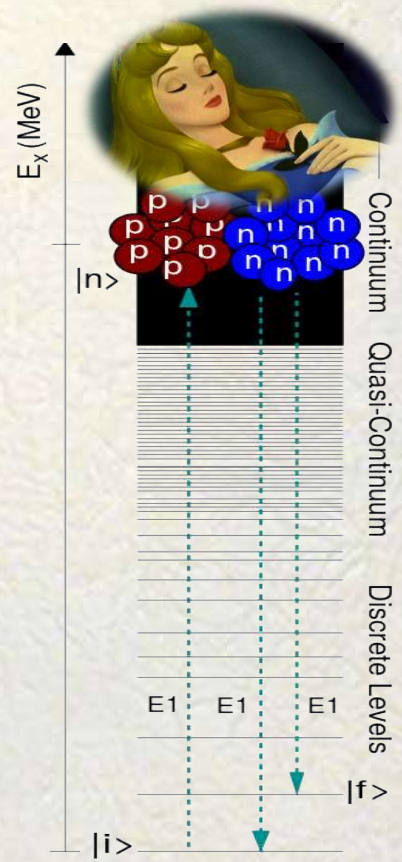
Nuclear polarizability: the sleeping beauty of nuclear physics

Nico Orce
ISOLDE Workshop – December 2015

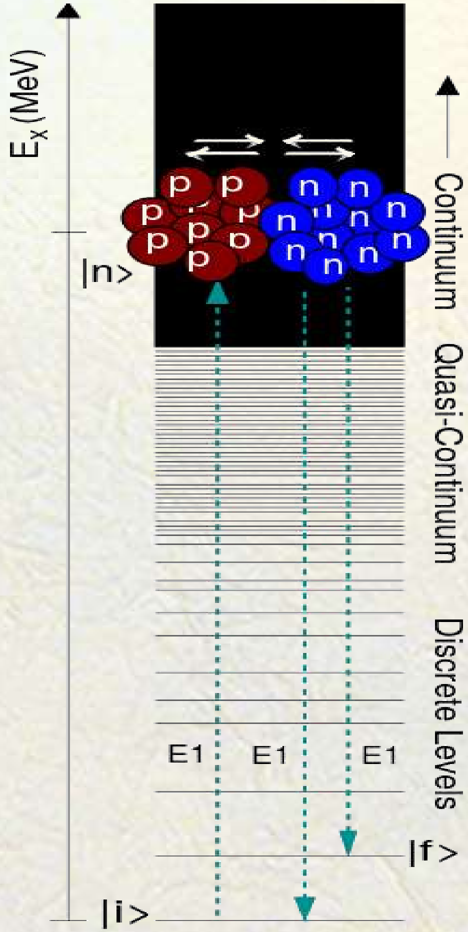
ARKADIĬ BENEDIKTOVICH MIGDAL
(1911–1991)



UNIVERSITY of the WESTERN CAPE

E1 Polarizability (another second order effect)

Virtual excitations via the GDR may affect B(E2) and Q_s values (Eichler 1964)

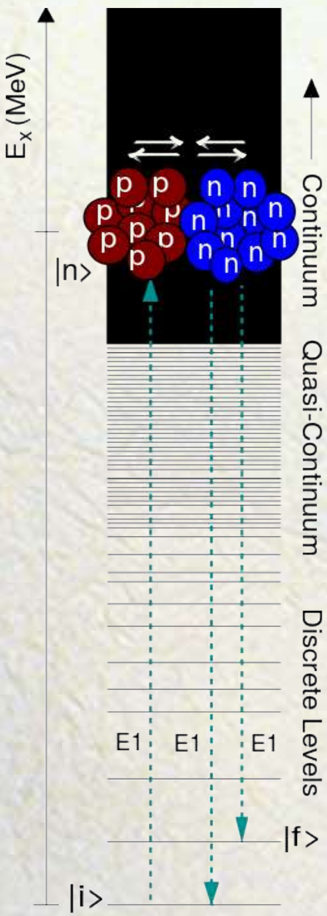


Ground state

$$\alpha = 2e^2 \sum_n \frac{\langle i \parallel \hat{E}1 \parallel n \rangle \langle n \parallel \hat{E}1 \parallel i \rangle}{E_\gamma}$$

Large E1 matrix elements via virtual excitations of the GDR may polarize the shape of the ground and excited states

Nuclear Polarizability, α
Interplay between Macro + Micro



Hydrodynamic Model (Migdal 1945)

$$\boxed{\alpha = \frac{e^2 R^2 A}{40 a_{\rm sym}}}$$

$$a_{\rm sym}(\rho_n - \rho_p)^2/\rho$$

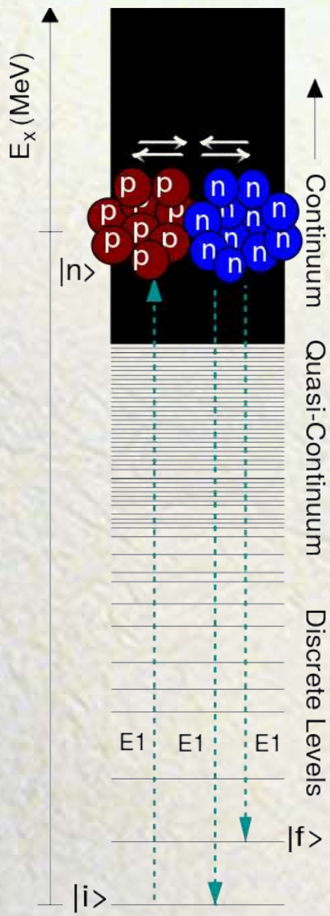
Semiclassical: interpenetrating proton and neutron fluids

Second-order Perturbation Theory (Migdal 1945)

$$\boxed{\alpha = 2e^2 \sum_n \frac{\langle i \parallel \hat{E}1 \parallel n\rangle\langle n \parallel \hat{E}1 \parallel i\rangle}{E_\gamma} = \frac{\hbar c}{2\pi^2}\sigma_{-2}}$$

A.B. Migdal, J. Exp. Theor. Phys. USSR **15**, 81 (1945)

Nuclear Polarizability, α
Interplay between Macro + Micro



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$$\alpha = 2e^2 \sum_n \frac{\langle i \| \hat{E}1 \| n \rangle \langle n \| \hat{E}1 \| i \rangle}{E_\gamma} = \frac{\hbar c}{2\pi^2} \sigma_{-2}$$

$$\sigma_{-2} = 2.25\ A^{5/3}\ \mu\text{b/MeV}$$

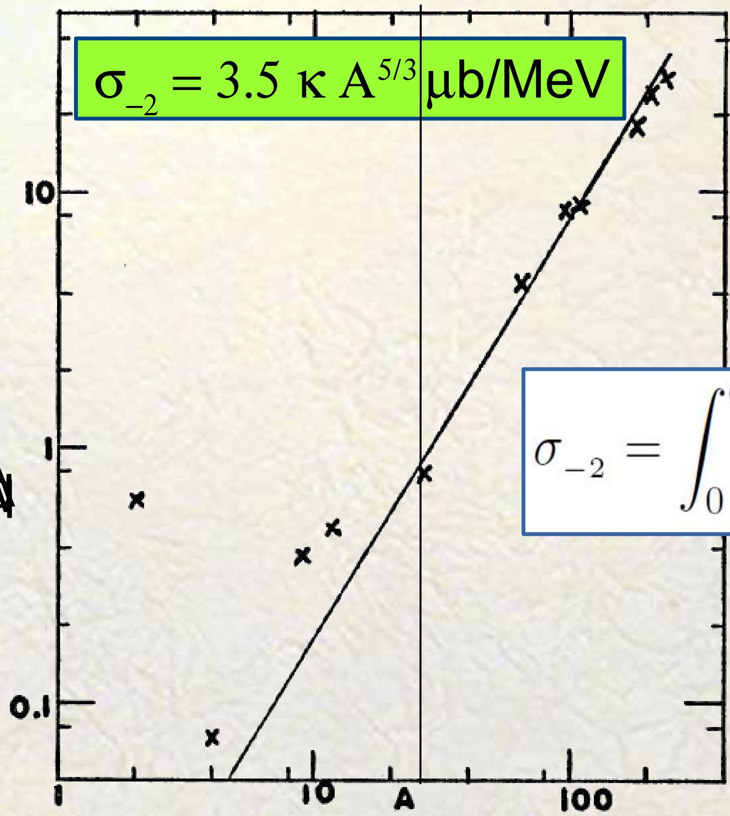
$$R = r_0 A^{1/3}\ \text{fm}$$

$$a_{\text{sym}} = 23\ \text{MeV}$$

A.B. Migdal, J. Exp. Theor. Phys. USSR **15**, 81 (1945)

σ_{-2} vs A in stable nuclei

Levinger confirmed Migdal's power law, but with a different coefficient **(1957)**



