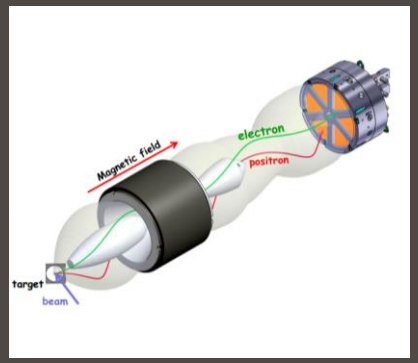
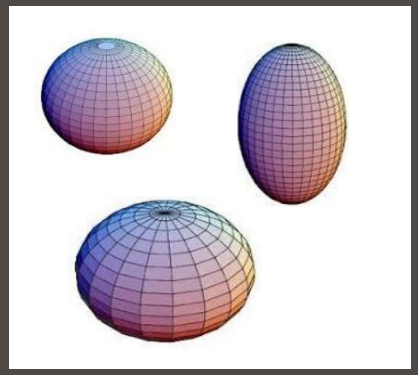
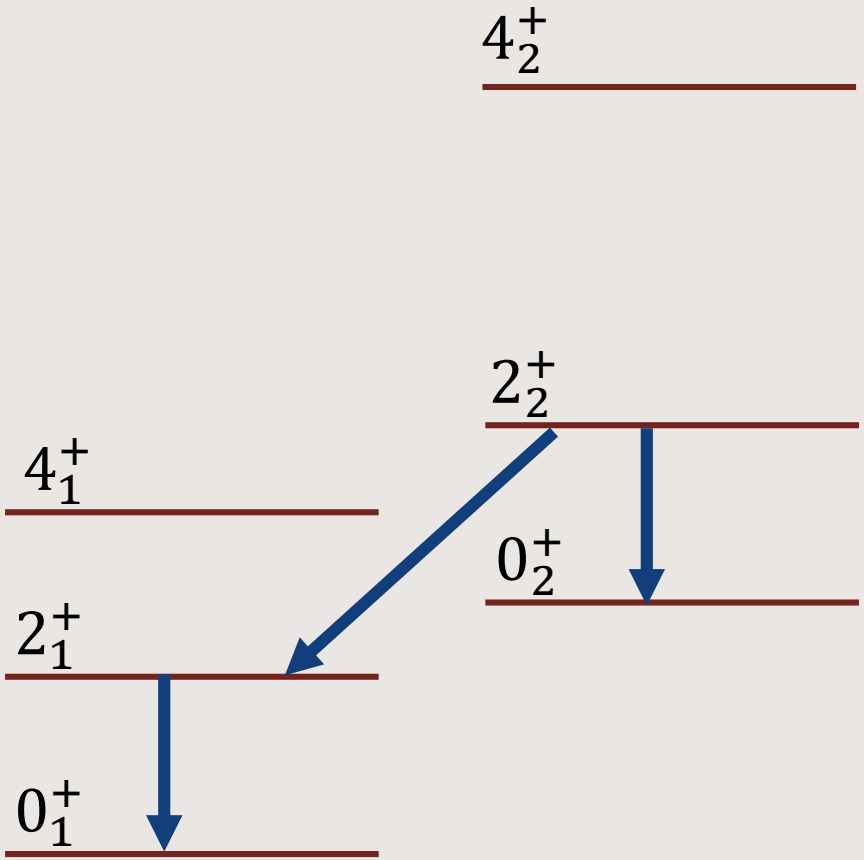
Electric Monopole Transition Strengths in Stable Nickel Isotopes

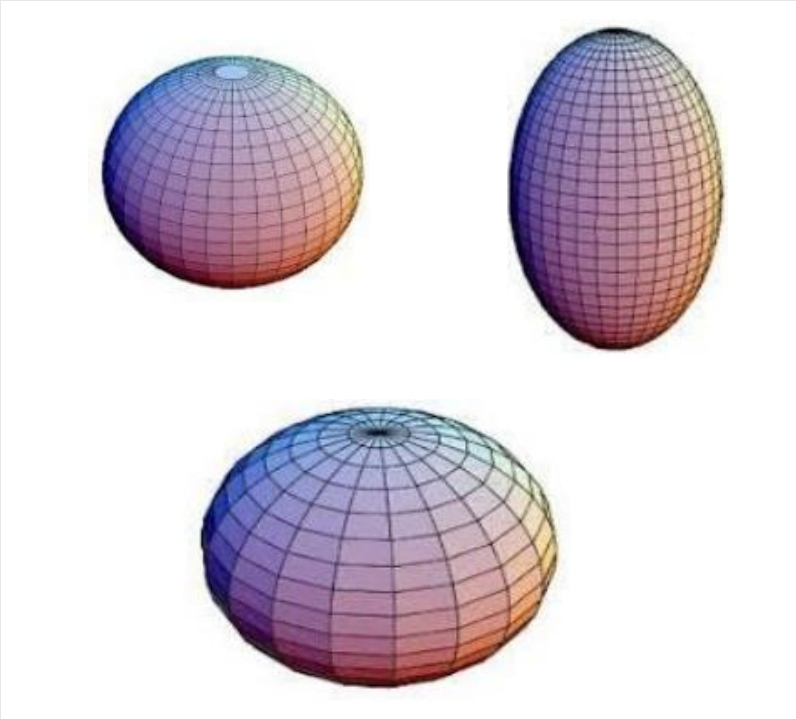
Lee J. Evitts | PhD Student | TRIUMF & University of Surrey





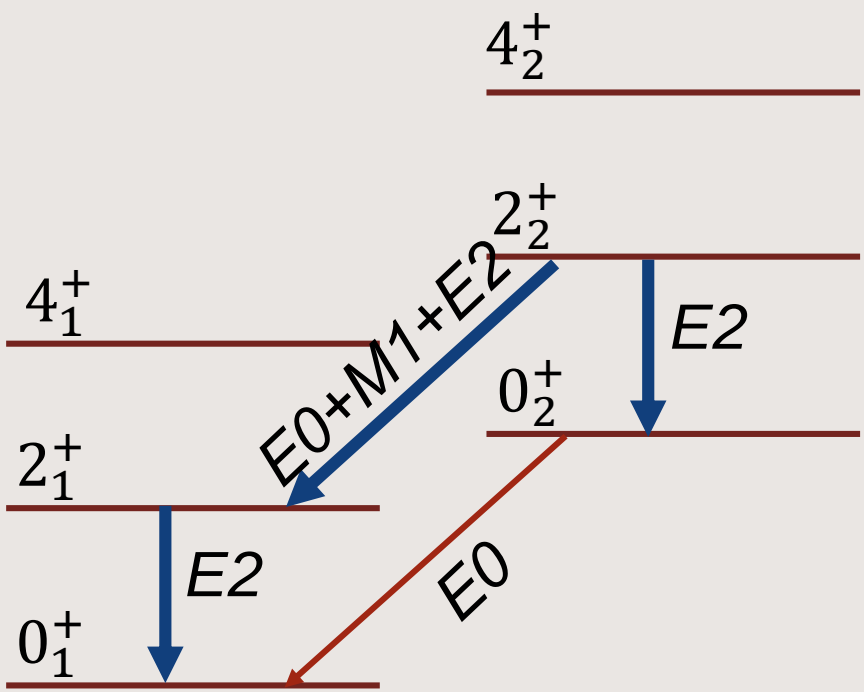
Shape Coexistence





K. Heyde & J. Wood, Rev Mod Phys 83 (2011)
A. Poves, K. Heyde, J. Wood *et al.* J. Phys G 43 (2016)

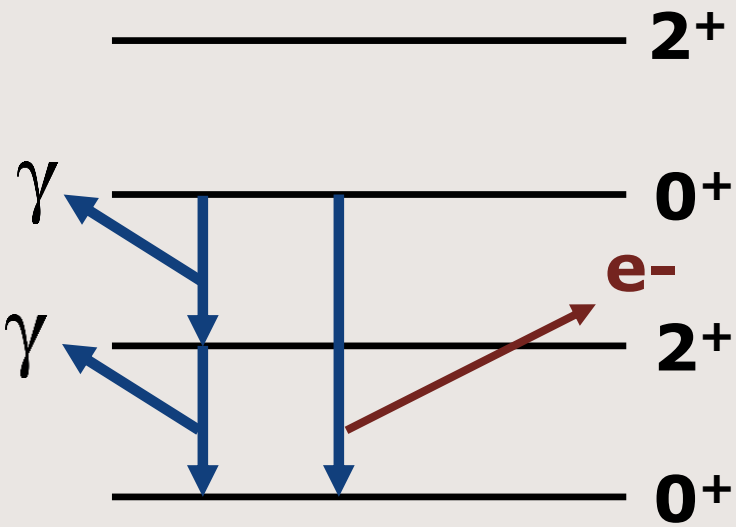
Shape Coexistence



- *E0* transitions often overlooked in interpretation
- Particularly *E0* contribution in mixed transitions
- $M(E0) = \sum_k e_k r_k^2$

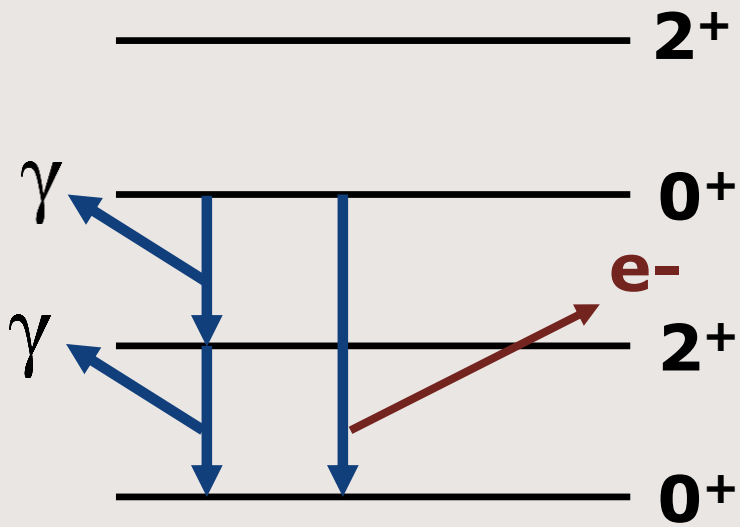
  e_k is effective charge
  r_k is radius
  of kth nucleon

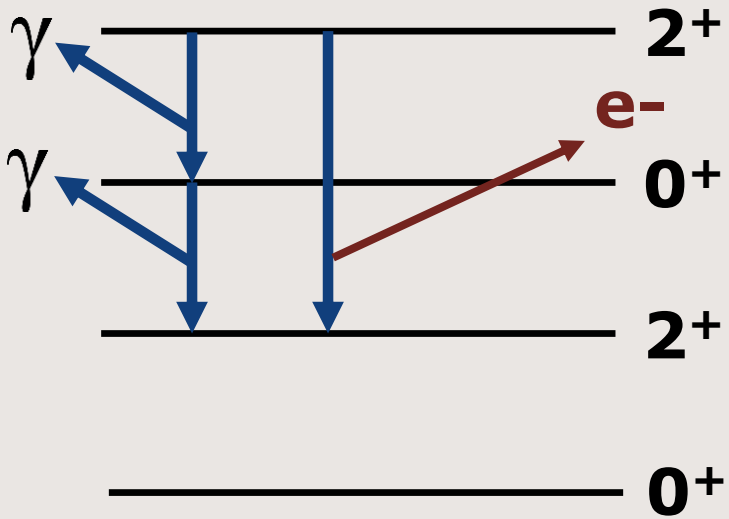
E0 Transitions



- Between 0^+ states, decay only via *E0* transitions
- γ-ray decay forbidden in *E0* transitions due to conservation of angular momentum

