UNIVERSITY OF NOTRE DAME

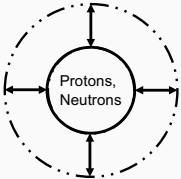
INSTITUTE FOR STRUCTURE AND NUCLEAR ASTROPHYSICS

Are the Molybdenums Fluffy Too?

Kevin B. Howard

Conference in Collective Motion in Nuclei under Extreme Conditions (COMEX6)
Cape Town, ZA
November 1, 2018

Isoscalar Giant Monopole Resonance: Our window to K_∞



- For spherical nuclei, radially symmetric vibration of nuclear density
- Scaling model relates E_{ISGMR} directly with K_A:

$$E_{\text{ISGMR}} = \hbar\sqrt{\frac{K_A}{m\langle r_0^2\rangle}}$$

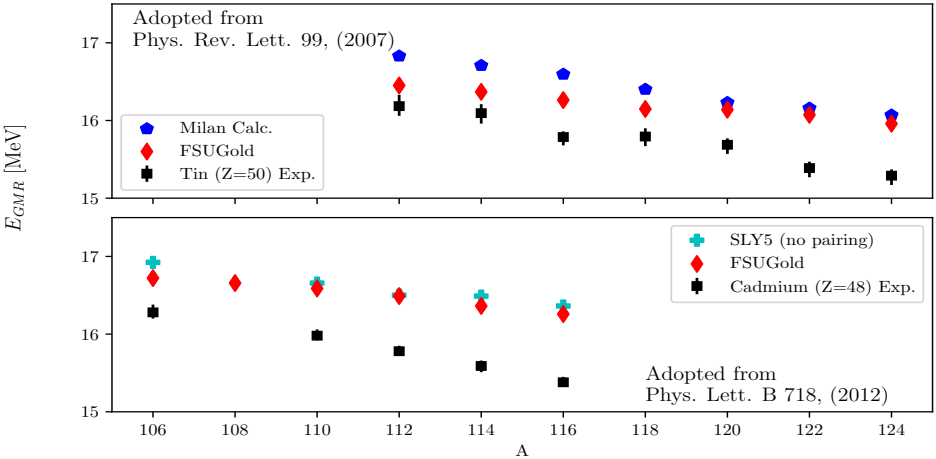
RAPID COMMUNICATIONS

PHYSICAL REVIEW C **76**, 031301(R) (2007)

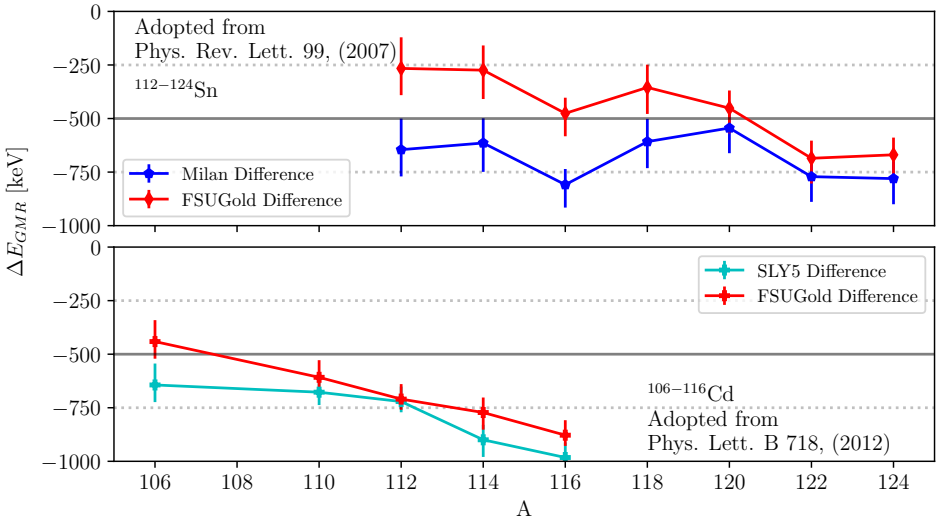
Why is the equation of state for tin so soft?

