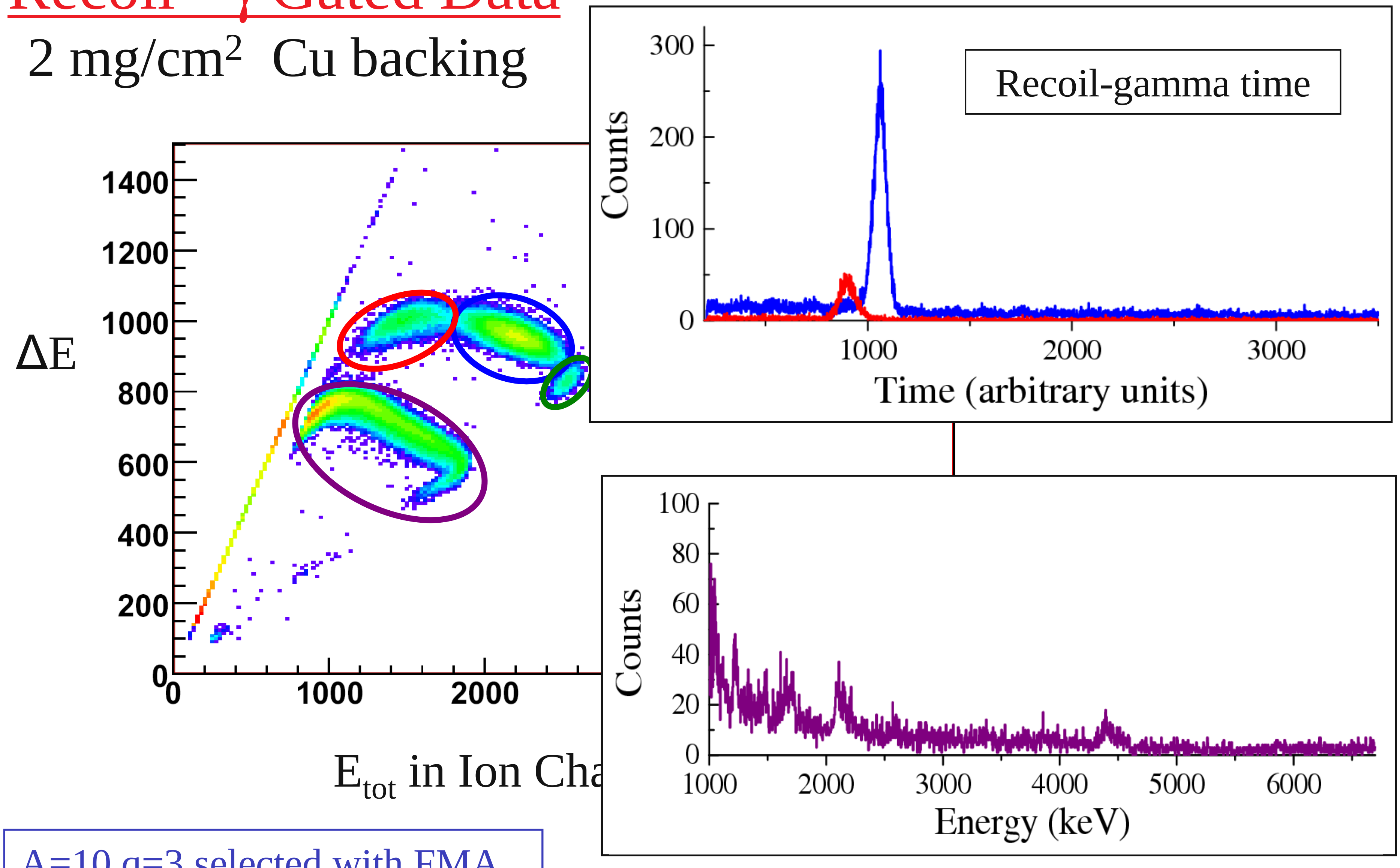
Well defined recoil direction

Well defined gamma direction

Control of state population

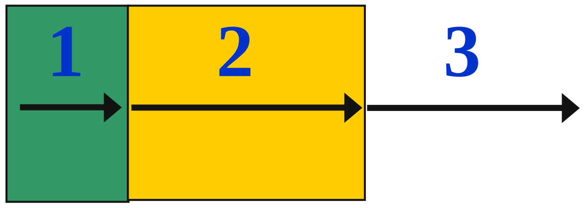
Recoil - γ Gated Data

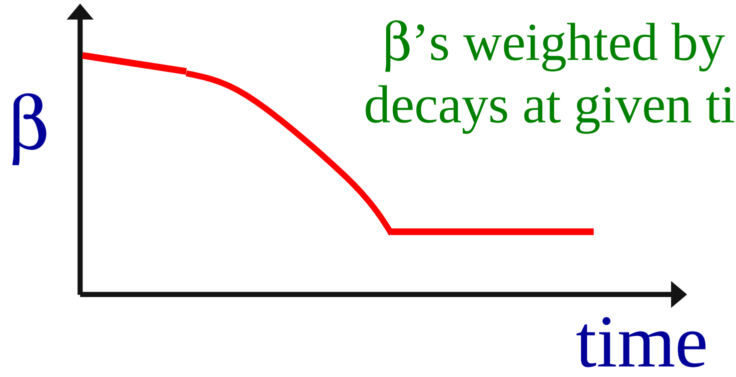
2 mg/cm^2 Cu backing



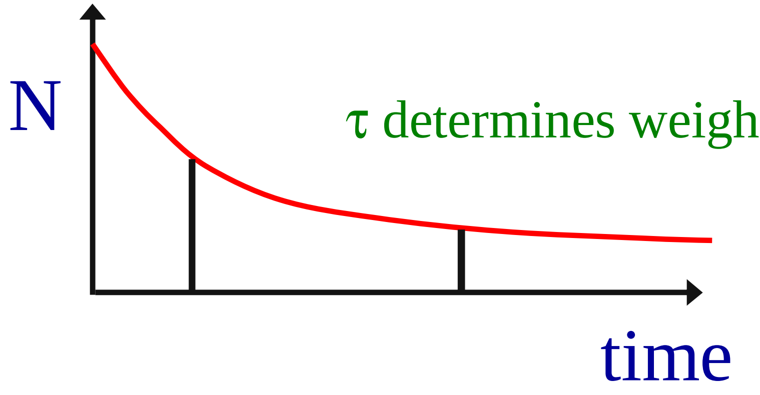
A=10 q=3 selected with FMA

Extracting the lifetime from mean β



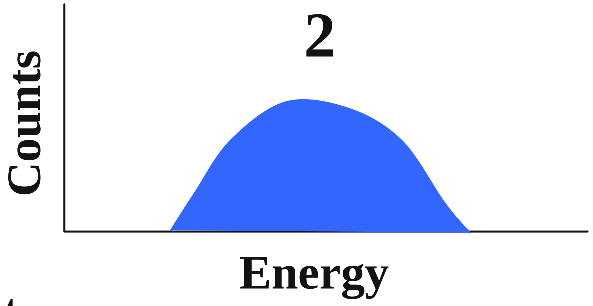


β's weighted by # of decays at given time t



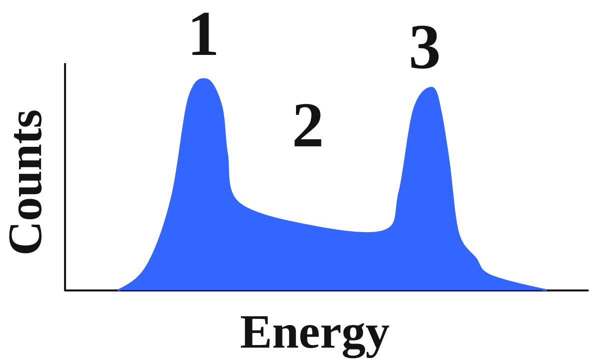
τ determines weight

Ideally you want all decays in the stopping material

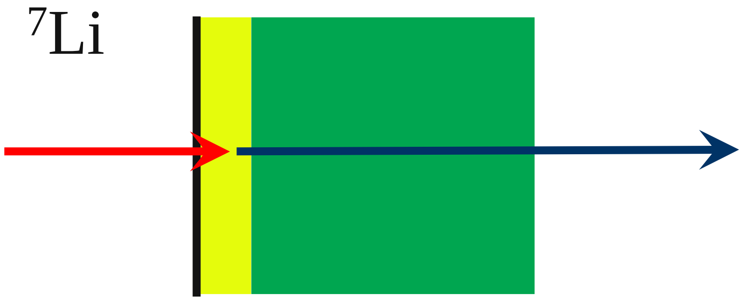


But…

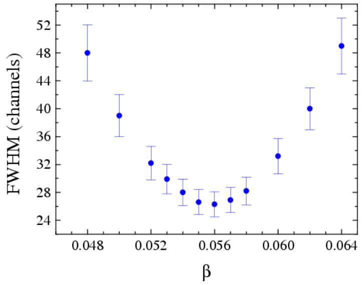
- Need some finite thickness of production material
- Need nuclei to recoil out of target



