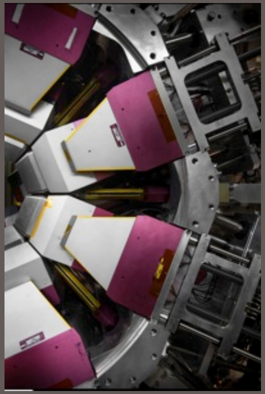
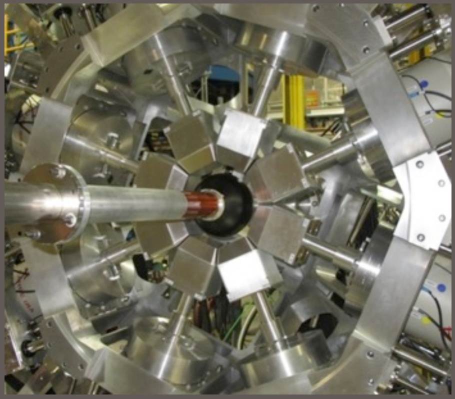
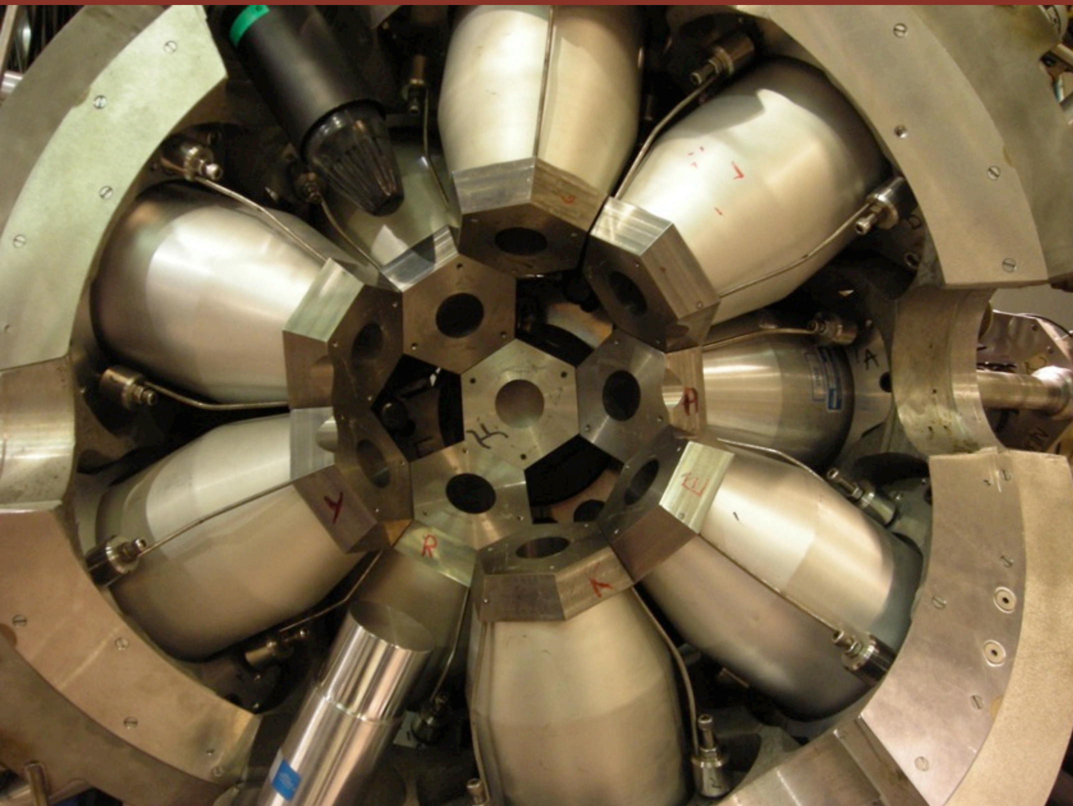
Lifetime Measurements for the Determination of Electric Monopole Transition Strengths



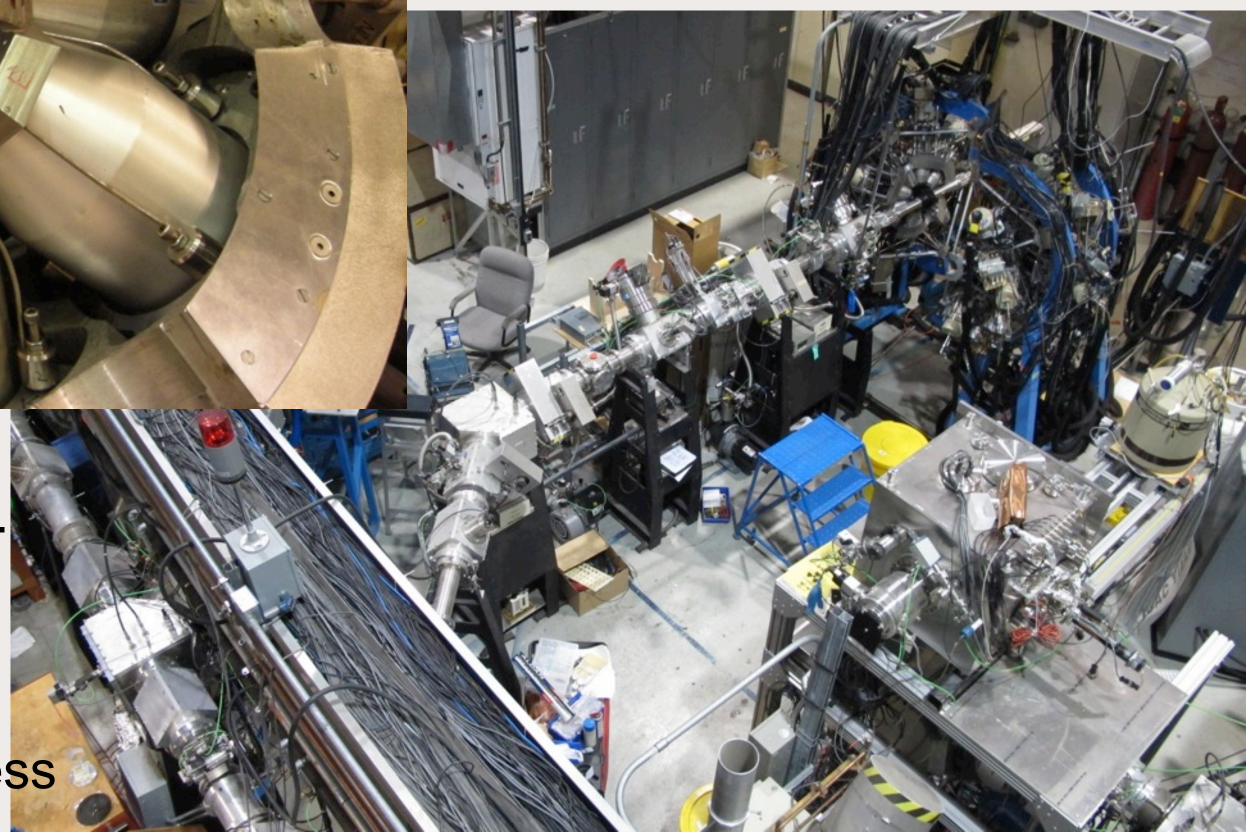


Adam Garnsworthy | Research Scientist | TRIUMF

The 8π Spectrometer at TRIUMF-ISAC



Performed decay spectroscopy at TRIUMF-ISAC-I from Feb 2002 to Dec 2013



Researchers from 24 institutions from 8 countries.

>25 post-docs,
5PhD, 12MSc, 1MPhys
12 Grad. Students in progress

The 8π Spectrometer at TRIUMF-ISAC

TRIUMF

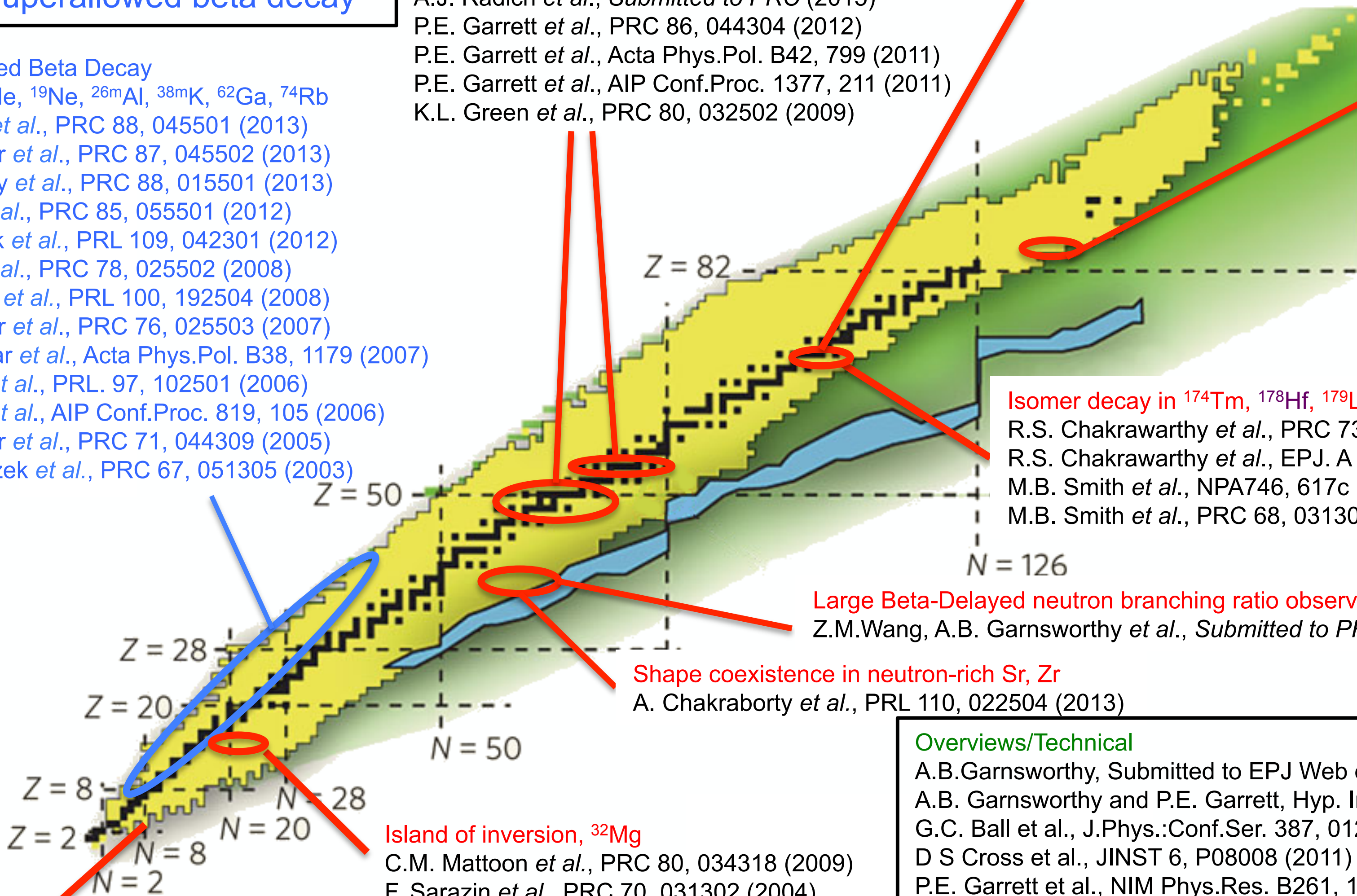
35 publications including 4 PRLs
22 on Nuclear Structure
13 on Superallowed beta decay

Superallowed Beta Decay
^{10}C, ^{14}O, ^{18}Ne, ^{19}Ne, ^{26m}Al, ^{38m}K, ^{62}Ga, ^{74}Rb
R. Dunlop *et al.*, PRC 88, 045501 (2013)
G.F. Grinyer *et al.*, PRC 87, 045502 (2013)
A.T. Laffoley *et al.*, PRC 88, 015501 (2013)
P. Finlay *et al.*, PRC 85, 055501 (2012)
S. Triambak *et al.*, PRL 109, 042301 (2012)
P. Finlay *et al.*, PRC 78, 025502 (2008)
K.G. Leach *et al.*, PRL 100, 192504 (2008)
G.F. Grinyer *et al.*, PRC 76, 025503 (2007)
E.F. Zganyar *et al.*, Acta Phys.Pol. B38, 1179 (2007)
B. Hyland *et al.*, PRL. 97, 102501 (2006)
B. Hyland *et al.*, AIP Conf.Proc. 819, 105 (2006)
G.F. Grinyer *et al.*, PRC 71, 044309 (2005)
A. Piechaczek *et al.*, PRC 67, 051305 (2003)

High-statistics studies of Cd, Sn, Xe
A.J. Radich *et al.*, *Submitted to PRC* (2015)
P.E. Garrett *et al.*, PRC 86, 044304 (2012)
P.E. Garrett *et al.*, Acta Phys.Pol. B42, 799 (2011)
P.E. Garrett *et al.*, AIP Conf.Proc. 1377, 211 (2011)
K.L. Green *et al.*, PRC 80, 032502 (2009)

Half Life of geochronometer, ^{176}Lu
G.F. Grinyer *et al.*, PRC 67, 014302 (2003)

Structure of $^{219-223}$Rn towards a RnEDM search



Isomer decay in ^{174}Tm, ^{178}Hf, ^{179}Lu
R.S. Chakrawarthy *et al.*, PRC 73, 024306 (2006)
R.S. Chakrawarthy *et al.*, EPJ. A 25, S1, 125 (2005)
M.B. Smith *et al.*, NPA746, 617c (2004)
M.B. Smith *et al.*, PRC 68, 031302 (2003)

Large Beta-Delayed neutron branching ratio observed from ^{102}Rb
Z.M.Wang, A.B. Garnsworthy *et al.*, *Submitted to PRC* (2015)

Shape coexistence in neutron-rich Sr, Zr
A. Chakraborty *et al.*, PRL 110, 022504 (2013)

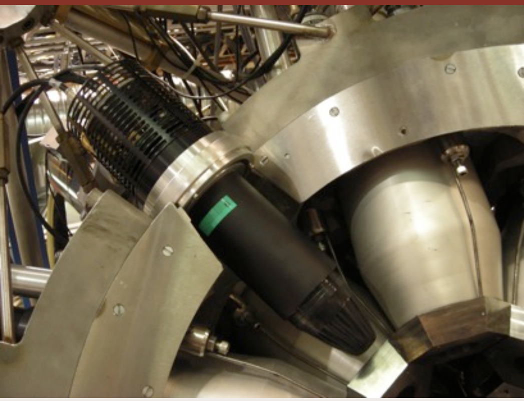
Island of inversion, ^{32}Mg
C.M. Mattoon *et al.*, PRC 80, 034318 (2009)
F. Sarazin *et al.*, PRC 70, 031302 (2004)

^{11}Li beta-delayed neutron emission
C.M. Mattoon *et al.*, PRC 75, 017302 (2007)

Overviews/Technical
A.B.Garnsworthy, Submitted to EPJ Web of Conf.s (2014)
A.B. Garnsworthy and P.E. Garrett, Hyp. Int. 225, 121 (2014)
G.C. Ball et al., J.Phys.:Conf.Ser. 387, 012014 (2012)
D S Cross et al., JINST 6, P08008 (2011)
P.E. Garrett et al., NIM Phys.Res. B261, 1084 (2007)
G.C. Ball et al., J.Phys.(London) G31, S1491 (2005)
S.J. Williams et al., J.Phys.(London) G31, S1979 (2005)

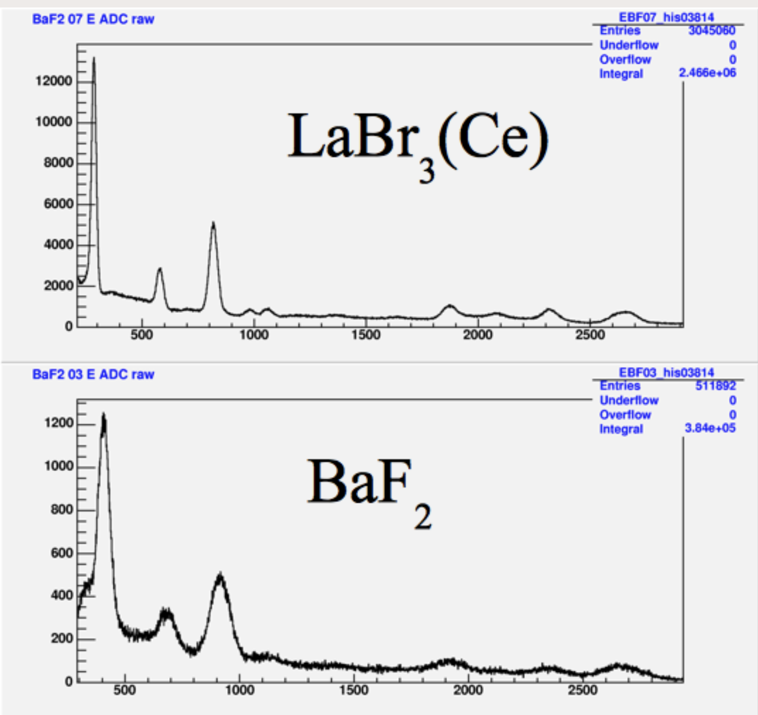
DANTE

Di-pentagonal Array for Nuclear Timing Experiments



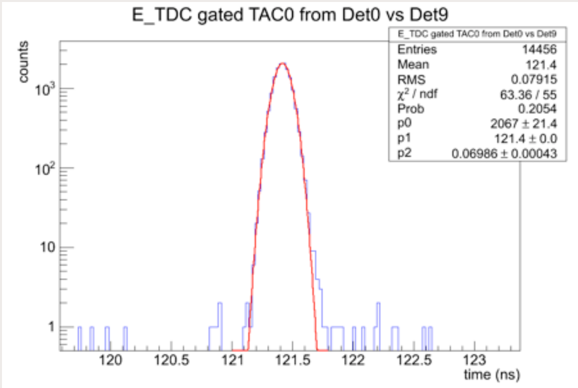
Fast-timing allows the determination of transition rates

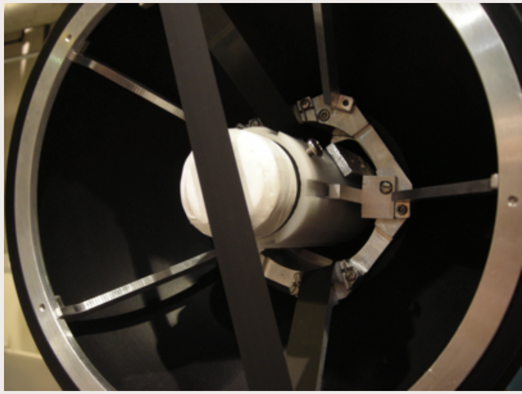
-BaF_2, truncated cone;
base 4cm, front 2cm, length 3cm
-$LaBr_3$(Ce) 2”x2” cylinder



Superior Energy resolution (x3) and efficiency (x2)

LaBr-LaBr FWHM <200 ps



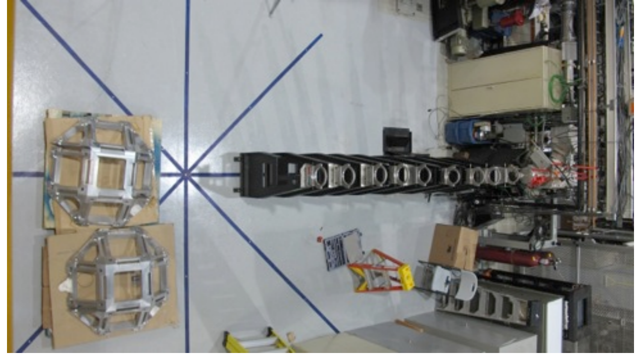


Fast Zero-degree scintillator for β-γ timing. BC422Q = 0.7ns

D.Cross et al., JINST 06, P08008 (2011)