J. Piekarewicz
Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
(Received 10 May 2007; published 4 September 2007)

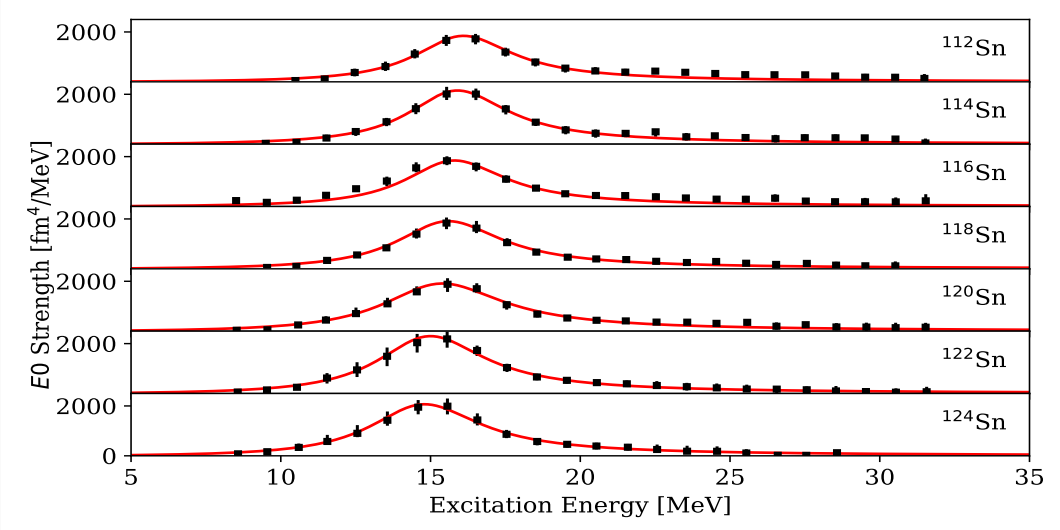
Softness in Open Shells?



Softness in Open Shells?

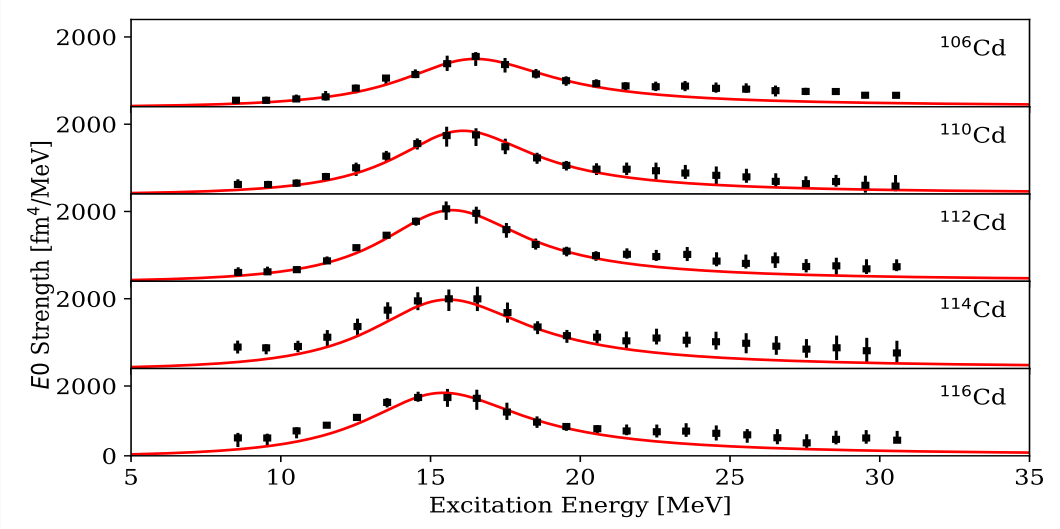


Softness in Open Shells?



Nucl. Phys. A **788**, (2007)

Softness in Open Shells?



Phys. Lett. B **718**, (2012)

Current Status

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **37** (2010) 064038 (10pp) doi:10.1088/0954-3899/37/6/064038

Do we understand the incompressibility of neutron-rich matter?