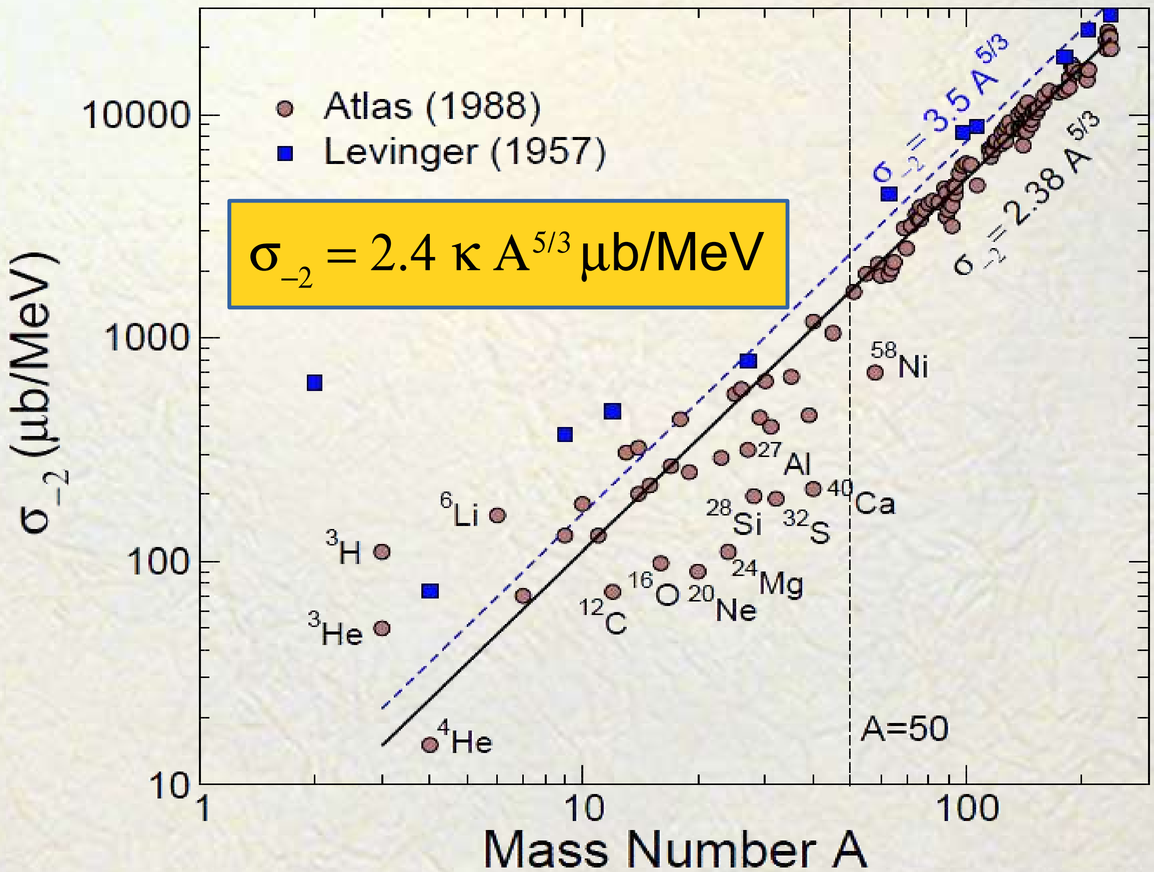
$\sigma_{-2} = 3.5\ \kappa\ A^{5/3}\ \mu b/MeV$

$$\sigma_{-2} = \int_0^\infty \frac{\sigma_{total}(E_\gamma)}{E_\gamma^2}\, dE_\gamma$$

The κ polarizability parameter: deviations from the GDR effects

New power-law formula for σ_{-2}

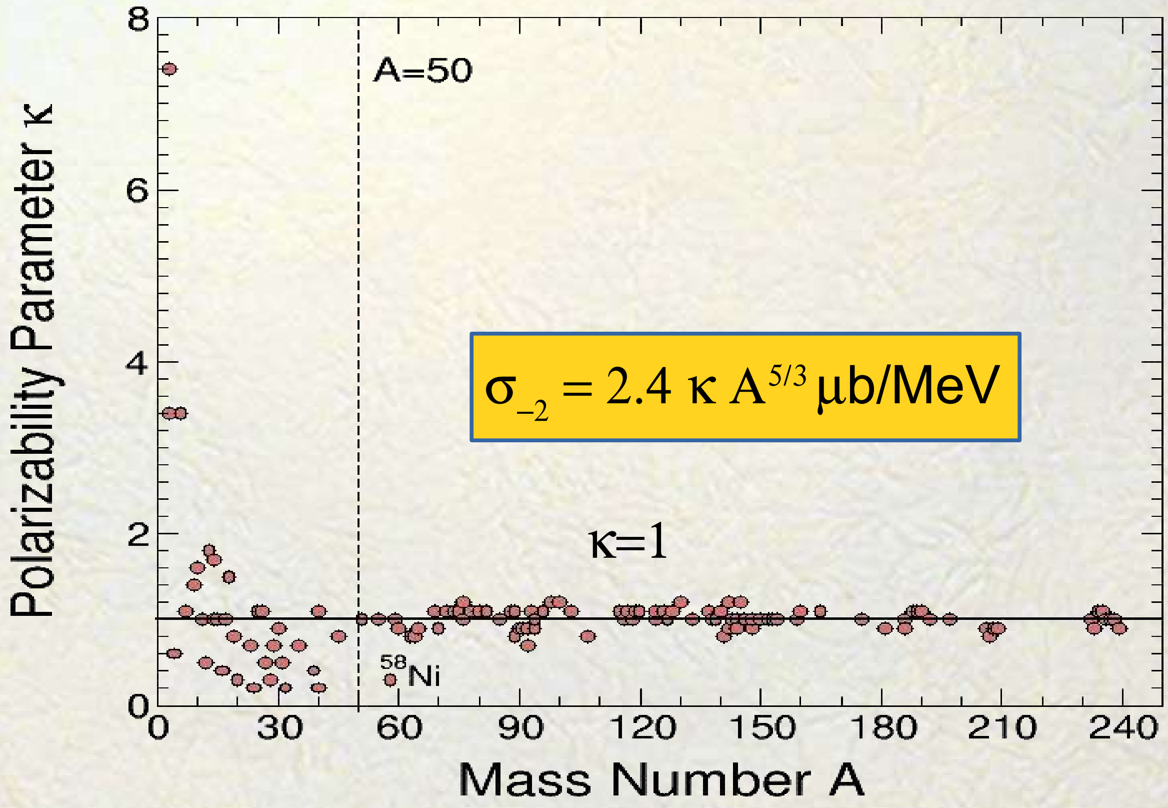
Dietrich and Berman photoneutron cross-section evaluation (**1988**)



J. N. Orce, Phys. Rev. C **91**, 064602 (2015)

σ_{-2} vs A

The κ polarizability parameter: deviations from the GDR effects



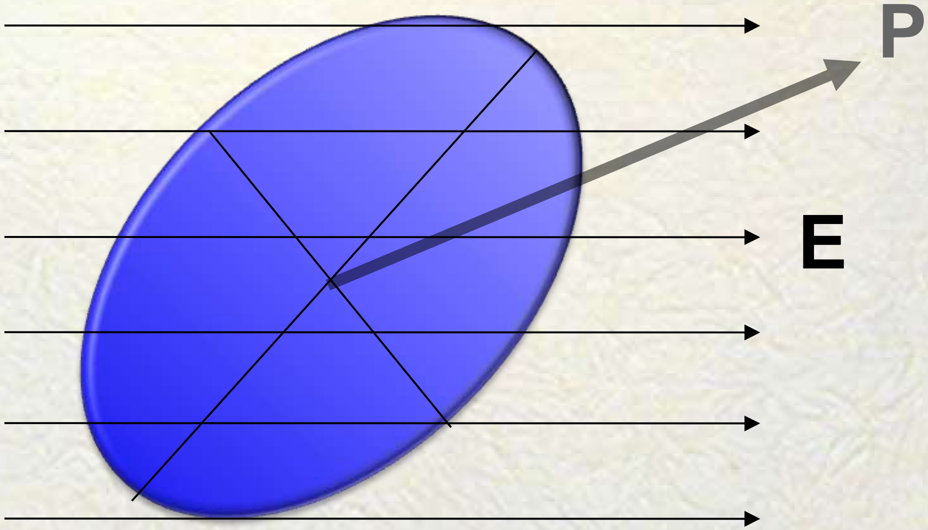
$$\sigma_{-2} = 2.4\ \kappa\ A^{5/3}\ \mu b/MeV$$

$\kappa > 1$ for light loosely bound nuclei (also from Coulex: ^{6}Li, ^{7}Li, ^{17}O)

$\kappa < 1$ for $T_z = 0$ self-conjugate nuclei: missing (γ,p) contribution (Morinaga)

$\mathbf{P} = \alpha\, \mathbf{E}$

The torque produced by the interaction between **E** and **P** may set the nucleus into rotation → **enhancement of quadrupole collectivity**



Deformed nucleus in an external homogeneuos electric field, **E**

Polarization potential reduces the effective quadrupole potential

K. Alder, A. Winther - Electromagnetic Excitation (1975) – Appendix J

$$V_{eff}(t) = V_0(t)\ (\ 1 - V_{pol}(t))$$
$$= V_0(t)\left(1 - z\frac{a}{r(t)}\right).$$

$$z = \frac{10 Z_t \alpha}{3 Z_p R^2 a} \approx 0.005 \frac{E_p A_p}{Z_p^2 (1 + A_p/A_t)}$$ for κ=1

$$\alpha = \frac{\hbar c}{4\pi^2}\sigma_{-2} \qquad \sigma_{-2} = 3.5\ \kappa\ A^{5/3}\ \mu\text{b/MeV}$$

0.005 default value in GOSIA

Adjustable empirical E1 polarization strength (Hausser, Vermeer (1960-70s))

Polarization potential reduces the effective quadrupole potential

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$$\cancel{\alpha = \frac{\hbar c}{4\pi^2}\sigma_{-2} \qquad \sigma_{-2} = 3.5\,\kappa\,A^{5/3}\ \mu\text{b/MeV}}$$

A factor of 2 wrong in Alder & Winther (Electromagnetic excitation)

+

New formula for σ_{-2}

Polarization potential reduces the effective quadrupole potential

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$\sigma_{-2} = 2.4\ \kappa\ A^{5/3}$ μb/MeV

$$z = 0.0077 \frac{E_p A_p}{Z_p^2(1 + A_p/A_t)}$$ for $\kappa = 1$

Polarization potential reduces the effective quadrupole potential

K. Alder, A. Winther - Electromagnetic Excitation (1975) – Appendix J

$$\begin{aligned} V_{eff}(t) &= V_0(t)\ (\ 1 - V_{pol}(t)) \\ &= V_0(t)\left(1 - z\frac{a}{r(t)}\right). \end{aligned}$$