E0 Transitions





- Between 0^+ states, decay only via *E0* transitions
- γ-ray decay forbidden in *E0* transitions due to conservation of angular momentum
- Between J^+ states, decay via *E0*+*M1*+*E2*

  (γ-rays only emitted in *M1*+*E2*)

Reduced *E0* Transition Strength: ρ^2 (*E0*)

- ρ^2(*E0*) links nuclear and electronic parts

$$\rho^2(E0) = \frac{1}{\Omega_k \cdot \tau_k}$$

- where:
  - Ω is electronic factor
    - Atomic theory, calculable with BrICC
  - τ is partial lifetime of *E0* transition, requires experimental data:
    - Parent half-life, *M1/E2* mixing ratio, internal conversion coefficient (α) and branching ratios

R.S. Hager & E.C. Seltzer, Nucl. Data Tables 6 (1969)

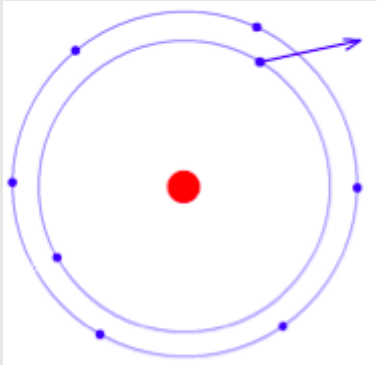
- ρ^2(*E0*) is dimensionless, given in milliunits (x 10^3)

T. Kibédi *et al*., NIM A 589 (2008) 202-229: http://bricc.anu.edu.au/

Internal Conversion

- $\lambda_{TOTAL} = \lambda_{\gamma} + \lambda_{IC} + \lambda_{\pi} + \lambda_{\gamma\gamma} + \lambda_{OTHERS}$
- Energy of de-excitation emits orbital electron (ICE)

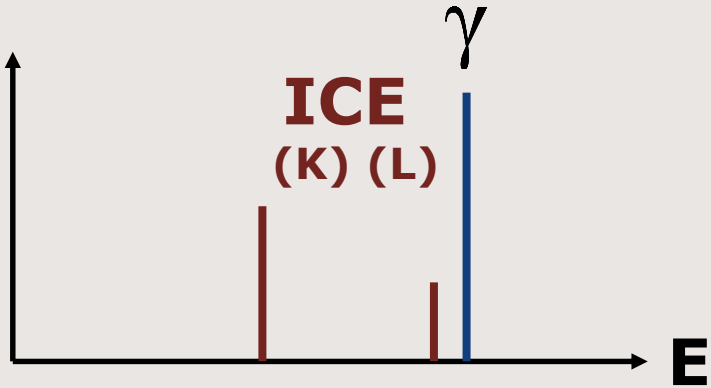
$$\mathrm{E}_{ICE} = \mathrm{E}_{\gamma} - \mathrm{B.E.}$$



- Internal Conversion Coefficient (ICC)

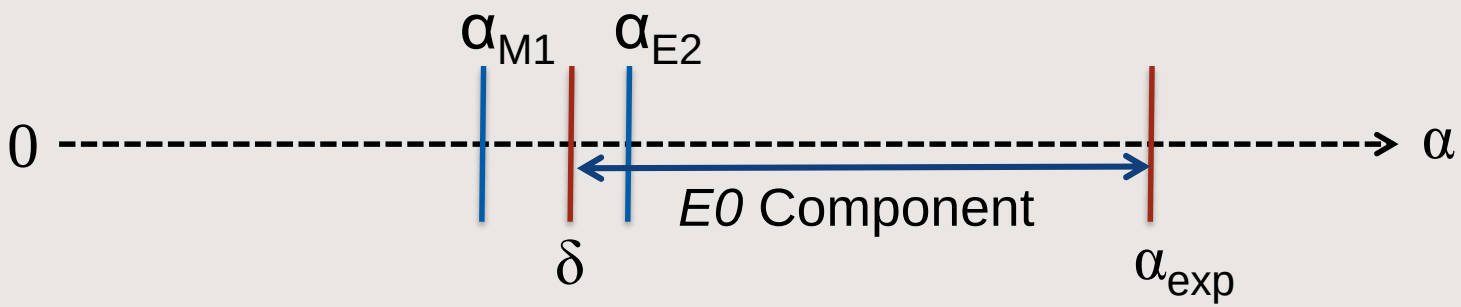
$$\alpha = {\lambda_{IC}}/{\lambda_{\gamma}}$$

- Ratio of K/L peaks can provide information on multipolarity of transition



E0 Transitions

- For a mixed transition (e.g. $2_2^+ \longrightarrow 2_1^+$ will be *E0+M1+E2*), need to separate *E0* electrons from *M1+E2*
- Can compare experimental α to *M1+E2* from BrIcc



- If exp. α is between *M1+E2*, vital to know mixing ratio

What ρ^2 (*E0*) can tell us

- State mixing :

$$\rho^2(E0) = \left(\frac{3Z}{4\pi}\right)^2 a^2(1-a^2)[\Delta(\beta^2)]^2$$

- Basic models have selection rules for *E0* transitions:
  - Spherical quadrupole vibrator :

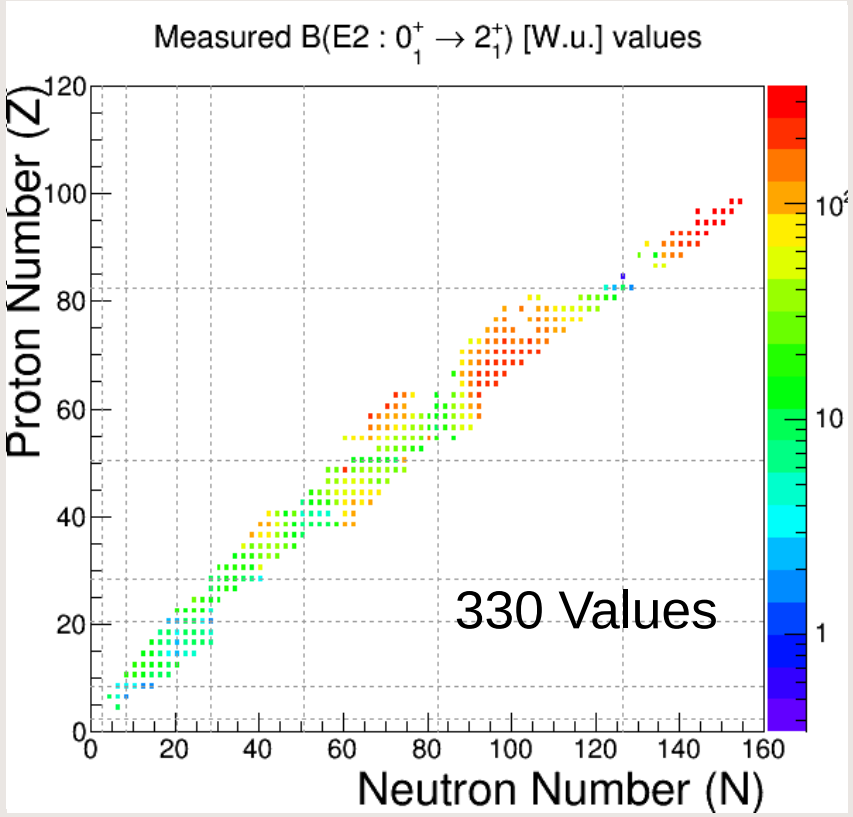
$$\Delta N_{PHONON} = 0, \pm 2$$

  - Deformed quadrupole rotor:

$$\Delta K = 0$$

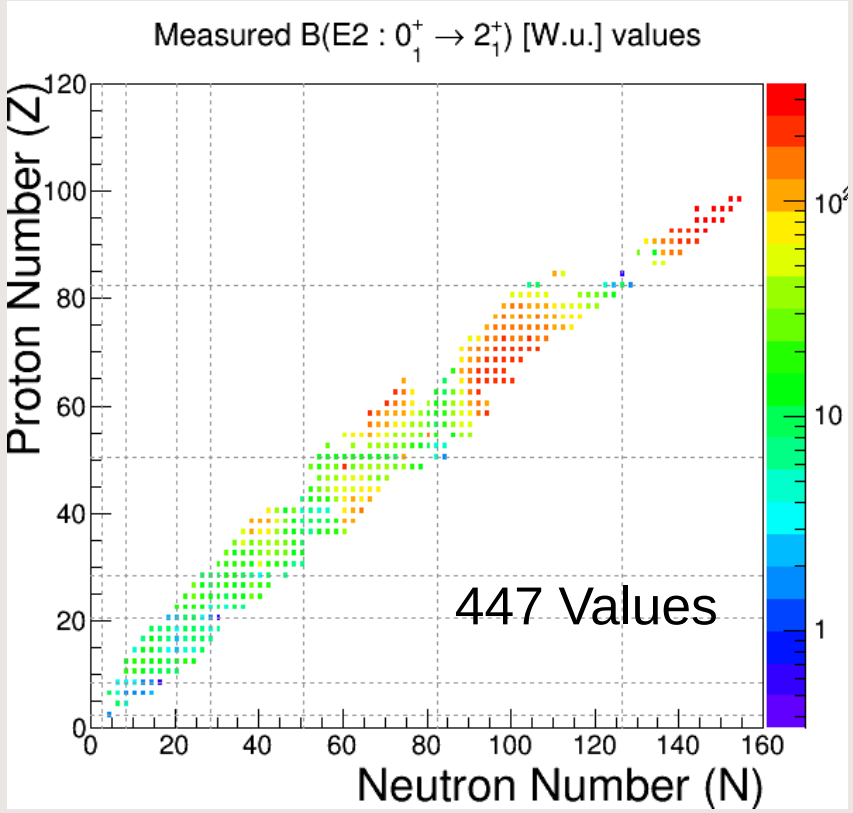
- A large *E0* strength is a key fingerprint of shape coexistence