J Piekarewicz

Department of Physics, Florida State University, Tallahassee, FL 32306, USA

PHYSICAL REVIEW C **86**, 024303 (2012)

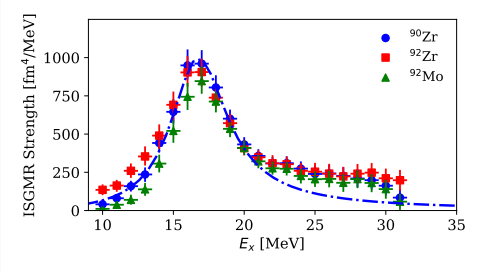
Giant monopole resonances and nuclear incompressibilities studied for the zero-range and separable pairing interactions

P. Veselý,[1,*] J. Toivanen,[1] B. G. Carlsson,[2] J. Dobaczewski,[1,3] N. Michel,[1] and A. Pastore[4]
[1]*Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL) FI-40014, Finland*
[2]*Division of Mathematical Physics, LTH, Lund University, P.O. Box 118, S-22100 Lund, Sweden*
[3]*Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland*
[4]*Université de Lyon, Université Lyon 1, CNRS/IN2P3 Institut de Physique Nucléaire de Lyon, F-69622 Villeurbanne cedex, France*
(Received 27 February 2012; revised manuscript received 10 July 2012; published 6 August 2012)

Motivation

Study systems near $Z = 40$, $N = 50$ closed shells (e.g., ^{94,96,97,98,100}Mo) to see how "softness" manifests.

- Softness of open-shell isotopes is still an open question
- No discernible difference in ^{90,92}Zr and ^{92}Mo:

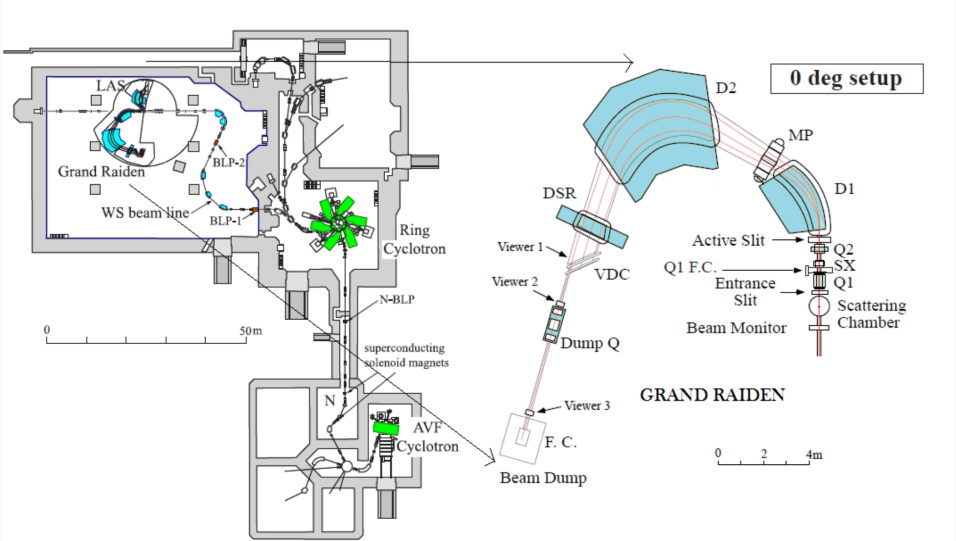


Gupta *et al.*, Phys. Rev. C **97**, (2018)

ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 788 (2007) 36c–43c
NUCLEAR PHYSICS A

The Giant Monopole Resonance in the Sn Isotopes: Why is Tin so "Fluffy"?

Research Center for Nuclear Physics (RCNP) & Grand Raiden



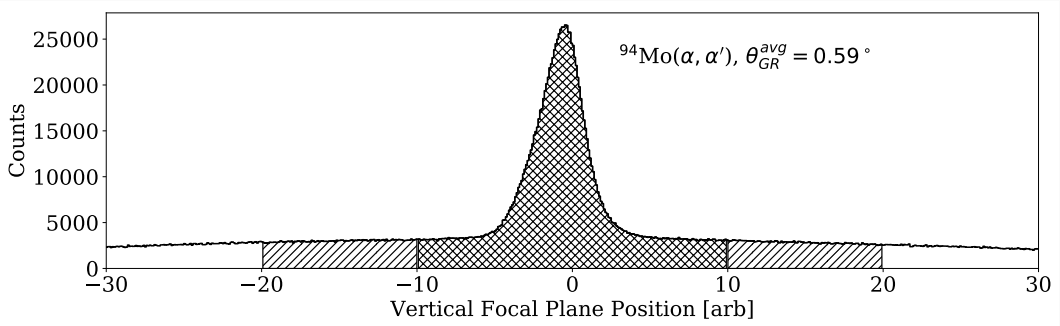
Research Center for Nuclear Physics (RCNP) & Grand Raiden, *cont.*

- Coupled AVF and ring cyclotrons deliver 386 MeV α-particles
- Enriched (> 95%) ^{94,96,97,98,100}Mo targets ($\sim$ 5 mg/cm^2)
- Focal plane: position-sensitive MWDCs and plastic scintillators for momentum analysis and particle identification.
- Major boon: Vertical focusing mode allows for *unambiguous* background estimation and subtraction.