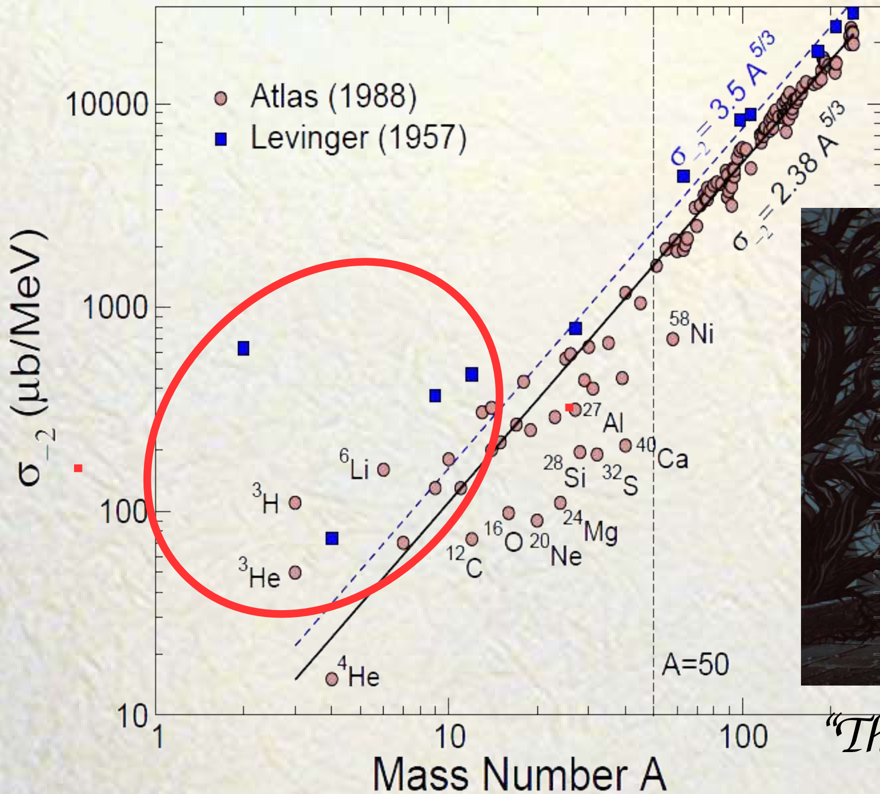
$$z = 0.0077\,\frac{E_p A_p}{Z_p^2(1 + A_p/A_t)}$$ for $\kappa=1$

An overall increase of 35% in the polarization potential

0.0077 should be the default value in GOSIA

"Tell me Prince, why light nuclei are more polarizable?" asked the Dragon.

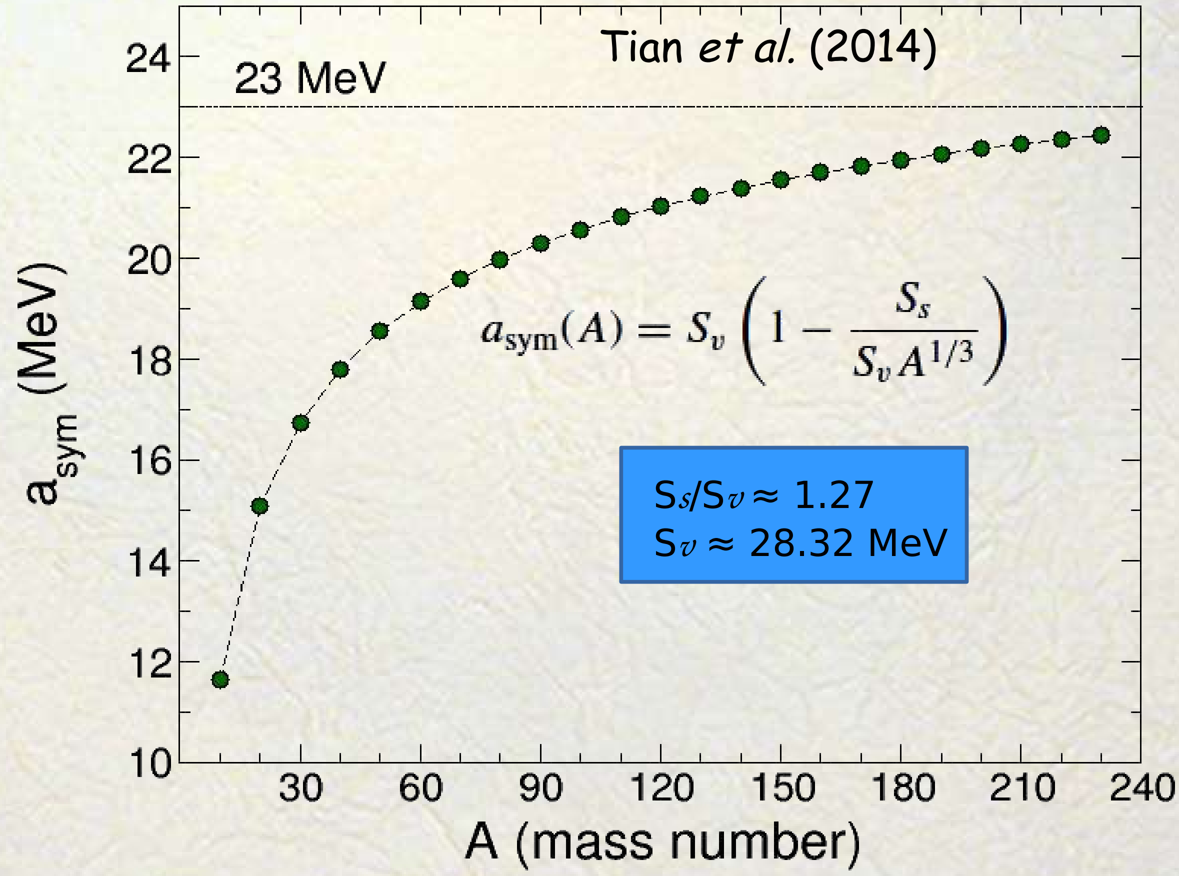
"Because they're loosely bound!" replied the Prince.



"That's insufficient!" fired the Dragon.

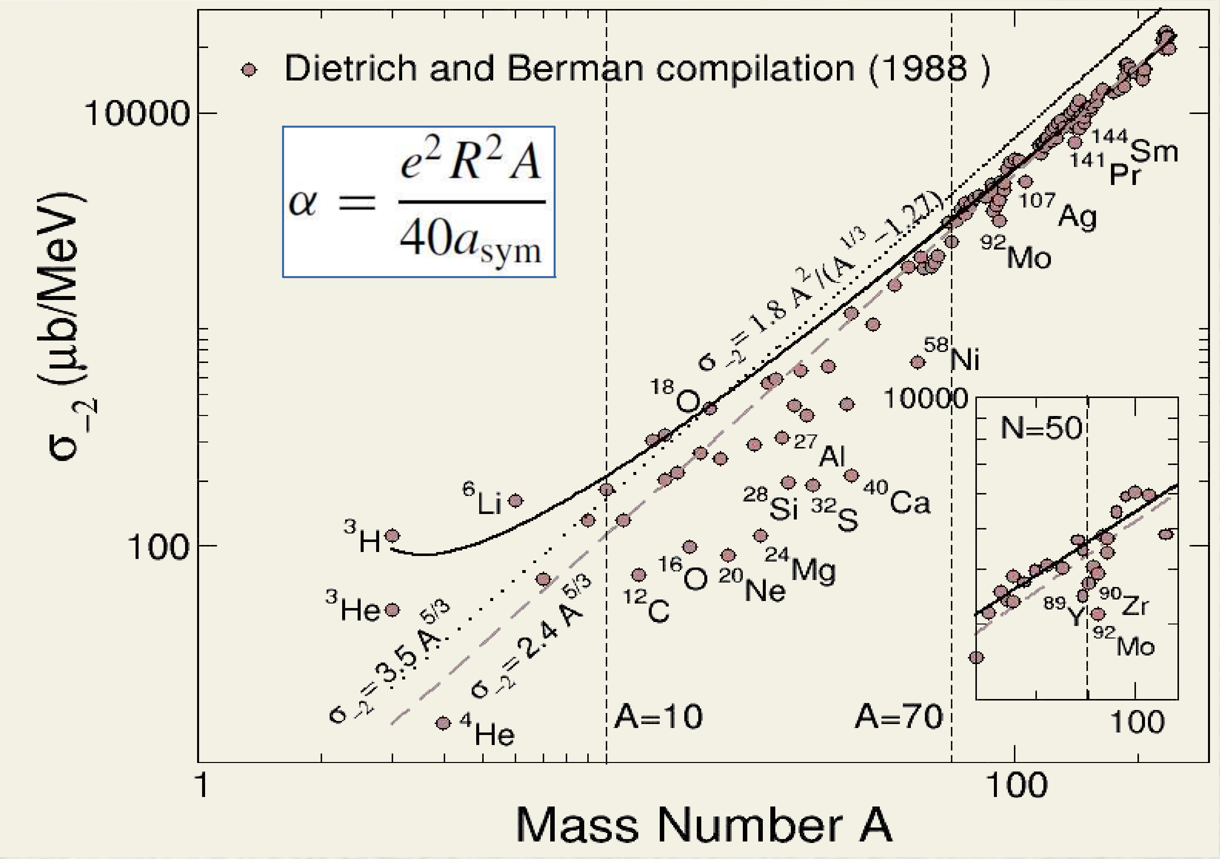
a_{sym} is not 23 MeV: $a_{sym}(A)$

From a global fit to the binding energies of isobaric nuclei with $A \geq 10$, extracted from the 2012 atomic mass evaluation



New formula for σ_{-2} from $a_{sym}(A)$

The increasing upbend observed as A decreases provides an explanation for the large GDR effects observed in light nuclei. It merges with data at A~70.