Measured ρ^2 (*E0*) values



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

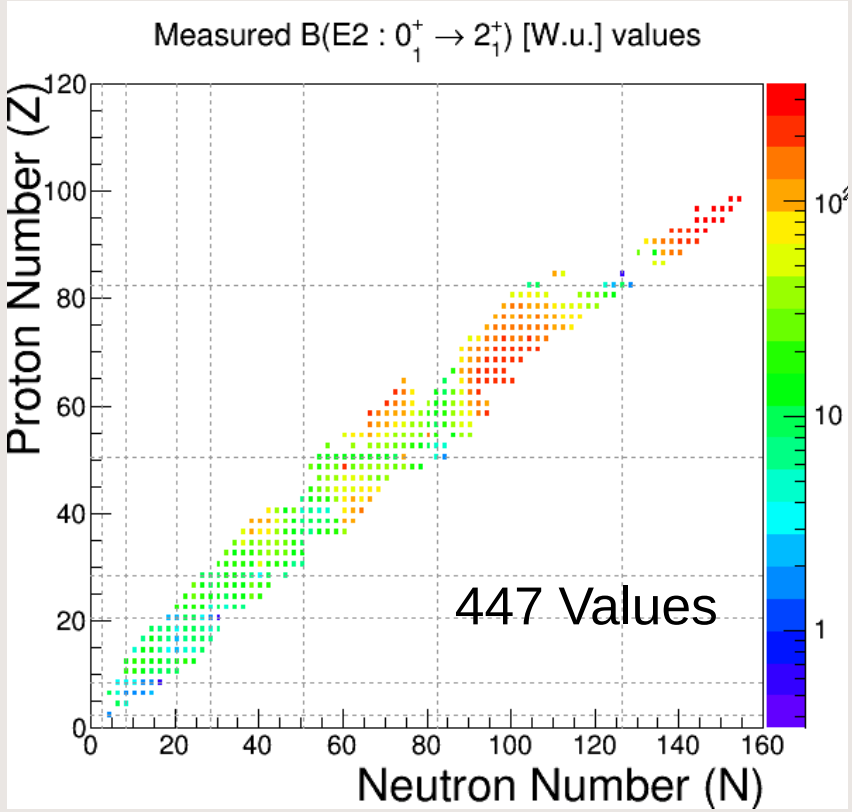
Measured ρ^2 (*E0*) values



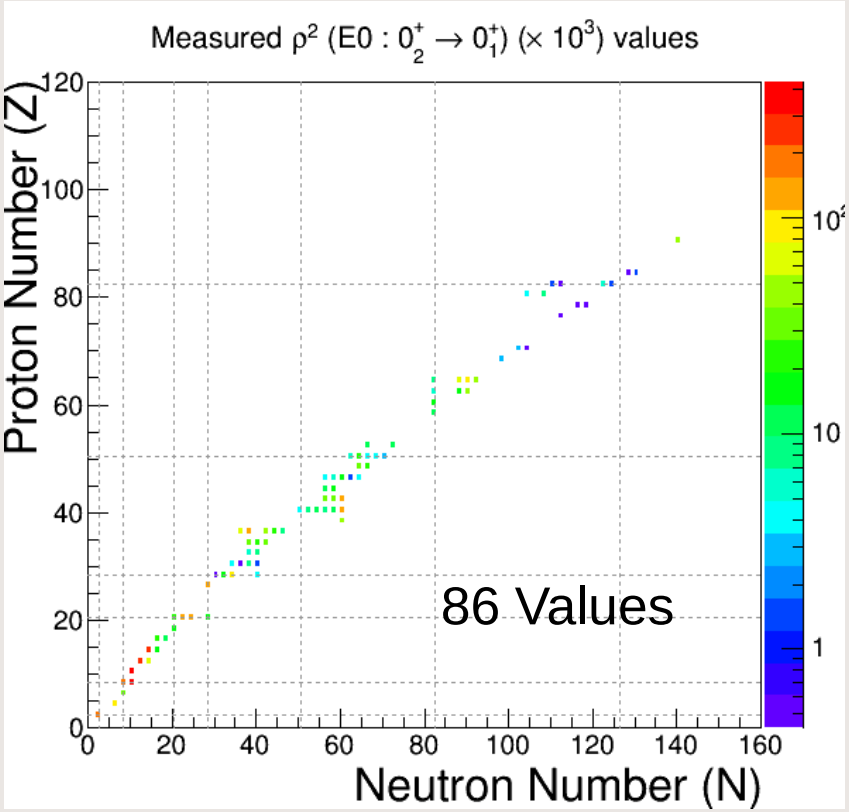
Pritychenko *et al.*, Atomic Data & Nucl. Data Tables, 107 (2016)

~120 new values in 15 years

Measured ρ^2 (*E0*) values



Pritychenko *et al.*, Atomic Data & Nucl. Data Tables, 107 (2016)



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

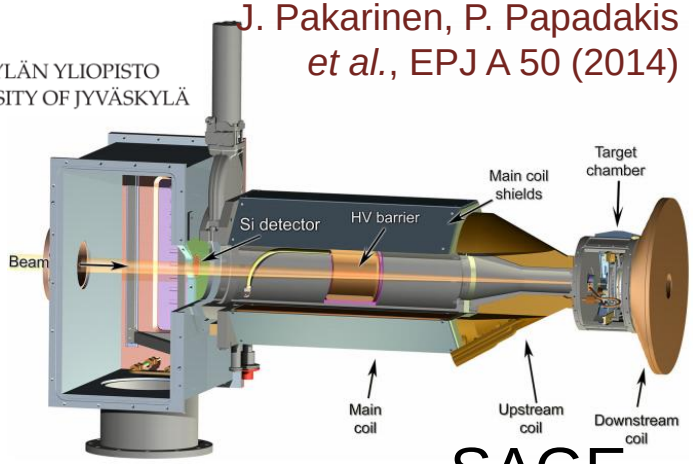
~120 new values in 15 years

Electron data exists for 51 new values, awaiting half-life measurement

Modern Electron Spectrometers

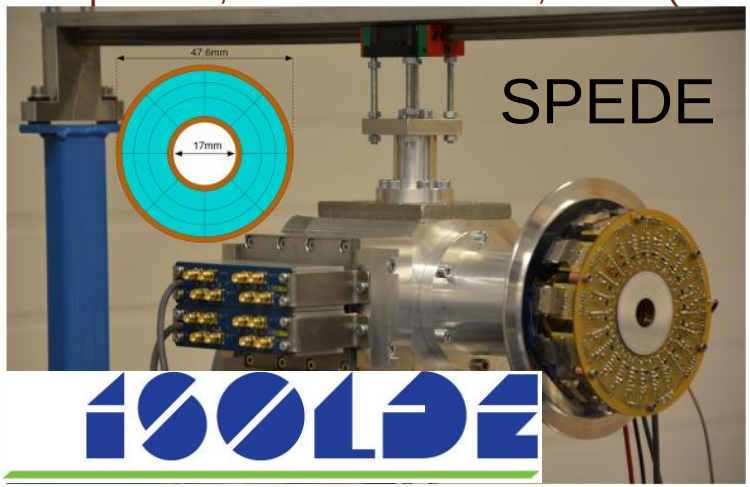
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

J. Pakarinen, P. Papadakis *et al.*, EPJ A 50 (2014)



SAGE

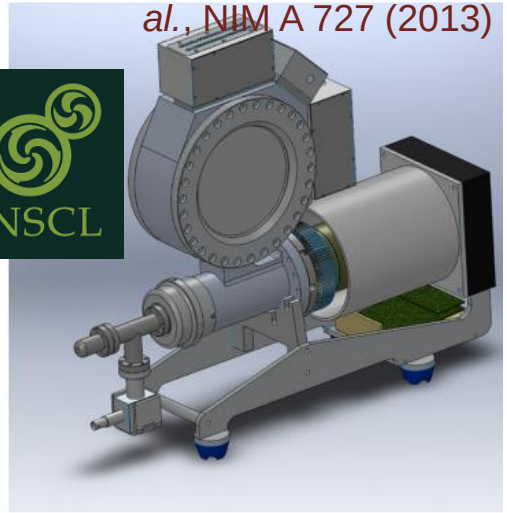
P. Papadakis, J. Pakarinen *et al.*, JPS 6 (2015)



SPEDE

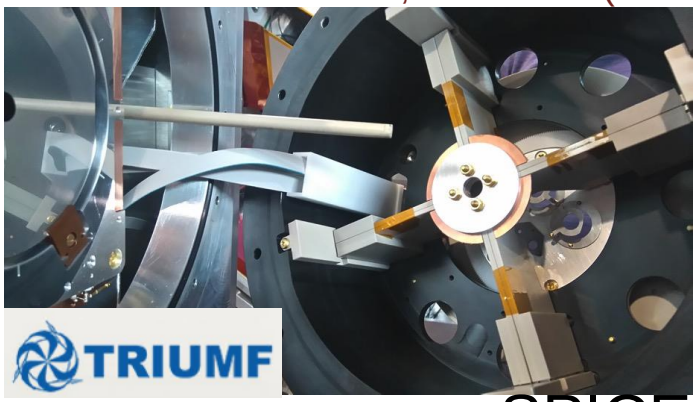
ISOLDE

N. Larson, S.N. Liddick *et al.*, NIM A 727 (2013)



NSCL

S. Ketelhut, L.J. Evitts *et al.*, NIM A 753 (2014)

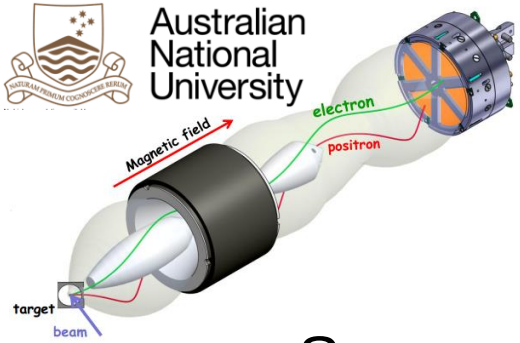


TRIUMF

SPICE

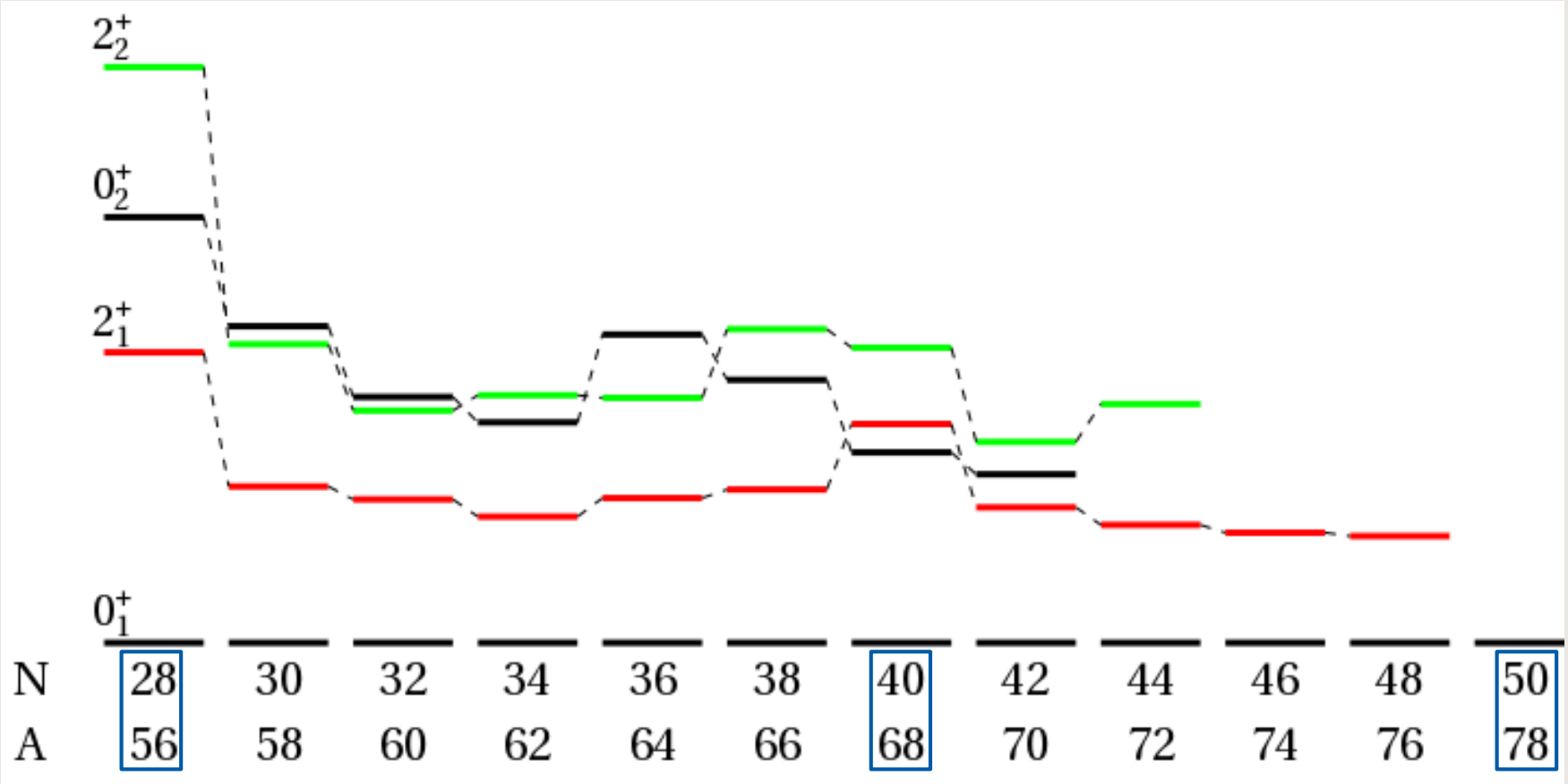
T. Kibedi, A.E. Stuchbery *et al.*, EPJ WoC 35 (2012)