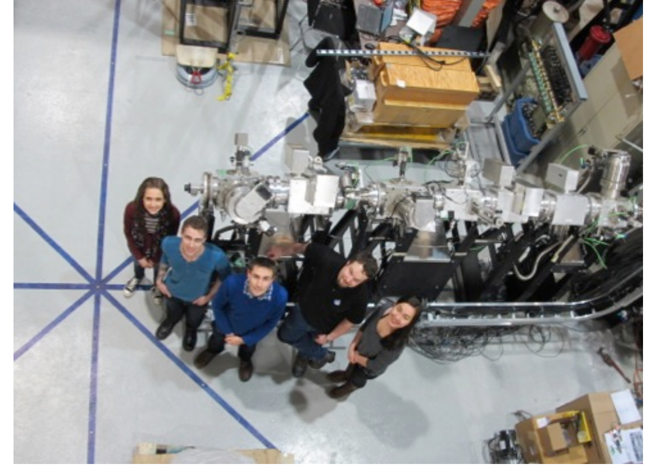
GRIFFIN Installation in 2014

Jan ⟶

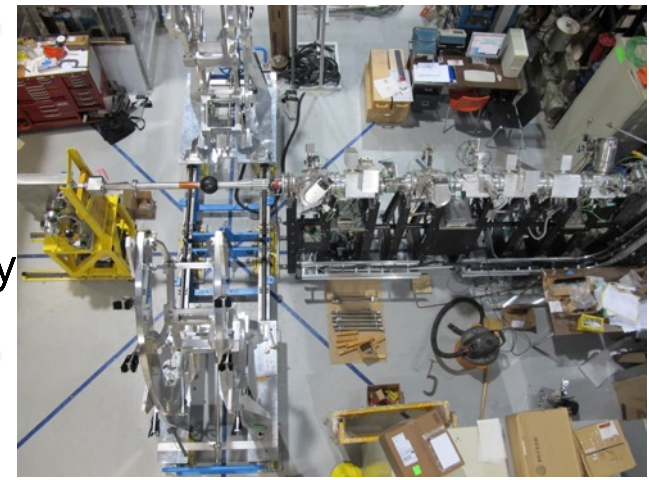


Feb ⟶

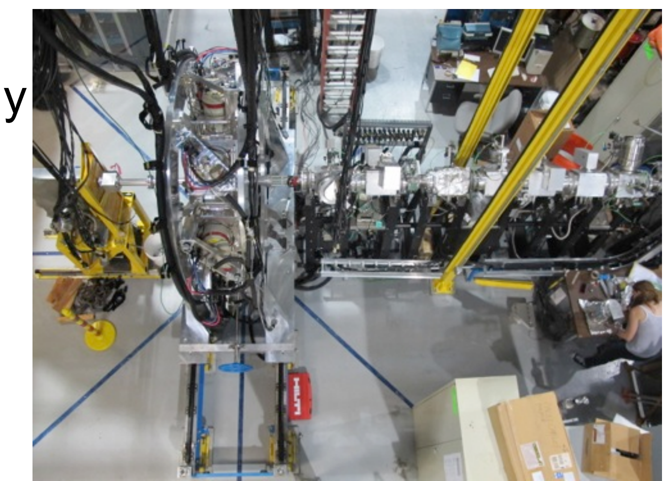
Apr ↓

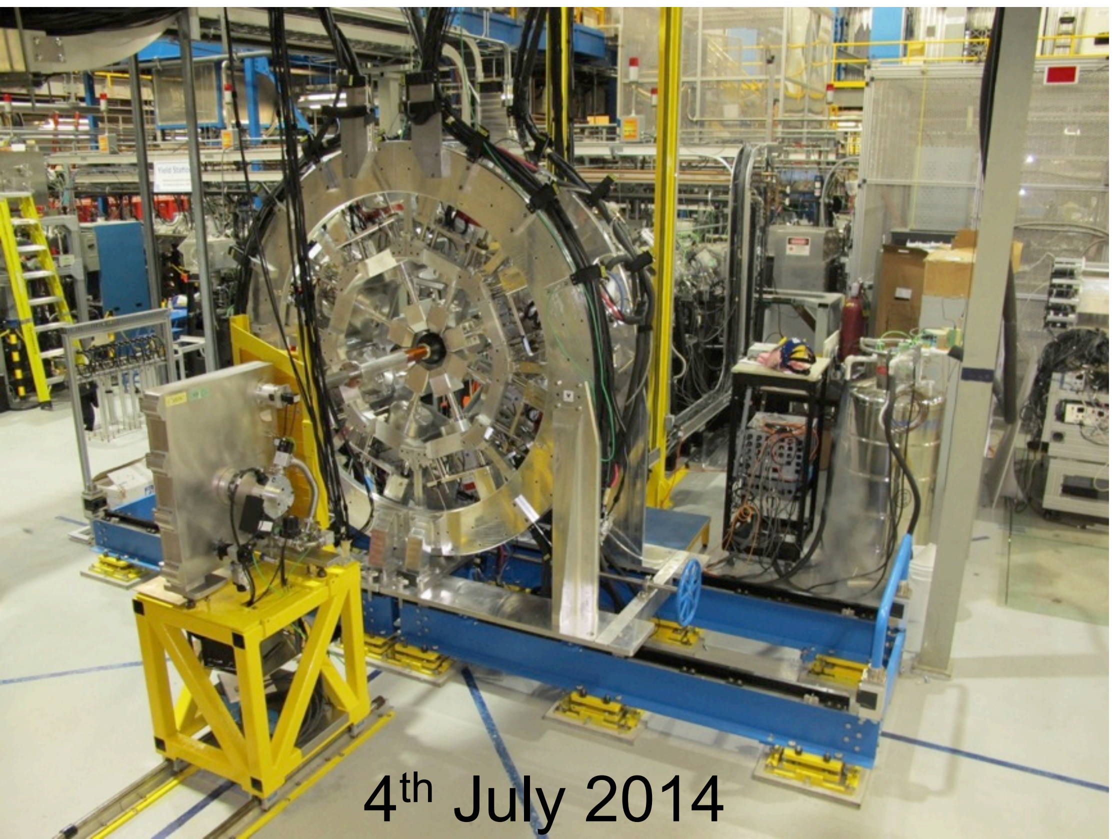


May ↓



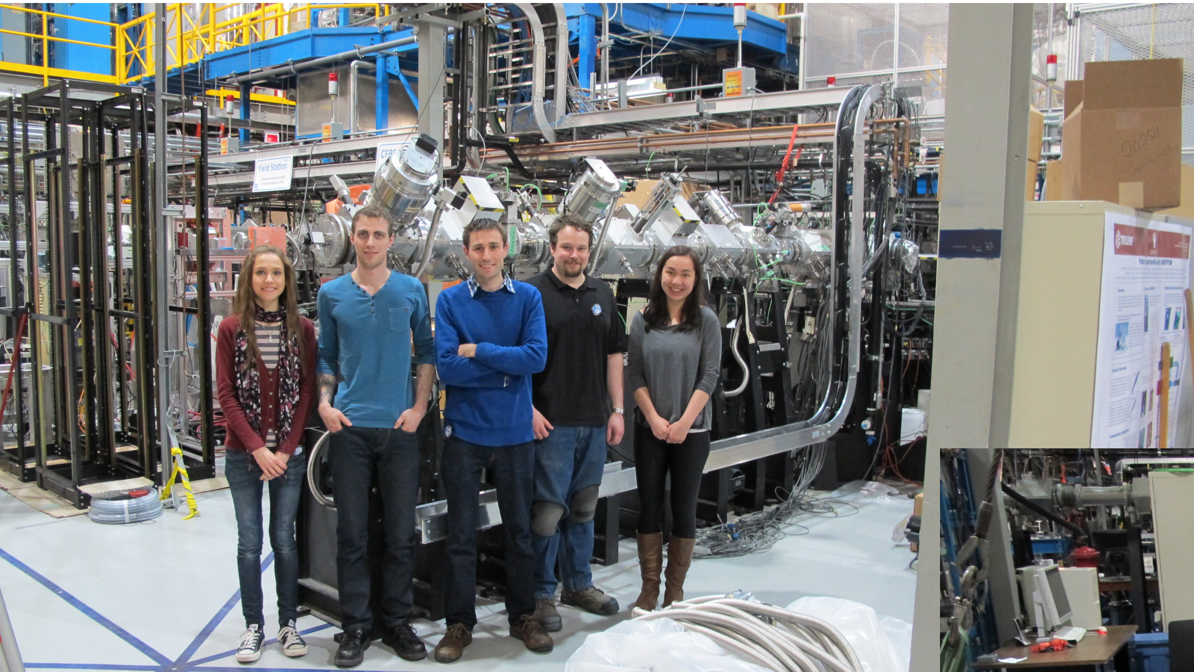
July

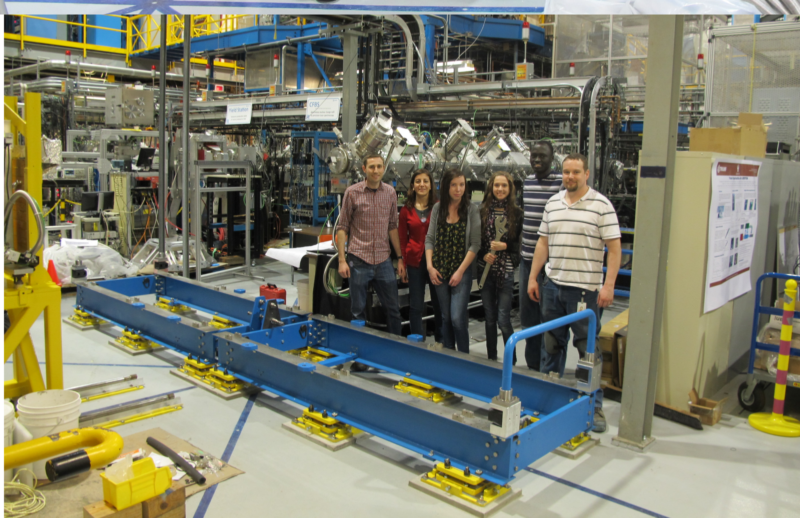


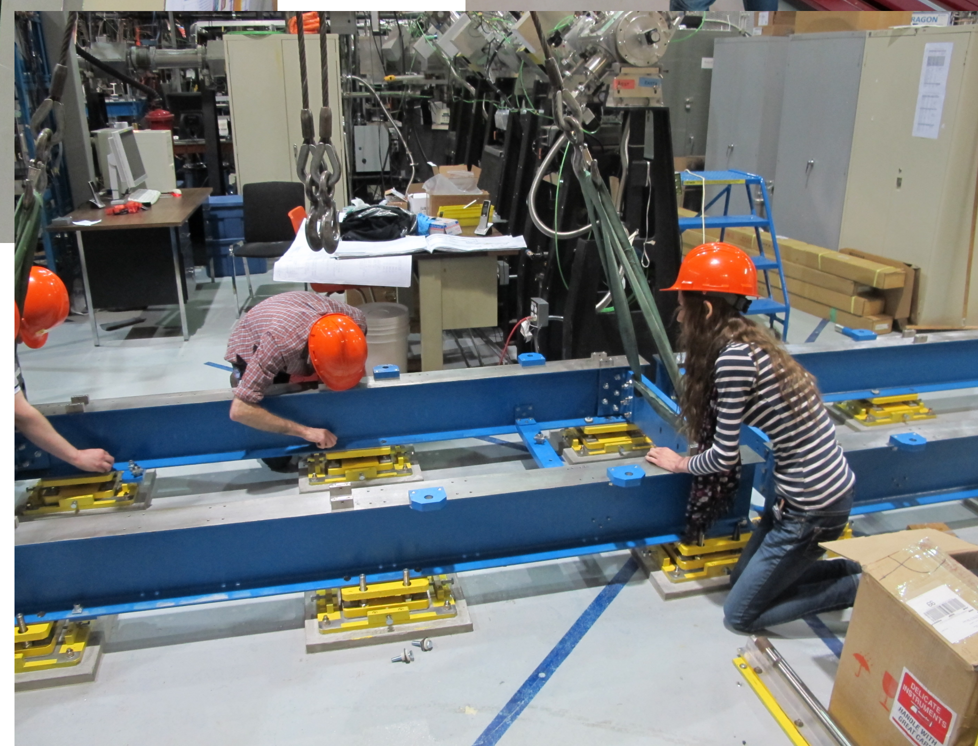


4th July 2014

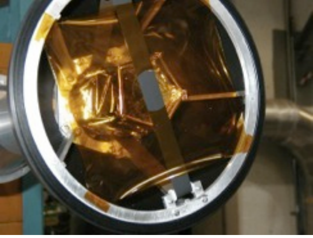
Surrey MPhys Student, Lisa Morrison GRIFFIN Installation in 2014







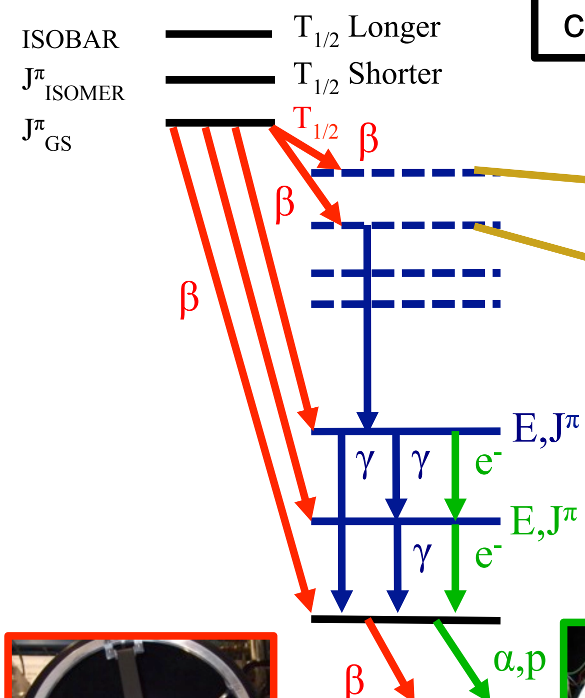
GRIFFIN Facility at TRIUMF
Sensitive Decay Spectroscopy

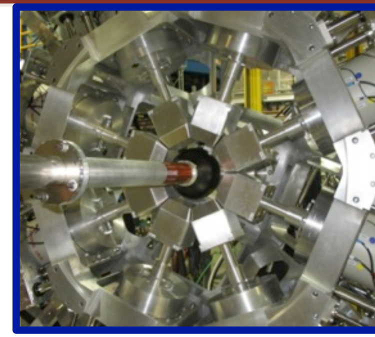


GRIFFIN

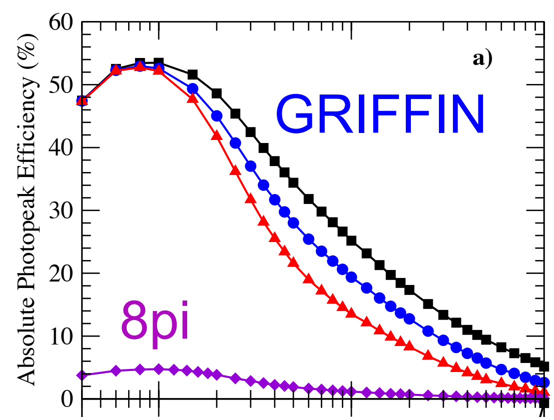
Fast, in-vacuum tape system
Enhances decay of interest

Initial operation in fall 2014. Fully commissioned in 2015

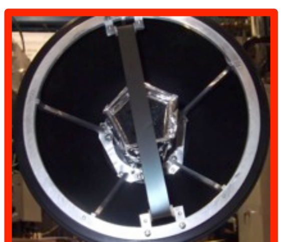




HPGe: 16 Clovers
Detect gamma rays and determines branching ratios, multipolarities and mixing ratios



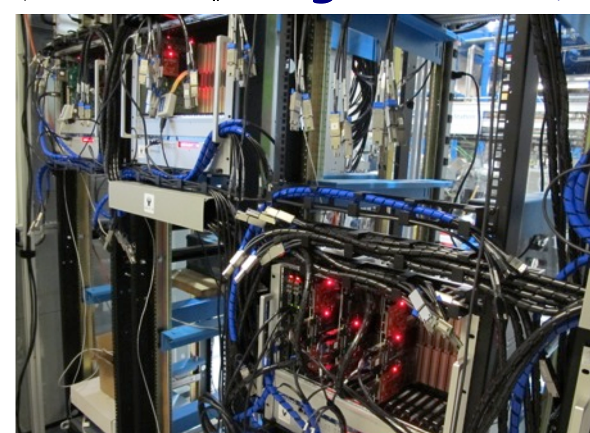
Digital DAQ



SCEPTAR: 10+10 plastic scintillators
Detects beta decays and determines branching ratios

PACES: 5 Cooled Si(Li)s
Detects Internal Conversion Electrons and alphas/protons

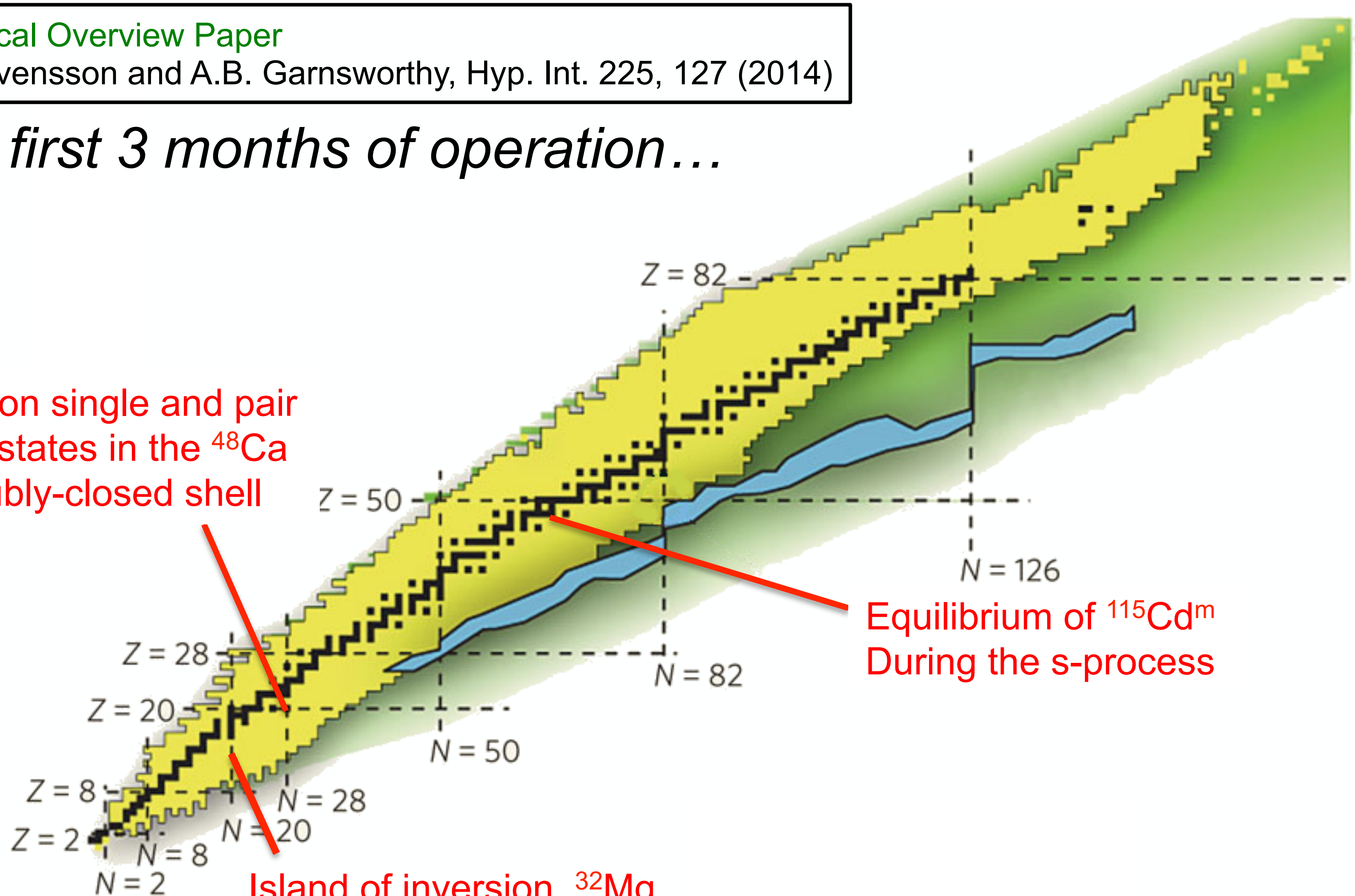
DESCANT
Detects neutrons to measure beta-delayed neutron branching ratios



The GRIFFIN Spectrometer at TRIUMF-ISAC

Technical Overview Paper
C.E. Svensson and A.B. Garnsworthy, Hyp. Int. 225, 127 (2014)

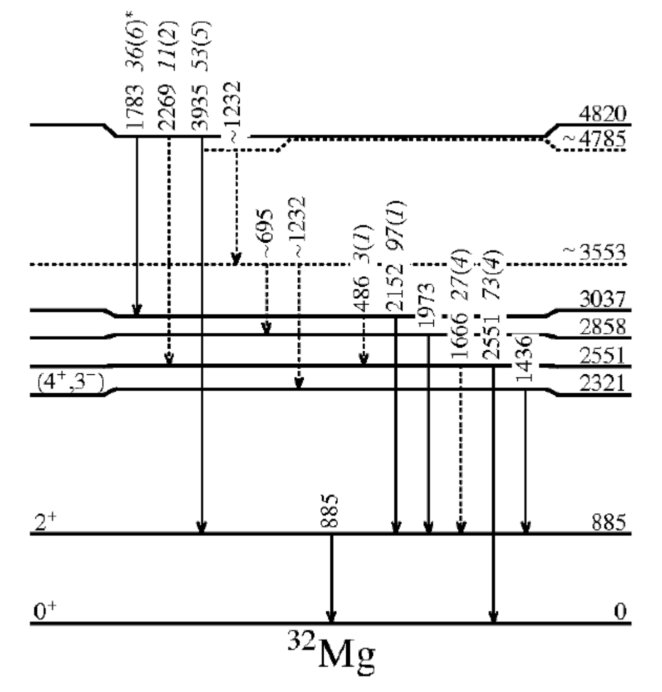
The first 3 months of operation…



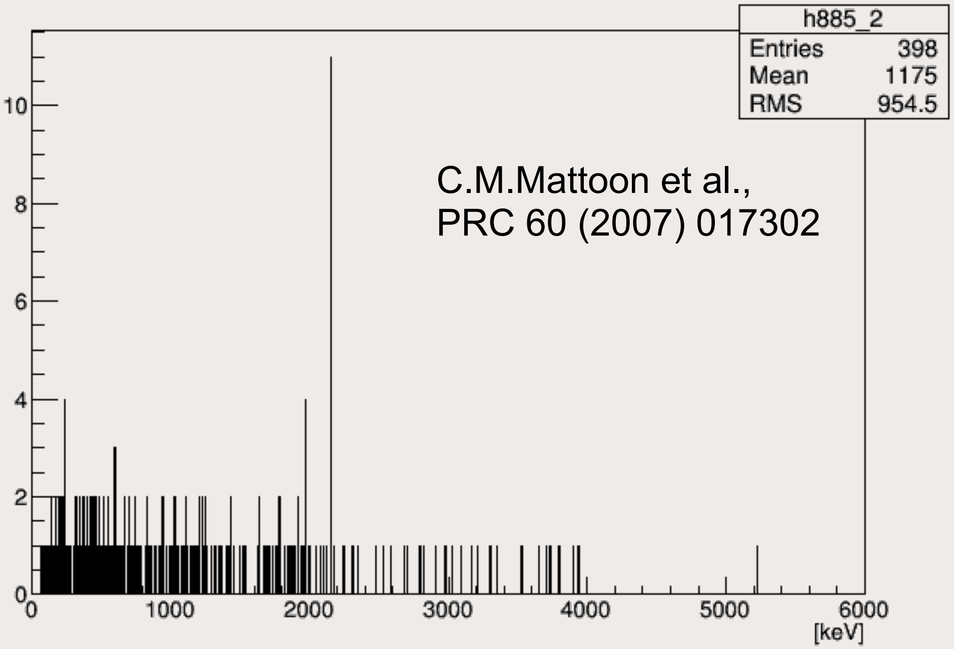
Over 70 scientists from 12 countries have now joined the collaboration