Results (1): First excited State with $J^{\pi}=2^{+}$ at 3367 keV

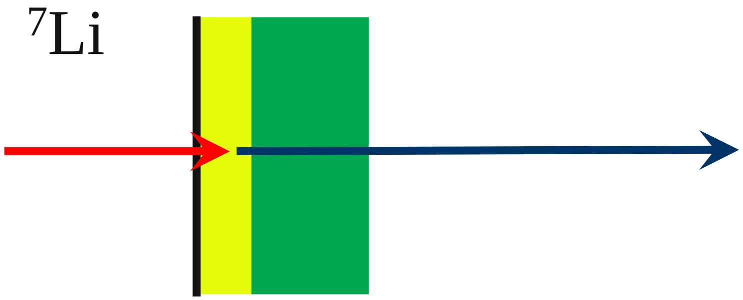


66µg/cm^2 ^{7}Li on 6.95mg/cm^2 Au

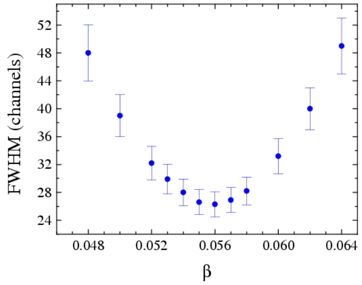


$\beta = 0.0525(5)$

$\tau = 245(35)\text{fs}$

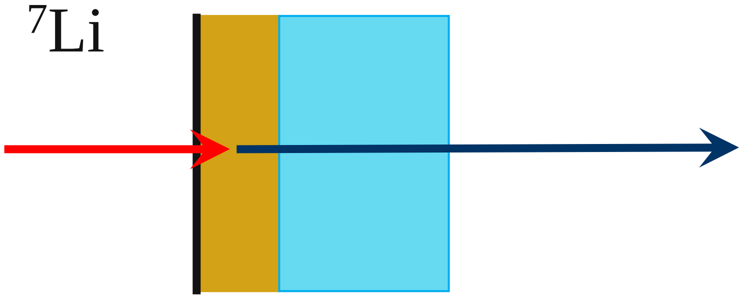


115µg/cm^2 ^{7}Li on 2.69mg/cm^2 Au

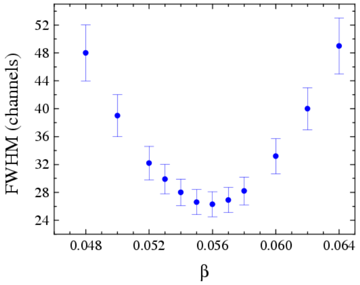


$\beta = 0.0560(5)$

$\tau = 290(^{+200}_{-100})\text{fs}$



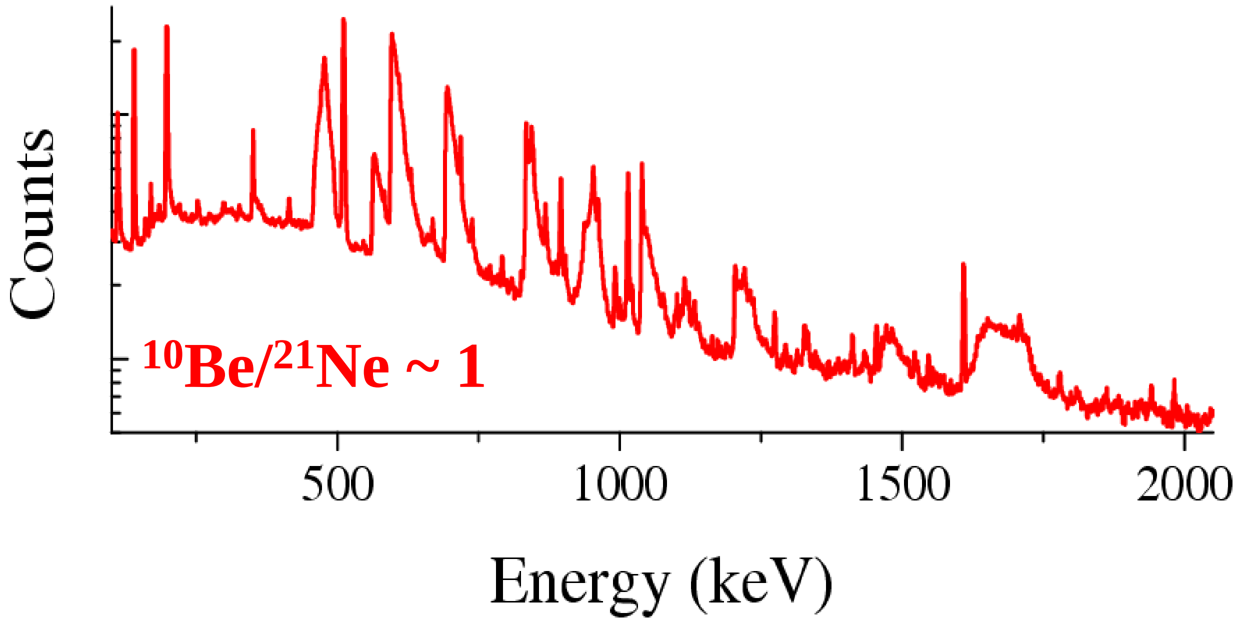
288µg/cm^2 ^{7}LiF$_2$ on 2.48mg/cm^2 Cu

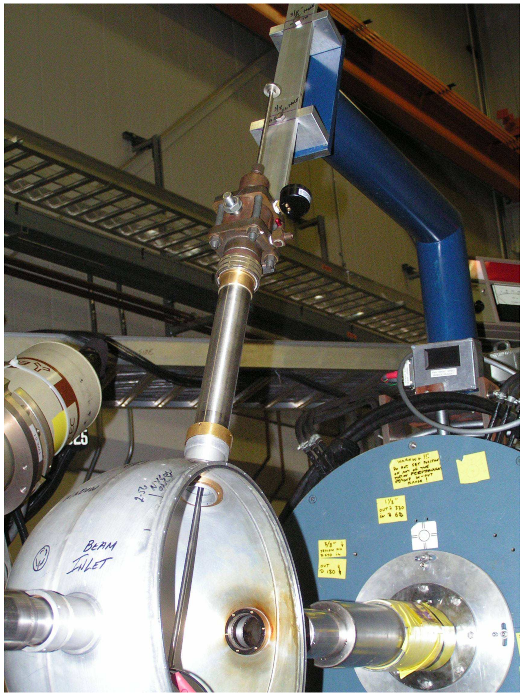


$\beta = 0.0535(5)$

$\tau = 270(^{+100}_{-60})\text{fs}$

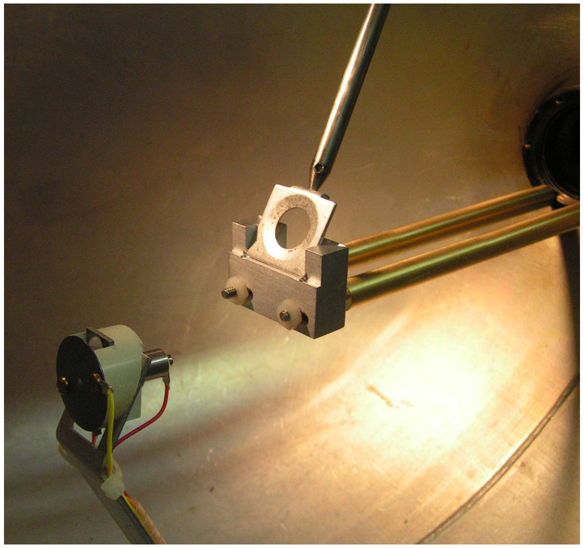
Target Oxidation Issues





Lithium is volatile and oxidizes easily. A new vacuum interlock was developed to move from the evaporator to Gammasphere at $\sim 10^{-5}$ torr.