Australian National University



Super-e

Motivation for Ni isotopes



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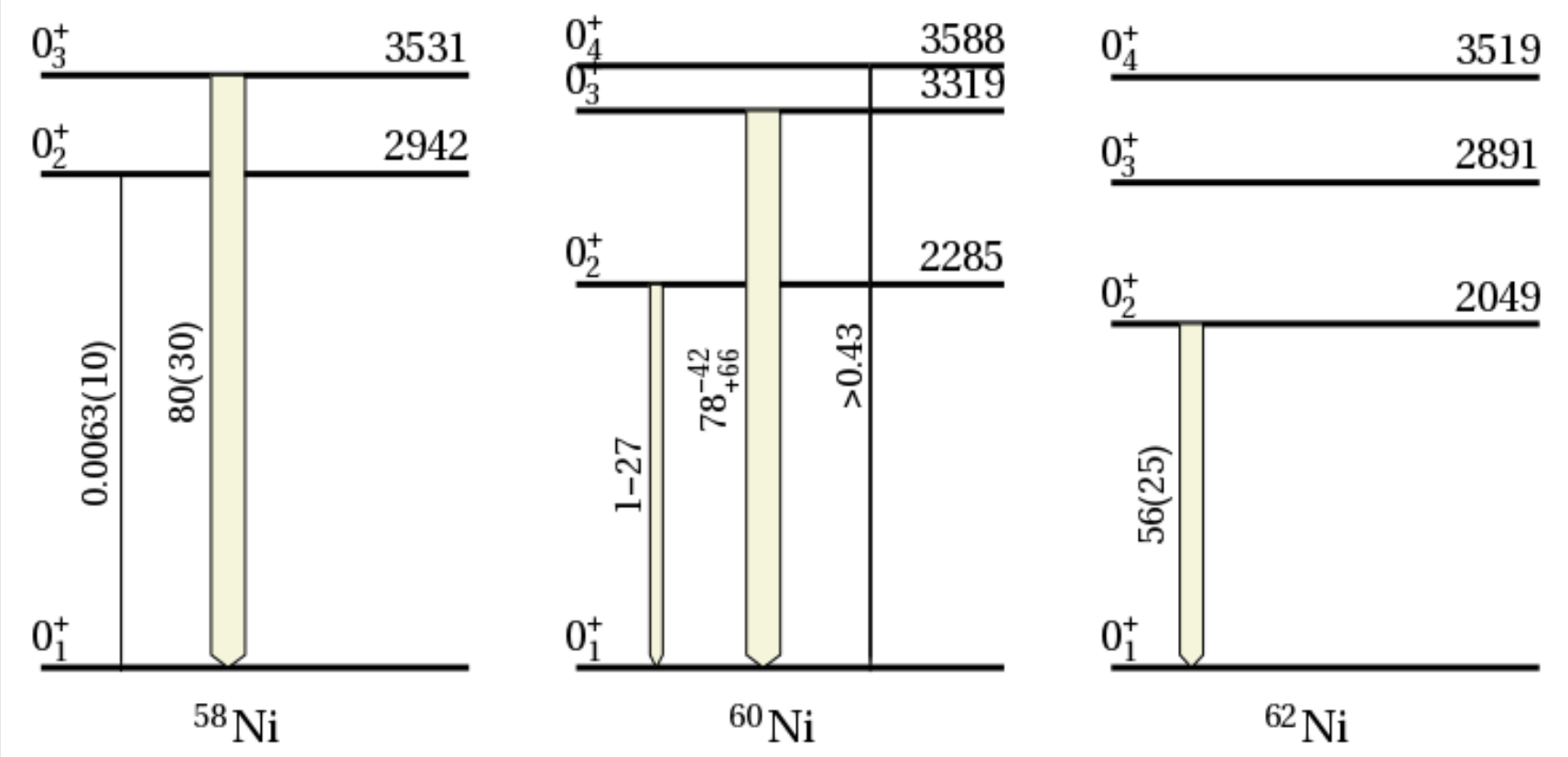
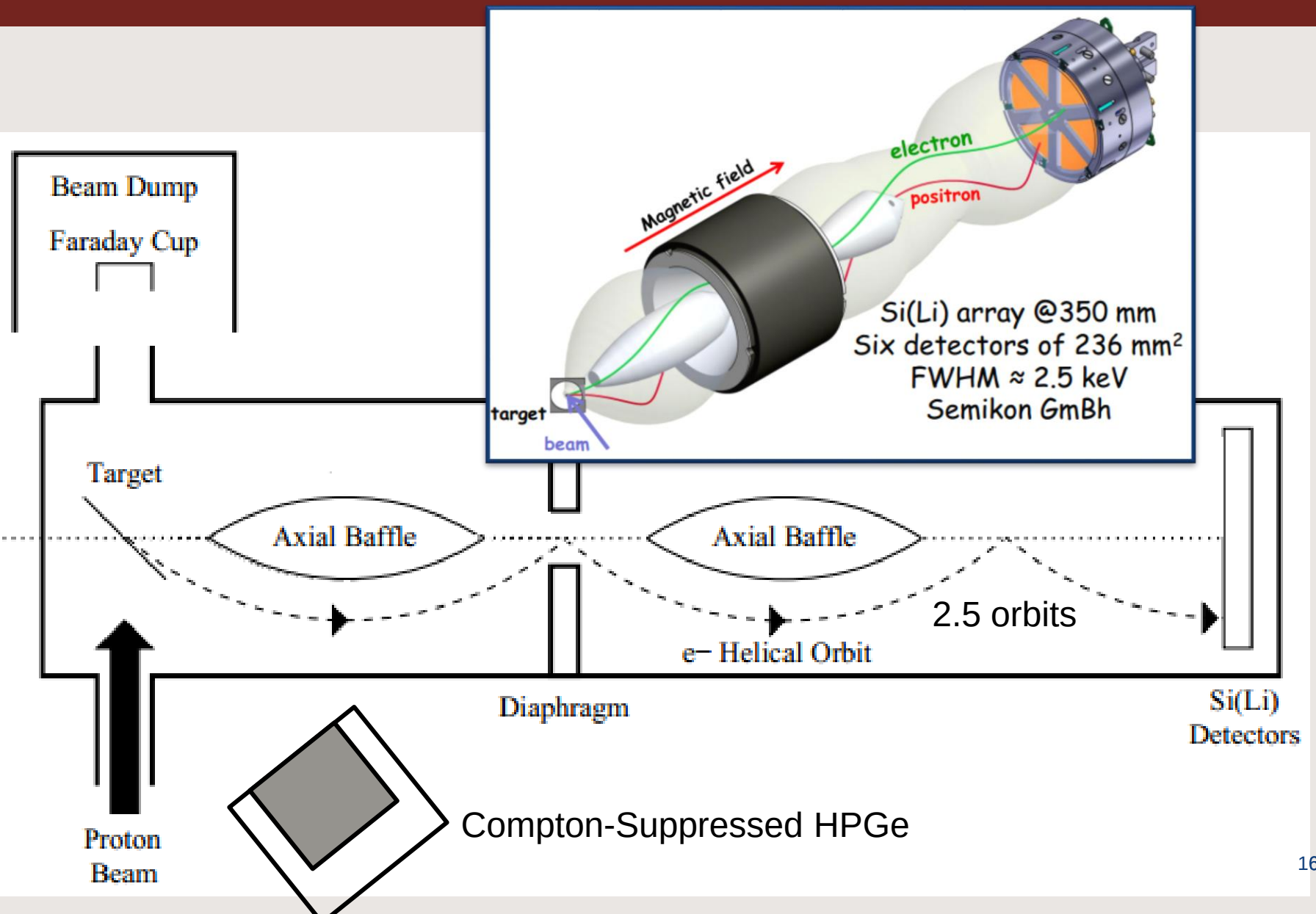
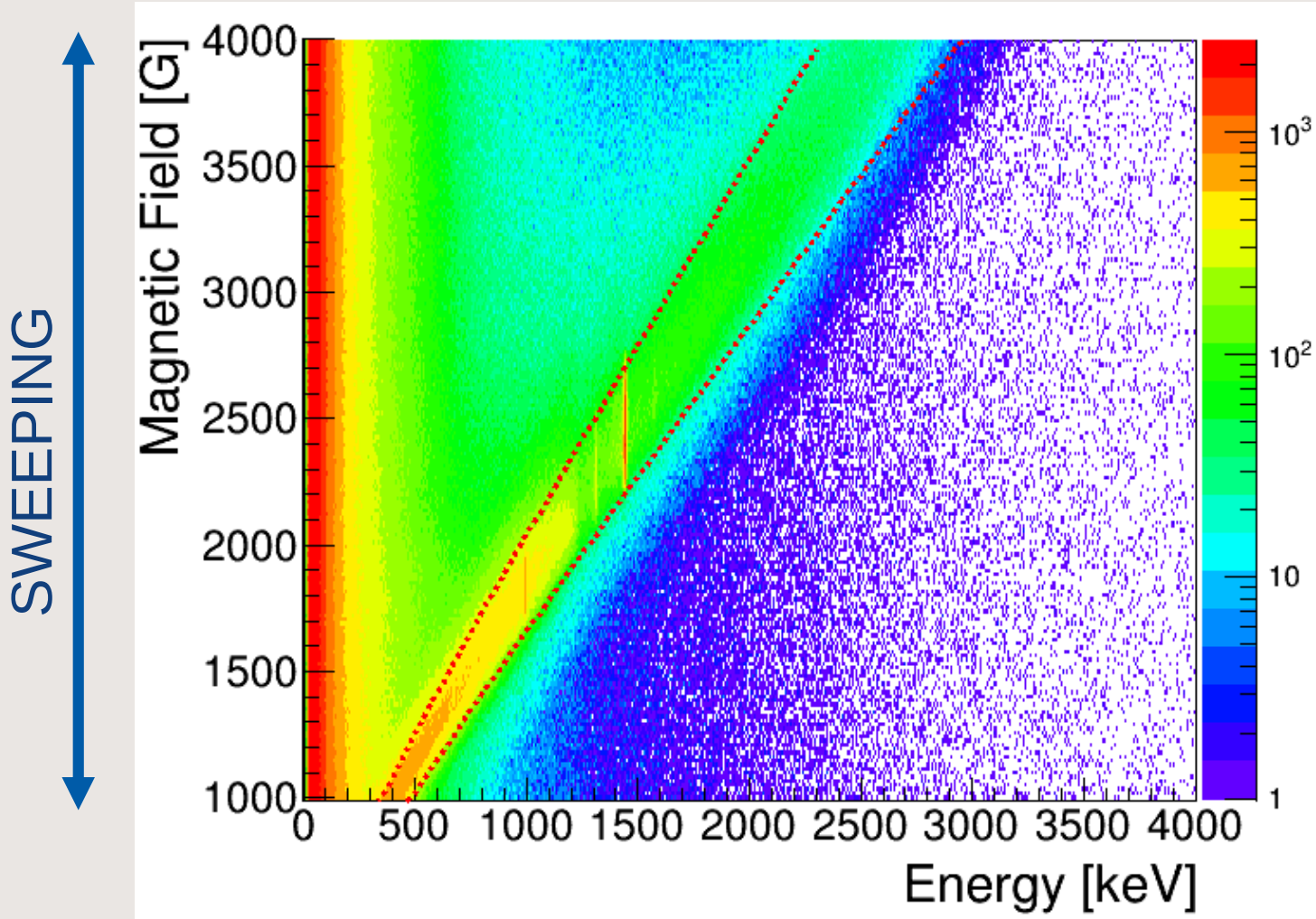