^{32}Na decay with 8pi and GRIFFIN

Fred Sarazin, *Colorado School of Mines*



γ-γ coincidences with first 2^+-0^+ transition, [883,887] keV

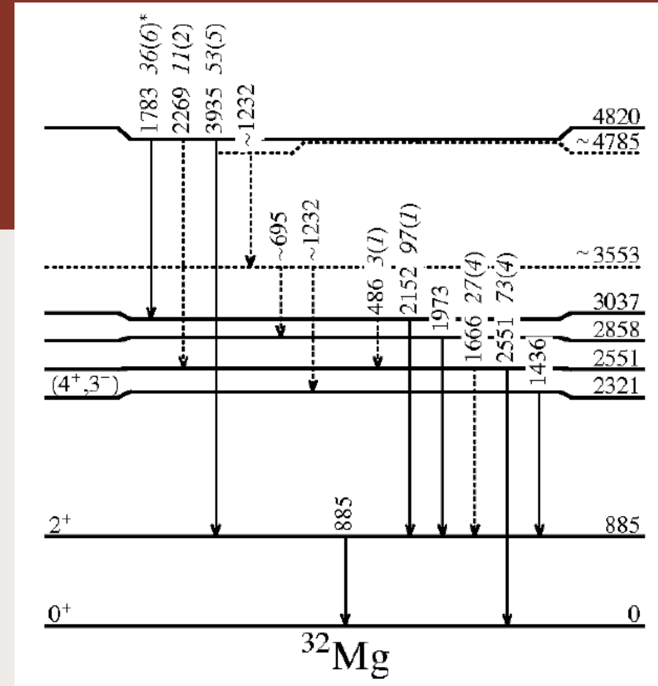


8pi: 2-3 pps, 5 days

TRIUMF

^{32}Na decay with 8pi and GRIFFIN

Fred Sarazin, *Colorado School of Mines*



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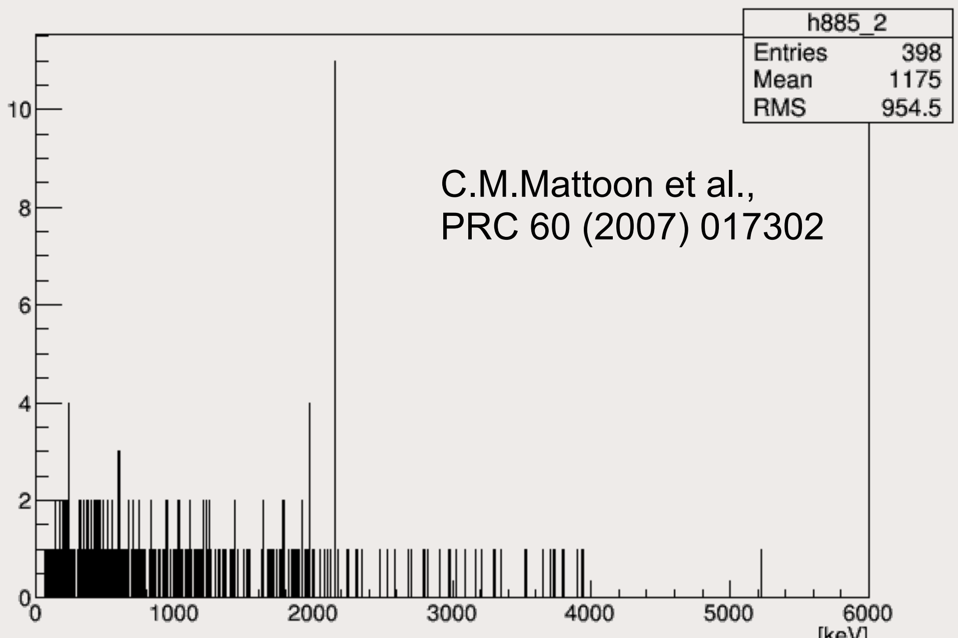

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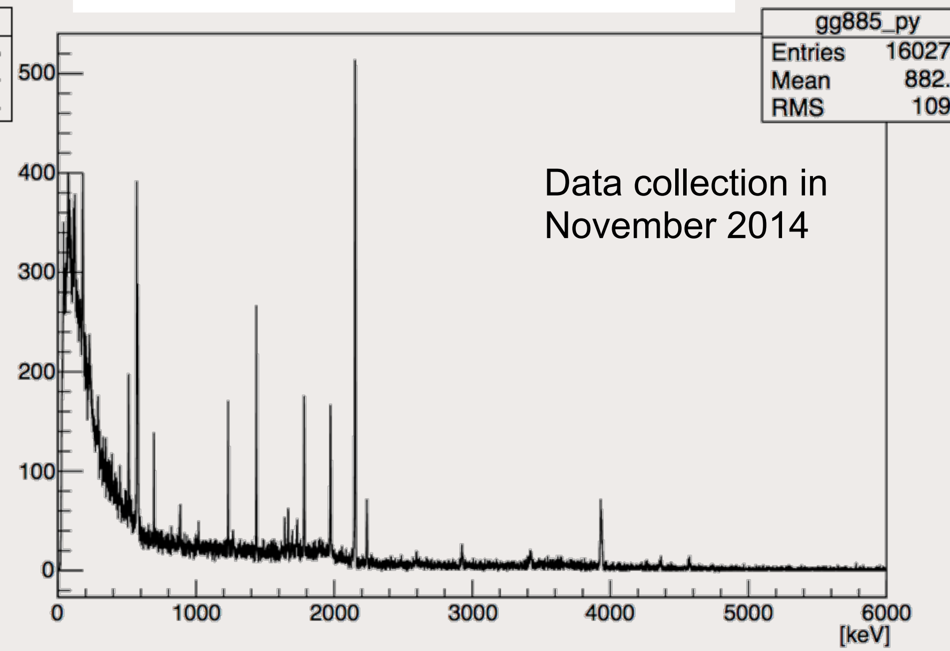
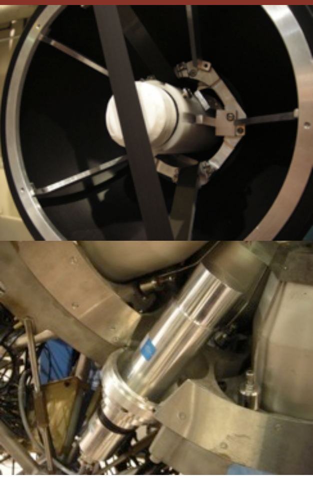


GRIFFIN: ~9 pps, ~2 days

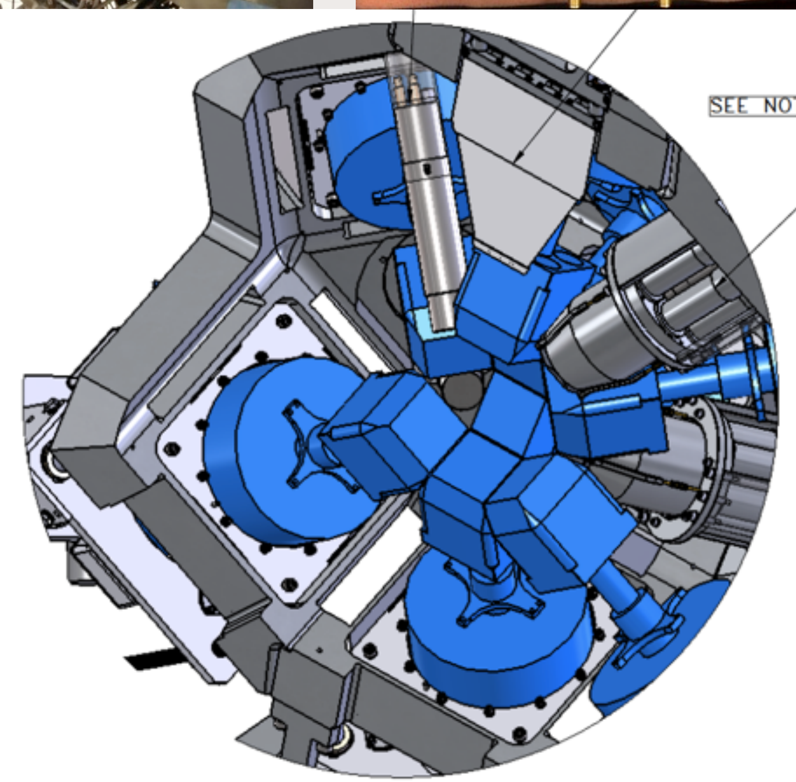
TRIUMF

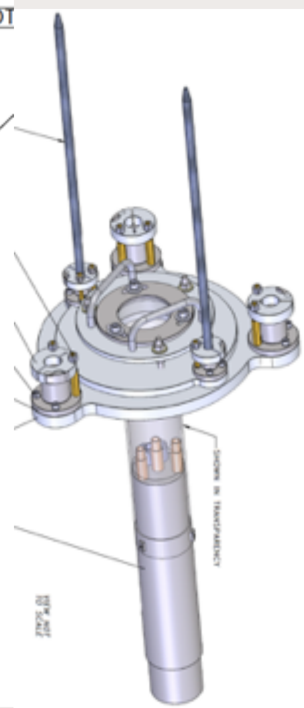
$LaBr_3$

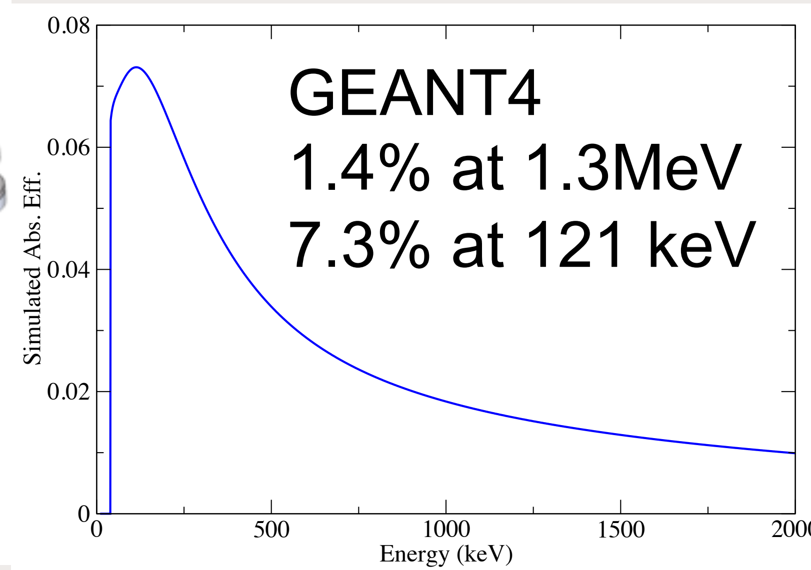
Fast-Scintillator Array for Excited-State Lifetime Timing



- Eight $LaBr_3$(Ce) 2”x2” cylindrical crystal
- Source-detector distance=12.5 cm.
- GEANT4 simulated efficiency 1.4%@1.3MeV
- LaBr-LaBr FWHM <200 ps achieved in 8pi analogue electronics
- Fast Zero-degree scintillator for β-γ timing. BC422Q = 0.7ns



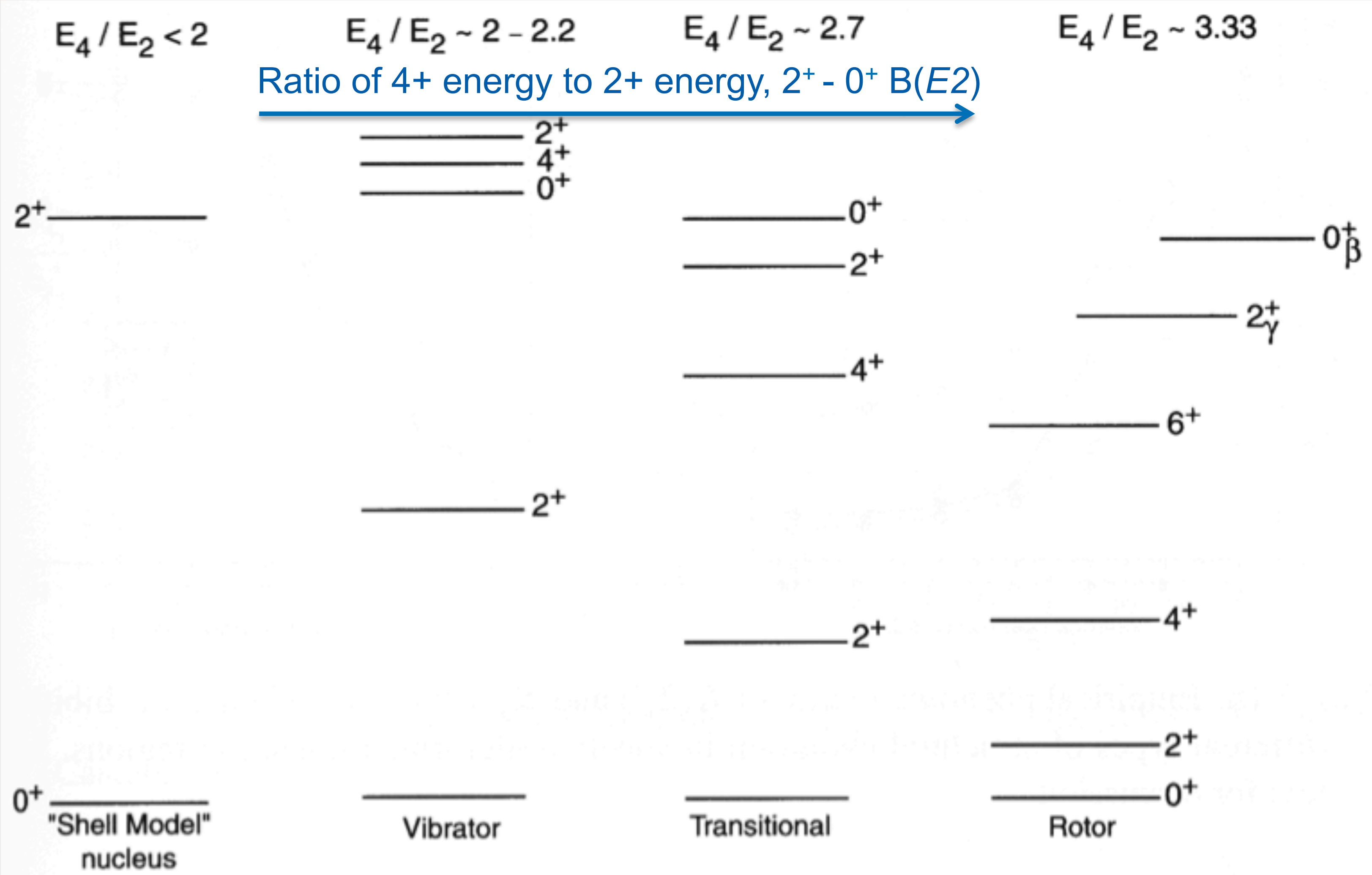




TRIUMF

Lifetime Measurements for the Determination of Electric Monopole Transition Strengths

Excitation Mechanisms of Nuclei



Ratio of 4+ energy to 2+ energy, 2^+ - 0^+ B(*E*2)

Closed-Shell ← Mid-Shell

First 2+ energy

Figure from: R. Casten, Nuclear Structure from a Simple Perspective (2000)

Evolution of Structure

- Peaks/troughs at magic numbers
- Smooth transition away from magic numbers

What mechanisms drive the transition from spherical, single-particle structures to deformed, collective excitations?

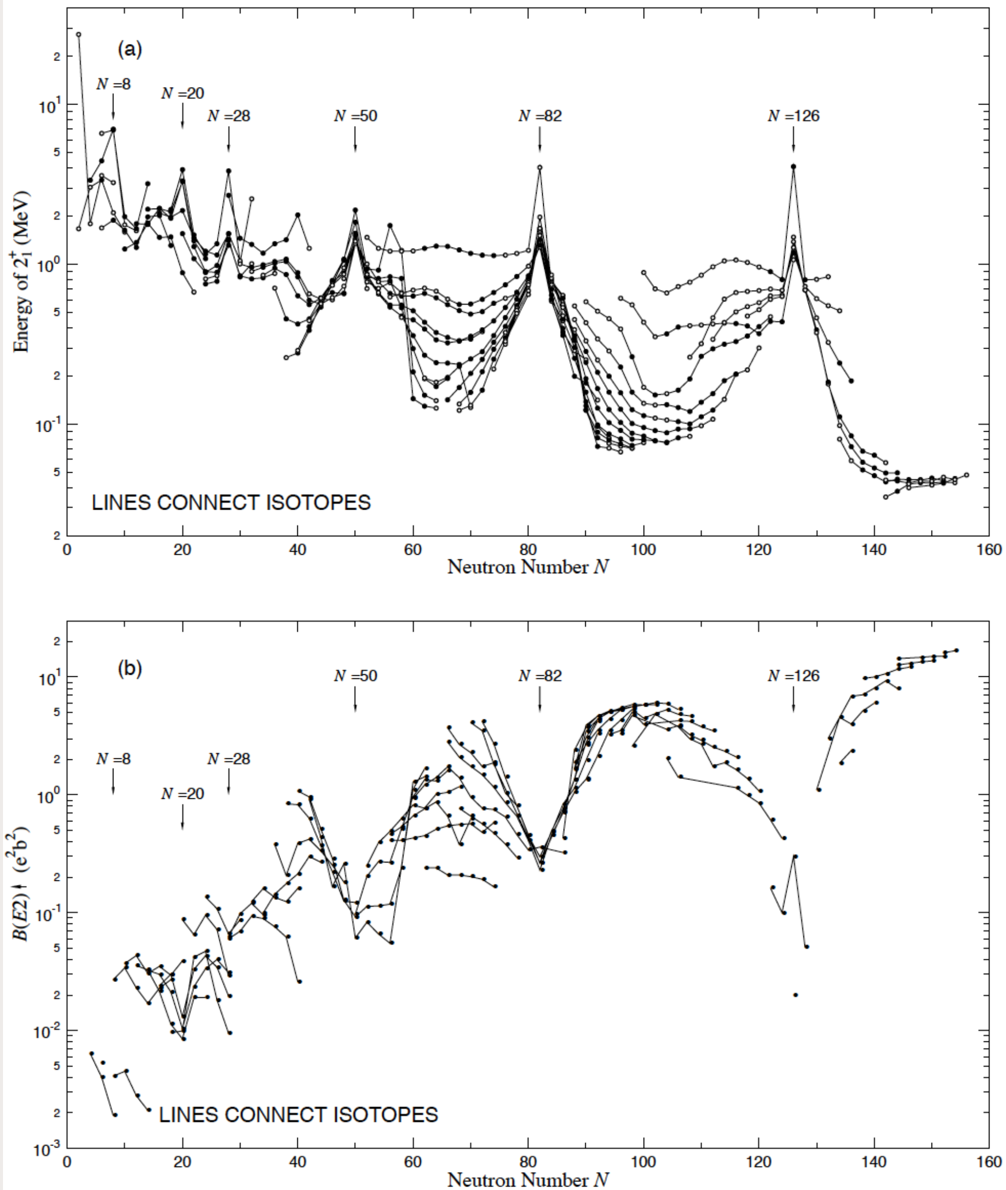


Figure from S. Raman, C.W. Nestor, JR., P. Tikkanen, Atomic Data and Nuclear Data Tables 78, 1 (2001).