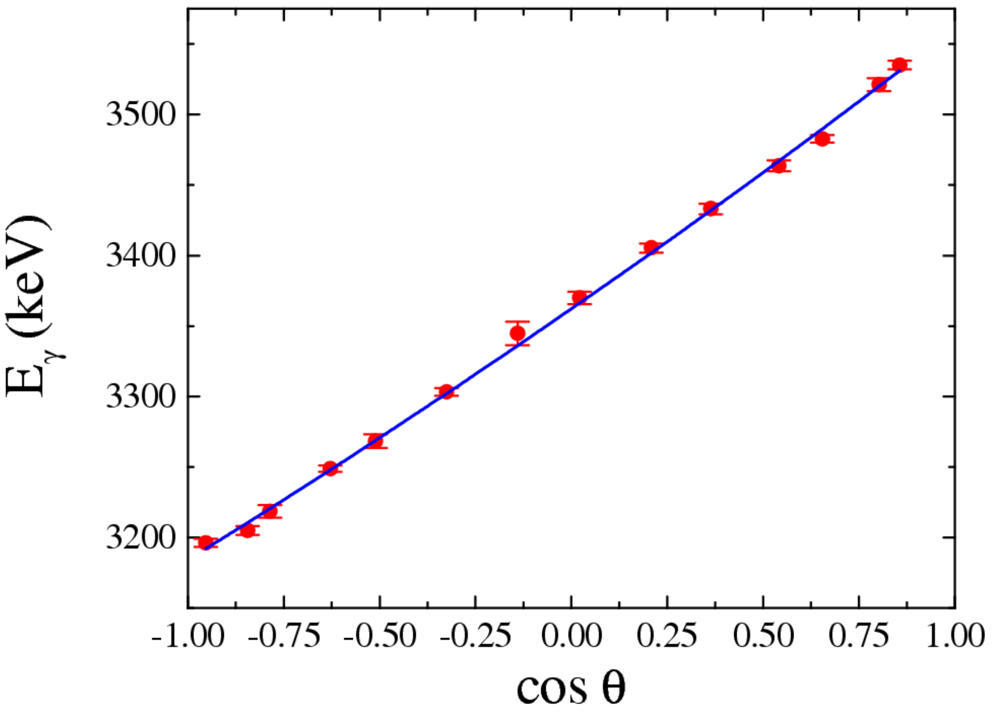
This reduced the contamination by a factor 10. With better vacuum, we expect another factor 10

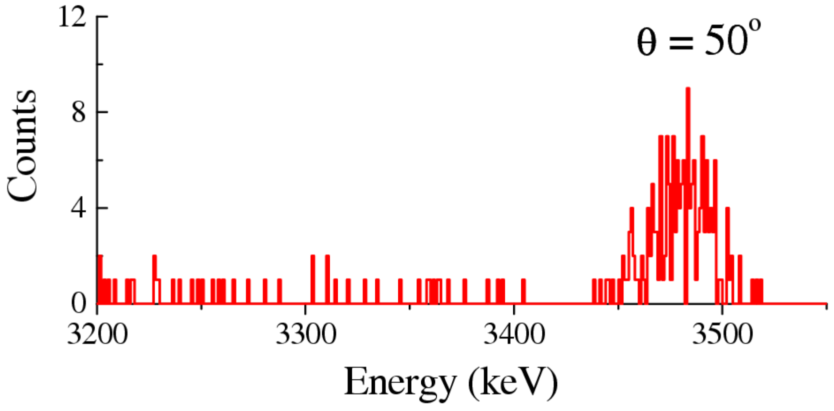


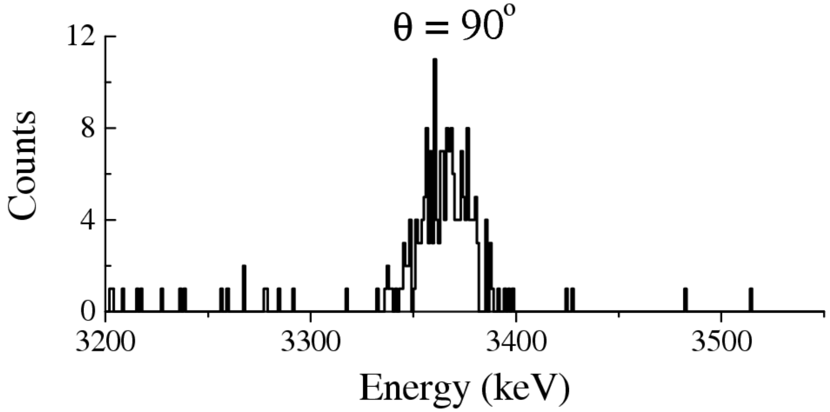
Traditional DSAM analysis……and GS alignment

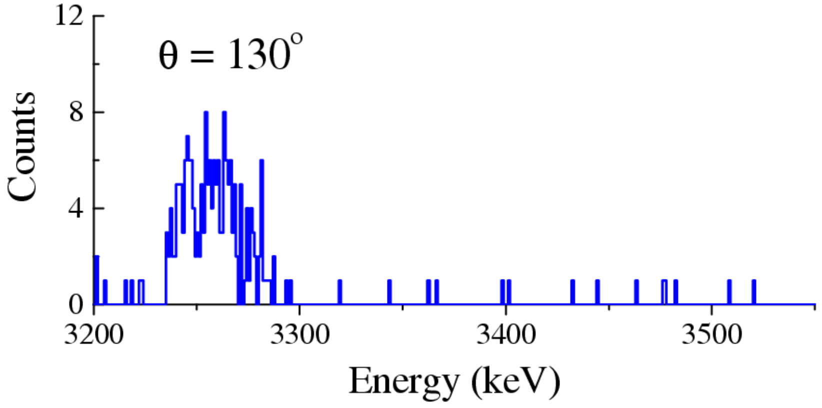
$$E_\gamma = E_o\left(\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}\right)$$