A. Passoja *et al.*, NPA 363 (1981)

Super-e at ANU

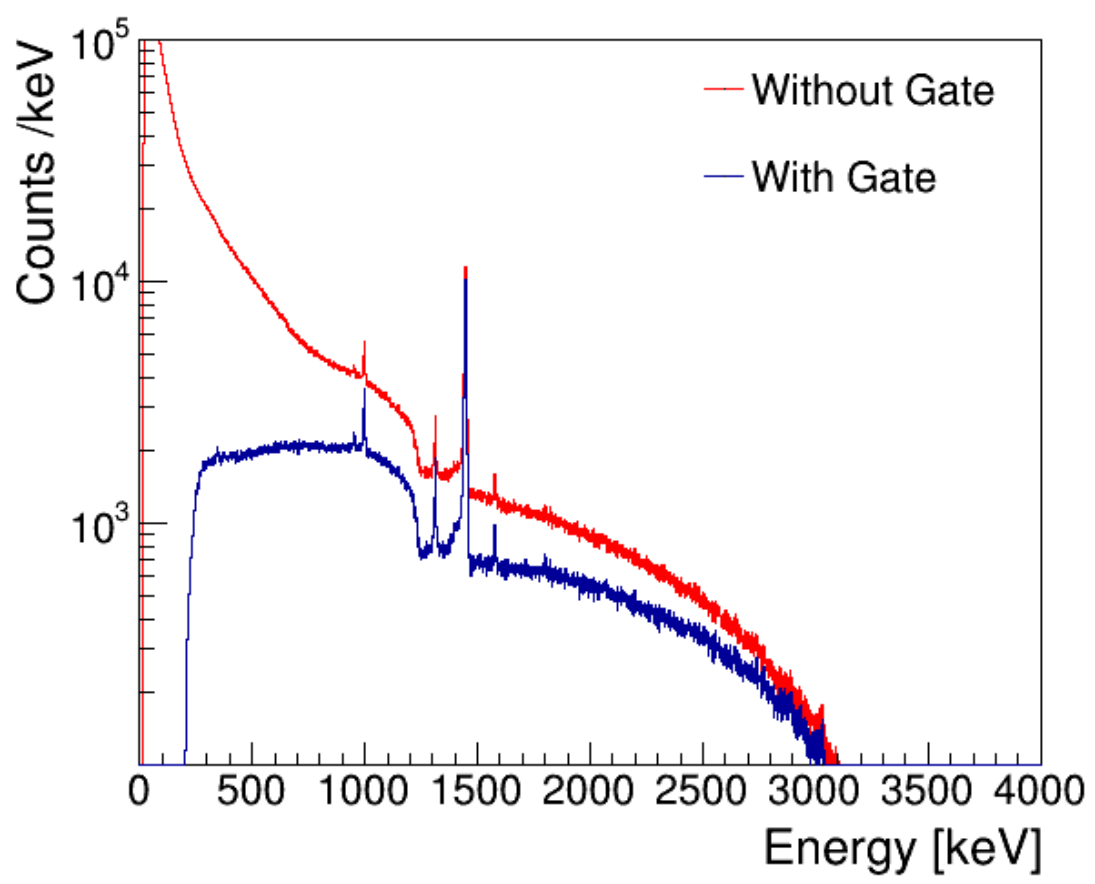


Super-e at ANU



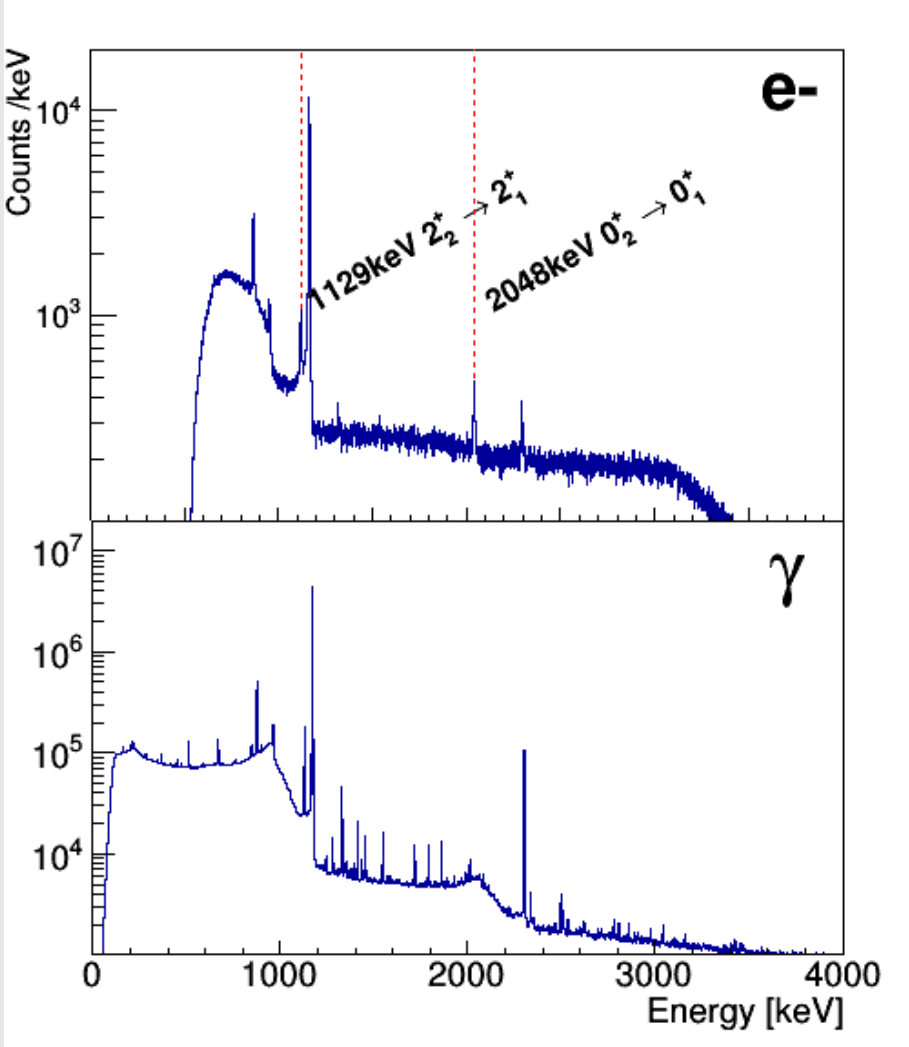
Super-e at ANU

e- spectrum with gate improves peak-to-background



^{62}Ni

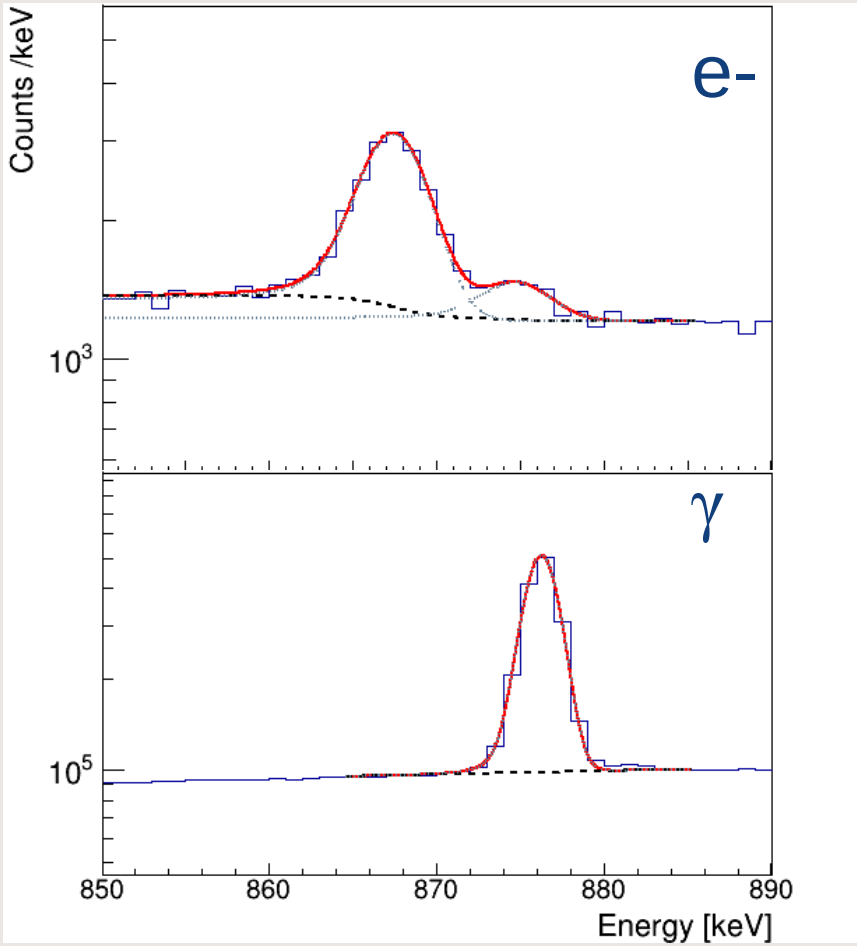
- ^{62}Ni (p, p') at 4.7MeV
- Contaminants from (p, γ) channel



^{62}Ni

E2 α are well reproduced

Transition	Energy (keV)	α_{BrIcc} (x 10^{-4})	α_{EXP} (x 10^{-4})
$0_2^+ \longrightarrow 2_1^+$	876	3.35(5)	3.31(14)
$2_2^+ \longrightarrow 0_1^+$	2302	4.42(6)	4(1)