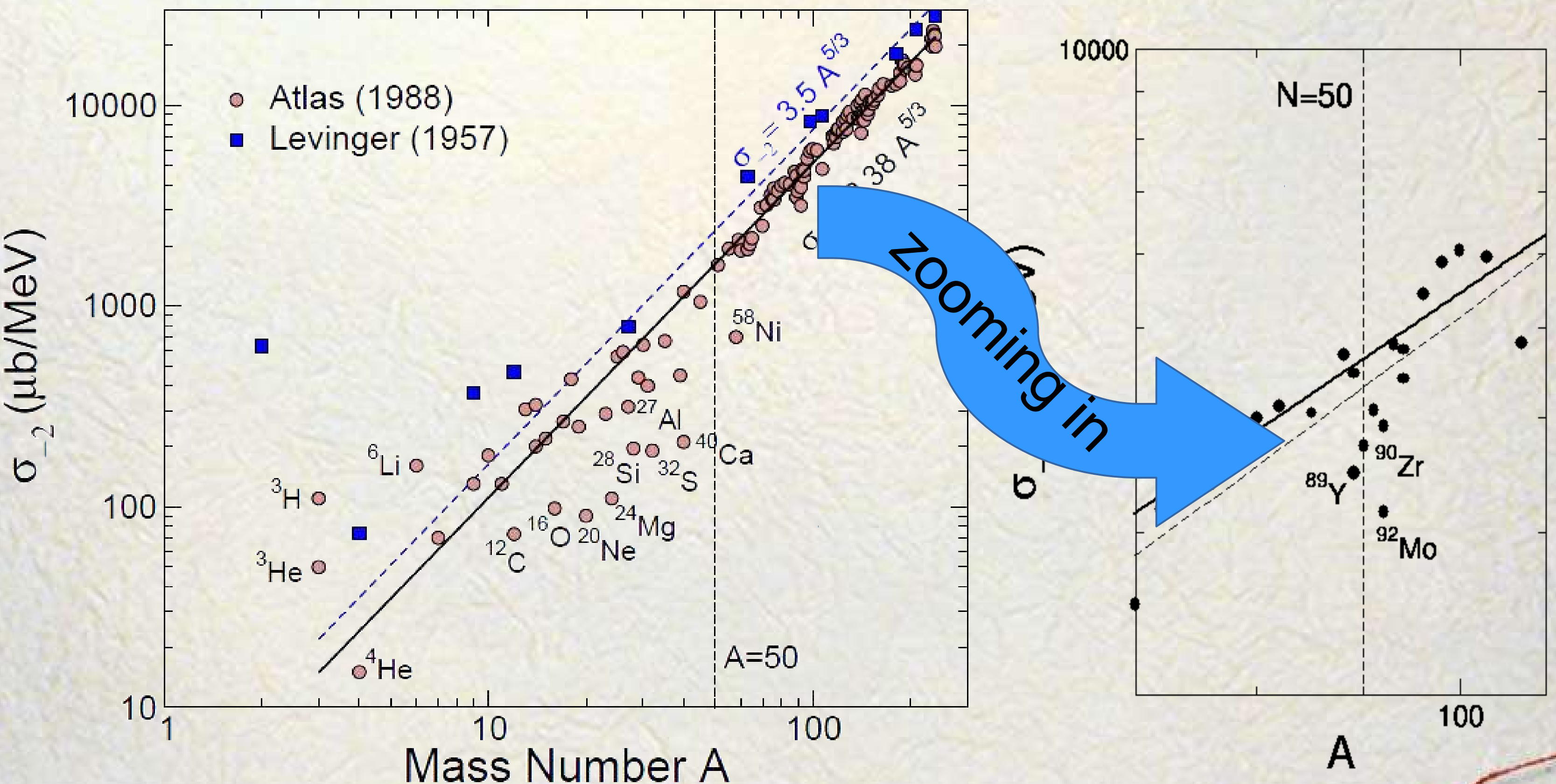


$\kappa > 1$ for light loosely bound nuclei

The validity of the hydrodynamic model to be tested for the lightest A < 10 nuclei

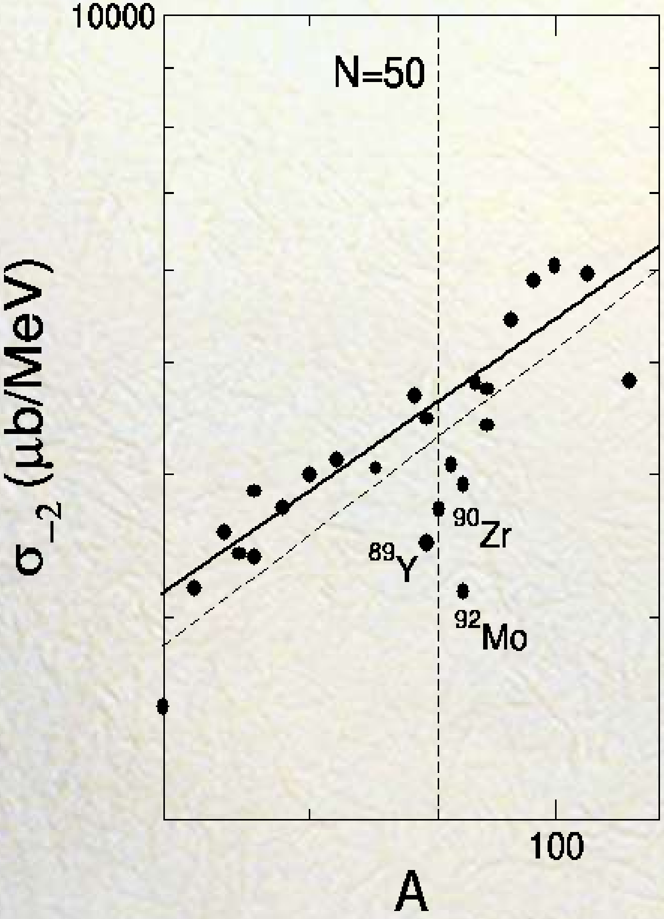
Deviations from GDR effects in semimagic nuclei: k<1

Shell effects: hindrance of nuclear collectivity!



Deviations from GDR effects in semimagic nuclei: k<1

Shell effects: hindrance of nuclear collectivity!



"My brave companion, are these shell effects?" asked the astonished prince

"Yeah, but they yield only ***~2-3% decrease in the B(E2) values!*** *" replied his horse.*

$B(E2; 0^+ \rightarrow 2^+)$ value in ^{18}O

Long-standing discrepancy between Coulex and high-precision lifetime measurement

A DBLA MEASUREMENT OF THE LIFETIME OF THE FIRST EXCITED LEVEL IN ^{18}O AND A CRITICAL COMPARISON OF LIFETIME RESULTS BY DIFFERENT METHODS

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Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J1J0

Received 26 November 1980

(Revised 22 July 1981)

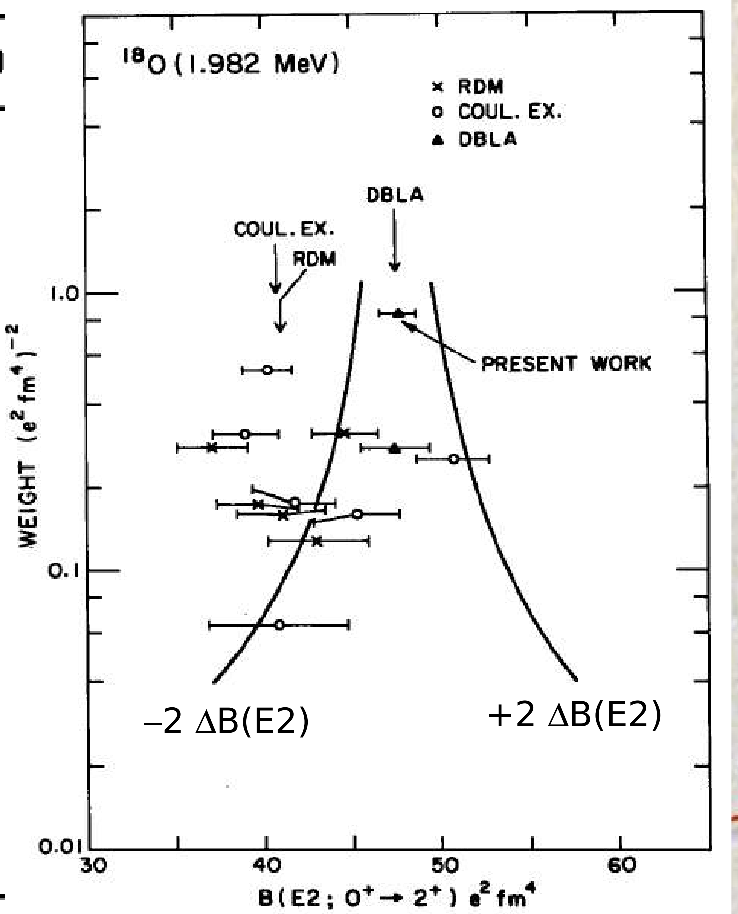
Abstract: An accurate measurement of the lifetime of the 1.982 MeV level in ^{18}O has been obtained by bombarding ^4He and ^1H implanted targets with beams of 34 and 47 MeV ^{18}O ions. The mean lifetime determined by fitting the Doppler-broadened γ-ray lineshapes with experimentally determined stopping powers was 2.80 ± 0.07 ps. A detailed comparison of the mean lifetime values obtained by different techniques for this level and several other sd shell transitions suggest that recent Coulomb excitation $B(E2; 0^+ \rightarrow 2^+)$ values for ^{18}O are ≈ 10% too small.