100 μg/cm² ⁷Li on 2.33 mg/cm² Au

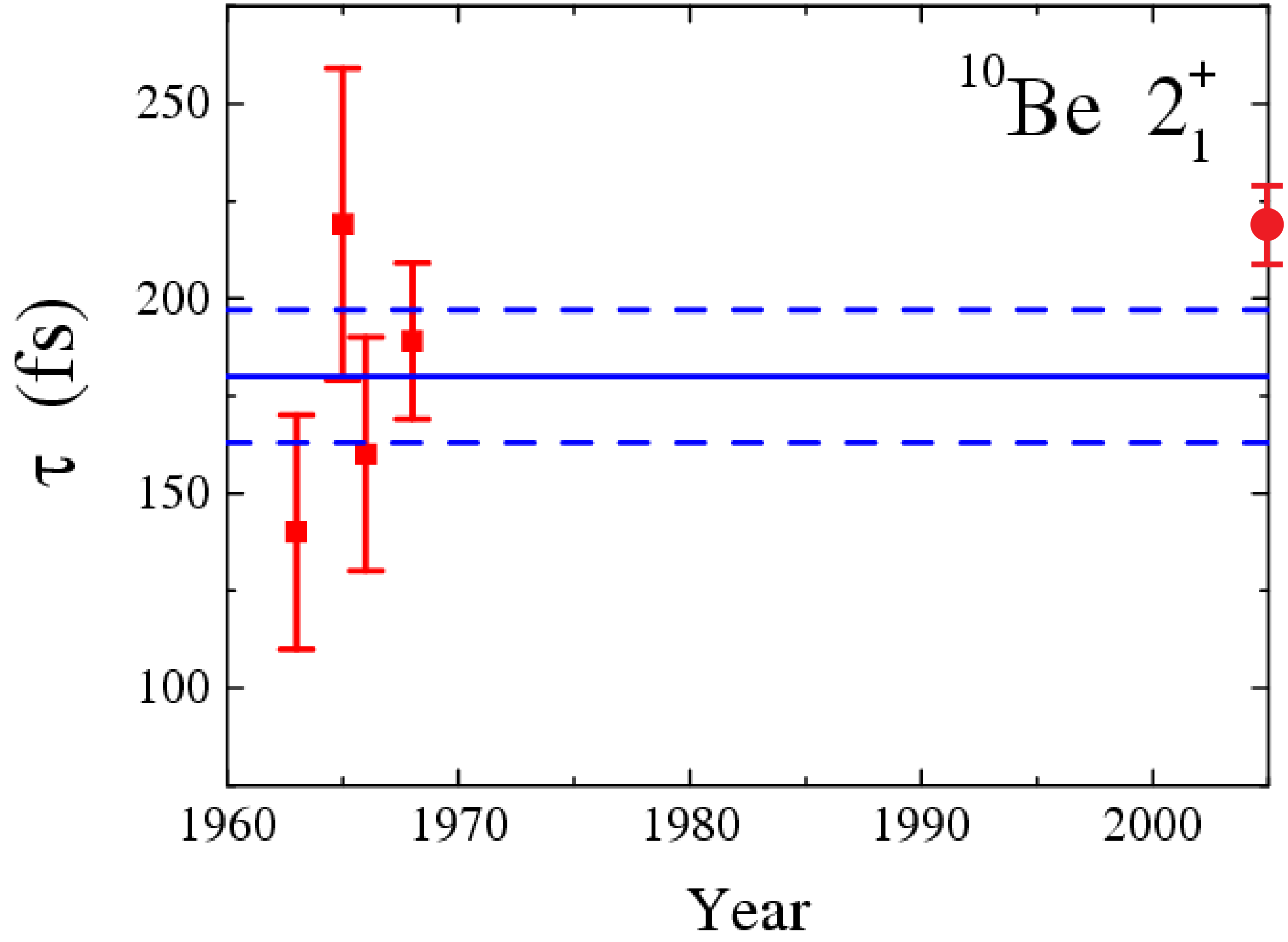








Results so far for 3369keV J=2 state



First J = 2^+ state in ^{10}Be

NNDC transition strength

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

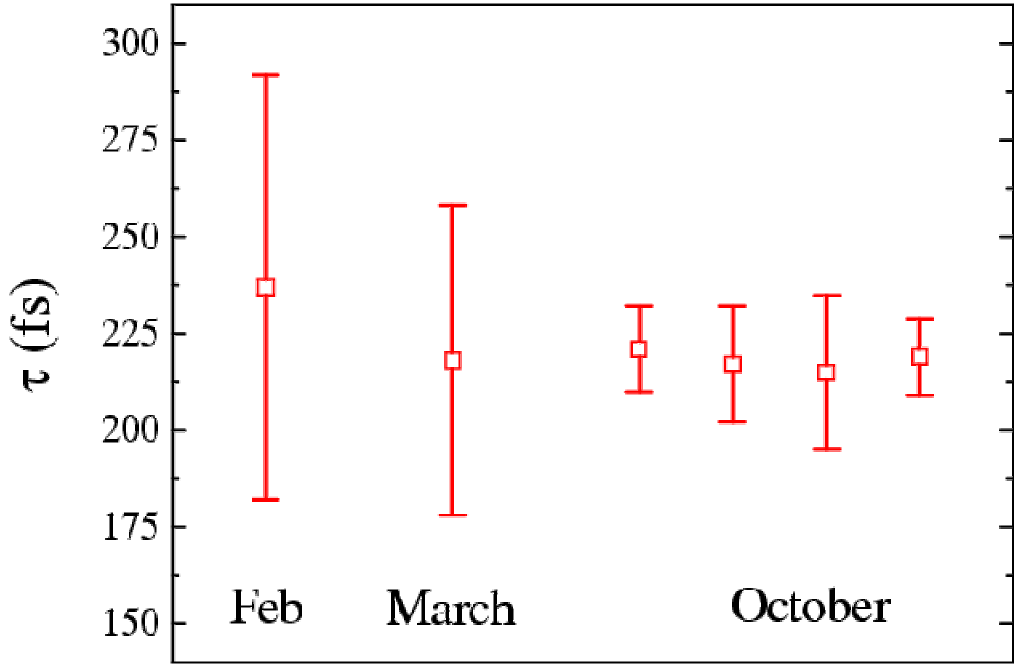
Revised transition strength

$$B(E2;2_1^+ \rightarrow 0_1^+) = 8.7(3)e^2\,fm^4$$

Ab-initio transition strength

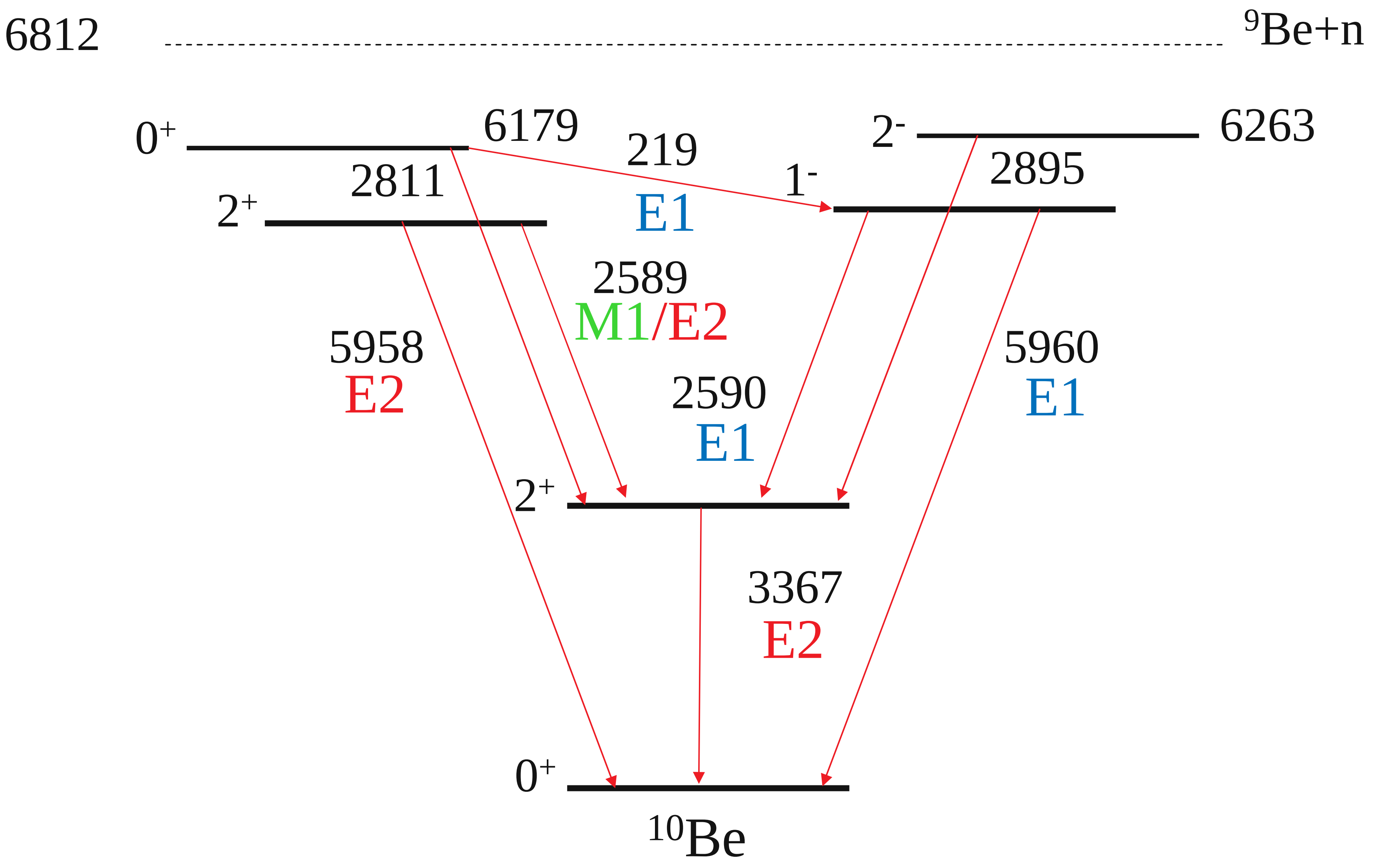
$$B(E2;2_1^+ \rightarrow 0_1^+) = 7.89(30)e^2\,fm^4$$

$$\boxed{\tau = 217(\pm 7)_{stat}(\pm ??)_{sys}}$$

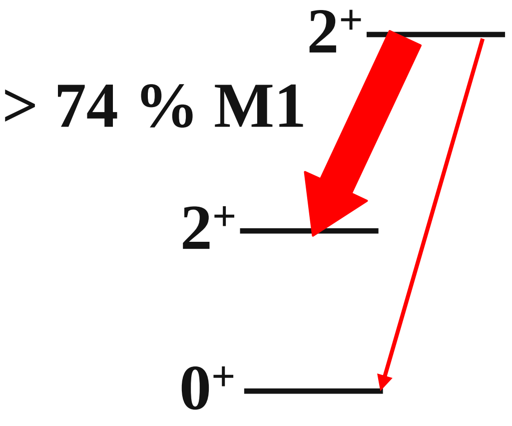


Theory seems pretty darn good at calculating E2 strengths

The Bound States of ^{10}Be



Decay of the second 2^+ state



2^+

> 74 % M1

2^+

0^+

$|\delta| < 0.60$

M.L. Roush *et al*., Nucl. Phys. **A128**, 401 (1969).