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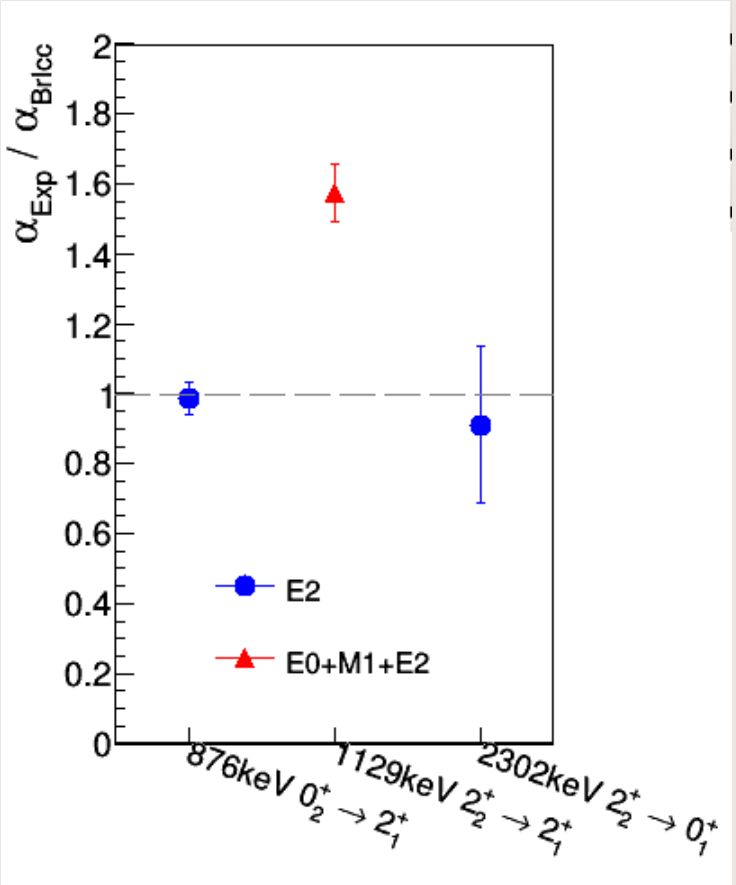
$0_2^+ \longrightarrow 2_1^+$	876	3.35(5)	3.31(14)
$2_2^+ \longrightarrow 0_1^+$	2302	4.42(6)	4(1)

Re-measurement of q^2

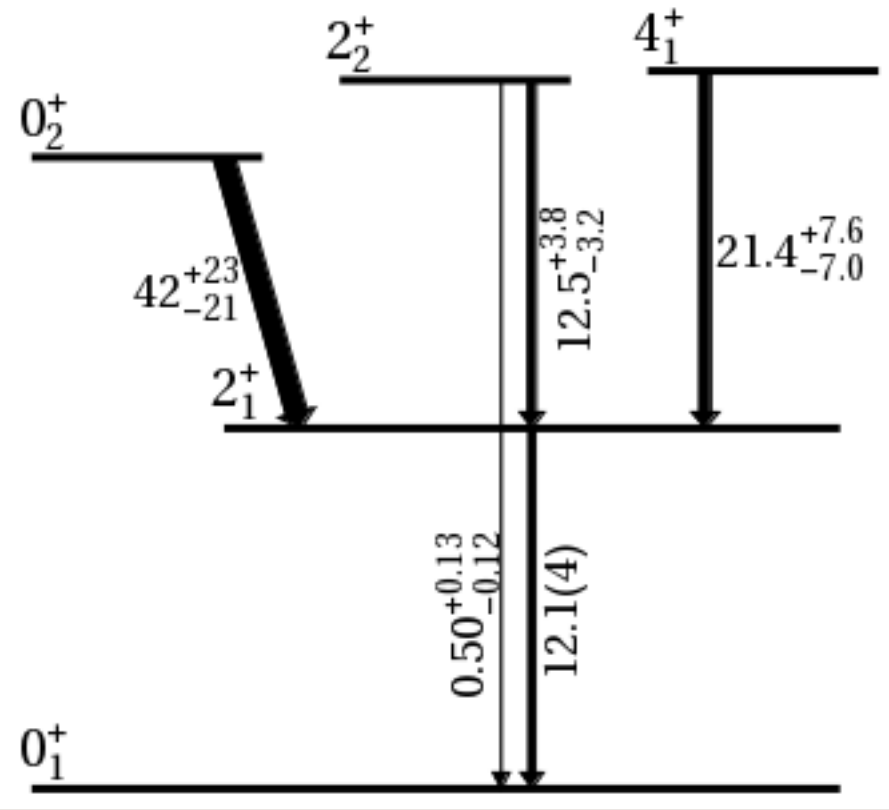
Transition	Energy (keV)	Lit. q^2	Exp. q^2
$0_2^+ \longrightarrow 0_1^+$	2048	0.084(11)	0.109(4)



$$q^2 = \frac{I(E0)}{I(E2)}$$

^{62}Ni

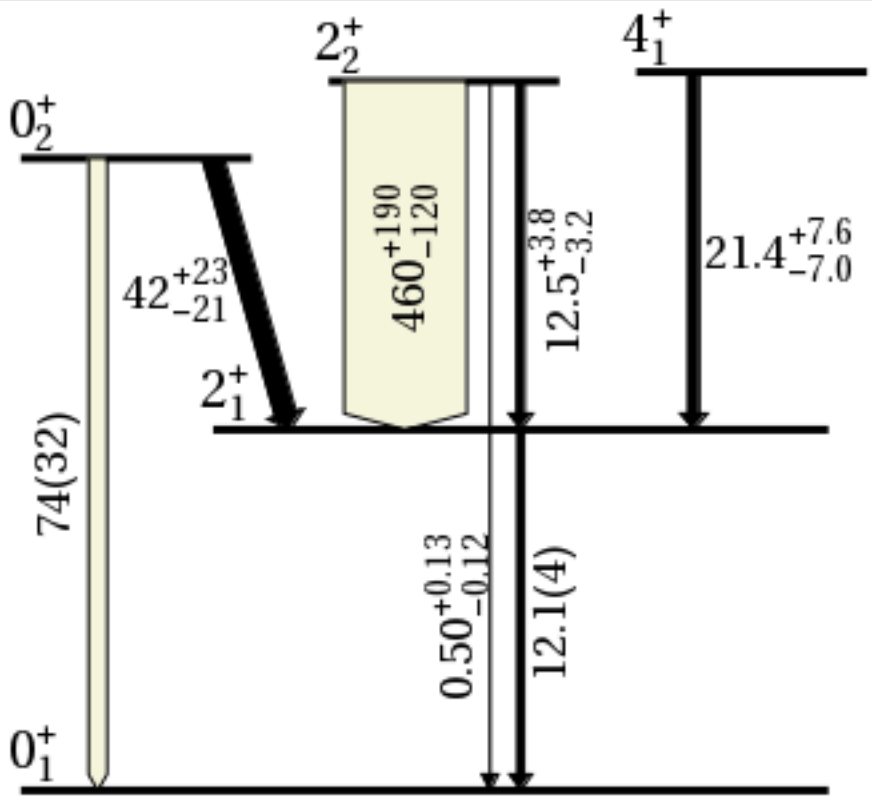
- Previously considered a spherical vibrator due to energy levels and *B(E2)* values



Latest review of results by A. Chakraborty *et al.*, PRC 83, 034316 (2011)

^{62}Ni

- Previously considered a spherical vibrator due to energy levels and *B(E2)* values
- But an *E0* transition is forbidden in model if phonon changes by 1

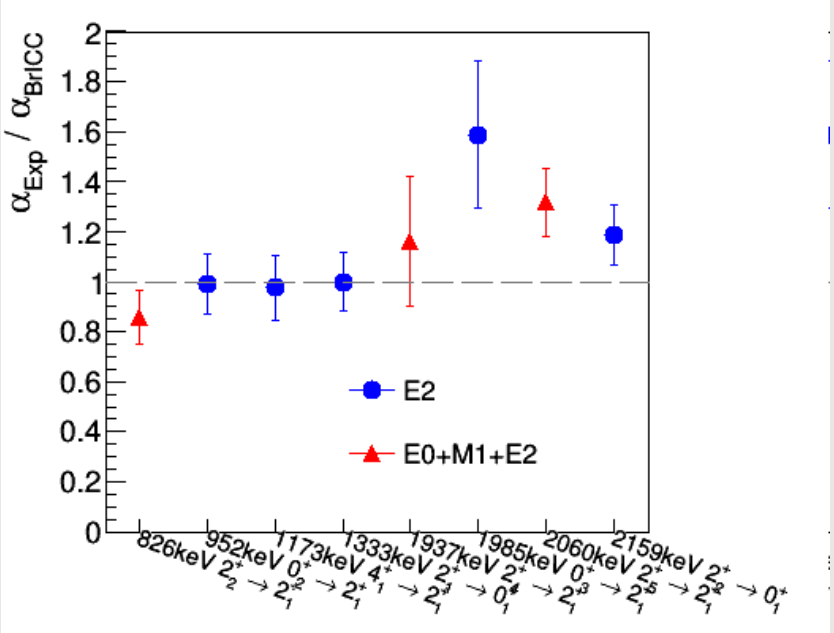


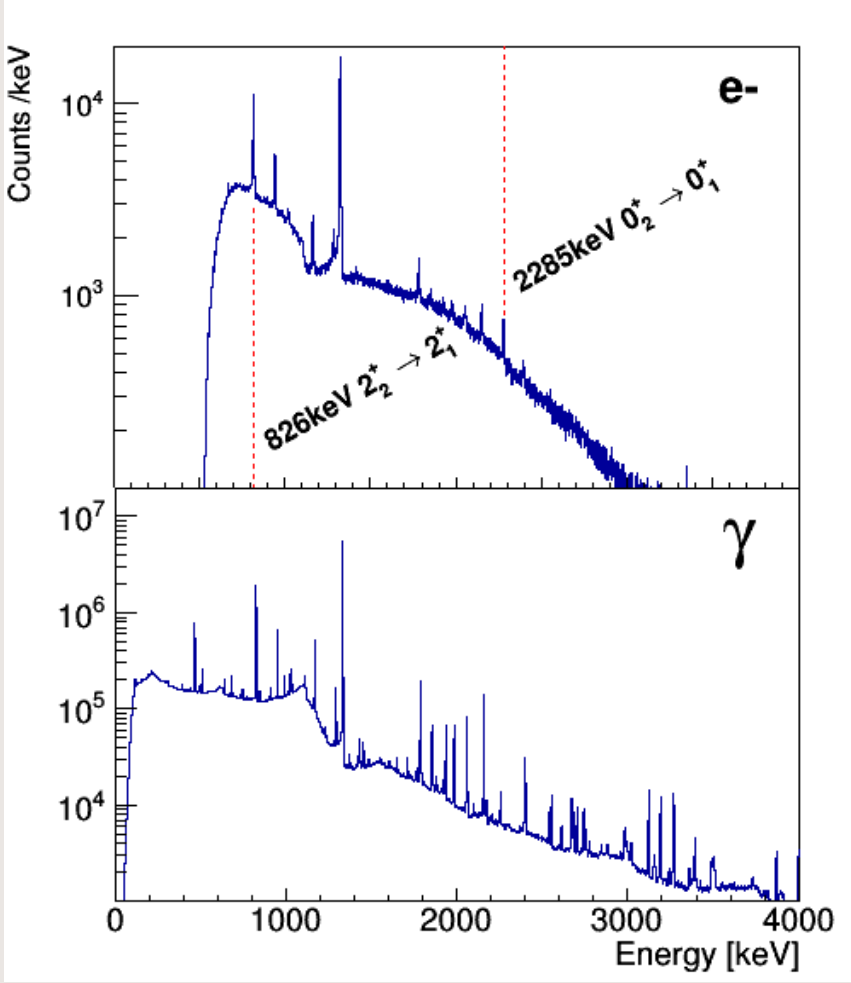
Latest review of results by A. Chakraborty *et al.*, PRC 83, 034316 (2011)