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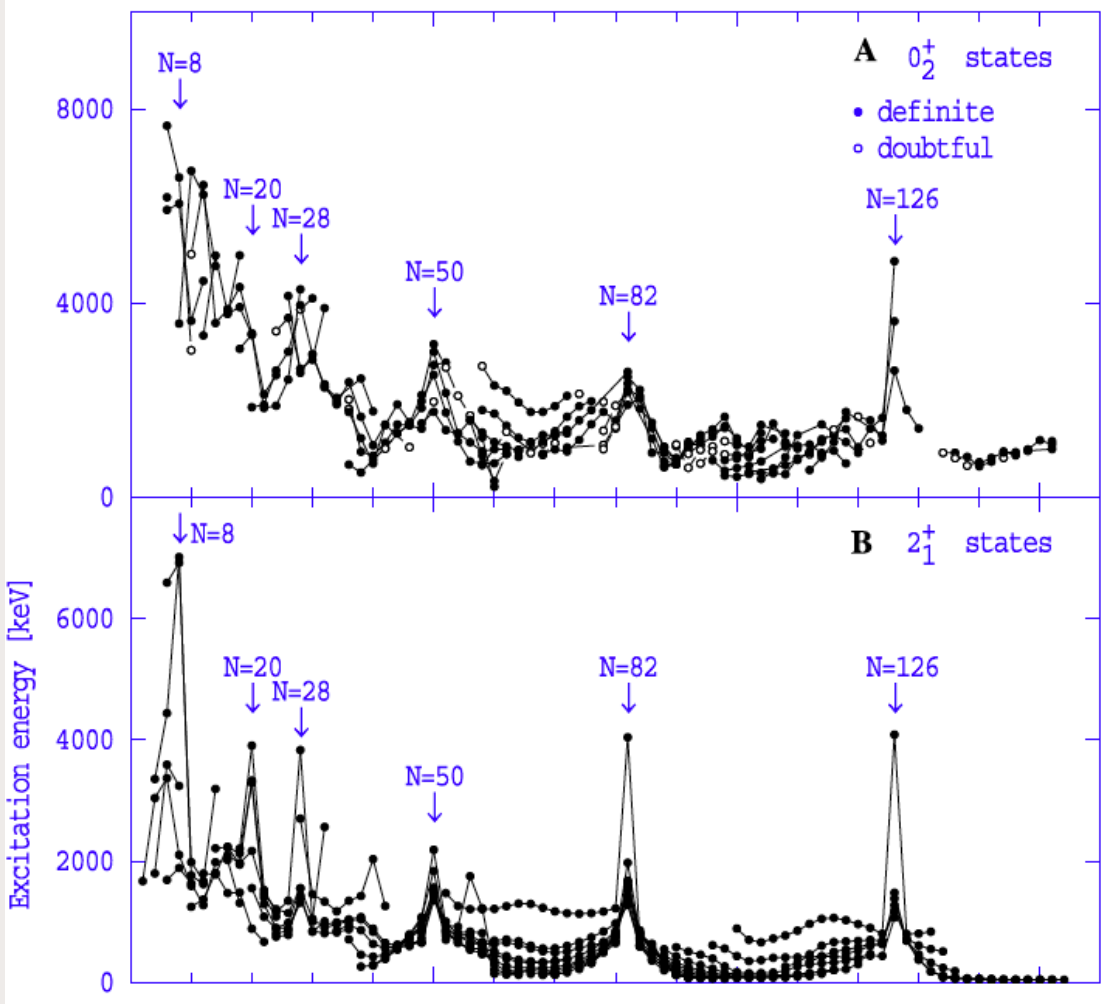

Figure from T. Kibédi and R.H. Spear, Atomic Data and Nuclear Data Tables 89, 77 (2005).

TRIUMF

Evolution of Structure

- Peaks/troughs at magic numbers
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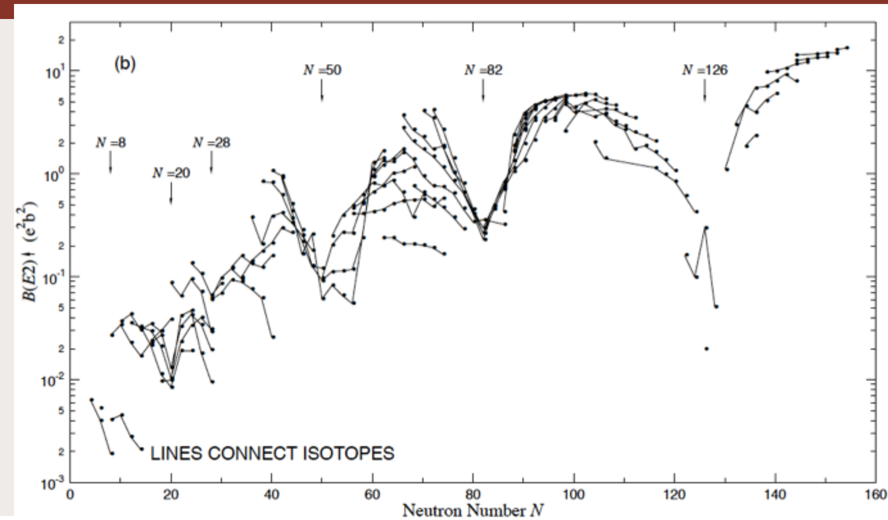

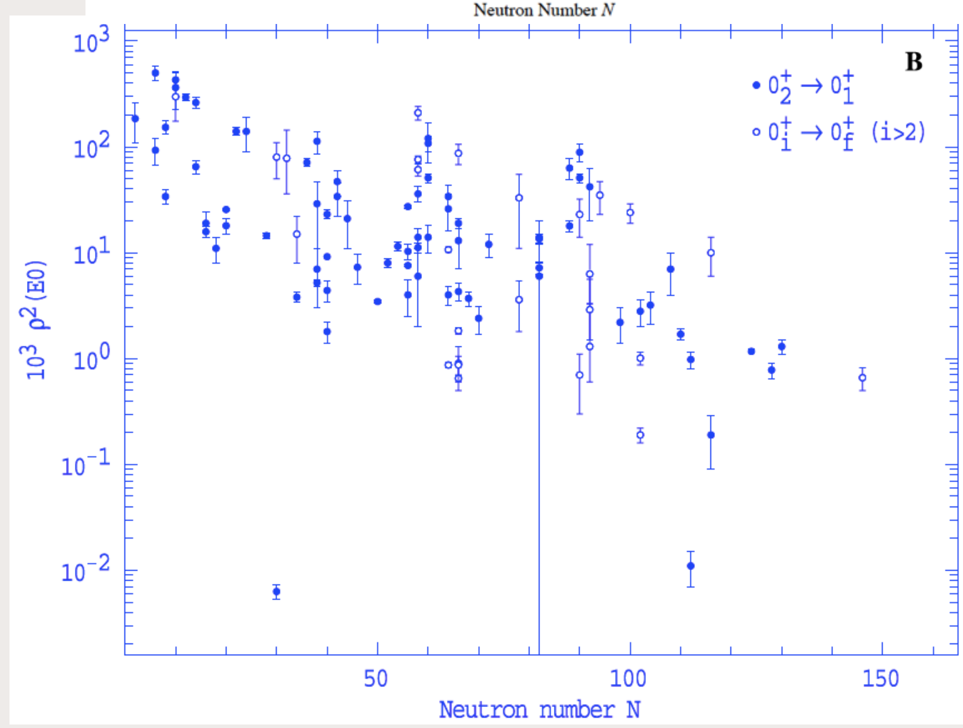

Figures from S. Raman, C.W. Nestor, JR., P. Tikkanen, Atomic Data and Nuclear Data Tables 78, 1 (2001), and T. Kibédi and R.H. Spear, Atomic Data and Nuclear Data Tables 89, 77 (2005).

Theoretical Interpretation

- Shell Model

  J.L. Wood, Nucl. Phys. A 651, 323 (1999).

$$\rho^2 = 0.5A^{-\frac{2}{3}}$$

- Beta Vibration

  P.E. Garrett, J. Phys. G: Nucl. Part. Phys. 27, R1 (2001).

$$\rho^2(\mathrm{E0}; n_\beta = 1 \to n_\beta = 0) = \frac{9}{8\pi^2} Z^2 \beta_0^4 \frac{E(2_1^+)}{E(0_\beta^+)}$$

- IBA

  P. Van Isacker, Nuclear Data Sheets 120, 119 (2014).

  S. Zerguine et al., PRL 101, 022502 (2008).

  G. Ilie and R.F.Casten, Phys. Rev. C 84, 064320 (2011).

TRIUMF

Theoretical Interpretation

Shell Model

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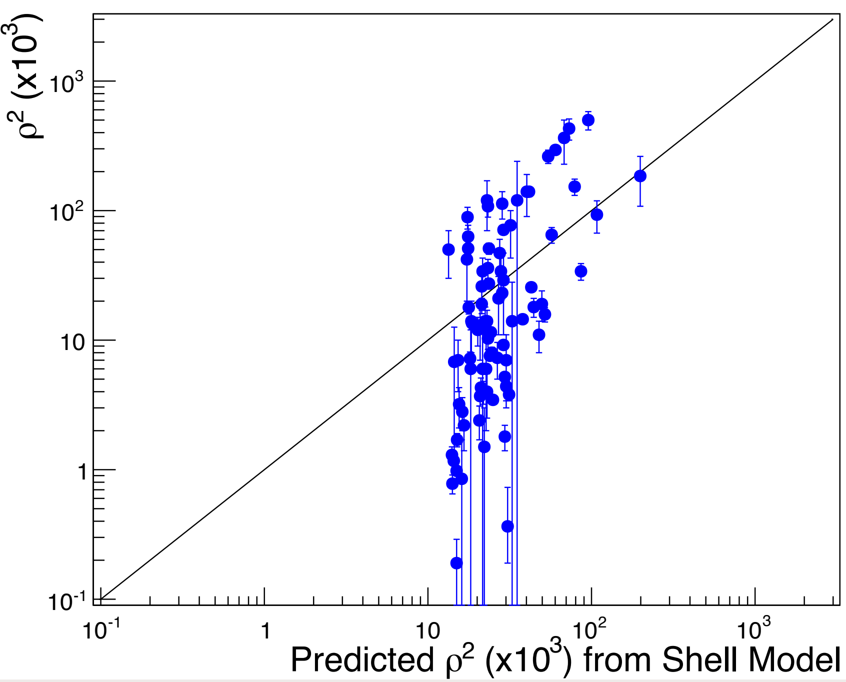

J.L. Wood, Nucl. Phys. A 651, 323 (1999).

Beta Vibration

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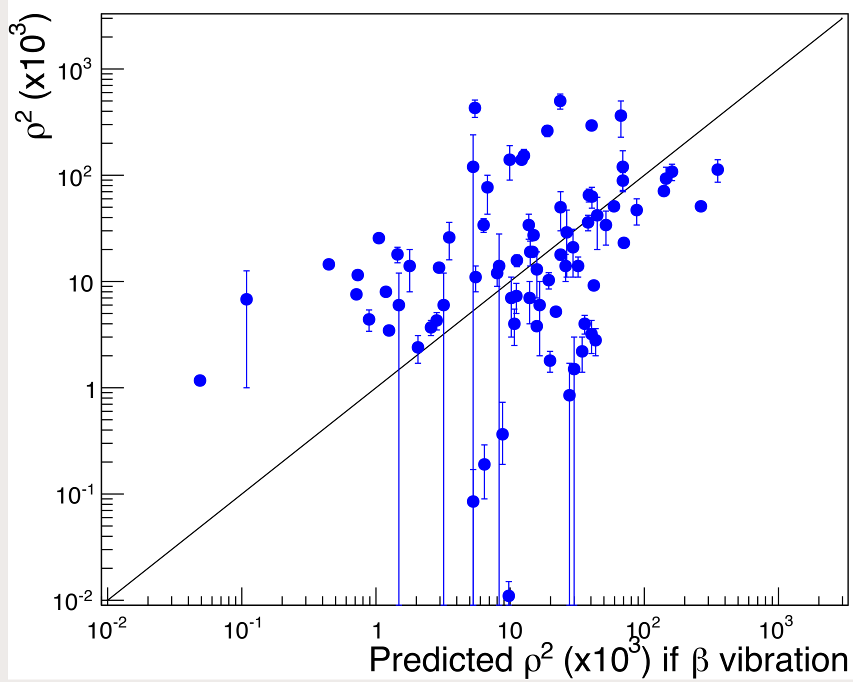

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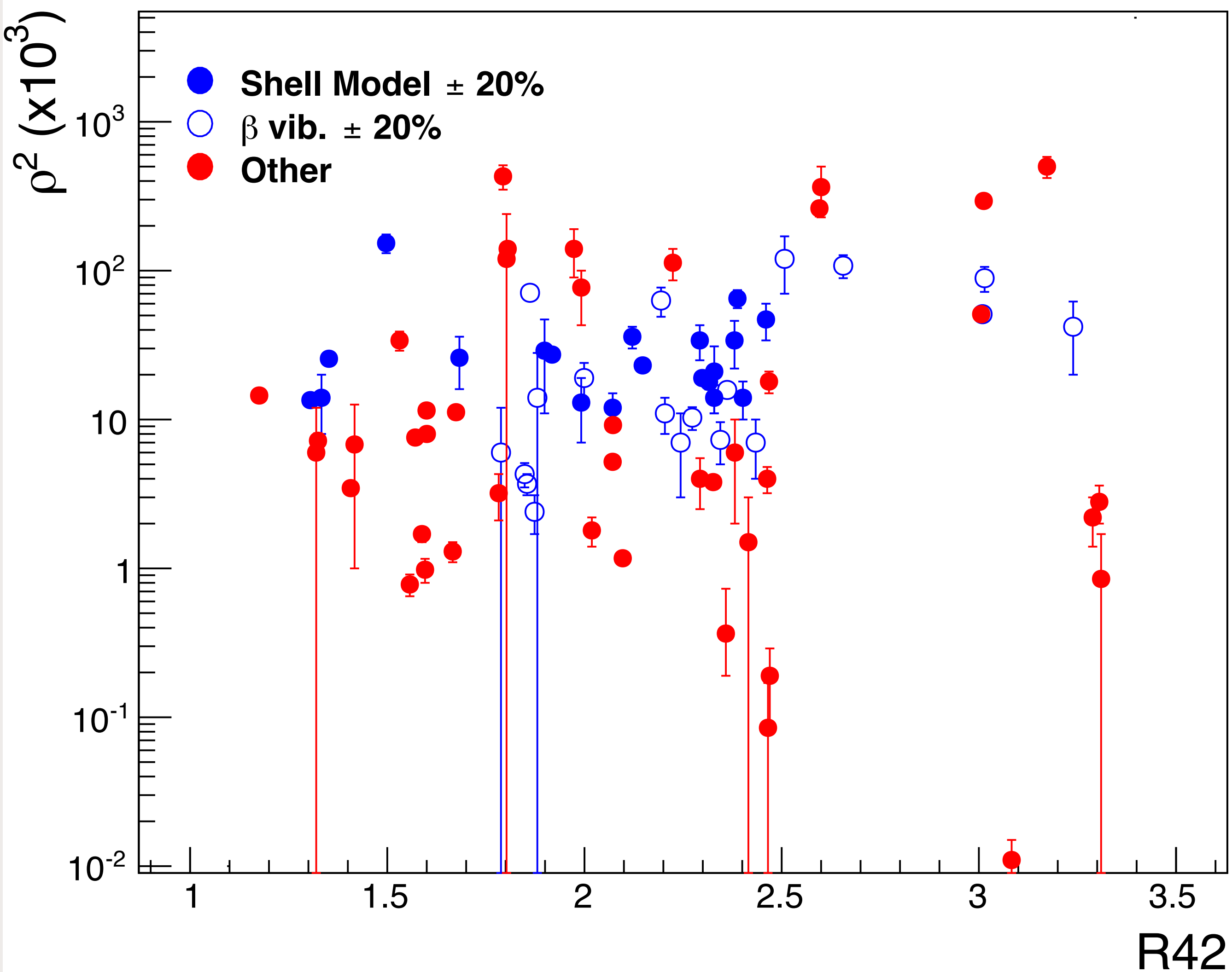
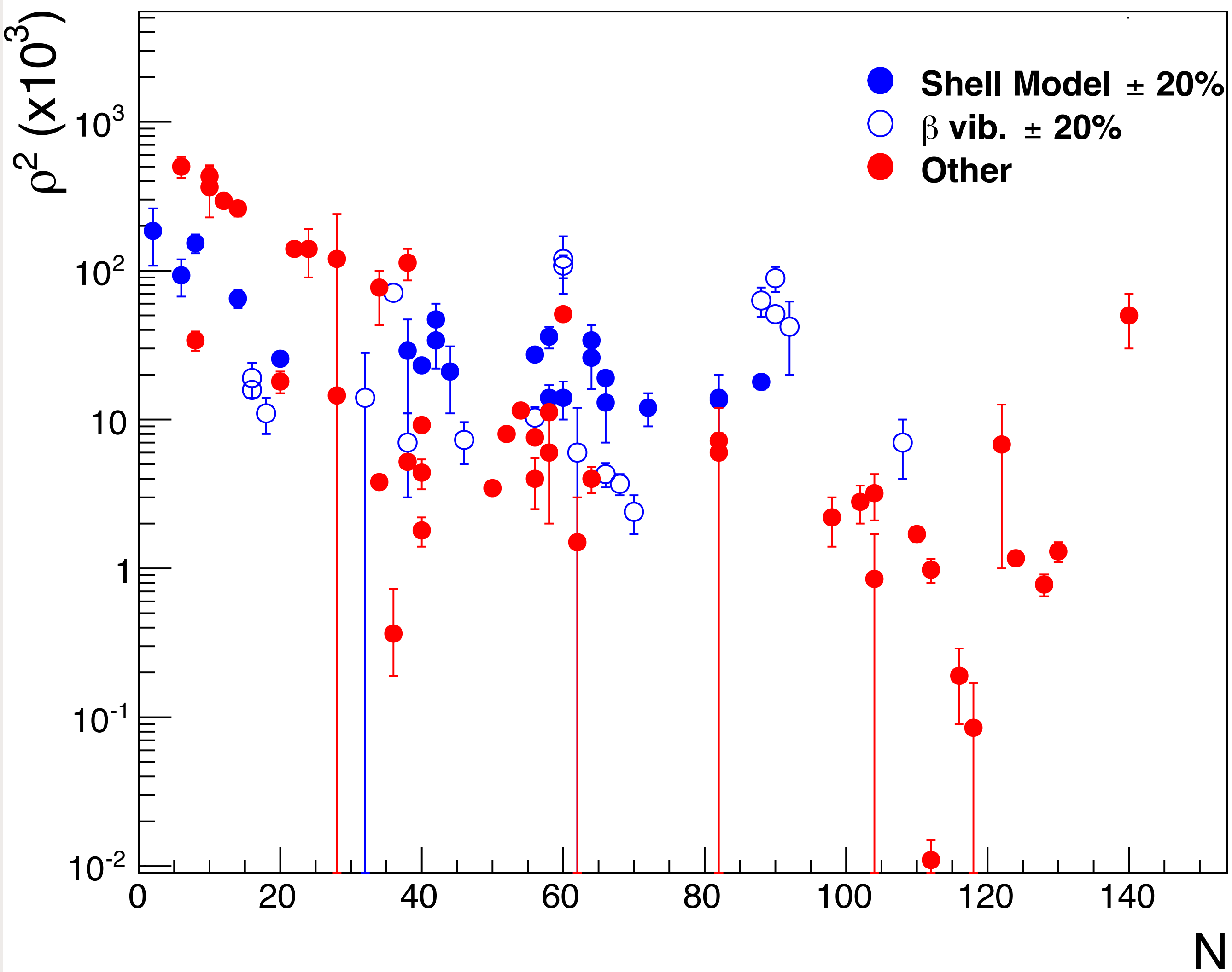

Shell Model ± 20%
β vib. ± 20%
Other
ρ^2 (x10^3)
10^3
10^2
10
1
10^{-1}
10^{-2}
1
1.5
2
2.5
3
3.5
R42

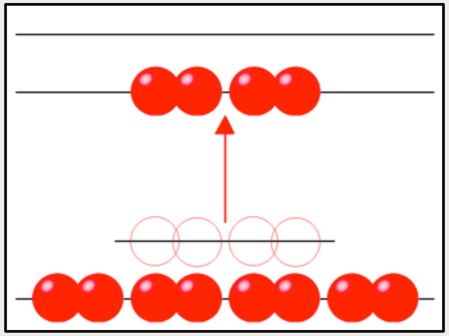


Shell Model ± 20%
β vib. ± 20%
Other
$\rho^2\ (\times 10^3)$
10^3
10^2
10
1
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
N

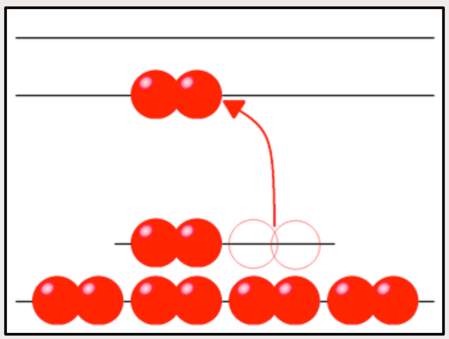
TRIUMF

Particle-Hole Excitations

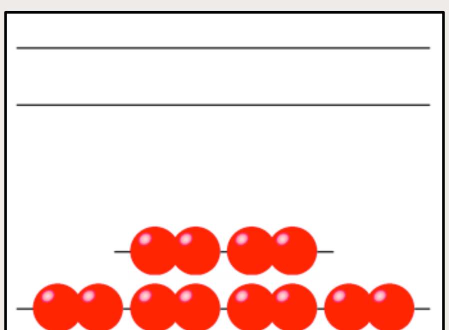
K.Heyde *et al.*, PRC 25, 3160 (1982)