$2_2^+ \rightarrow 2_1^+$	>90	$90(3)\%$
$2_2^+ \rightarrow 0_1^+$	<10	$10(3)\%$
	NDS	**^{11}Li, βn**

$$\Gamma_{tot} = \frac{1}{1+\delta^2}(\delta^2\Gamma_{E2}+\Gamma_{M1})_2 + (\Gamma_{E2})_0$$

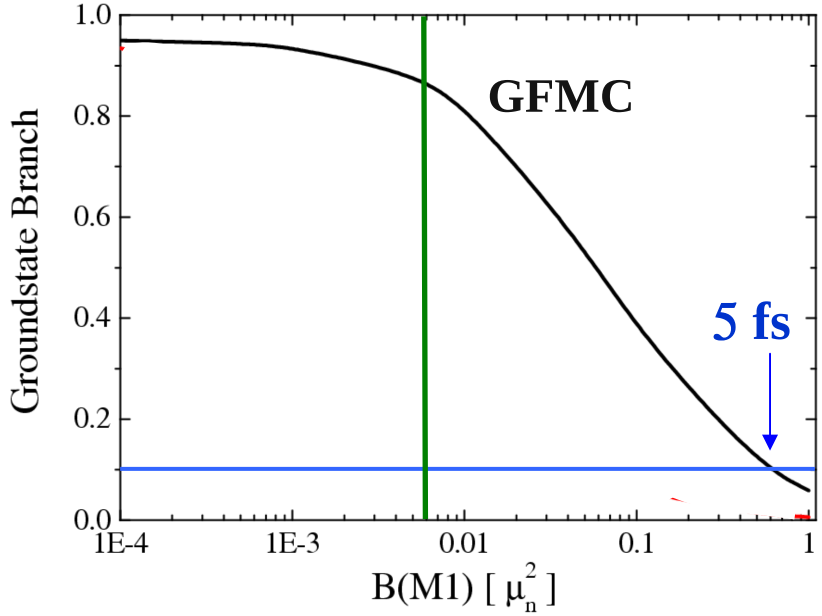
GFMC

$$B(E2;2_2^+ \rightarrow 0_1^+) = 2.08(26)e^2\,fm^4$$

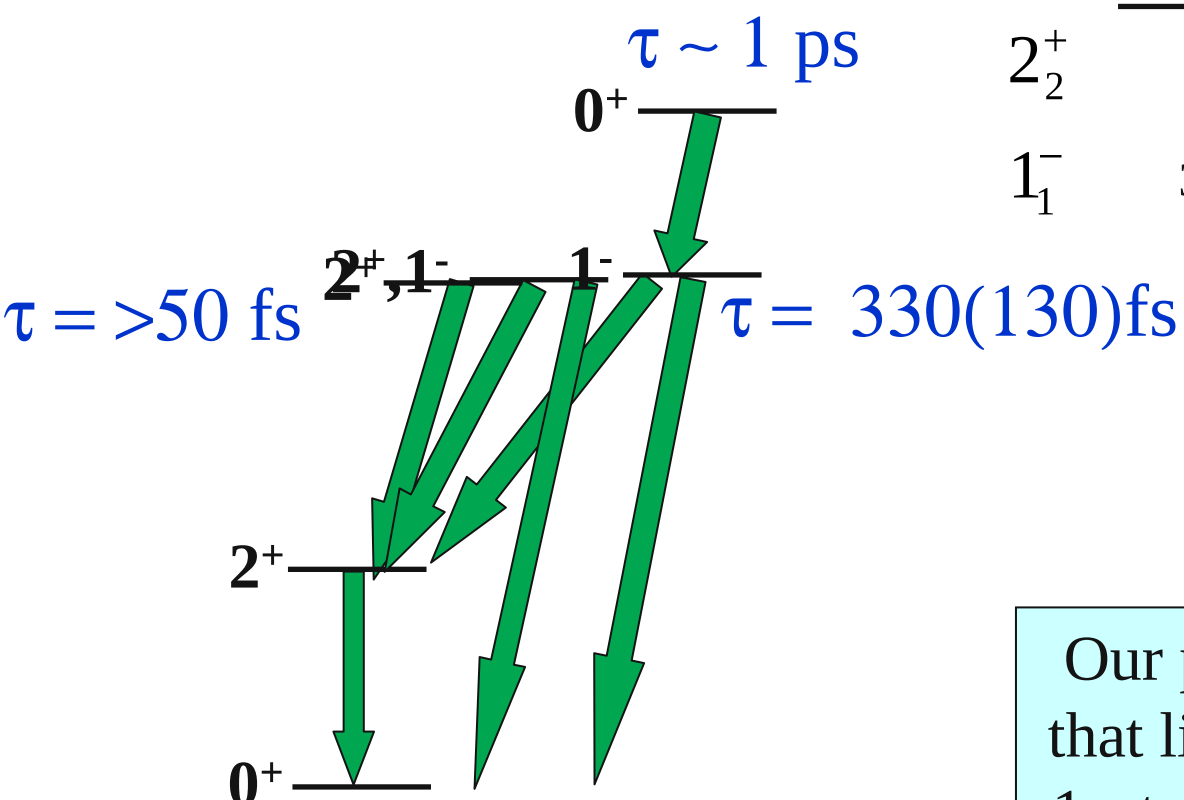
$$B(E2;2_2^+ \rightarrow 2_1^+) = 6.9(10)e^2\,fm^4$$

VMC

$$B(M1;2_2^+ \rightarrow 2_1^+) \sim 0.006\mu_n^2$$



Lifetime of $2^+/1^-$ doublet



^{11}Li β-delayed 1-n emission

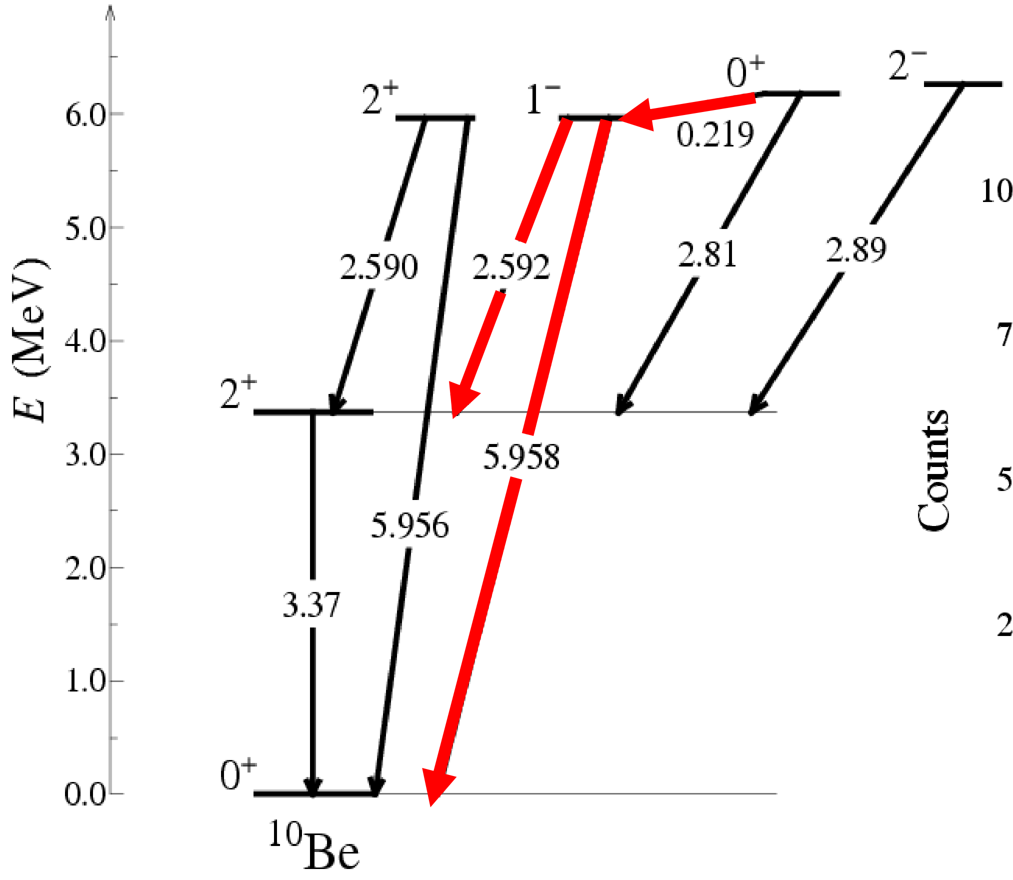
	ISOLDE	TRIUMPH
2_2^+	> 50 fs	86(11) fs
1_1^-	330(130) fs	< few 100 fs