B(E2; $0^+ \rightarrow 2^+$) value in ^{18}O

Long-standing discrepancy between Coulex and high-precision lifetime measurement

Summary of the $B(E2; 0^+ \rightarrow 2^+)$ values for the 1.982 MeV state of ^{18}O obtained by different techniques

Method		$B(E2; 0^+ \rightarrow 2^+)$ $(e^2 \cdot fm^4)$
Recoil distance		41.0 ± 2.5 [a])
		37.2 ± 1.9
		39.8 ± 2.4
		43.0 ± 2.8
		44.6 ± 1.8 [b])
	wt. mean	41.1 ± 1.0
DBLA		47.5 ± 1.9
		47.6 ± 1.1
	wt. mean	47.6 ± 1.0
Coulex		41.7 ± 2.4
		50.7 ± 2.0 [a, c])
		40.7 ± 4.0 [d])
		40.1 ± 1.5
		45.3 ± 2.5
		39.0 ± 1.8
	wt. mean	40.8 ± 0.9



B(E2; $0^+ \rightarrow 2^+$) value in ^{18}O

Long-standing discrepancy between Coulex and high-precision lifetime measurement

PHYSICAL REVIEW C VOLUME 19, NUMBER 5 MAY 1979

Photonuclear cross sections for ^{18}O

J. G. Woodworth, K. G. McNeill,* J. W. Jury,† R. A. Alvarez, B. L. Berman, D. D. Faul, and P. Meyer
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 24 July 1978; revised manuscript received 27 November 1978)

All the major photonuclear cross sections for ^{18}O, including $\sigma(\gamma,p)$, $\sigma[(\gamma,n)+(\gamma,np)]$, and $\sigma(\gamma,2n)$, were measured as a function of photon energy from threshold to 42 MeV. The photon energy resolution was between 200 and 300 keV. The source of radiation was the monoenergetic photon beam obtained from the annihilation in flight of fast positrons. The partial photoneutron cross sections were determined by neutron multiplicity counting, and the average neutron energies for both single- and double-photoneutron events were determined simultaneously with the cross-section data by the ring-ratio technique. The photoproton cross section was determined by counting the delayed neutrons from the β-decay of the residual ^{17}N nuclei. Integrated cross sections were extracted from the data and compared with sum-rule predictions. Resonances in the pygmy-resonance region exhibit substantial decay branching to negative-parity states in ^{17}O.

TABLE IV. Integrated cross sections for ^{18}O (integrated up to 41.8 MeV).

Reaction	σ_{int} (MeV mb)	σ_{int} (sum-rule units)	σ_{-1} (mb)	σ_{-2} (mb MeV^{-1})
^{18}O(γ,p)	44.4	0.17	1.66	0.064
^{18}O(γ,n)	121.5	0.46	5.93	0.342
^{18}O$(\gamma,2n)$	76.7	0.29	3.14	0.141
^{18}O(γ,n_t)	198.3	0.74	9.08	0.483
^{18}O(γ,tot)	242.6	0.91	10.73	0.547

B(E2; $0^+ \rightarrow 2^+$) value in ^{18}O

Long-standing discrepancy between Coulex and high-precision lifetime measurement

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$\sigma_{-2} = 547$ μb/MeV = 2.4 κ $A^{5/3}$ μb/MeV

κ=1.84

$$z = 0.0077\ \kappa\ \frac{E_p A_p}{Z_p^2(1 + A_p/A_t)}$$

Polarization potential (Orce, 2015)

$$z = \frac{10 Z_t \alpha}{3 Z_p R^2 a} \approx 0.005\ \frac{E_p A_p}{Z_p^2(1 + A_p/A_t)}$$

Default polarization potential (Winther-de Boer, GOSIA)

The remarkable case of ^{18}O

B(E2; $0^+ \rightarrow 2^+$) value in ^{18}O

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$\sigma_{-2} = 547\ \mu b/MeV = 2.4\ \kappa\ A^{5/3}\ \mu b/MeV$ → $\kappa=1.84$

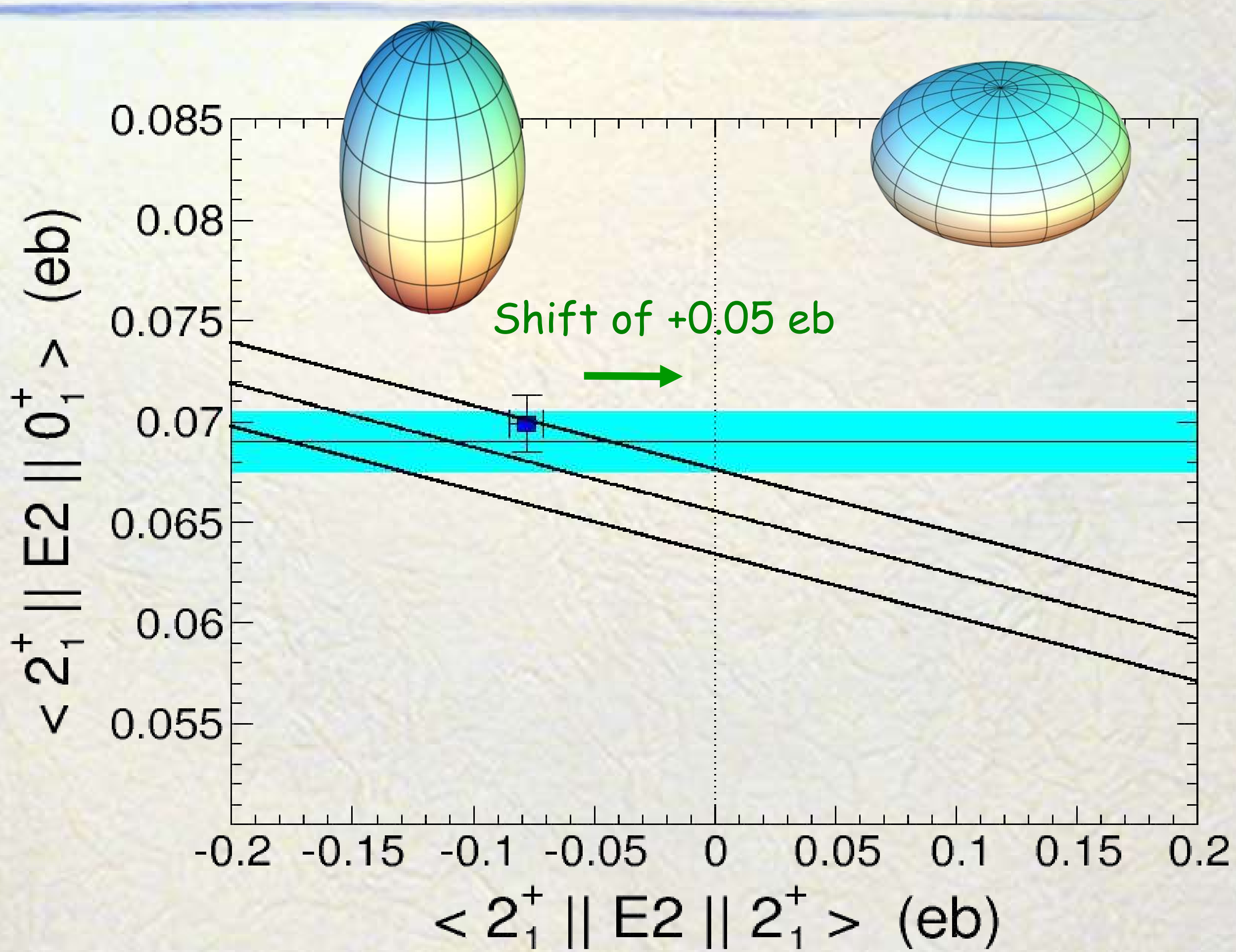
$$z = 0.0077\ \kappa\ \frac{E_p A_p}{Z_p^2 (1 + A_p/A_t)}$$

Polarization potential (Orce, 2015)

B(E2) values underestimated in previous Coulex measurements by ~10%!

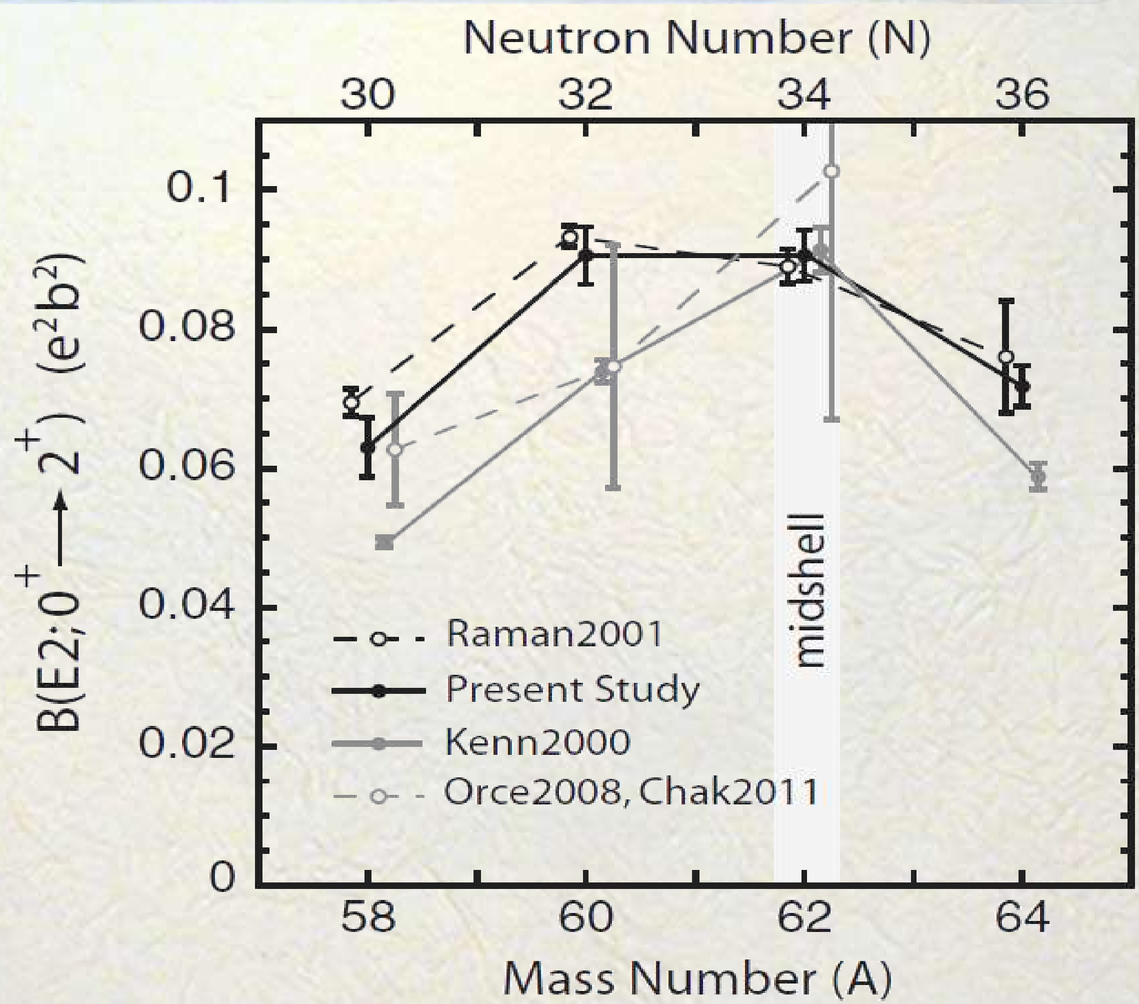
Nuclear polarization effects in Coulomb excitation studies