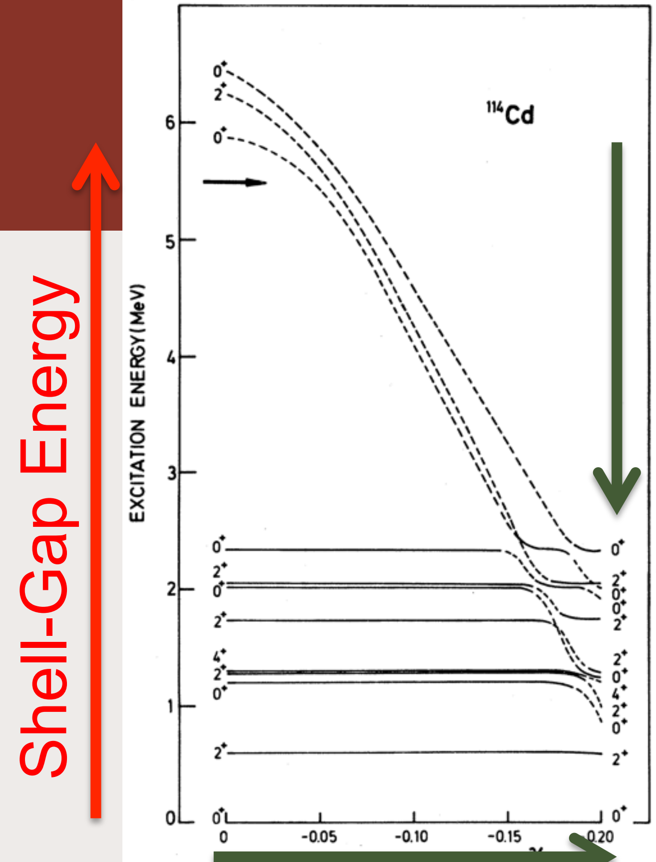
4p - 4h



2p - 2h



Ground State

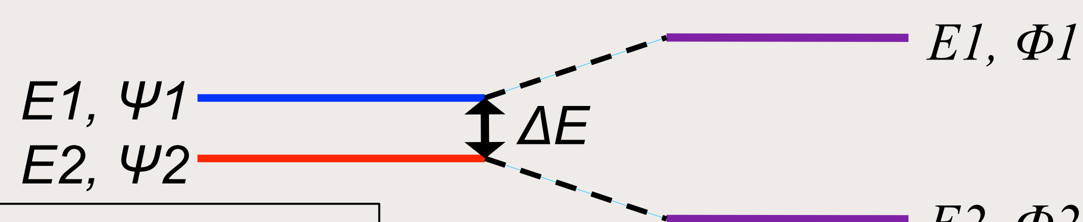


pn interaction strength

Effect of attractive proton-neutron residual interaction

State mixing

Unperturbed Wavefunctions → Mixing → Mixed Wavefunctions



Where: $\alpha^2 + \beta^2 = 1$

The amount of mixing depends on the mixing amplitude and the initial separation energy of the states (ΔE)

TRIUMF

Co-Existing Nuclear Shapes

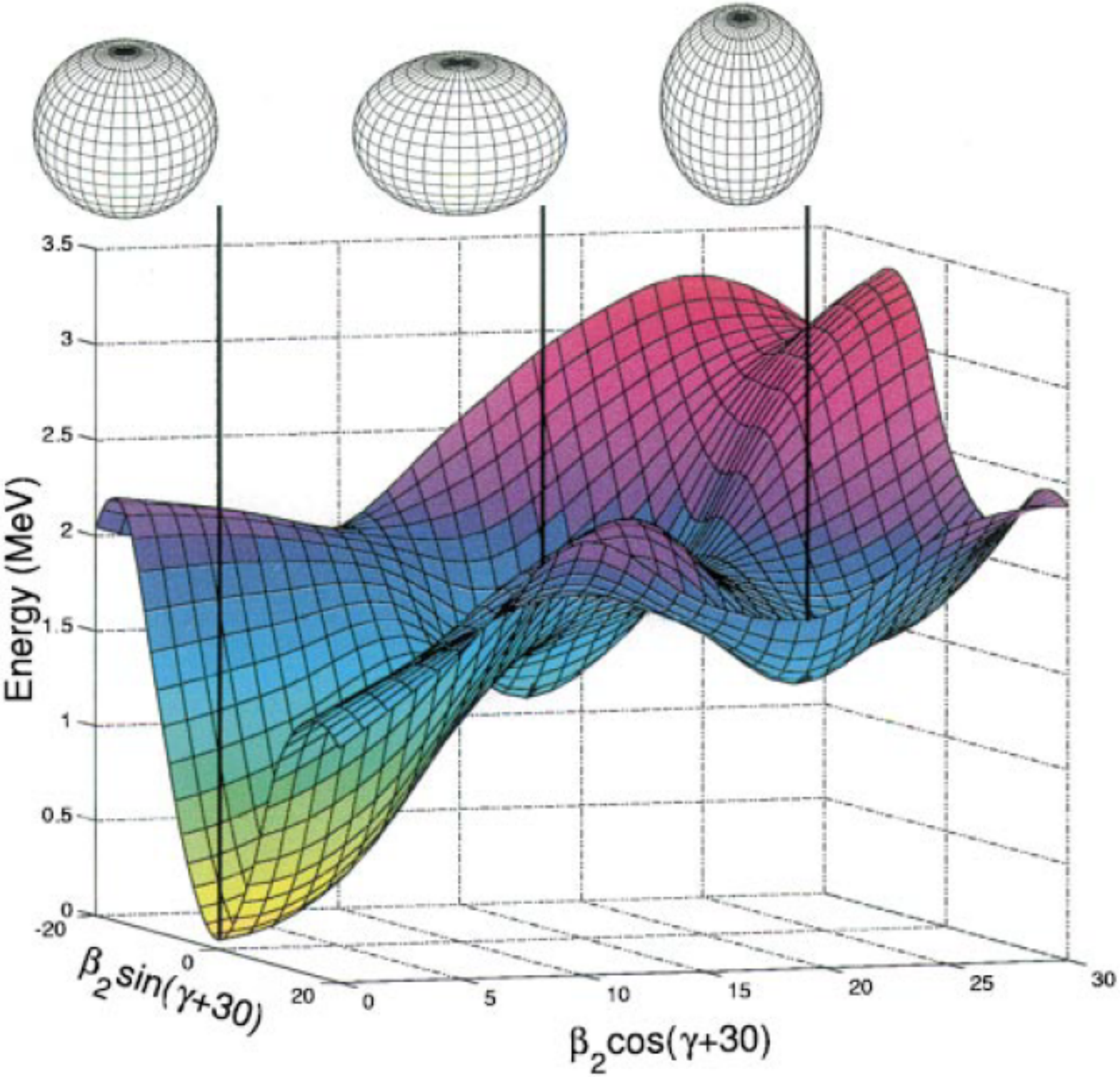


Figure from A.N. Andreyev, *et al*., Nature 405, 430 (2000).

Letter to Nature, May 2000
"A triplet of differently shaped spin-zero states in the atomic nucleus ^{186}Pb"

^{186}Pb: Z=82, N=104

Recent review by Heyde and Wood, Reviews of Modern Physics 83, 1467 (2011)

Review notes severe lack of experimental data:
-particle transfer
-mean square charge radii
-*B(E2)*, $\langle Q^2 \rangle$
-*E0* strengths

E0 Transition Strengths

Recall that:

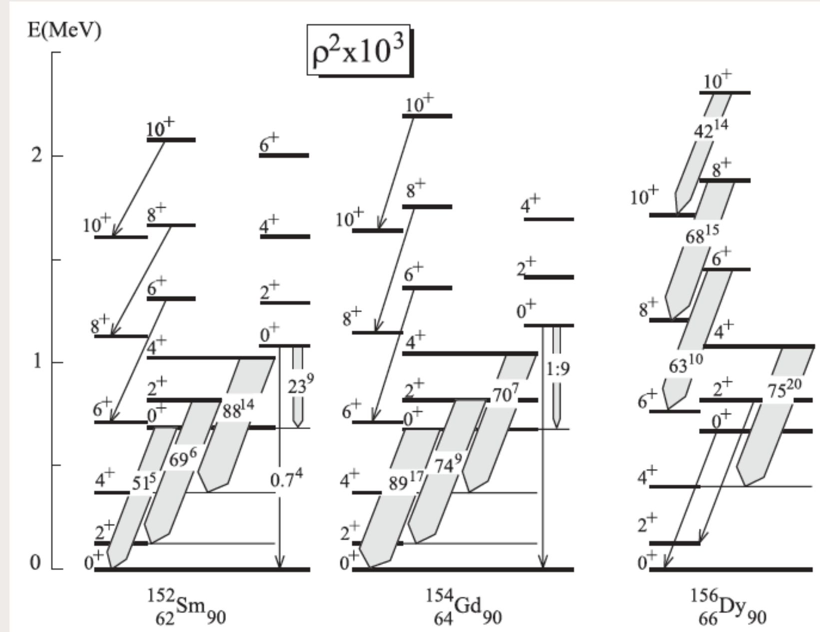
$$\Phi_1 = \alpha\Psi_1 + \beta\Psi_2$$
$$\Phi_2 = -\beta\Psi_1 + \alpha\Psi_2$$

where: $\alpha^2 + \beta^2 = 1$

For a transition between these states the $E0$ strength, $\rho_{if} = \frac{\langle \Phi_1 | \mathrm{m}(E0) | \Phi_2 \rangle}{eR^2}$

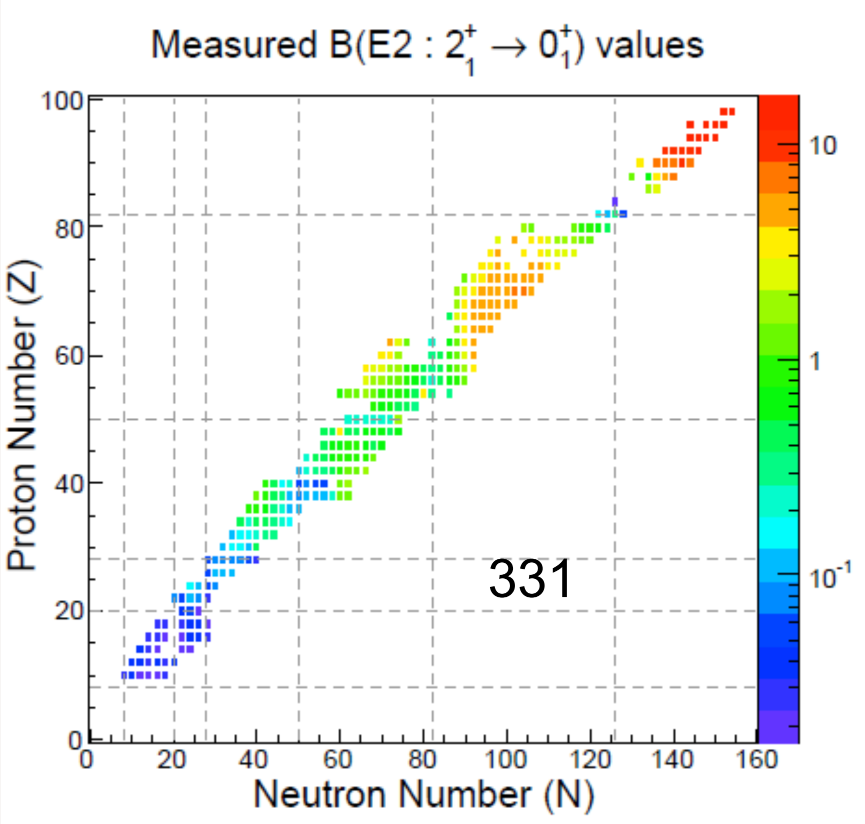
where e = electric charge and $R = 1.2A^{\frac{1}{3}} fm$ and

$$\langle \Phi_1 | \mathrm{m}(E0) | \Phi_2 \rangle \simeq \alpha\beta\Delta\langle r^2 \rangle$$



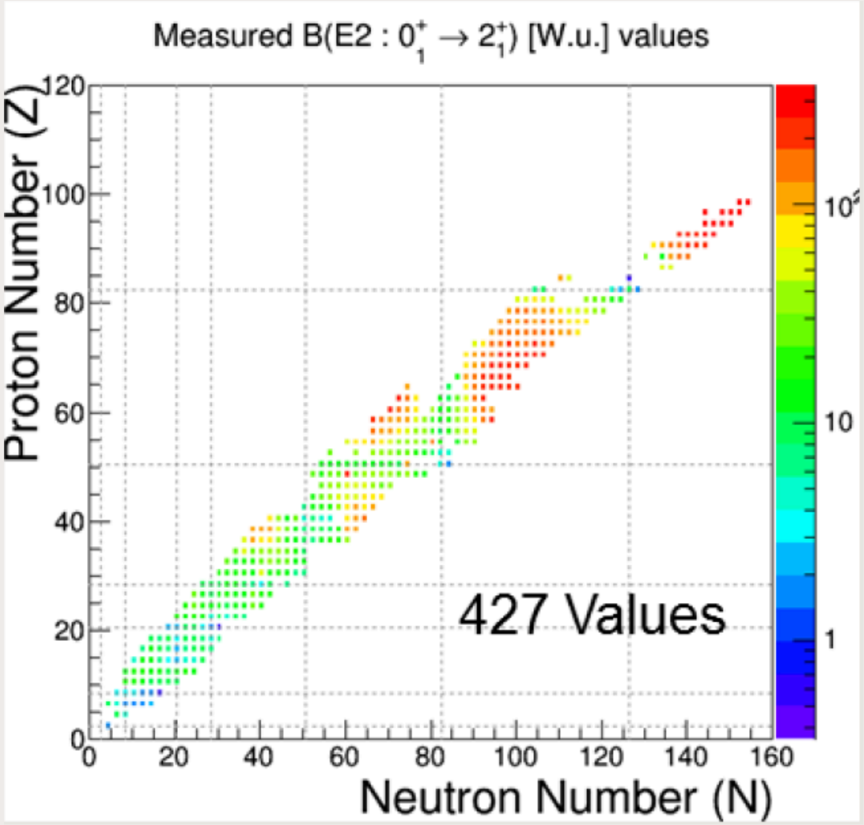
Therefore the *E0* strength is directly proportional to the difference in deformation and the amount of mixing

Measured *B(E2)* values



Raman et al., Data Nucl. Data Tables, 78 (2001)

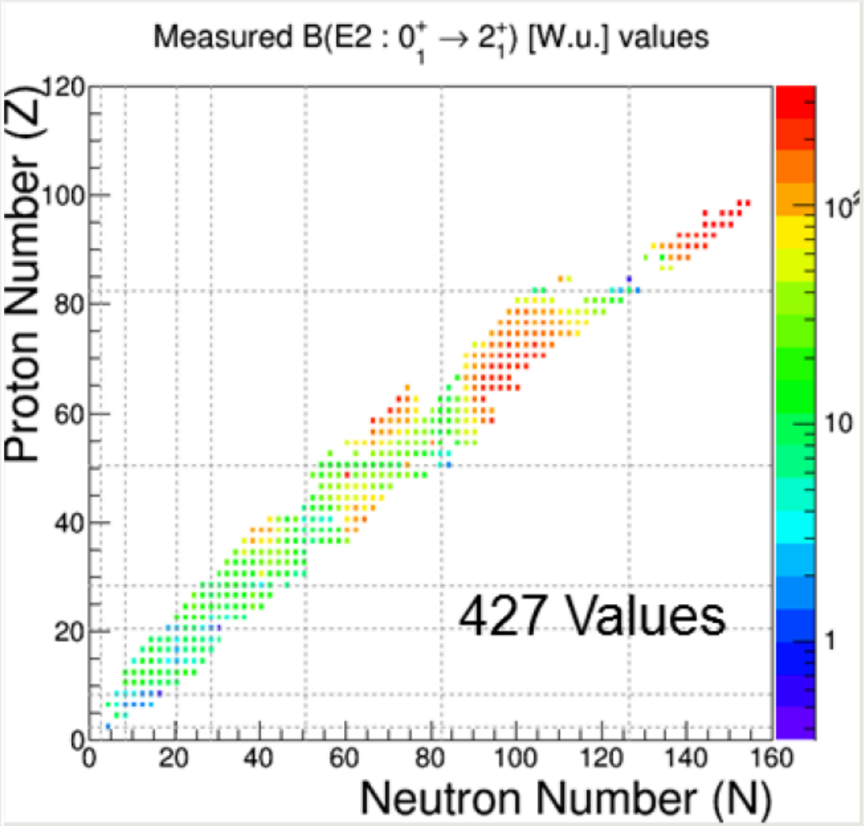
Measured *B(E2)* values

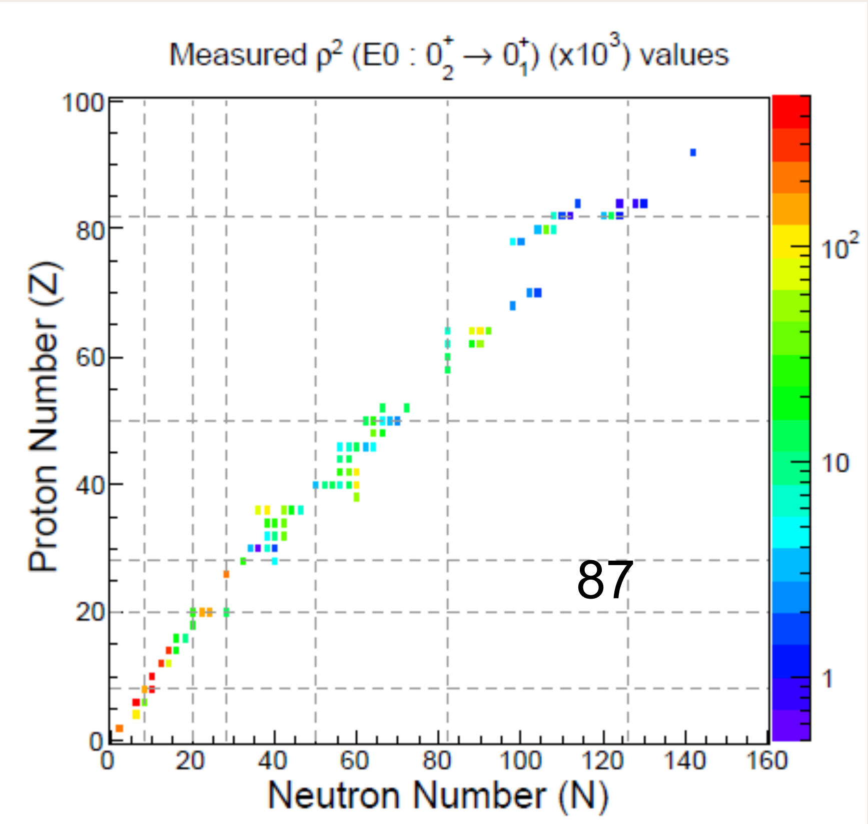


Raman et al., Data Nucl. Data Tables, 78 (2001)

Pritychenko et al., arXiv:1312.5975 [nucl-th] (Dec 2014)

Measured ρ^2 values





Raman et al., Data Nucl. Data Tables, 78 (2001)

Kibedi & Spear, Data Nucl. Data Tables, 89, (2005)

Pritychenko et al., arXiv:1312.5975 [nucl-th] (Dec 2014)

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Measuring ρ^2 values

$$\rho^2(\mathrm{E0}) = q_K^2(\mathrm{E0/E2}) \times \frac{\alpha_K(\mathrm{E2})}{\Omega_K(\mathrm{E0})} \times W_\gamma(\mathrm{E2}).$$

ρ^2 from branching ratio and parent state partial decay constant of *E2* gamma ray

$$q_K^2(\mathrm{E0/E2}) = \frac{I_K(\mathrm{E0})}{I_K(\mathrm{E2})}$$

q^2 found from ICE spectroscopy

$$q_K^2(\mathrm{E0/E2}) = \frac{I_\pi(\mathrm{E0})}{I_\pi(\mathrm{E2})} \times \frac{\Omega_K(\mathrm{E0})}{\Omega_\pi(\mathrm{E0})} \times \frac{\alpha_\pi(\mathrm{E2})}{\alpha_K(\mathrm{E2})}$$