^{60}Ni

- ^{60}Ni (p, p') at 6.8MeV

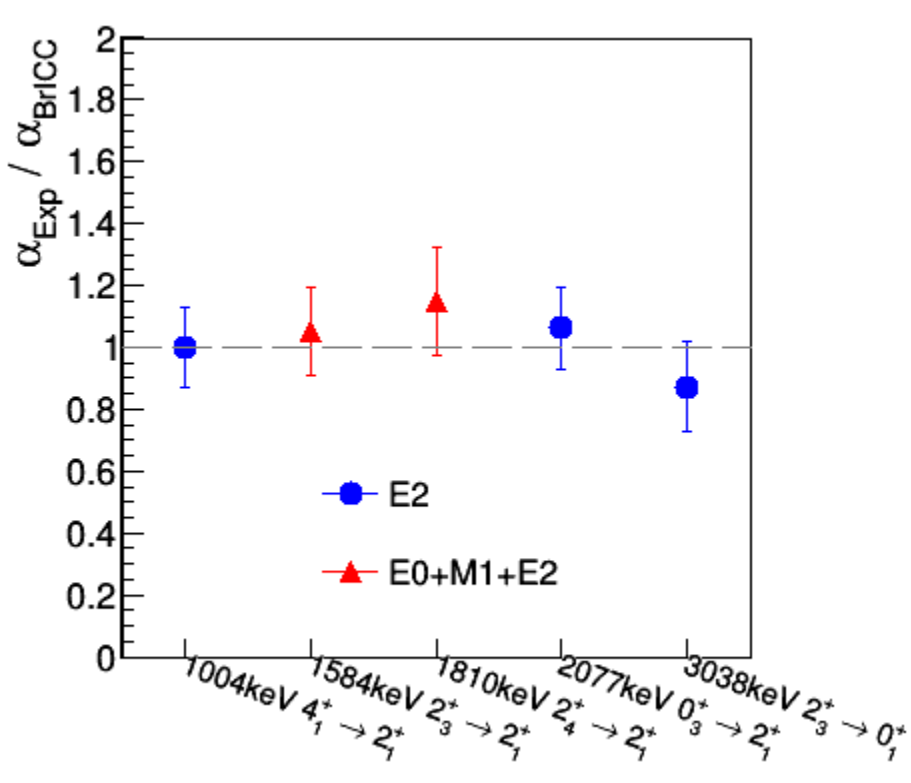
Transition	Energy (keV)	Lit. q^2	Exp. q^2
$0_2^+ \longrightarrow 0_1^+$	2285	0.074(16)	0.051(7)

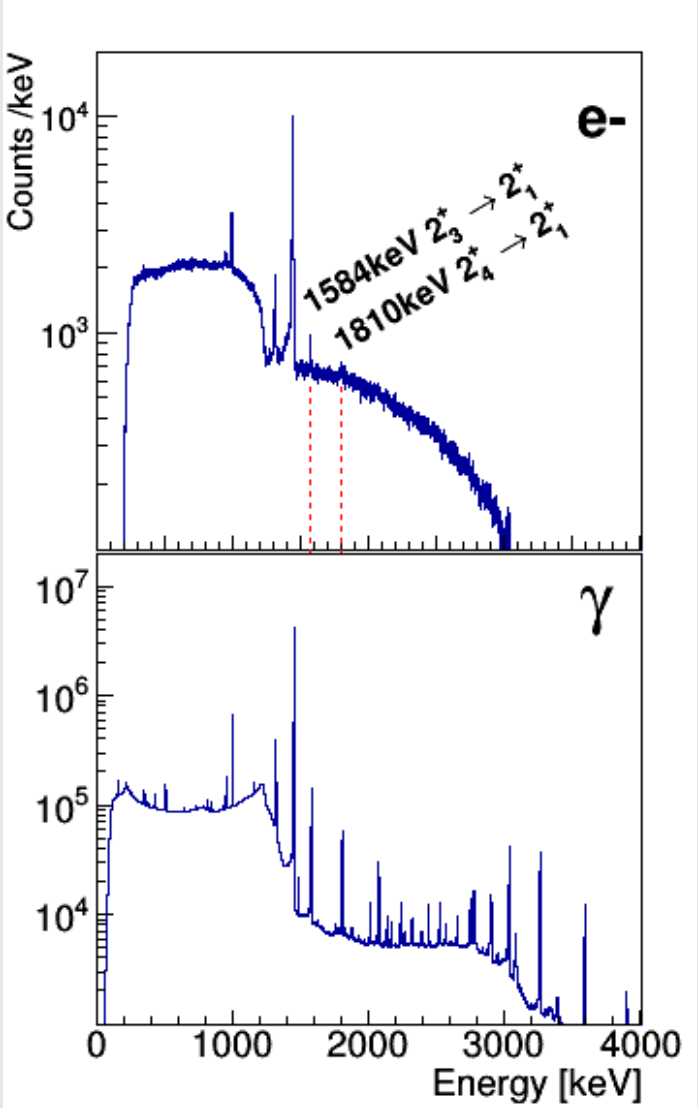




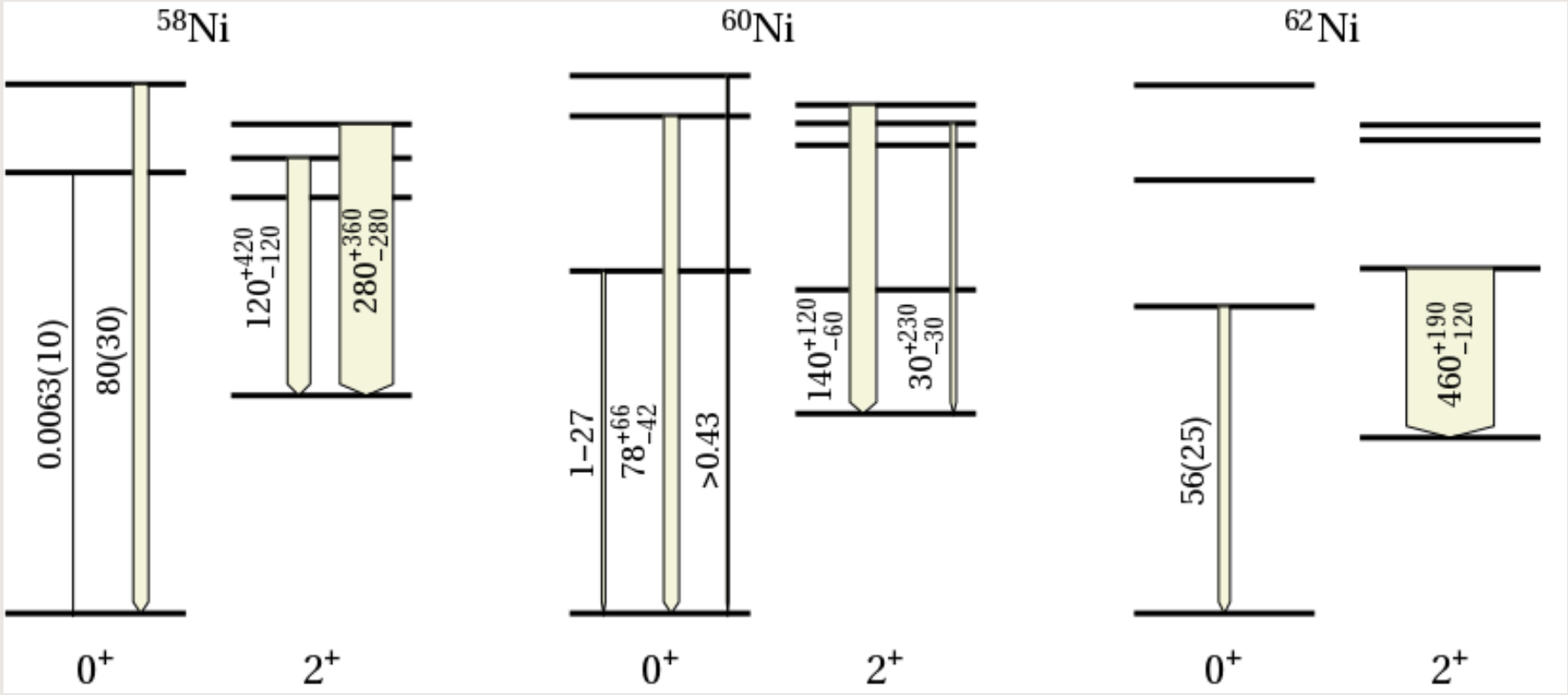
^{58}Ni

- ^{58}Ni (p, p') at 9.2MeV





E0 Strengths along Ni isotopes



PRELIMINARY

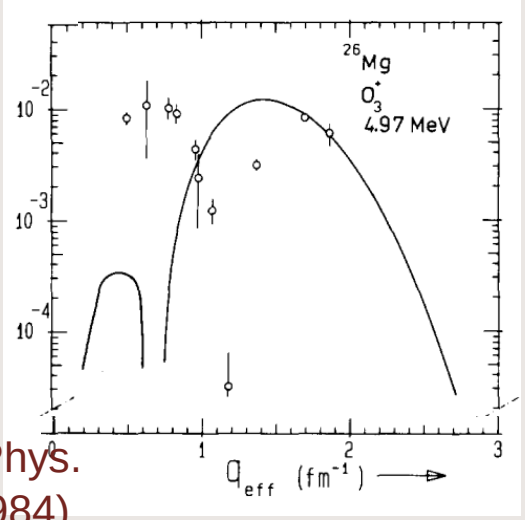
New microscopic model for *E0* transitions

1. Orbital occupations calculated with standard shell model
2. HO radial wavefunctions replaced with EDF calculations carried out with Skyrme form
3. Self-consistent rearrangement of protons as response to added density of valence proton

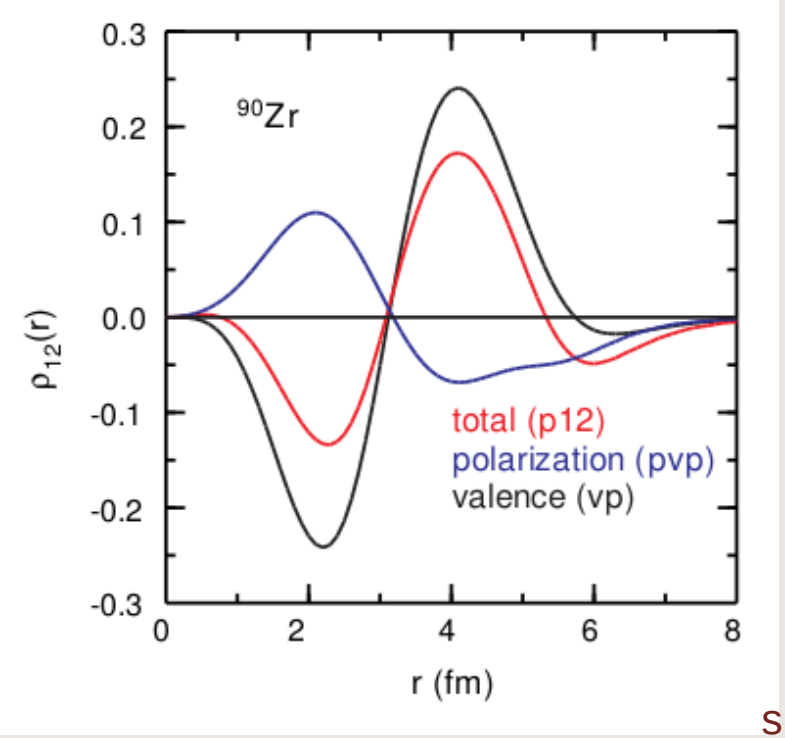
B.A. Brown *et al.*, submitted to PRC (2016)