Quadrupole moments of first 2+ state more oblate



Ni isotopes

Discrepancy between Coulex and high-precision lifetime measurement



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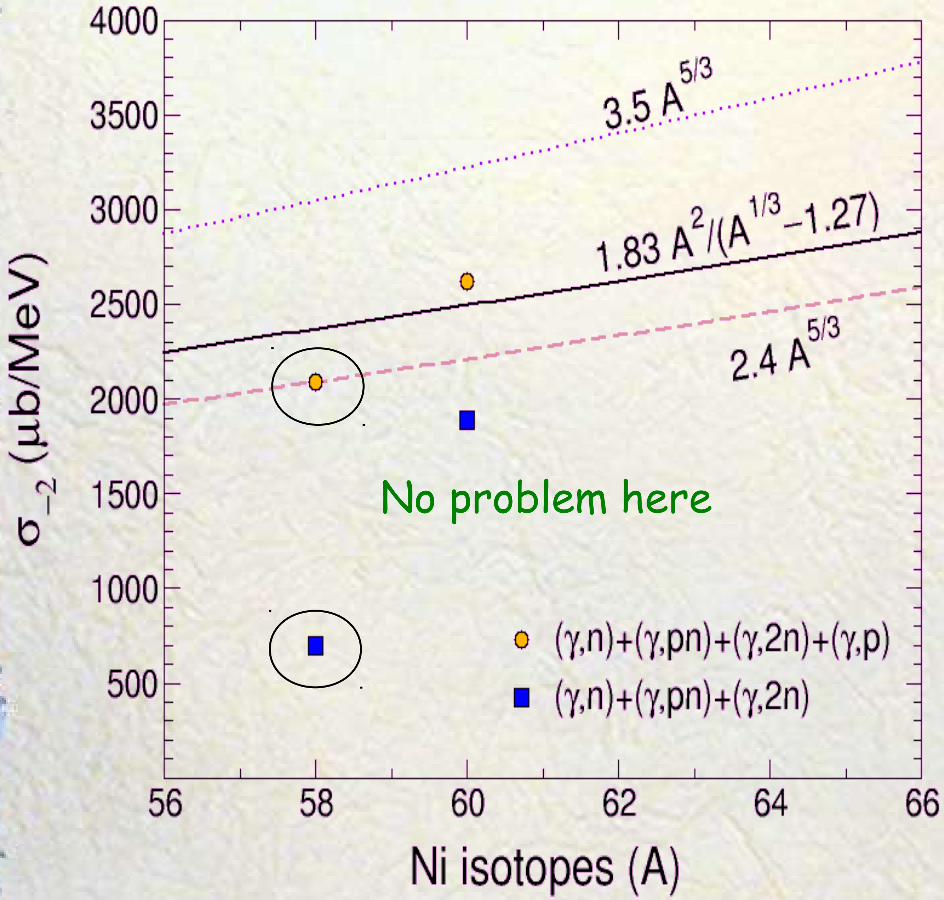
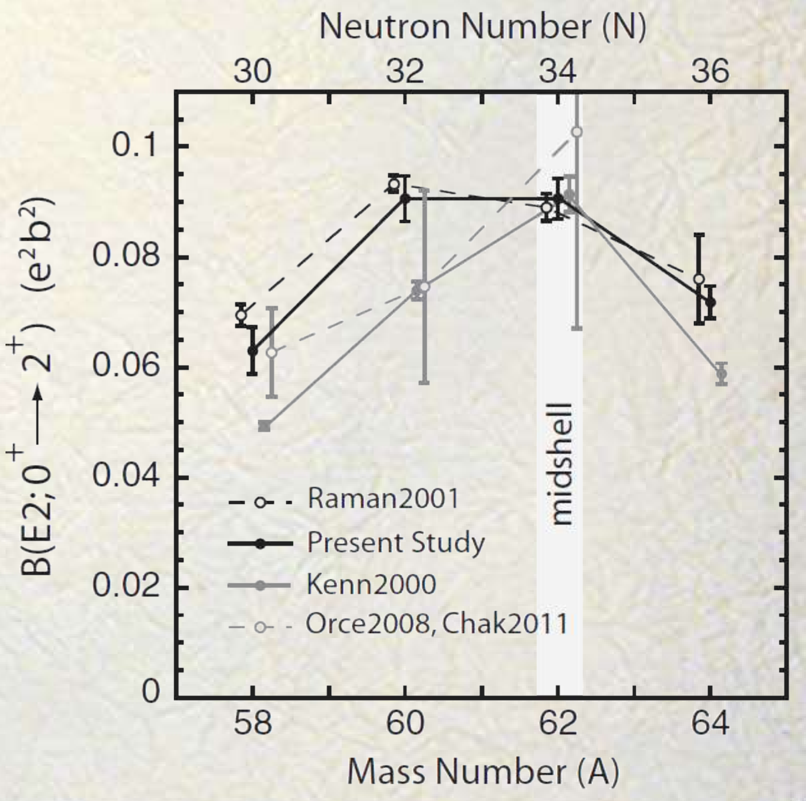


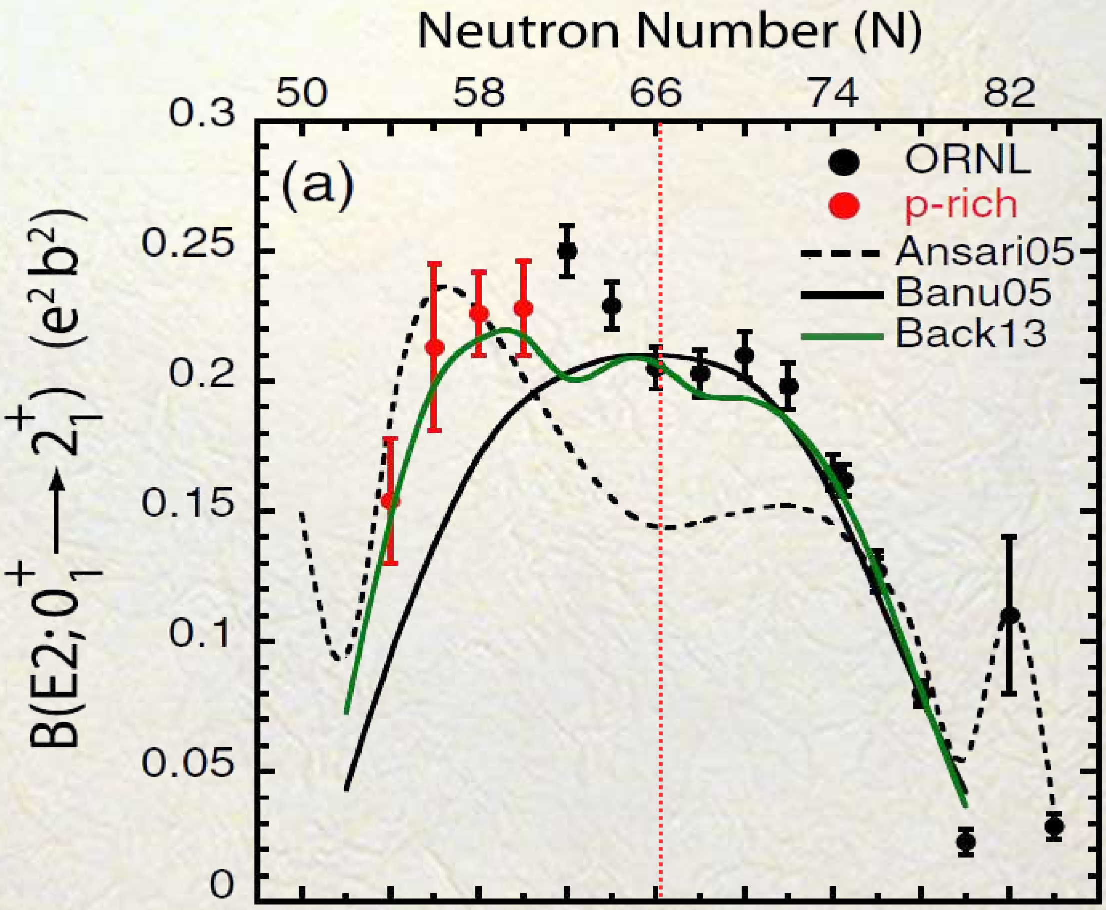


Allmond *et al.*, Phys.Rev. C **92** (R) (2014)