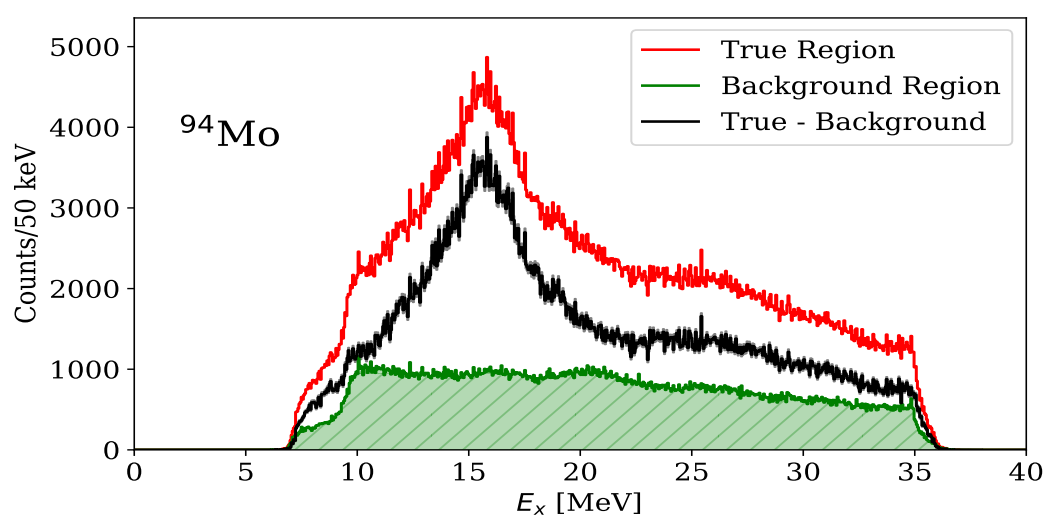
Research Center for Nuclear Physics (RCNP) & Grand Raiden, *cont.*

- Coupled AVF and ring cyclotrons deliver 386 MeV α-particles
- Enriched (> 95%) ^{94,96,97,98,100}Mo targets ($\sim$ 5 mg/cm^2)

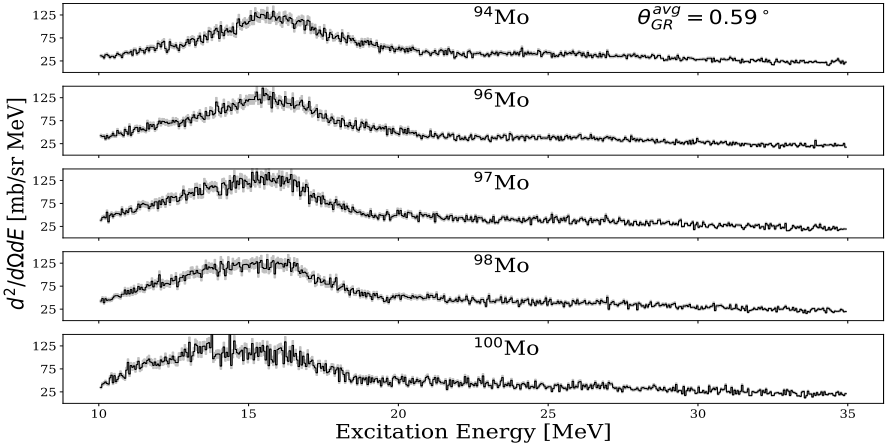
- Focal plane: position-sensitive MWDCs and plastic scintillators for momentum analysis and particle identification.
- Major boon: Vertical focusing mode allows for *unambiguous* background estimation and subtraction.



e.g., ^{94}Mo background subtraction



Putting it together: 0° spectra for $^{94-100}$Mo



Strength Distribution Extraction

Multipole Decomposition Analysis (MDA)