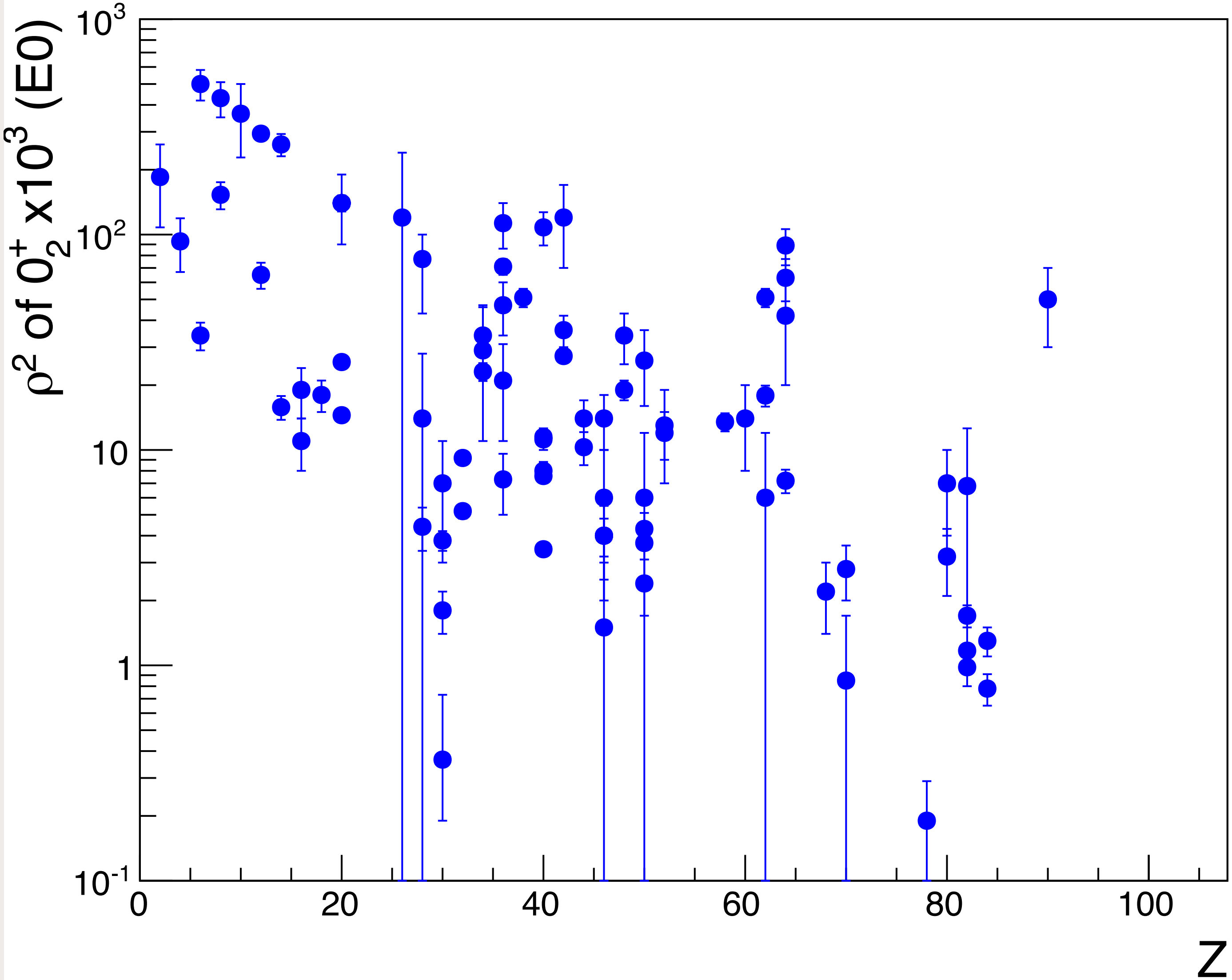
or from IPF spectroscopy

W_γ(E2) can be found from Coulex or from **direct lifetime measurement**

Present Knowledge of *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

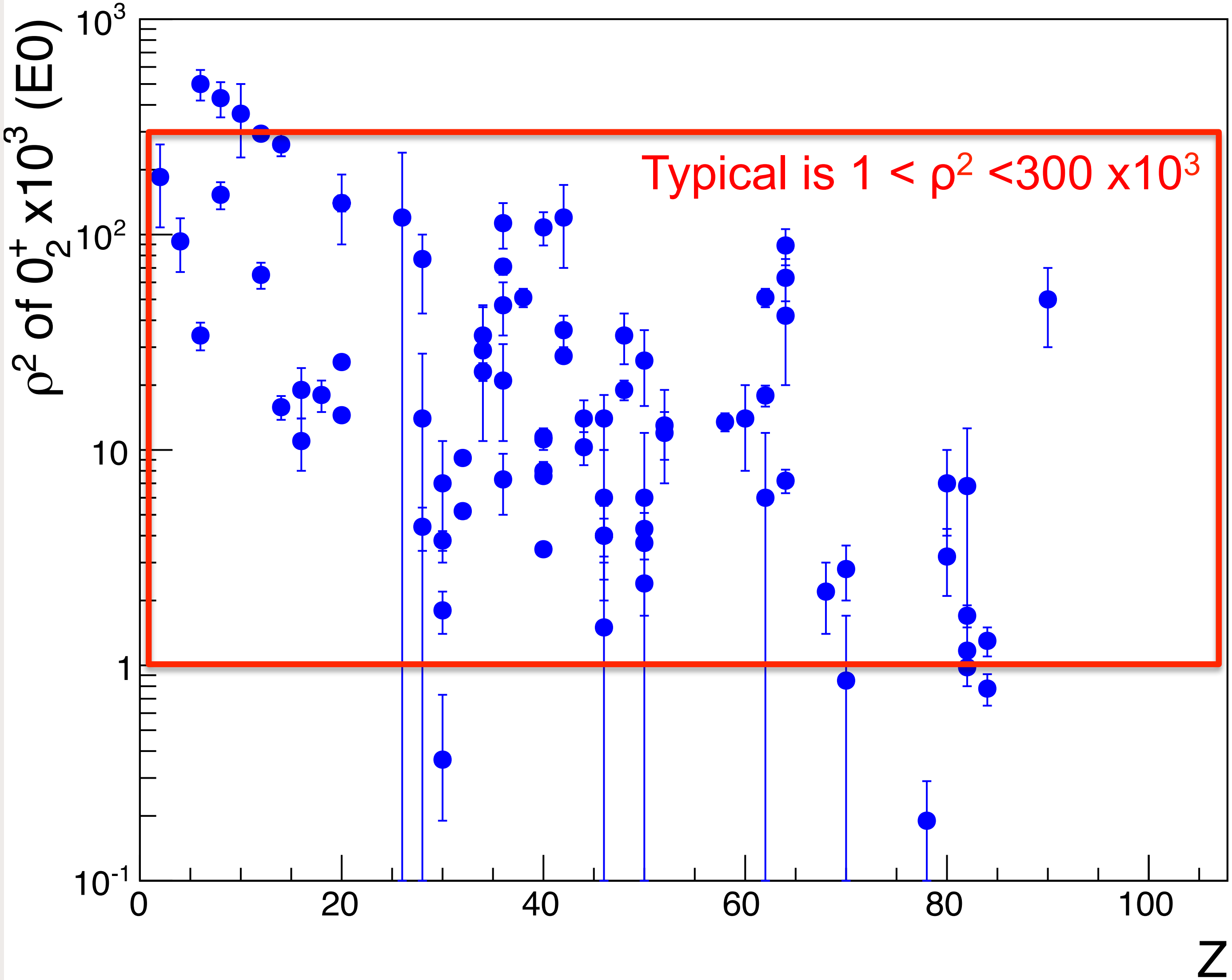
87 ρ^2 values of first excited 0^+ to GS 0^+ known



Present Knowledge of *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

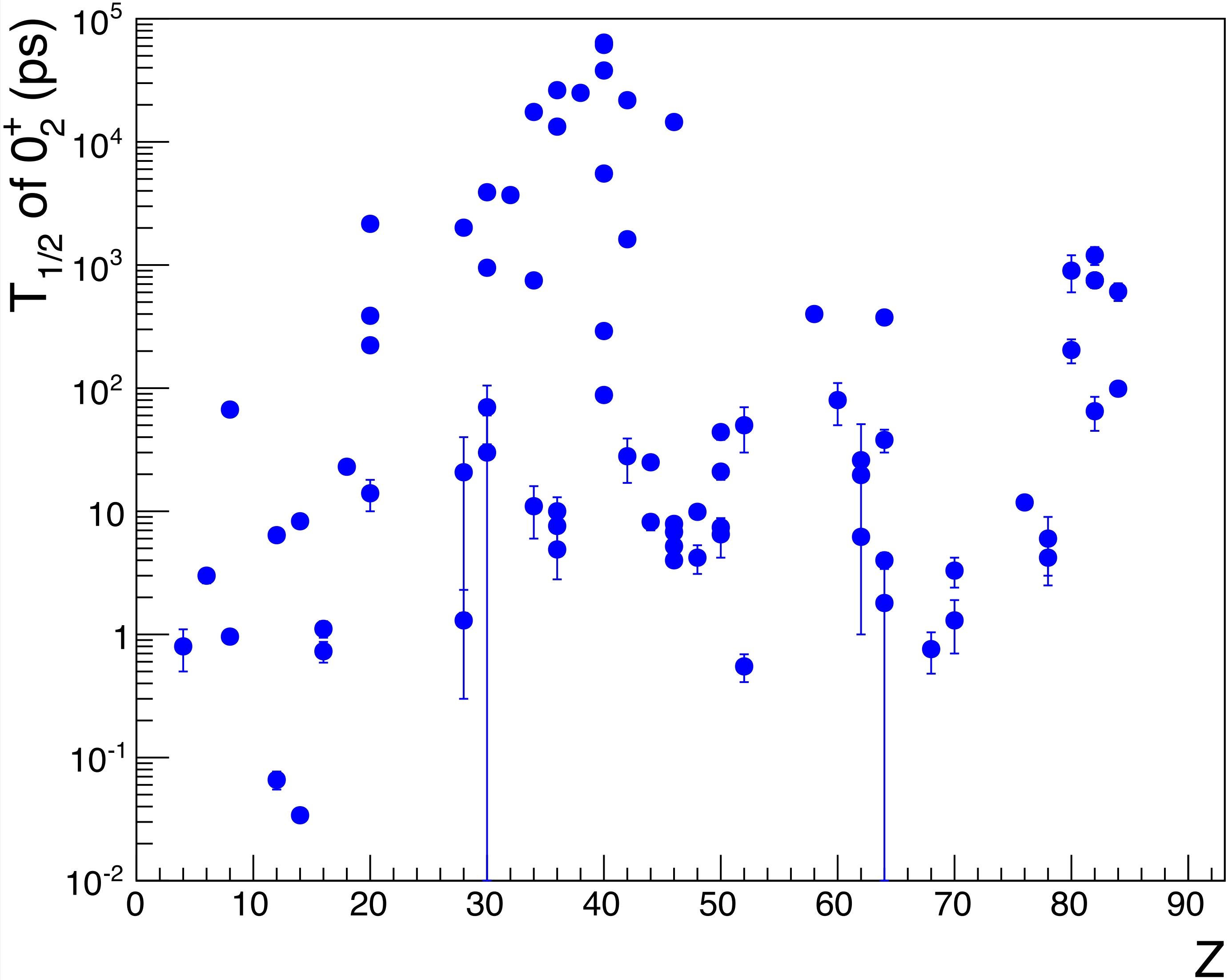
87 ρ^2 values of first excited 0^+ to GS 0^+ known



Present Knowledge of *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

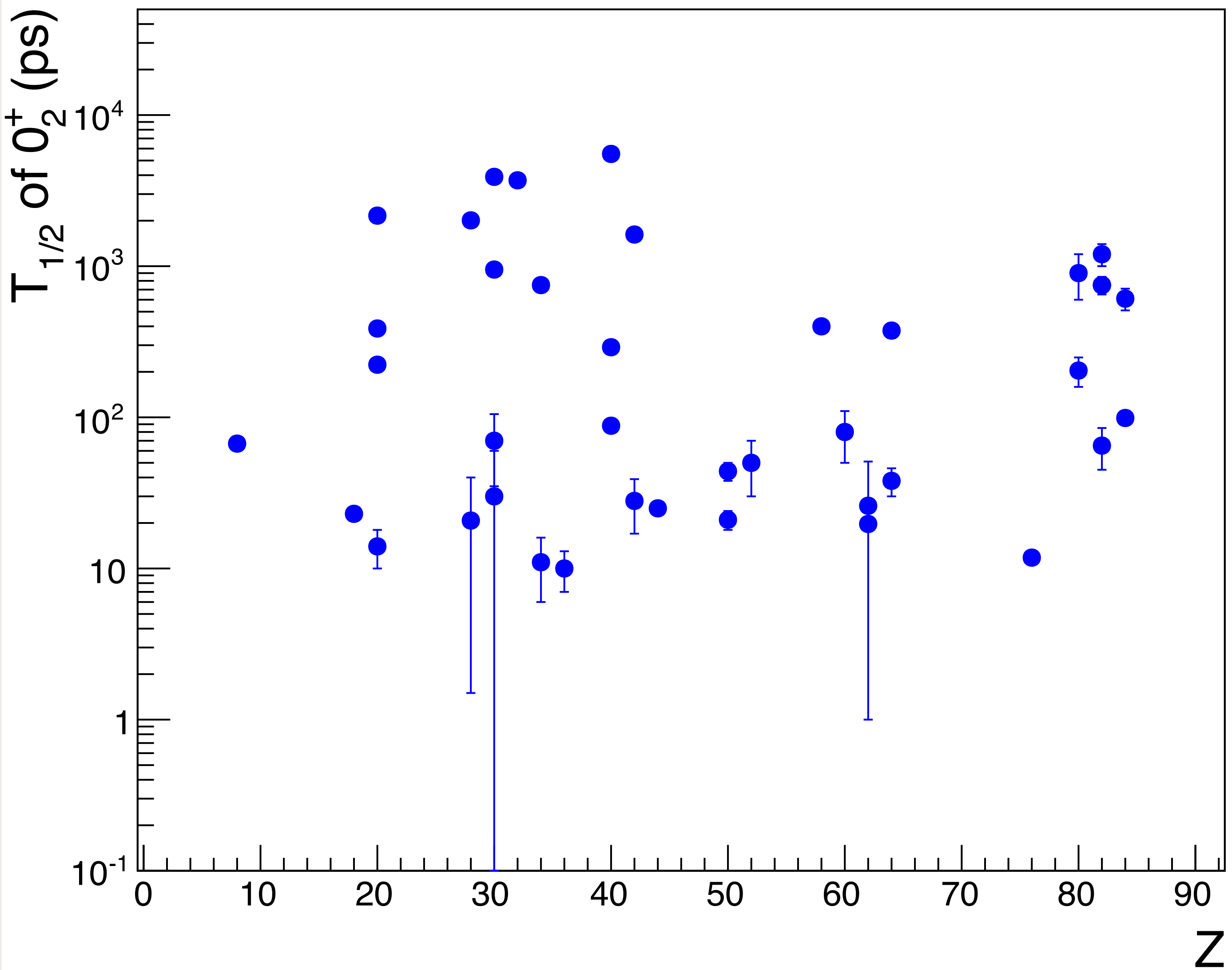
87 ρ^2 values of first excited 0^+ to GS 0^+ known



Present Knowledge of *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

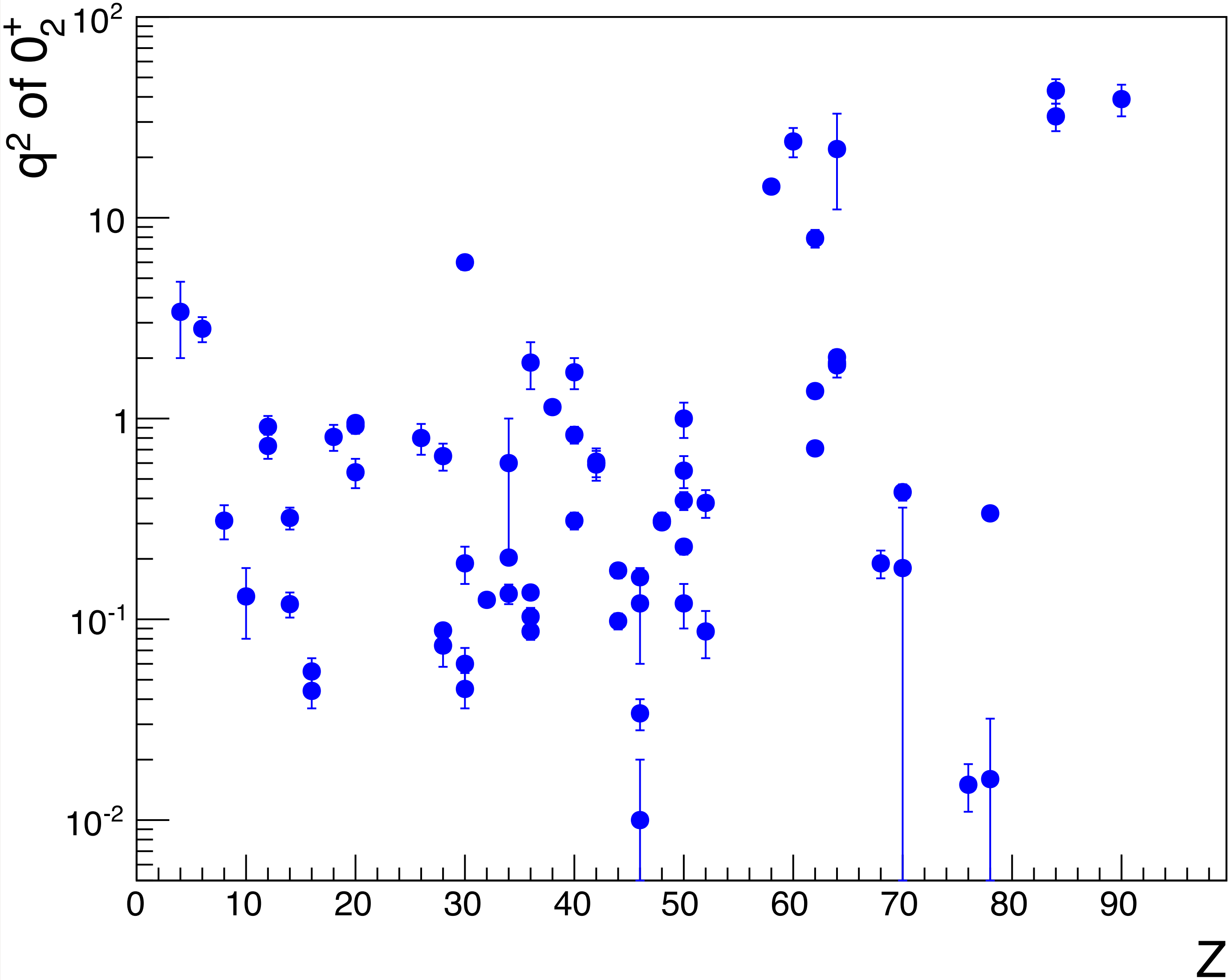
40 ρ^2 values of first excited 0^+ to GS 0^+ known with 10ps < $T_{1/2}$ < 10ns



Present Knowledge of *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

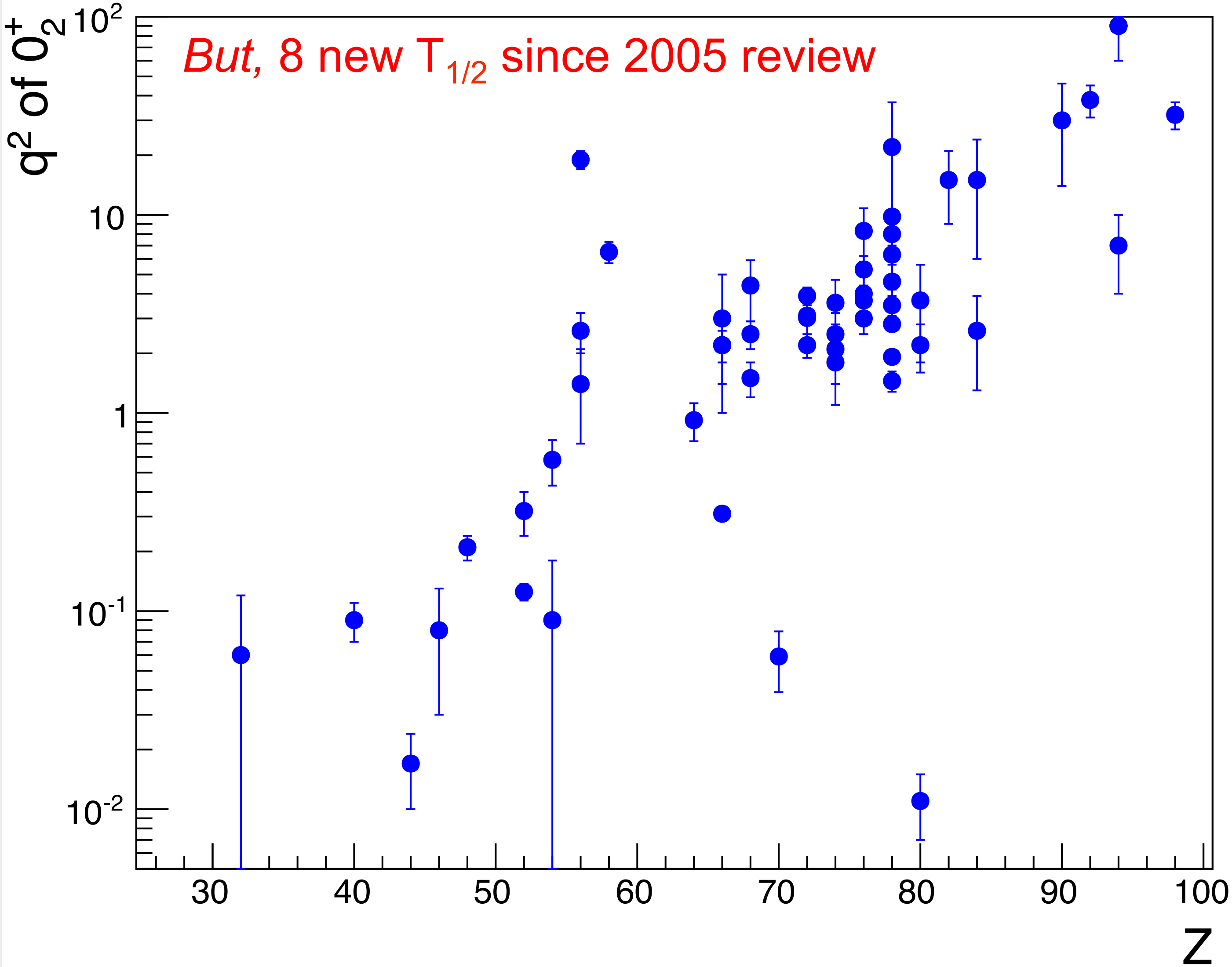
87 ρ^2 values of first excited 0^+ to GS 0^+ known



Half-life required to determine *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

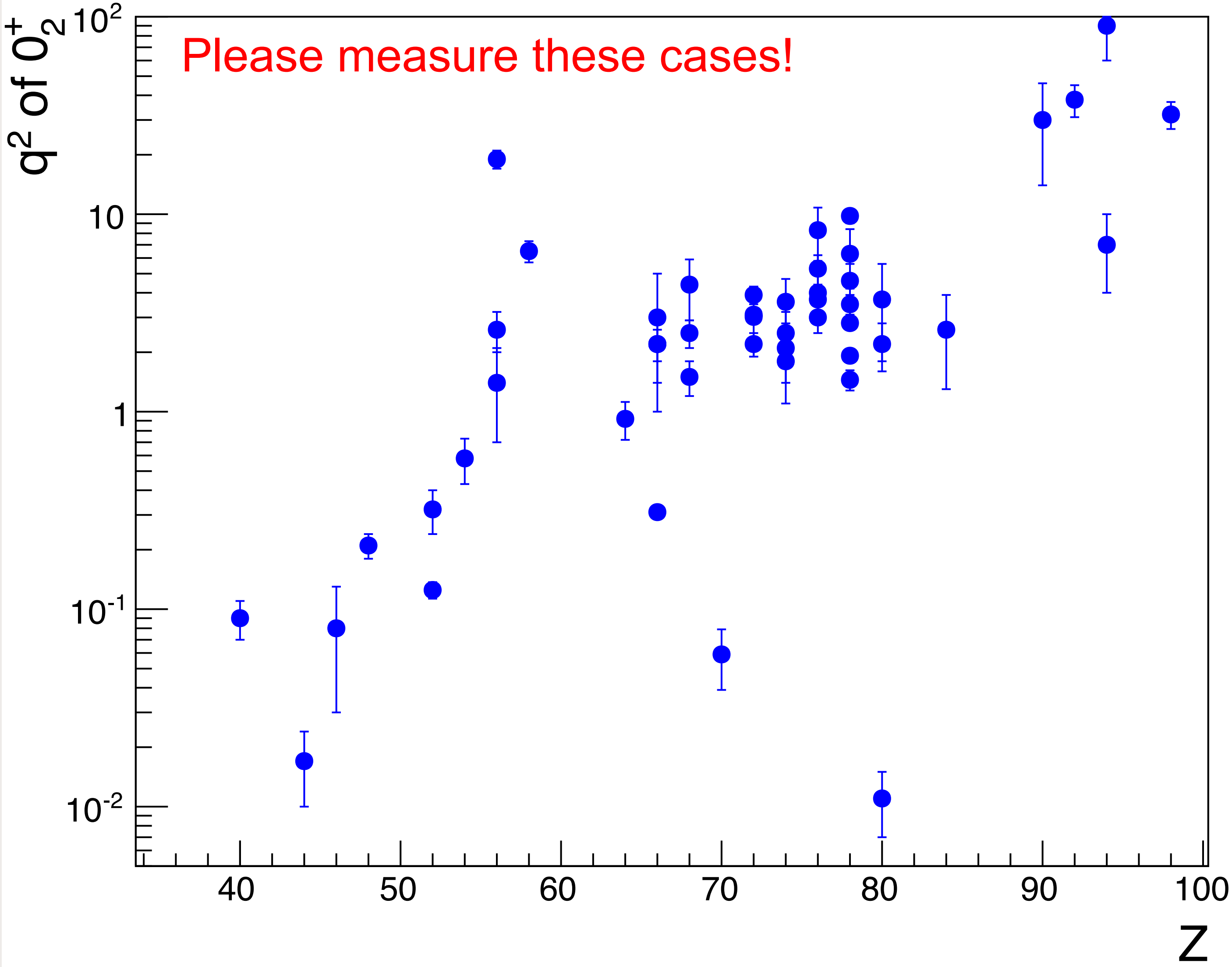
59 q^2 values known but no $T_{1/2}$ of first excited 0^+ to GS 0^+ known



Half-life required to determine *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

51 q^2 values known but no $T_{1/2}$ of first excited 0^+ to GS 0^+ known



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Half-life required to determine *E0* strengths

Kibédi and Spear,
Atomic. Data and Nucl. Data Tables 89, 77 (2005).