Tin isotopes

Discrepancy between Coulex and high-precision lifetime measurement

Enhancement of B(E2) values + weak shell gap @ N=66

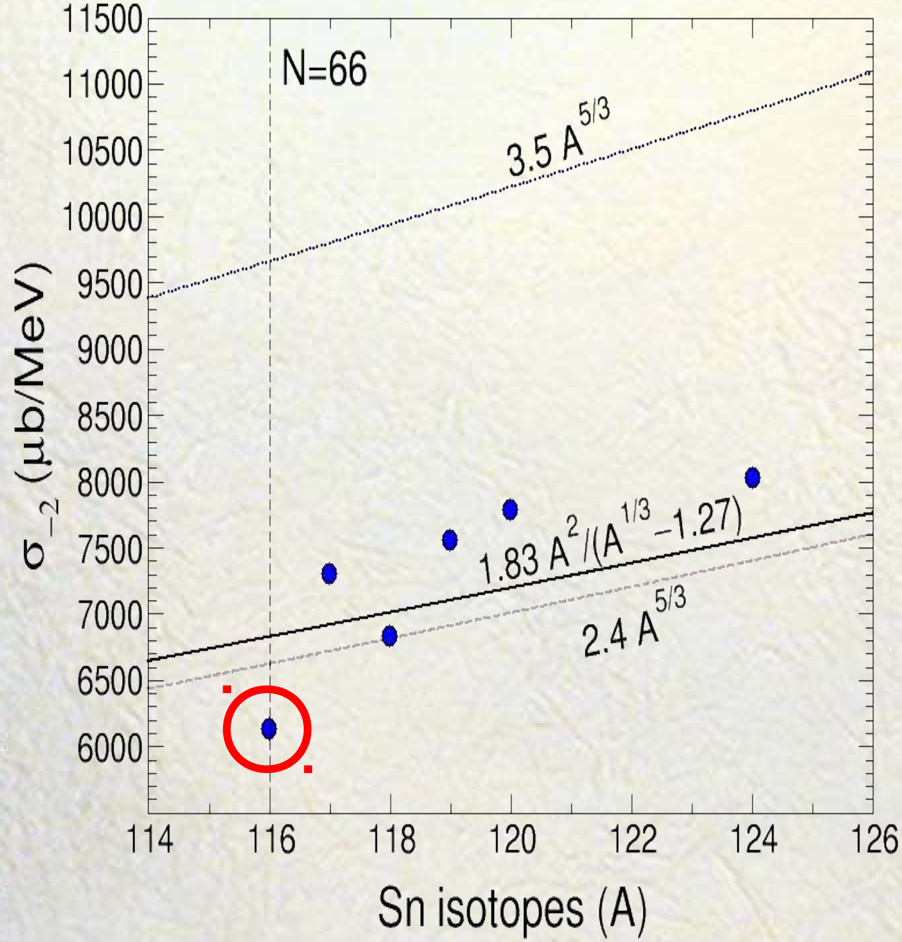


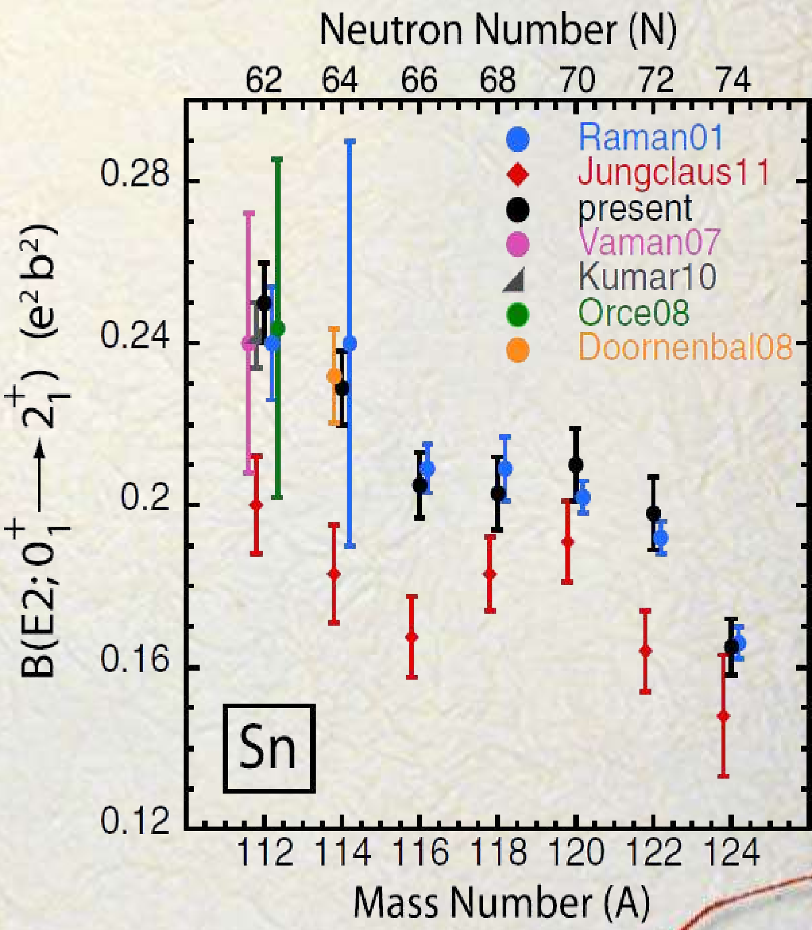
Allmond *et al.*, Phys.Rev. C **92** (R) (2015)

Tin isotopes

Discrepancy between Coulex and high-precision lifetime measurement

Weak shell gap @ N=66





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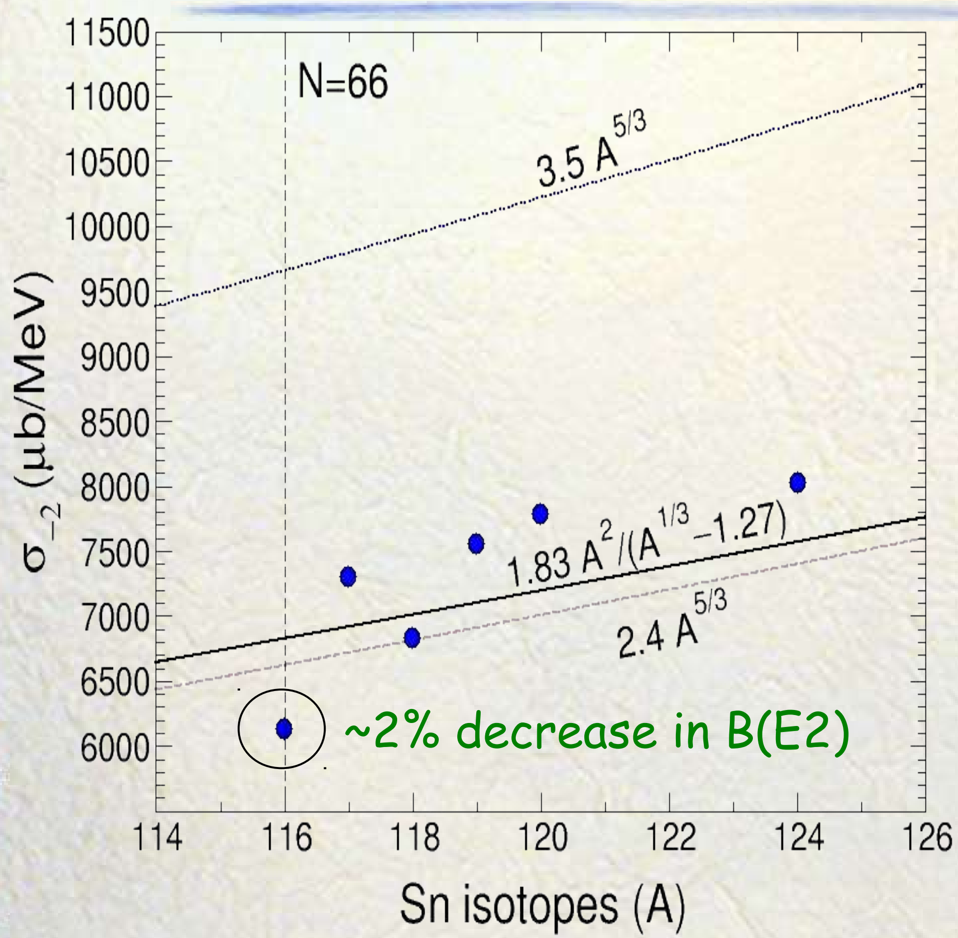
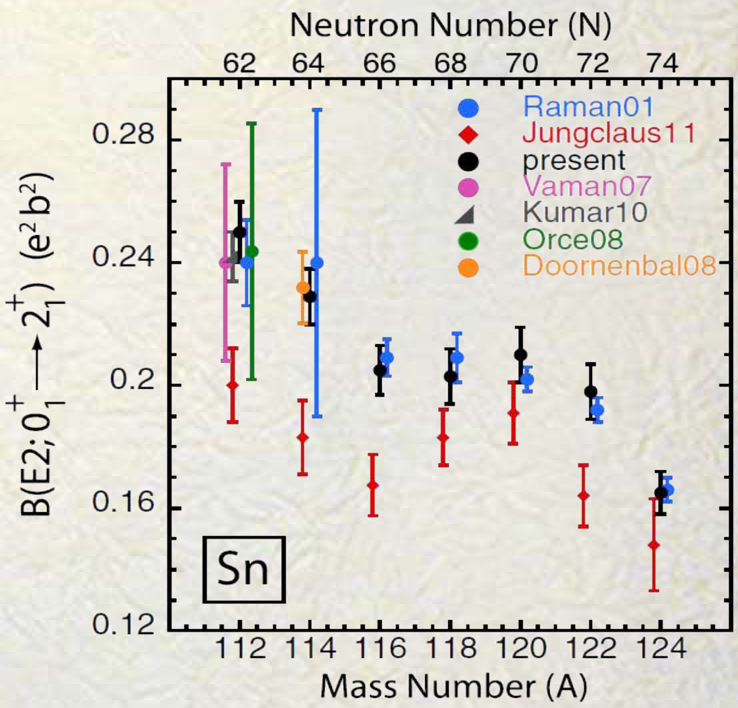
Discrepancy between Coulex and high-precision lifetime measurement