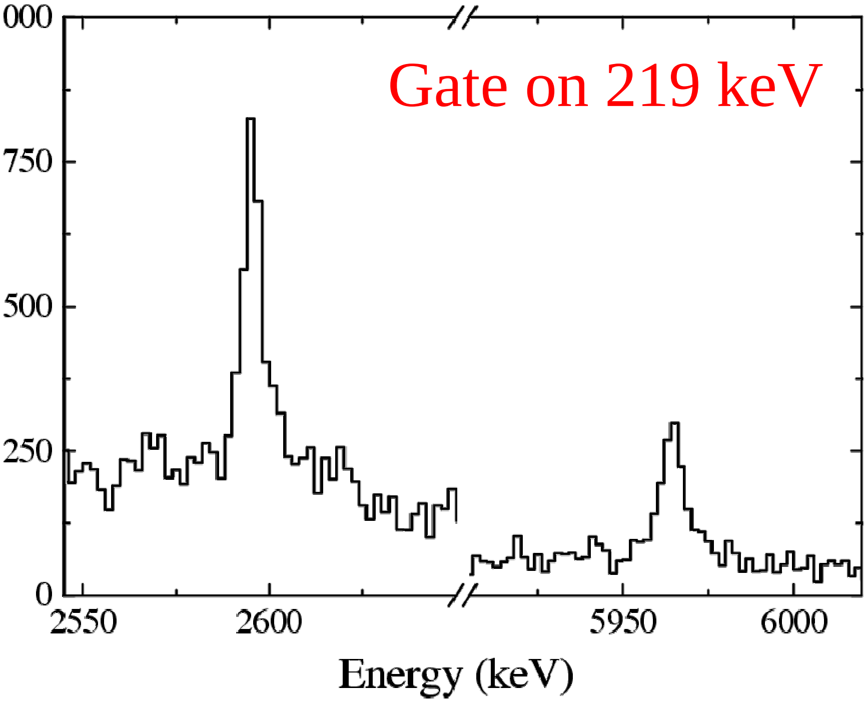
Our preliminary indication is that lifetimes of both $J=2^+$ and 1^- state are significantly faster than the ISOLDE results

Gamma-gamma analysis for branching ratio

- Previous measurements fit doublet
- γ-γ isolates 1⁻ branch

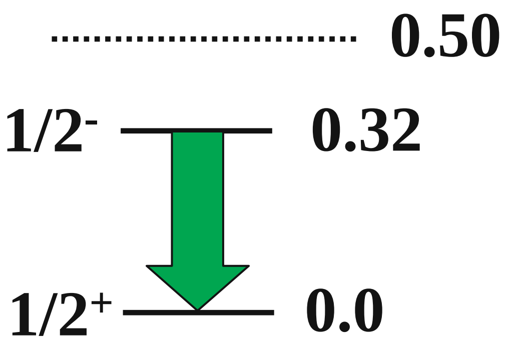
	$1^- \to 2^+_1$	$1^- \to 0^+_1$
NDS	17^{+6}_{-10}	83^{+10}_{-6}
^{11}Li βn	35(15)	65(15)
Present	41(4)	59(4)





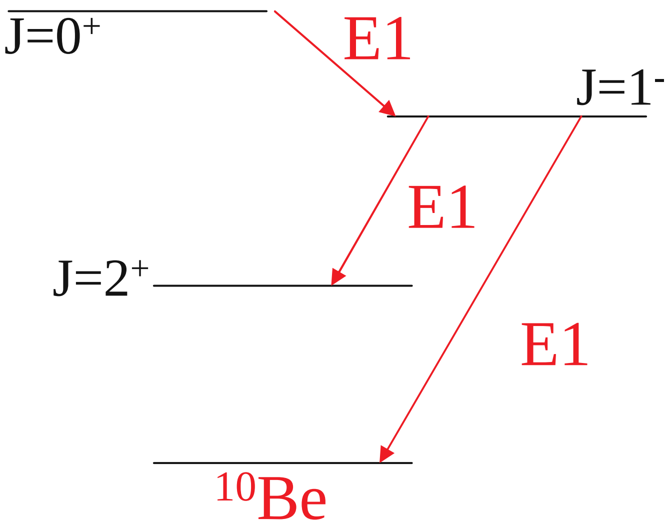
Electric Dipole Physics…….hints of Halos

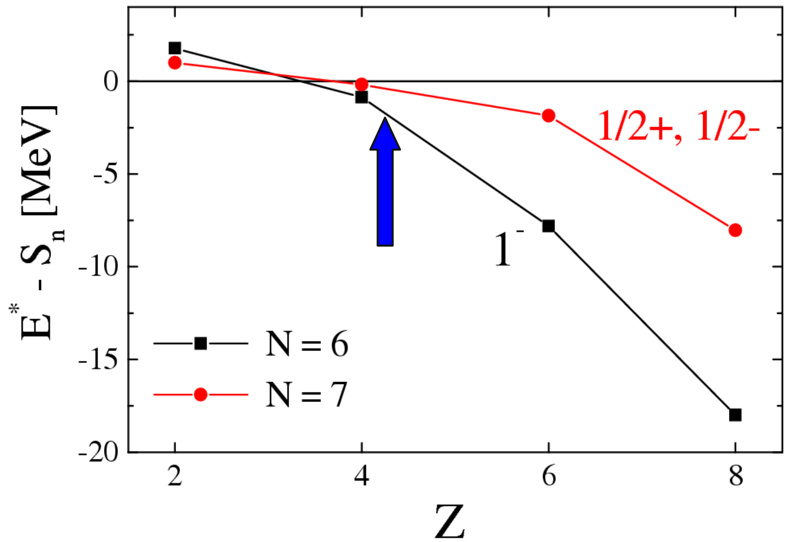
“Classic” halo nucleus ^{11}Be



B(E1) = 0.12(1) e^2fm^2

D.J. Millener et al., Phys. Rev. C **28**, 497 (1983).





^{10}Be B(E1) in e^2fm^2

	$1^- \rightarrow 2^+_1$	$1^- \rightarrow 0^+_1$
GFMC	2.4×10^{-2}	7.4×10^{-3}
MO		2.4×10^{-3}
Exp	$2(1) \times 10^{-5}$	$7(3) \times 10^{-6}$

MO : N. Itagaki and S. Okabe, Phys. Rev. C **61**, 044306 (2000).

Exp : H.O.U. Fynbo, Nucl. Phys. **A736**, 39 (2004).

Conclusions

In Experiment

Precision spectroscopy near stability and “discovery” studies far from stability are BOTH important and complimentary approaches.

We must make precise measurements (improve technique). Reliable <5% DSAM measurement IS possible.

In Theory

We need to bridge what we learn from ab-initio calculations to more global models using NCSM, Hartree-Fock, Relativistic Mean Field and Density Functional approaches.