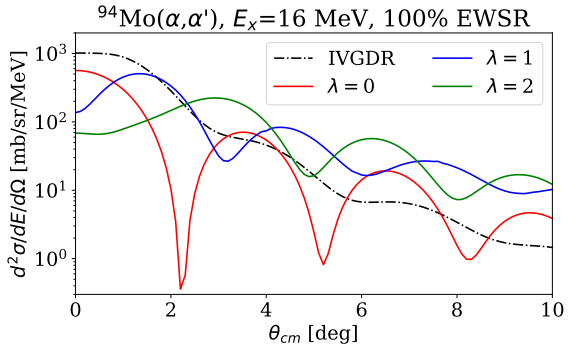
$$\frac{d^2\sigma^{\text{exp}}}{dEd\Omega_{\text{cm}}} = \sum_{\lambda} a_\lambda(E_x)\frac{d^2\sigma_\lambda^{\text{DWBA}}}{dEd\Omega_{\text{cm}}}$$

$$S_0(E_x) = \frac{2\hbar^2 A\langle r^2\rangle}{mE_x}a_0(E_x)$$

$$S_1(E_x) = \frac{3\hbar^2 A}{32\pi mE_x}a_1(E_x) \times \left(11\left\langle r^4\right\rangle - \frac{25}{3}\left\langle r^2\right\rangle^2 - 10\epsilon\left\langle r^2\right\rangle\right)$$

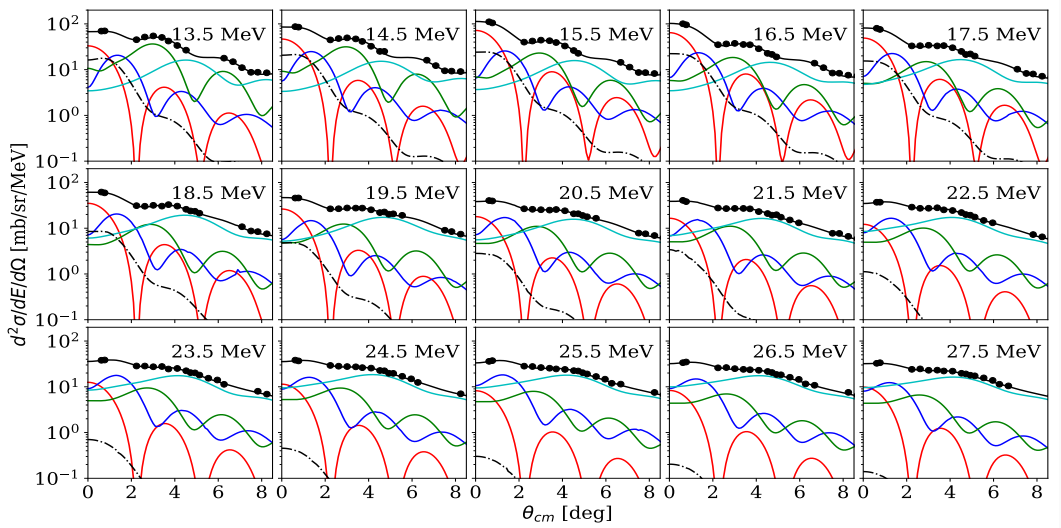
$$S_{\lambda\geq 2}(E_x) = \frac{\hbar^2 A}{8\pi mE_x}\lambda(2\lambda+1)^2\left\langle r^{2\lambda-2}\right\rangle a_\lambda(E_x)$$

- $\{a_\lambda(E_x)\}$ are highly correlated parameters
- Use EMCEE Markov-Chain-Monte-Carlo algorithm of Goodman & Weare to generate multidimensional probability distributions
  - Comm. in Appl. Math. and Comp. Sci. 5, **65** (2010)