Weak shell gap @ N=66



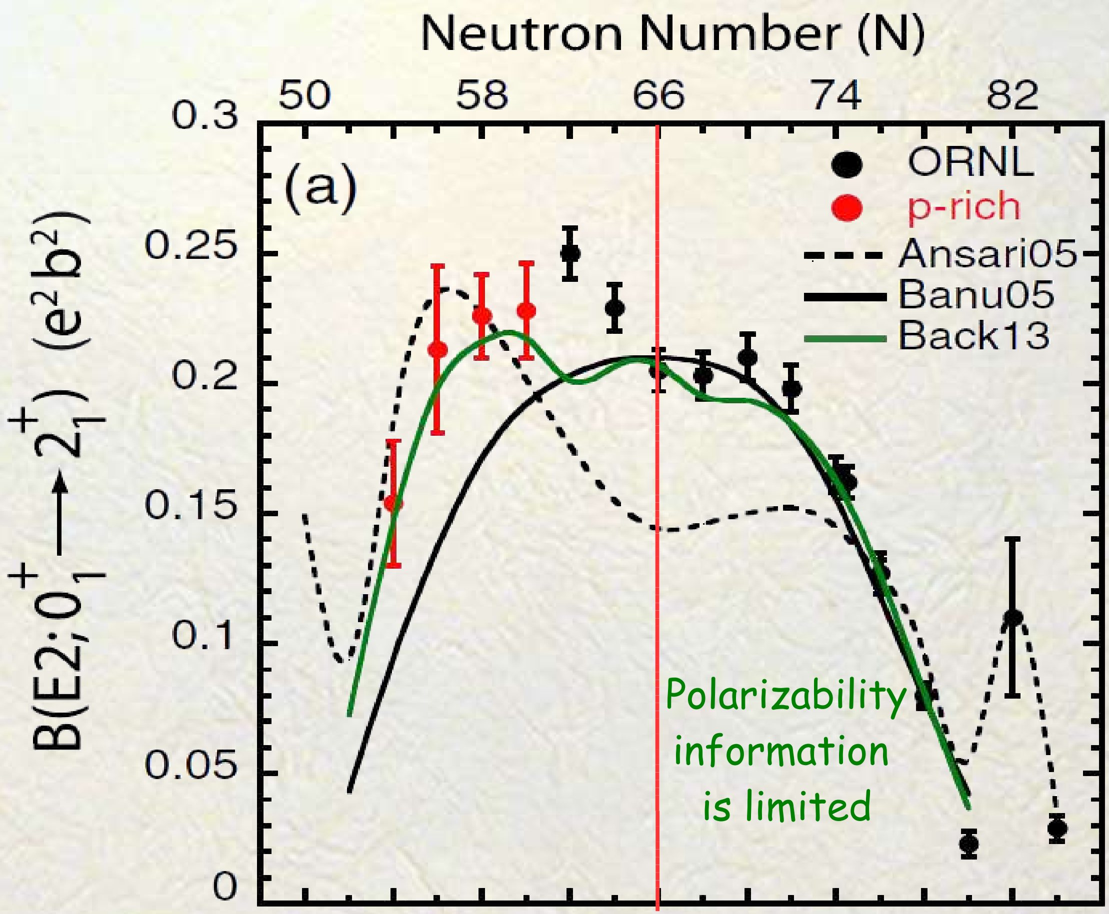


Allmond *et al.*, Phys.Rev. C **92** (R) (2015)

The reduction in polarizability does not account for such a difference

Proton-rich Sn isotopes

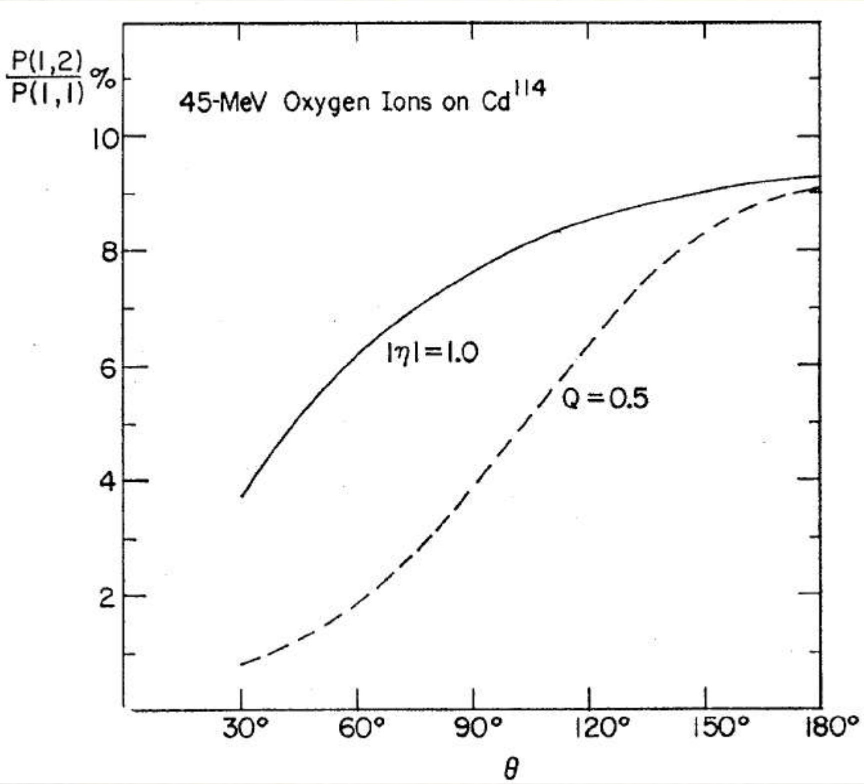
Large hindrance of polarizability could explain enhancement of B(E2) values, but…

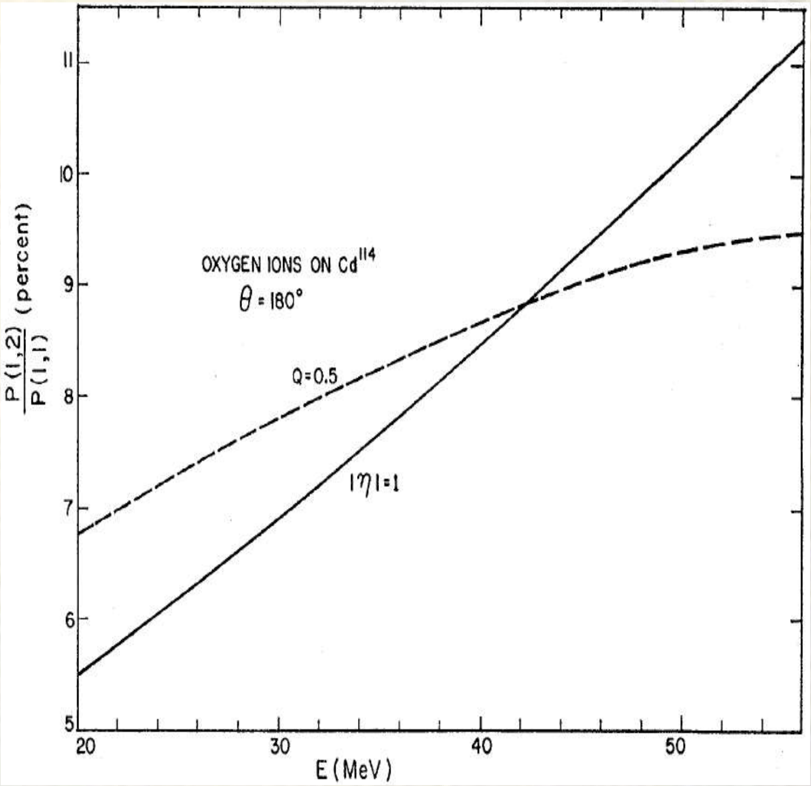


Allmond *et al.*, Phys.Rev. C **92** (R) (2015)

The good news

We can study both 2nd order effects (Eichler 1964)





The difference in the angular behavior or in the energy dependence may help distinguish between the two effects.

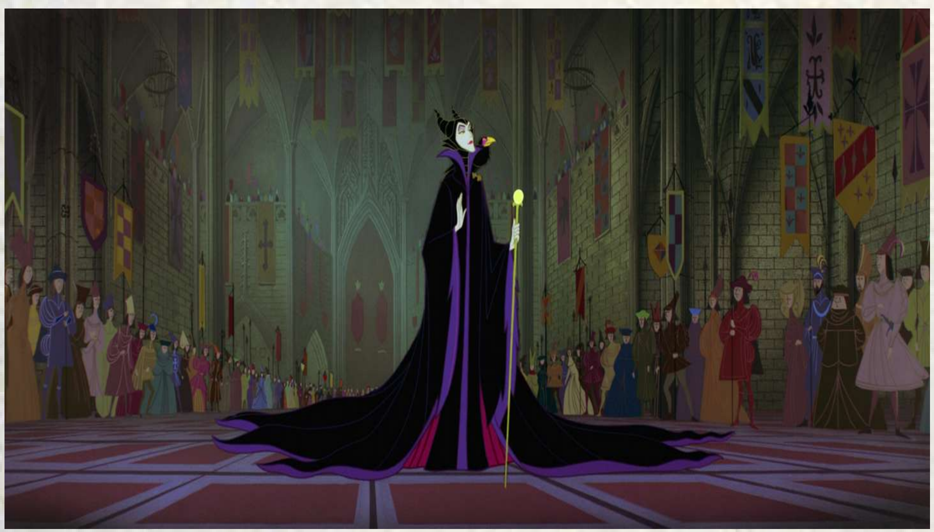
Nuclear polarization effects in Coulomb excitation studies

J. N. Orce[1, *]

[1] *Department of Physics, University of the Western Cape, P/B X17, Bellville, ZA-7535 South Africa*

The polarization potential induced by virtual electric-dipole excitations via the giant dipole resonance is 35% larger than expected. These polarization effects are sensitive to the nuclear binding energy and affect the extraction of reduced transition probabilities and spectroscopic quadrupole moments. Furthermore, this work provides a means to test the hydrodynamic model and constrain the nuclear symmetry energy through the study of Coulomb-excitation measurements well-below the Coulomb barrier, with negligible nuclear contributions.

PACS numbers: 21.10.Ky, 25.70.De, 25.20.-x, 25.20.Dc, 24.30.Cz



The princess polarizability has woken up!

Nuclear polarizability: the sleeping beauty of nuclear physics

Motives for Scientific Creativity

ARKADIĬ BENEDIKTOVICH MIGDAL
(1911–1991)

Not for you are passion and goldlust,
It is science that entices you.

Passion may fade and love is betrayed
But you cannot be deceived
By the bewitching structure of the cockroach.

N. Olennikov, Comic Verses

On the Psychology of Scientific Creativity
A.B. Migdal, Contemp. Phys. VOL. **20**, NO. 2, 121-148 (**1979)**