51 q^2 values known but no $T_{1/2}$ of first excited 0^+ to GS 0^+ known

Please measure these half lives!

Table 1: Medium-mass and Rare-earth region.

Nucleus	Energy 0_2^+ (keV)	Energy $0_2^+ \to 2_1^+$ (keV)	q^2
$^{88}_{40}Zr_{48}$	1521.4	464.37	0.09 (0.02)
$^{106}_{44}Ru_{62}$	990.62	720.55	0.017 (0.007)
$^{112}_{46}Pd_{66}$	890.4	541.61	0.08 (0.05)
$^{110}_{48}Cd_{62}$	1473.07	815.308	0.21 (0.03)
$^{120}_{52}Te_{68}$	1103.1	542.662	0.32 (0.08)
$^{122}_{52}Te_{70}$	1357.4	793.307	0.125 (0.012)
$^{118}_{54}Xe_{64}$	830.36	493.04	0.58 (0.15)
$^{124}_{56}Ba_{68}$	898	668.09	1.4 (0.7)
$^{134}_{56}Ba_{78}$	1760.56	1155.83	19 (2)
$^{136}_{56}Ba_{80}$	1578.99	760.493	2.6 (0.6)
$^{138}_{58}Ce_{80}$	1476.93	688.186	6.5 (0.8)
$^{150}_{64}Gd_{86}$	1207.1	569	0.92 (0.2)
$^{154}_{66}Dy_{88}$	660.55	326.21	2.2 (0.4)
$^{156}_{66}Dy_{90}$	675.6	537.83	3 (2)
$^{160}_{66}Dy_{94}$	1279.94	1193.15	2.2 (0.8)
$^{162}_{66}Dy_{96}$	1400.26	1319.6	0.31 (0.02)
$^{158}_{68}Er_{90}$	806.38	614.23	1.5 (0.3)
$^{162}_{68}Er_{94}$	1087.16	985.12	4.4 (1.5)
$^{164}_{68}Er_{96}$	1246.04	1154.66	2.5 (0.4)
$^{170}_{70}Yb_{100}$	1069.35	985.095	0.059 (0.02)

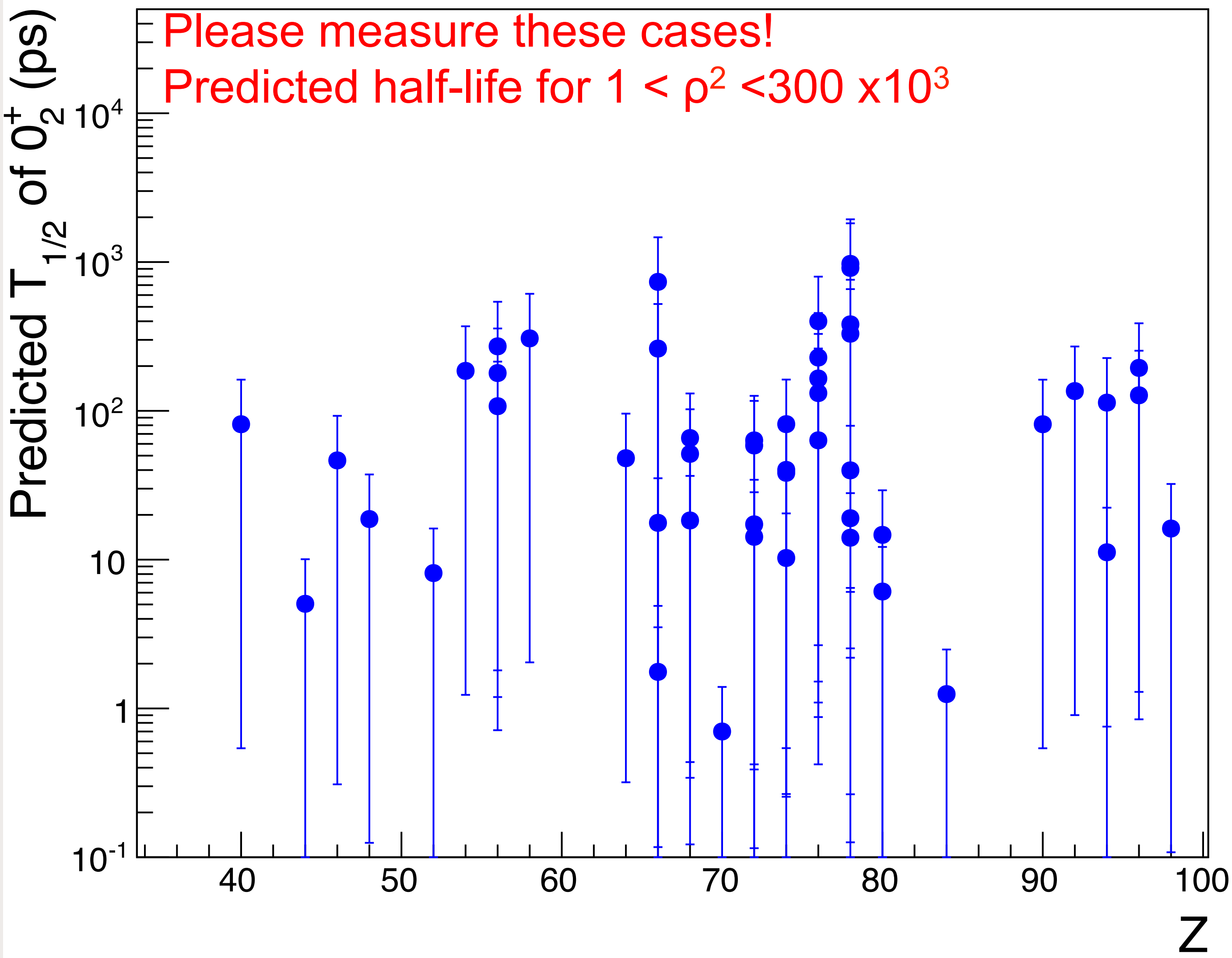
Table 2: Transitional metals to Actinides.

Nucleus	Energy 0_2^+ (keV)	Energy $0_2^+ \to 2_1^+$ (keV)	q^2
$^{172}_{72}Hf_{100}$	871.3	776.08	3.9 (0.4)
$^{174}_{72}Hf_{102}$	828.13	737.145	3.1 (1.2)
$^{176}_{72}Hf_{104}$	1149.94	1061.59	2.2 (0.3)
$^{178}_{72}Hf_{106}$	1199.38	1106.2	3.02 (0.13)
$^{172}_{74}W_{98}$	761.6	638.4	3.6 (1.1)
$^{174}_{74}W_{100}$	792.2	679.2	2.1 (0.7)
$^{176}_{74}W_{102}$	843.3	735	2.5 (0.7)
$^{182}_{74}W_{108}$	1135.82	1035.71	1.8 (0.7)
$^{172}_{76}Os_{96}$	758.27	530.5	8.3 (2.5)
$^{174}_{76}Os_{98}$	545.3	386.7	5.3 (0.9)
$^{176}_{76}Os_{100}$	601.2	466.1	3.7 (0.5)
$^{178}_{76}Os_{102}$	650.4	518	4 (1)
$^{180}_{76}Os_{104}$	736.3	604.19	3 (0.5)
$^{180}_{78}Pt_{102}$	478.13	324.92	9.8 (0.8)
$^{182}_{78}Pt_{104}$	499.5	344.9	4.6 (1)
$^{184}_{78}Pt_{106}$	491.78	328.8	3.5 (0.4)
$^{186}_{78}Pt_{108}$	471.51	279.98	6.3 (2.1)
$^{188}_{78}Pt_{110}$	798.76	533.13	1.92 (0.06)
$^{190}_{78}Pt_{112}$	920.86	625.06	1.45 (0.17)
$^{192}_{78}Pt_{114}$	1195.17	878.663	2.81 (0.2)
$^{190}_{80}Hg_{110}$	1278.6	862.28	3.7 (1.9)
$^{198}_{80}Hg_{118}$	1401.52	989.717	2.2 (0.6)
$^{200}_{80}Hg_{120}$	1029.34	661.401	0.011 (0.004)
$^{210}_{84}Po_{126}$	2608.58	1427.18	2.6 (1.3)
$^{228}_{90}Th_{138}$	831.8	774.041	30 (16)
$^{232}_{92}U_{140}$	691.2	643.628	38 (7)
$^{238}_{94}Pu_{144}$	941.5	897.42	90 (30)
$^{240}_{94}Pu_{146}$	860.7	817.876	7 (3)
$^{244}_{96}Cm_{148}$	984.9	941.935	210 (70)
$^{246}_{96}Cm_{150}$	1174.7	1131.85	220 (30)
$^{250}_{98}Cf_{152}$	1154.3	1111.58	32 (5)

Half-life required to determine *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

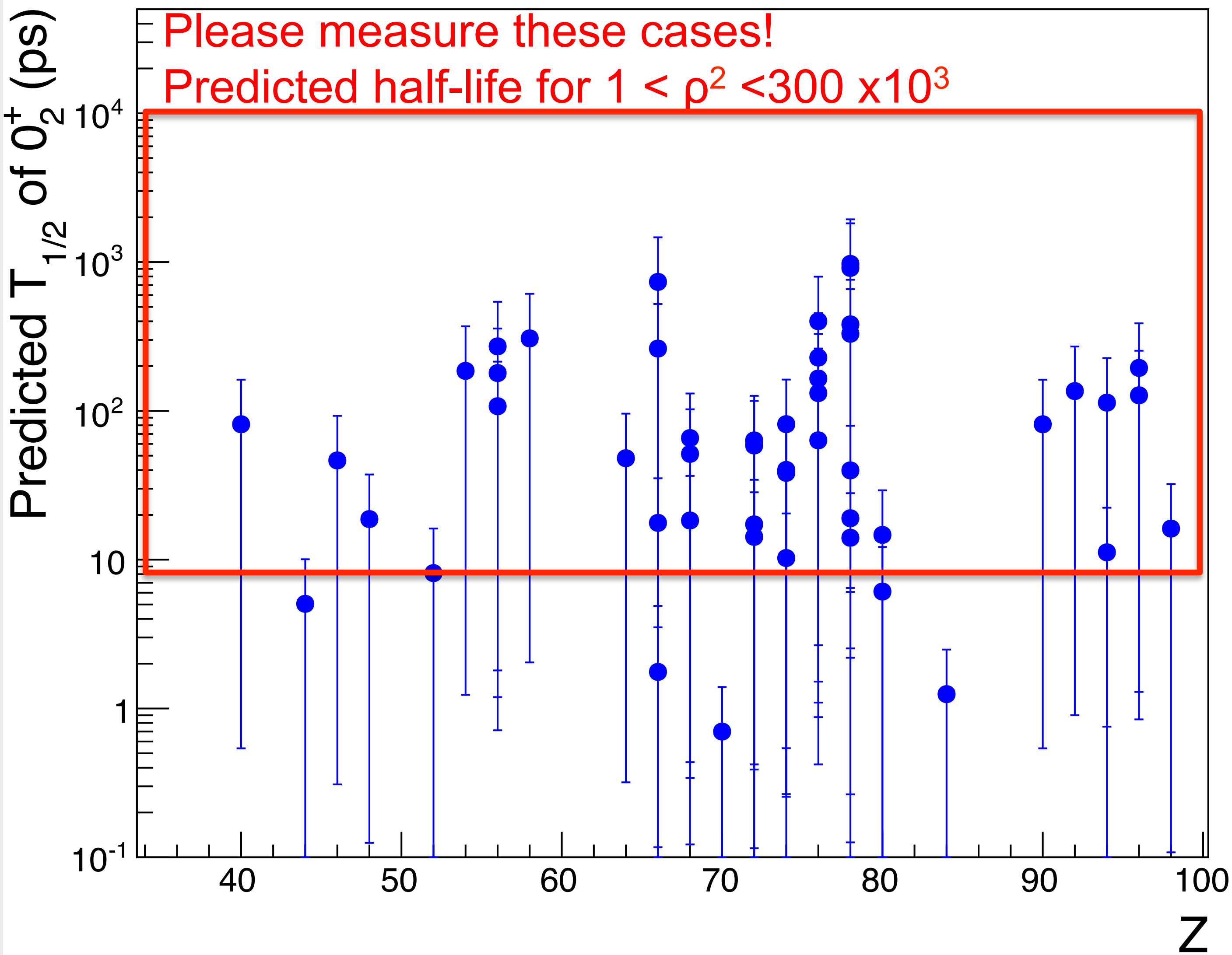
51 q^2 values known but no $T_{1/2}$ of first excited 0^+ to GS 0^+ known



Half-life required to determine *E0* strengths

Kibédi and Spear, Atomic. Data and Nucl. Data Tables 89, 77 (2005).

51 q^2 values known but no $T_{1/2}$ of first excited 0^+ to GS 0^+ known



Summary

- We do not have a universal and consistent description of 0^+ states in nuclei.
- *E0* transition strengths are a sensitive probe of nuclear structure. More data is required to properly map the systematic behavior.
- Half life measurements are an essential ingredient for determining ρ^2.
- 51 cases with electron work already completed.

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Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Thank you!
Merci

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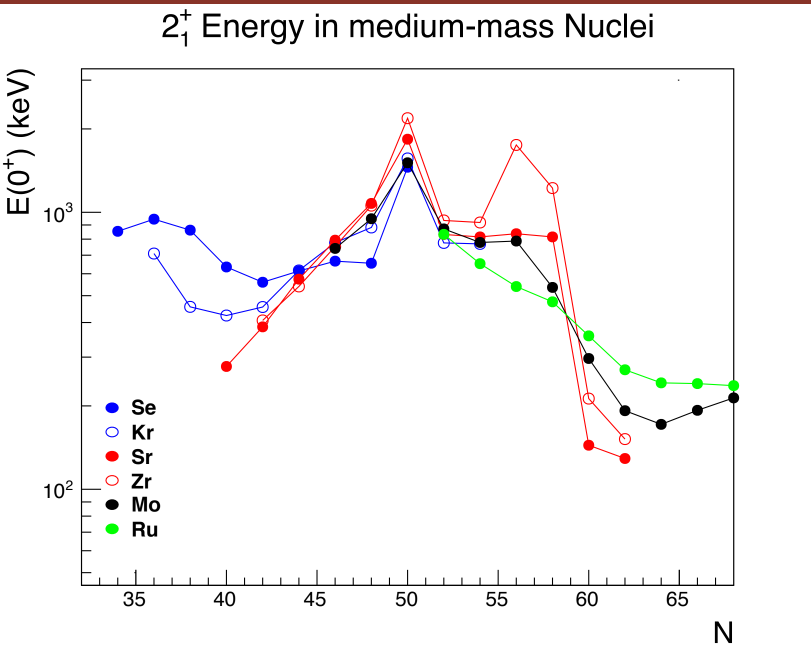
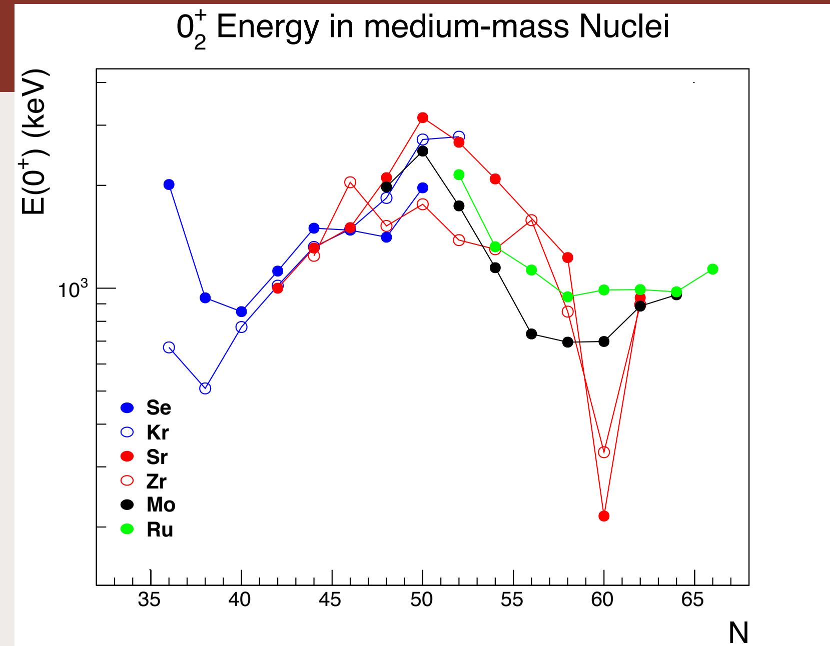
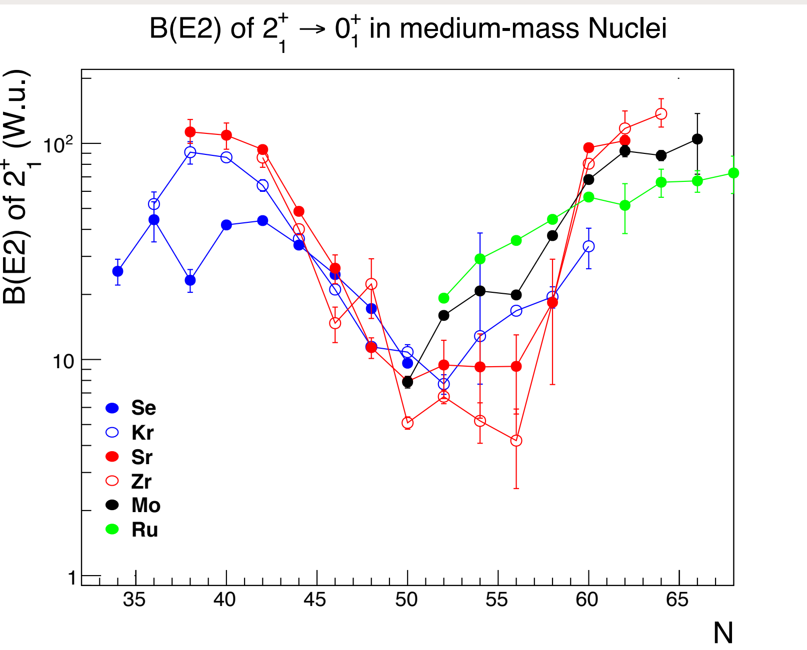
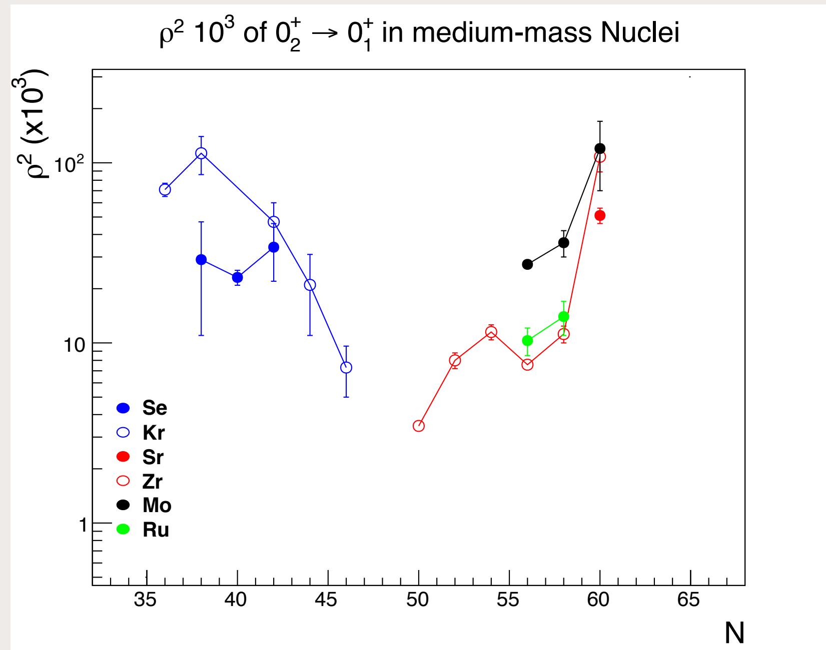
Medium-Mass Systematics