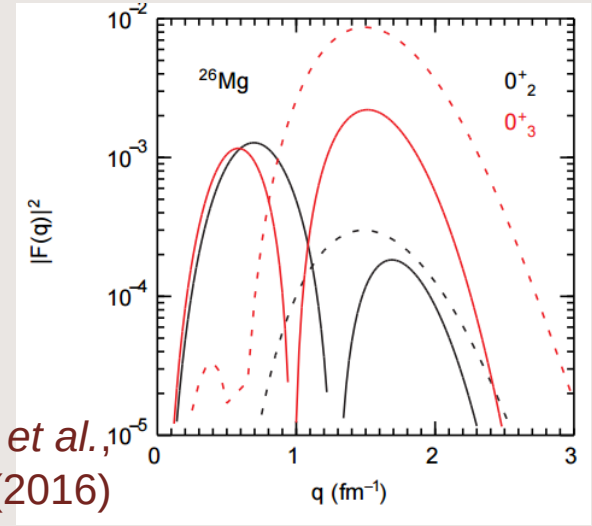
New microscopic model for *E0* transitions

Form factors for inelastic electron scattering are reproduced:



H. Blok, *et al.*, Phys. Lett. 149B, 441 (1984).





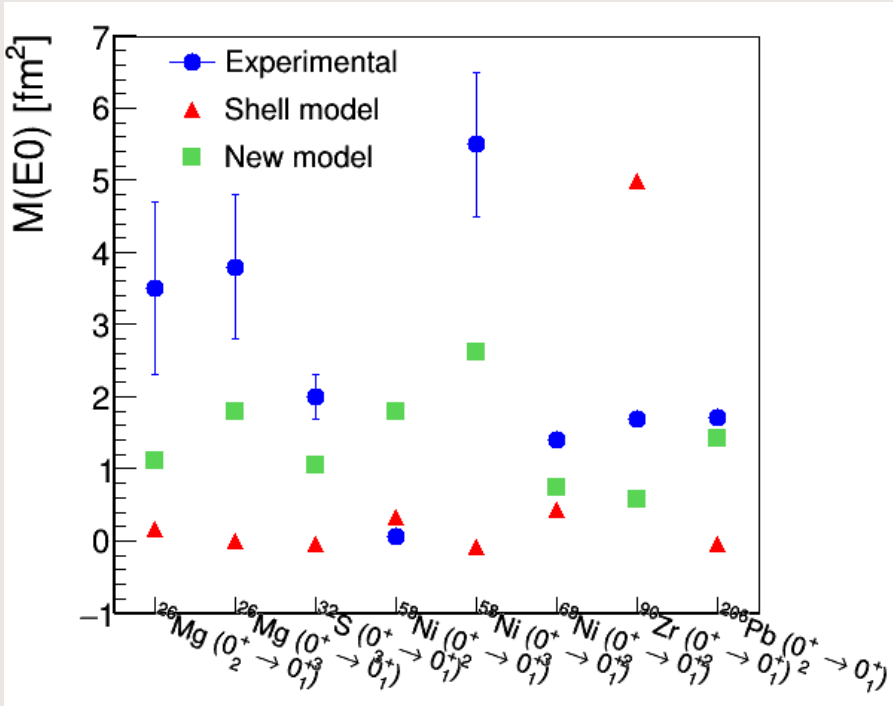
B.A. Brown *et al.*, submitted to PRC (2016)

New microscopic model for *E0* transitions

- Calculates ab in two state mixing scenario

$$\langle 0_1^+ | r^2 | 0_2^+ \rangle = \pm ab(\langle A | r^2 | A \rangle - \langle B | r^2 | B \rangle)$$

- and *E0* matrix elements $\rho(E0) = \frac{\langle f | M(E0) | i \rangle}{eR^2}$



	$J^\pi \rightarrow J^\pi$	Exp.	Shell Model	New Model
^{90}Zr	$0_2^+ \rightarrow 0_1^+$	1.70(3)	5.00	0.57
^{206}Pb	$0_2^+ \rightarrow 0_1^+$	1.72(6)	-0.04	1.43
^{68}Ni	$0_2^+ \rightarrow 0_1^+$	1.41(3)	0.43	0.74
^{58}Ni	$0_2^+ \rightarrow 0_1^+$	0.054(14)	0.33	1.80
^{58}Ni	$0_3^+ \rightarrow 0_1^+$	5.5(10)	-0.08	2.62
^{32}S	$0_3^+ \rightarrow 0_1^+$	2.0(3)	-0.04	1.06
^{26}Mg	$0_2^+ \rightarrow 0_1^+$	3.5(12)	0.16	1.11
^{26}Mg	$0_3^+ \rightarrow 0_1^+$	3.8(10)	0.00	1.79

New microscopic model for E0 transitions

Good reproduction for $0_N^+ \rightarrow 0_1^+$ but not for $2_2^+ \rightarrow 2_1^+$

	$J^\pi \rightarrow J^\pi$	Energy [keV]	Exp.	New Model
^{58}Ni	$2_2^+ \rightarrow 2_1^+$	1321		0.83
^{58}Ni	$2_3^+ \rightarrow 2_1^+$	1583	$7.5^{+26}_{-7.5}$	0.65
^{58}Ni	$2_4^+ \rightarrow 2_1^+$	1809	$11.4^{+14.7}_{-11.4}$	0.11
^{58}Ni	$2_5^+ \rightarrow 2_1^+$	2444		0.24
^{60}Ni	$2_4^+ \rightarrow 2_1^+$	1937	$3.8^{+29}_{-3.8}$	
^{60}Ni	$2_5^+ \rightarrow 2_1^+$	2060	$8.3^{+7.1}_{-3.6}$	
^{62}Ni	$2_2^+ \rightarrow 2_1^+$	1129	$15.3^{+6.3}_{-4.0}$	

Summary

- Excited states in $^{58, 60, 62}$Ni populated via (p, p') reaction with aim to measure *E0* transitions
- For each target, data was also taken in CAESAR HPGe array for re-measurement of mixing ratios
- A better picture of *E0* strengths along this chain of isotopes has been produced
- Analysis of this is on-going
- Can compare to and help improve A. Brown's new model on *E0* matrix elements

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Thank you! Merci

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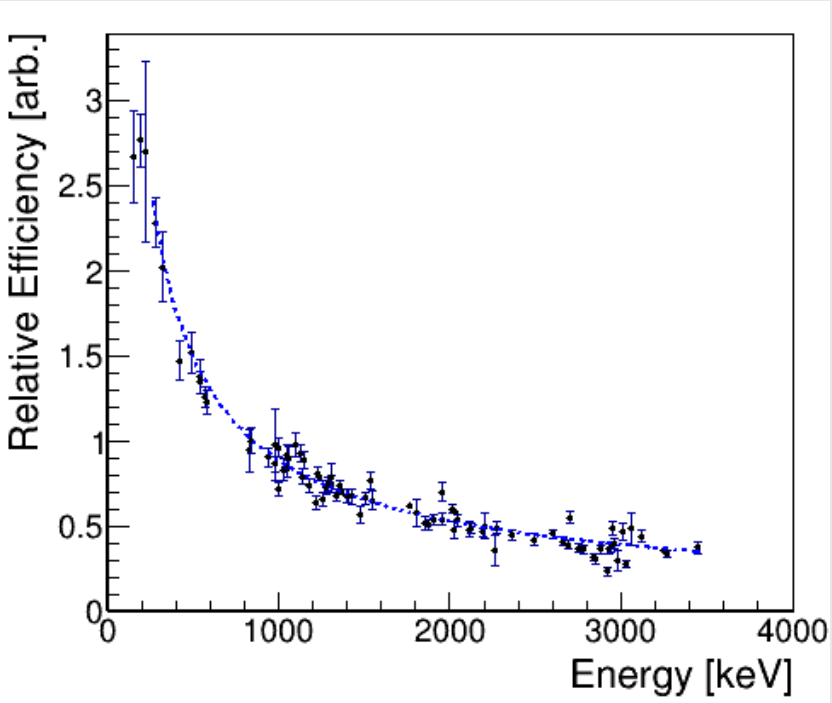

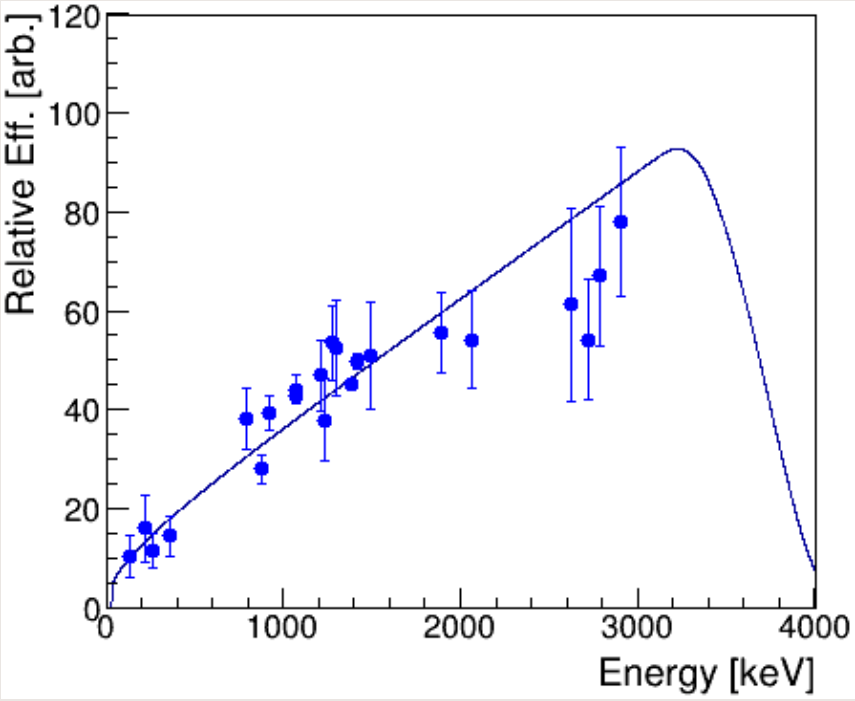

Error Contribution

e.g. in 58Ni rho2 (E0 : 24 - 21) = 280-280+360

	Contribution
Half-life	9.5%
BrIcc	14.5%
Mixing Ratio	6%
Branching Ratios	1.5%
HPGe counts	1%
HPGe efficiency	3%
e- counts	60%
e- efficiency	6%

Half-life required to determine *E0* strengths

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

Nucleus	Energy 0_2^+ (keV)	Energy $0_2^+ \rightarrow 2_1^+$ (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 $0_2^+ \rightarrow 2_1^+$ (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)