Spares

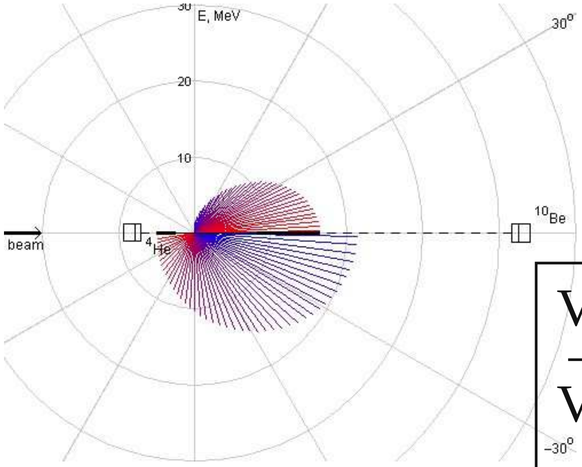
Choice of reaction

$^{7}Li(^{7}Li,\alpha)^{10}Be$

$Q = +14.784$ MeV

$E_b = 10$ MeV

Very high recoil velocity
($\beta_i = 6\%$)
evaporated target
good FMA separation
Low efficiency



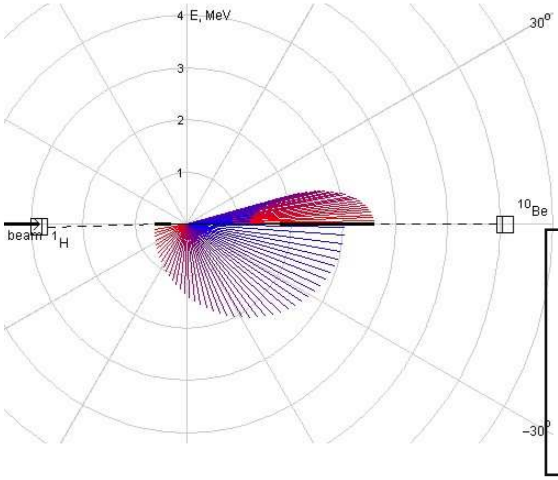
$$\frac{V_{\text{in\_c.m.}}}{V_{\text{of c.m.}}} \quad \boxed{> 1}$$

$^{2}H(^{9}Be,p)^{10}Be$

$Q = +4.588$ MeV

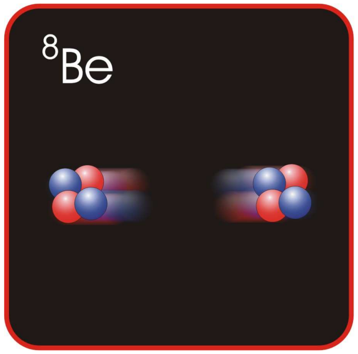
$E_b = 13.5$ MeV

Very high recoil velocity
($\beta_i = 6\%$)
implanted target
difficult FMA separation
High efficiency



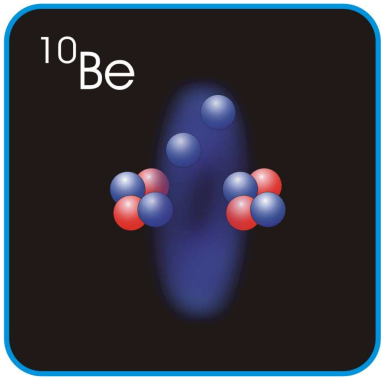
$$\frac{V_{\text{in\_c.m.}}}{V_{\text{of c.m.}}} \quad \boxed{< 1}$$

Simple toy model



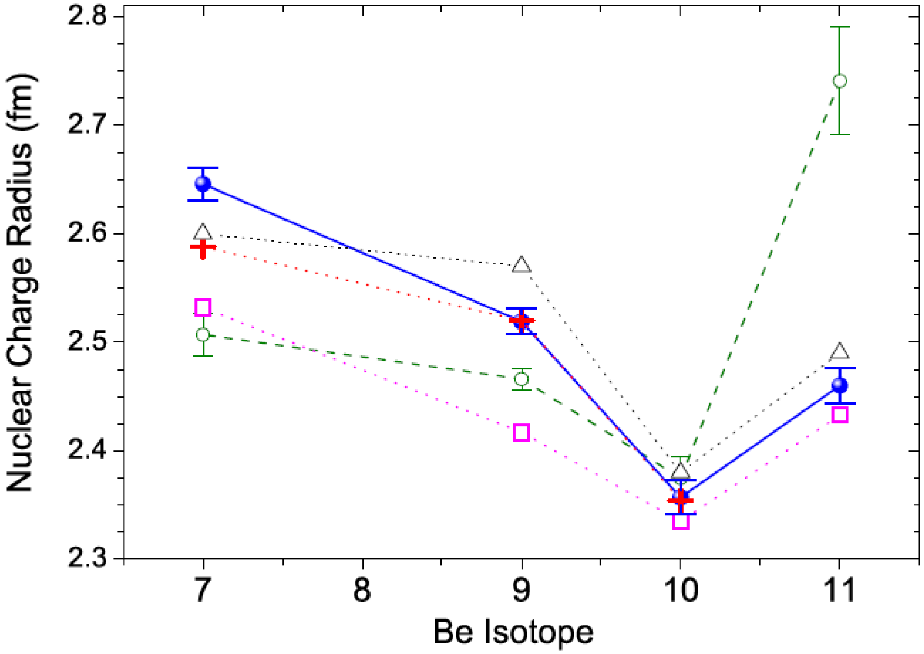
$$B(E2;2_1^+ \rightarrow 0_1^+)_{cal} = 14.8e^2\,fm^4$$

$$r = 2.6\,fm$$



$$B(E2;2_1^+ \rightarrow 0_1^+) = 7.8(10)e^2\,fm^4$$

$$r = 2.2\,fm$$

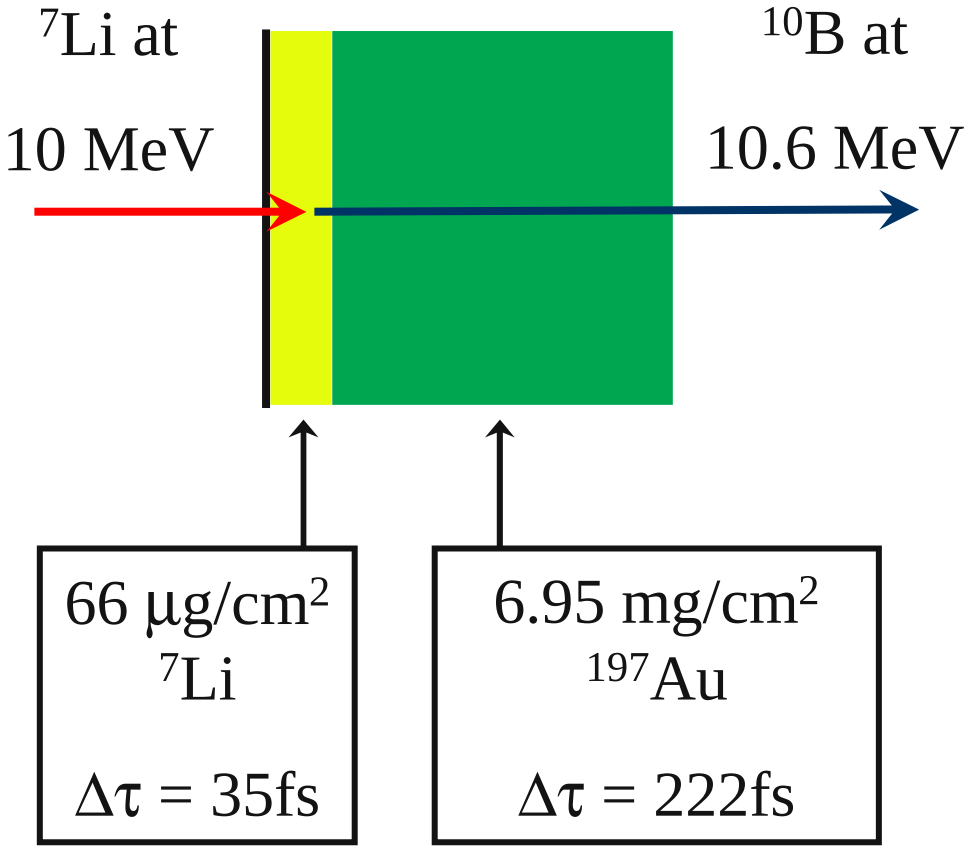


Nuclear Charge Radii of ^{7,9,10}Be and the one-neutron halo nucleus ^{11}Be

W. Nörtershäuser,[1,2] D. Tiedemann,[2] M. Žáková,[2] Z. Andjelkovic,[2] K. Blaum,[3] M. L. Bissell,[4] R. Cazan,[2] G.W.F. Drake,[5] Ch. Geppert,[6,7] M. Kowalska,[8] J. Krämer,[2] A. Krieger,[2] R. Neugart,[2] R. Sánchez,[6] F. Schmidt-Kaler,[9] Z.-C. Yan,[10] D. T. Yordanov,[3] and C. Zimmermann[7]

arXiv:0809.2607v1 [nucl-ex]