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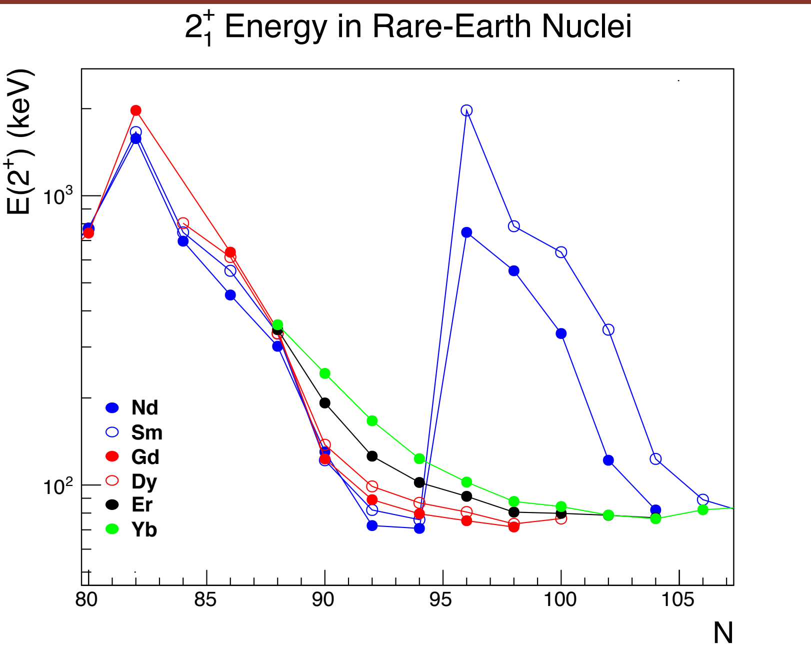
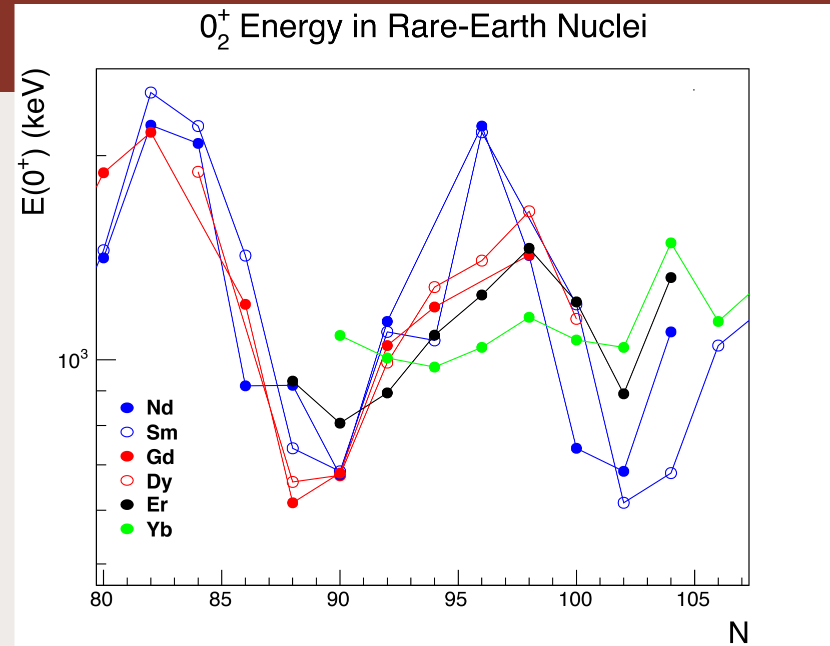
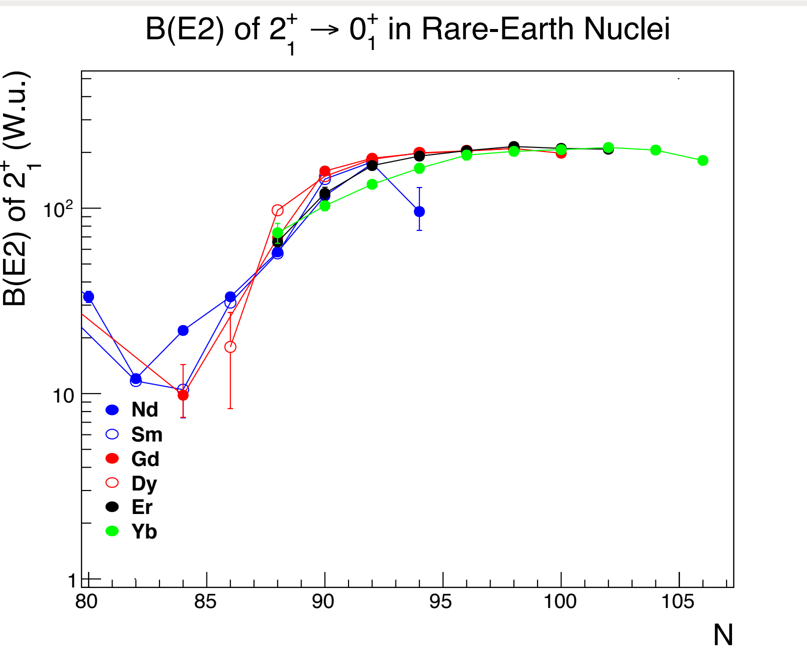
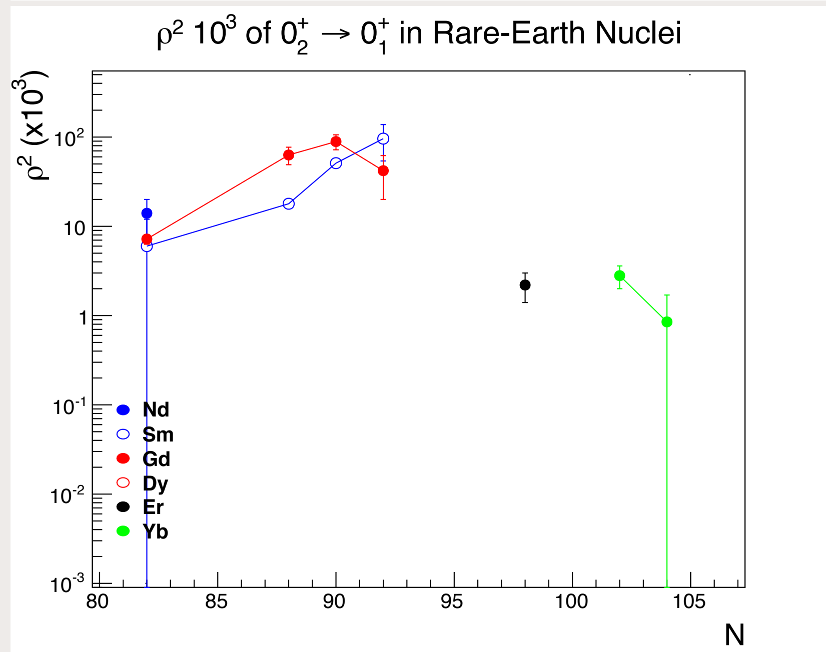
Rare-Earth Systematics









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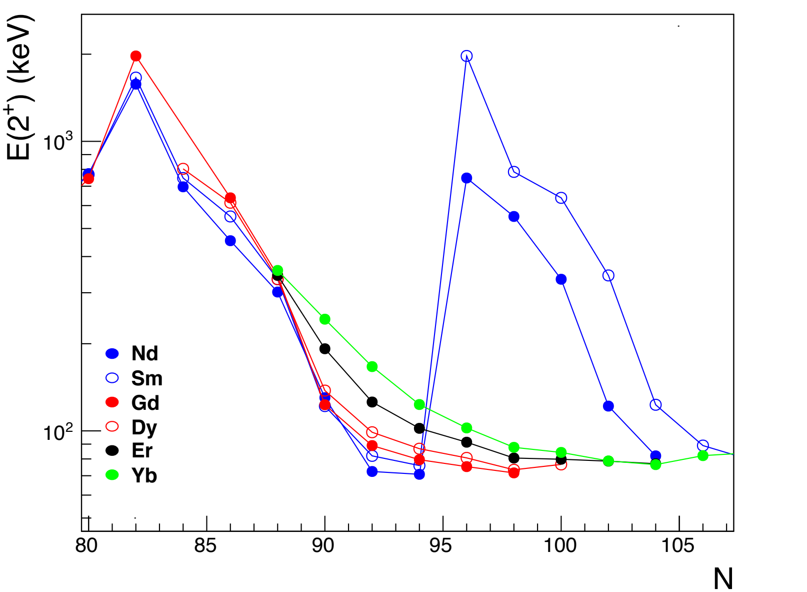
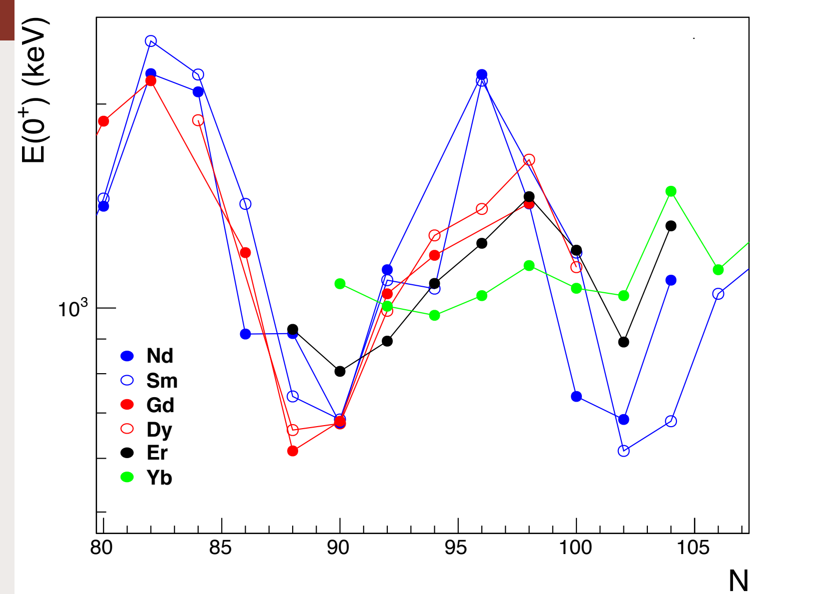
Rare-Earth Systematics

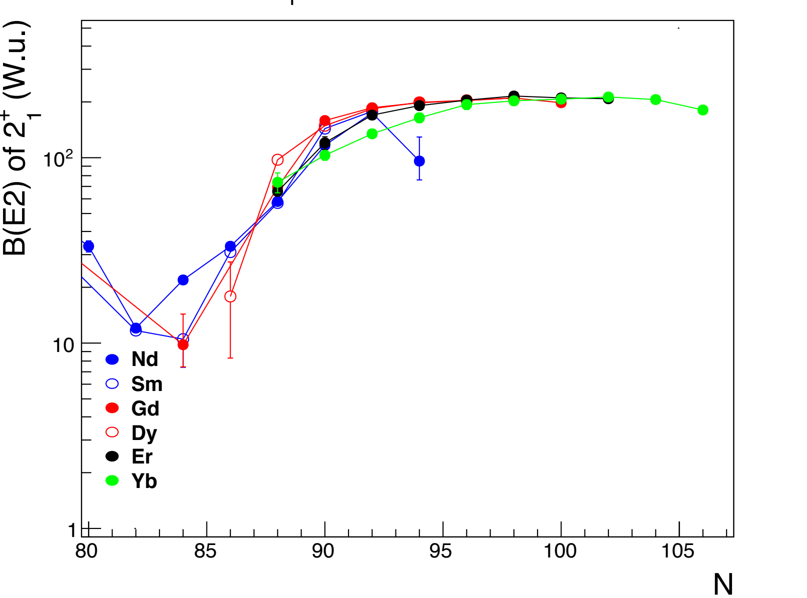
2_1^+ Energy in Rare-Earth Nuclei



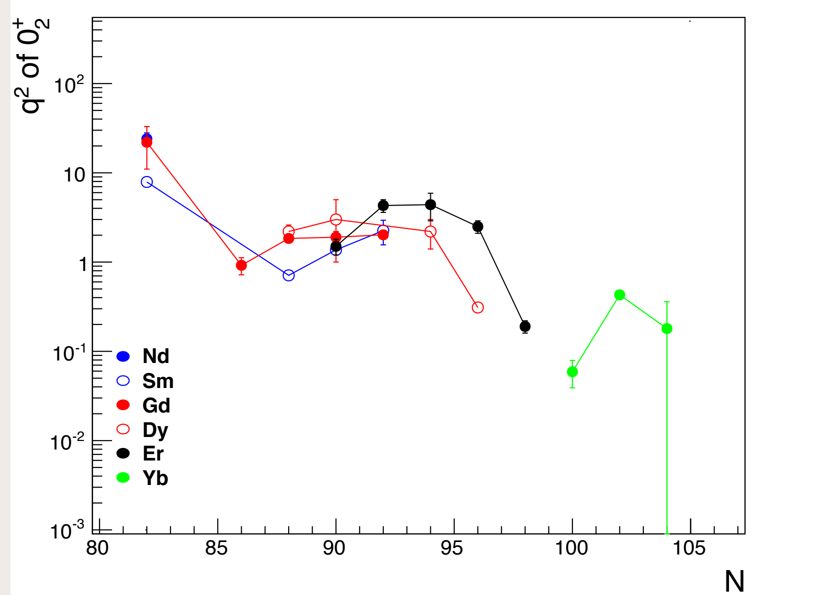
0_2^+ Energy in Rare-Earth Nuclei



B(E2) of $2_1^+ \rightarrow 0_1^+$ in Rare-Earth Nuclei



q^2 of $0_2^+ \rightarrow 0_1^+$ in Rare-Earth Nuclei



Kibédi and Spear,
Atomic. Data and Nucl. Data Tables 89, 77 (2005).

41 $T_{1/2}$ values known but no q^2 of first excited 0^+ to GS 0^+ known

Electron spectroscopy can measure these cases.

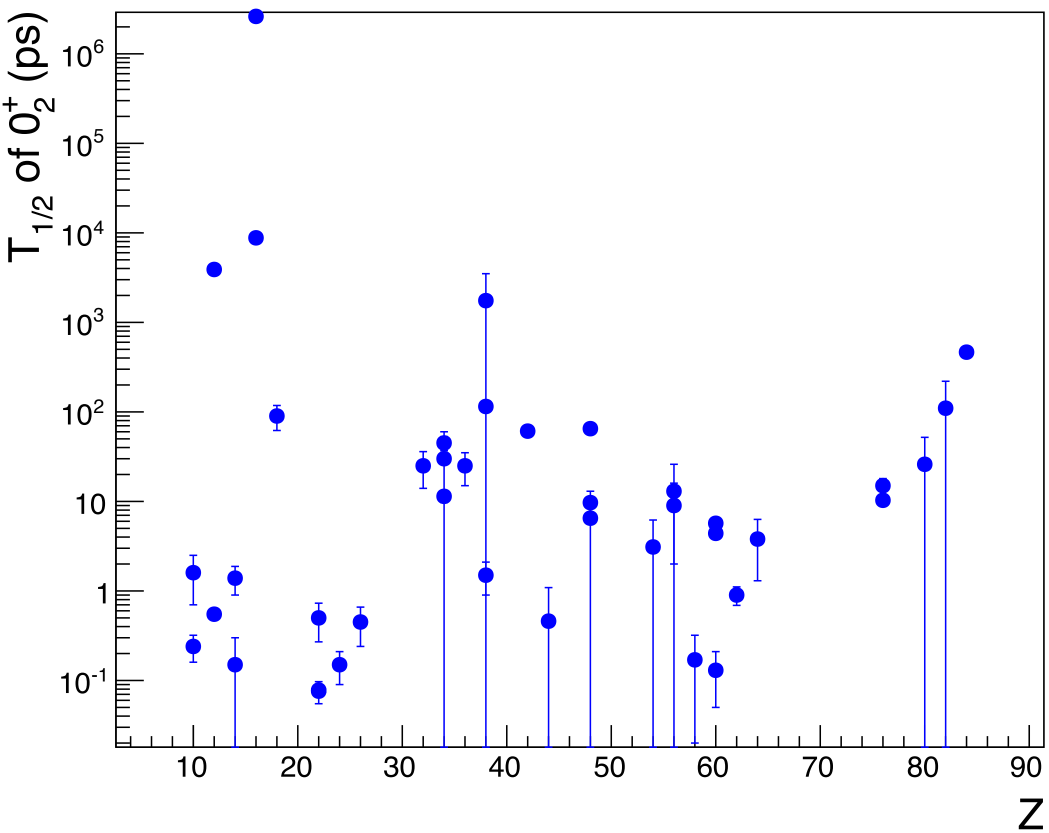


Table 1: $T_{1/2}$ of 0_2^+ state is known. A q^2 measurement will yield a ρ^2 value.

Nucleus	Energy 0_2^+ (keV)	Energy 2_1^+ (keV)	$T_{1/2}$ (ps)
$^{22}_{10}Ne_{12}$	6234.3	1274.58	0.24 (0.08)
$^{24}_{10}Ne_{14}$	4766.5	1981.6	1.6 (0.9)
$^{28}_{12}Mg_{16}$	3862.15	1473.54	0.55 (0.07)
$^{30}_{12}Mg_{18}$	1788.2	1482.8	3900 (400)
$^{26}_{14}Si_{12}$	3336.4	1797.3	1.39 (0.49)
$^{32}_{14}Si_{18}$	4983.9	1941.4	0.15 (0.15)
$^{36}_{16}S_{20}$	3346	3290.9	8800 (200)
$^{44}_{16}S_{28}$	1365	1315	2.619e+06 (26000)
$^{40}_{18}Ar_{22}$	2120.8	1460.85	90 (28)
$^{46}_{22}Ti_{24}$	2611	889.286	0.076 (0.021)
$^{48}_{22}Ti_{26}$	2997.22	983.539	0.078 (0.009)
$^{50}_{22}Ti_{28}$	3862.79	1553.78	0.5 (0.23)
$^{54}_{24}Cr_{30}$	2829.62	834.855	0.15 (0.06)
$^{56}_{26}Fe_{30}$	2941.5	846.778	0.45 (0.21)
$^{78}_{32}Ge_{46}$	1546.6	619.36	25 (11)
$^{78}_{34}Se_{44}$	1498.6	613.727	45 (8)
$^{80}_{34}Se_{46}$	1478.82	666.27	11.4 (1.7)
$^{82}_{34}Se_{48}$	1410.3	654.75	30 (30)
$^{84}_{36}Kr_{48}$	1837.3	881.615	25 (10)
$^{82}_{38}Sr_{44}$	1310.89	573.54	1750 (1750)
$^{88}_{38}Sr_{50}$	3156.19	1836.09	1.5 (0.6)
$^{96}_{38}Sr_{58}$	1229.28	814.93	115 (12)
$^{96}_{42}Mo_{54}$	1148.13	778.237	61 (8)
$^{96}_{44}Ru_{52}$	2148.78	832.56	0.46 (0.63)
$^{116}_{48}Cd_{68}$	1282.56	513.49	65 (4)
$^{118}_{48}Cd_{70}$	1285.61	487.77	9.7 (1.4)
$^{120}_{48}Cd_{72}$	1388.9	505.94	6.5 (6.5)
$^{120}_{54}Xe_{66}$	908.7	322.61	3.1 (3.1)
$^{142}_{56}Ba_{86}$	1535.53	359.596	9 (7)
$^{144}_{56}Ba_{88}$	1020.03	199.326	13 (13)
$^{142}_{58}Ce_{84}$	2031.01	641.282	0.17 (0.15)
$^{144}_{60}Nd_{84}$	2084.68	696.561	0.13 (0.08)
$^{148}_{60}Nd_{88}$	916.93	301.705	4.4 (0.3)
$^{150}_{60}Nd_{90}$	675.9	130.21	5.7 (0.3)
$^{154}_{62}Sm_{92}$	1099.26	81.981	0.9 (0.21)
$^{158}_{64}Gd_{94}$	1196.16	79.5128	3.8 (2.5)
$^{190}_{76}Os_{114}$	911.78	186.718	15 (3)
$^{192}_{76}Os_{116}$	956.54	205.794	10.3 (1.1)
$^{186}_{80}Hg_{106}$	523	405.33	26 (26)
$^{190}_{82}Pb_{108}$	658	773.9	110 (110)
$^{208}_{84}Po_{124}$	1271.6	686.526	465 (20)