Results (1): First excited State with $J^{\pi}=2^{+}$ at 3367 keV



^{7}Li at

10 MeV

^{10}B at

10.6 MeV

66 μg/cm^2
^{7}Li

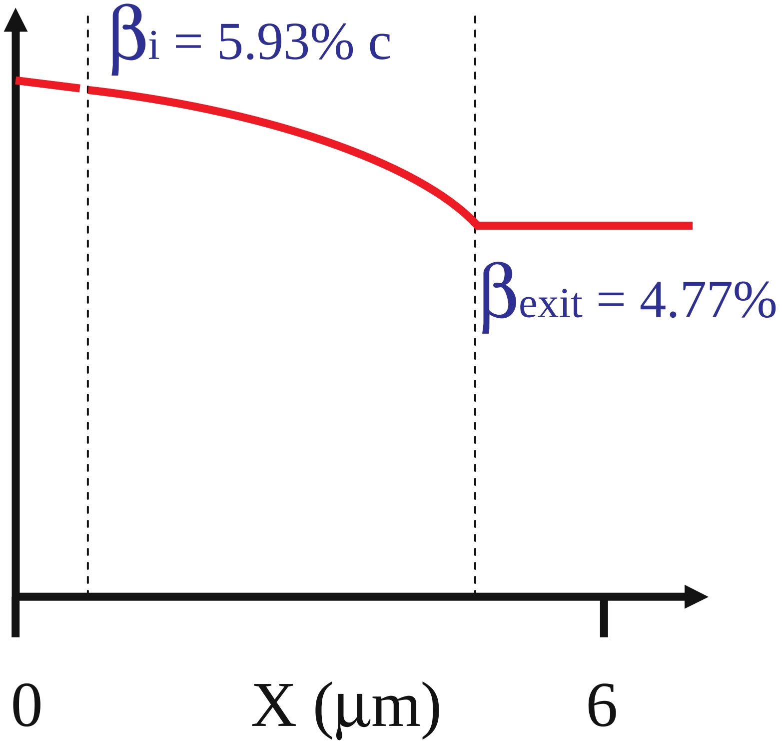
$\Delta\tau$ = 35fs

6.95 mg/cm^2
^{197}Au

$\Delta\tau$ = 222fs

^{7}Li(^{7}Li,α)^{10}Be(2^{+})

Q = 11.418 MeV



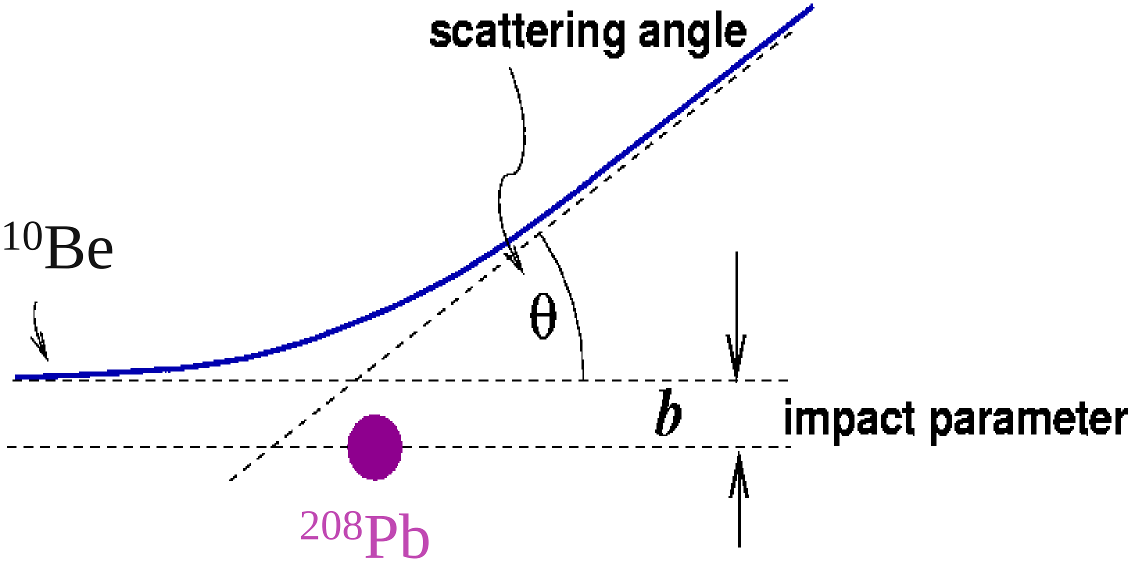
~17% of γ-rays in Li

~60% of γ-rays in Au

~23% of γ-rays in vacuum

An alternate approach: ^{10}Be Coulomb Excitation

^{10}Be was produced in a reactor using ^{9}Be(n,γ)^{10}Be and mass separated at ORNL. It is now being prepared as a beam, with expected intensity >10^9pps, as it has $T_{1/2}$=1.5Myr.



Is this a better approach?

Is it more precise?

Can one investigate the upper 5960keV $J^{\pi}=2^+,1^-$ doublet?

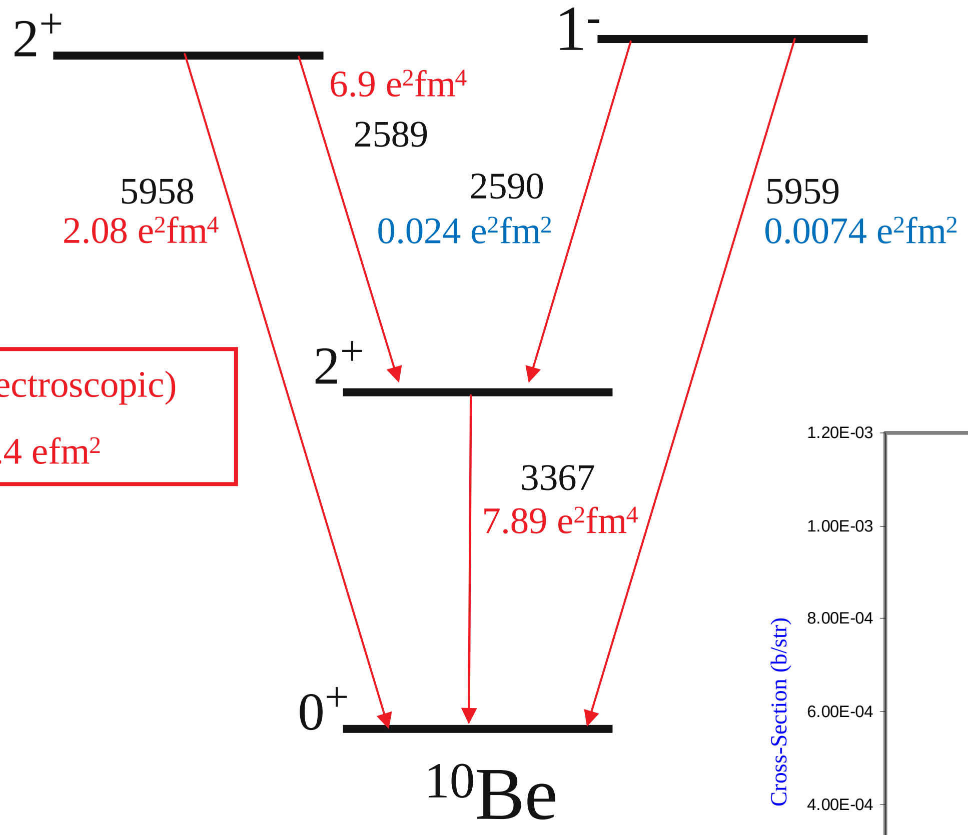
Can we cross-check our DSAM results?

A QUESTION OF NUMBERS

Coulomb Excitation: 45 MeV ^{10}Be on ^{206}Pb target

Q_{22} (spectroscopic)

+3.7 efm^2



Q_{22} (spectroscopic)

-5.4 efm^2

Ab-initio matrix elements (Wiringa / Pieper) into DeBoer / Winter inelastic excitation code (Esbensen).

Tough experiment:

Cross-sections are VERY low

Hard to get statistics to beat DSAM…but can confirm.

IF the beam >10^9 pps AND the B(E1) are large then the upper doublet might be investigated.