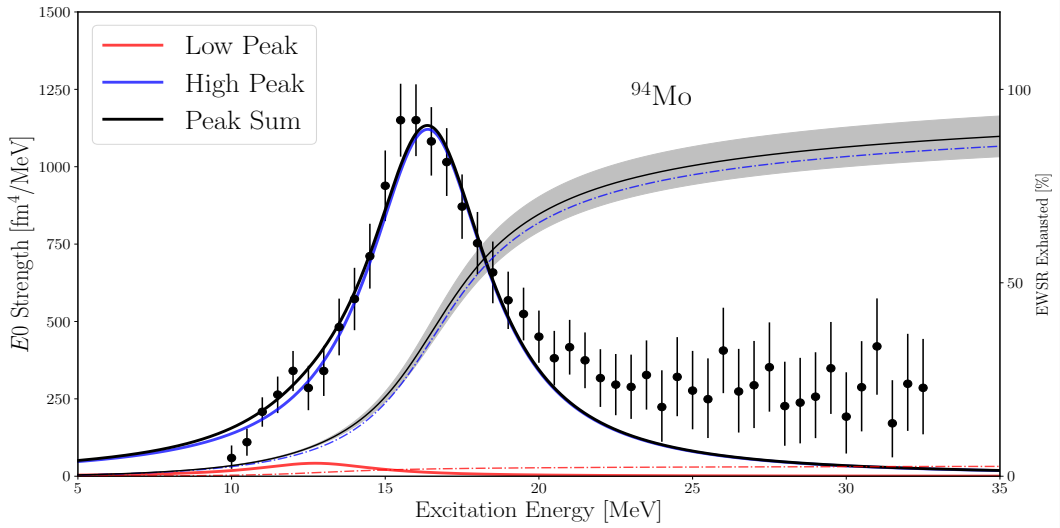
Contributions from the IVGDR were taken from available photoneutron data and subtracted from data prior to a MDA using only isoscalar form factors

Typical Results of Multipole Decomposition: ^{94}Mo

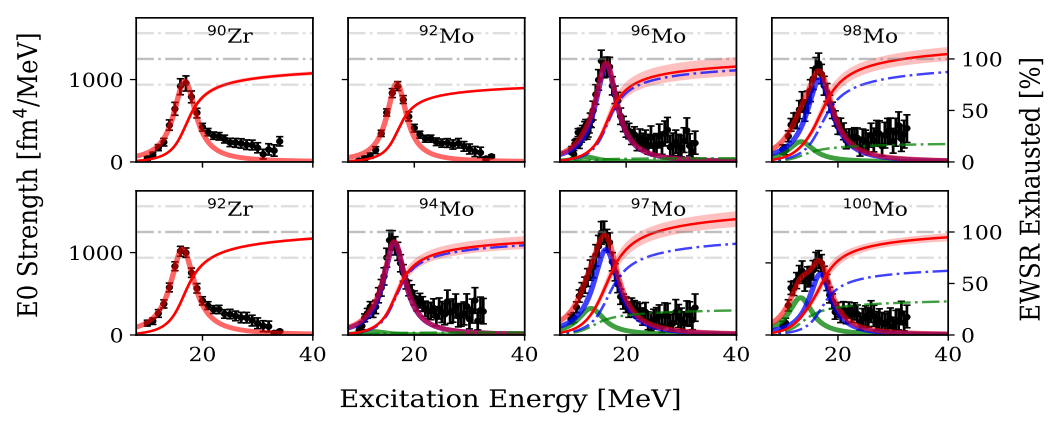


Monopole, Dipole, Quadrupole + others

$E0$ Strength Extraction for ^{94}Mo

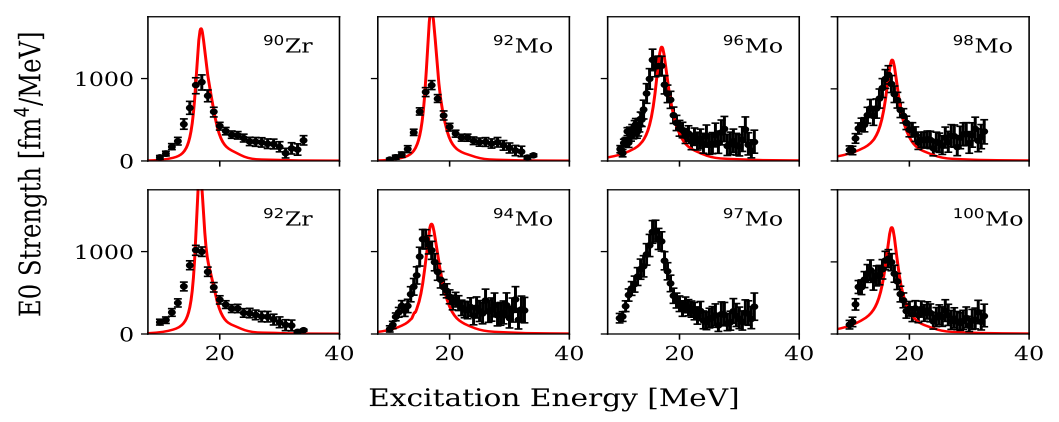


Fluffy, or no?



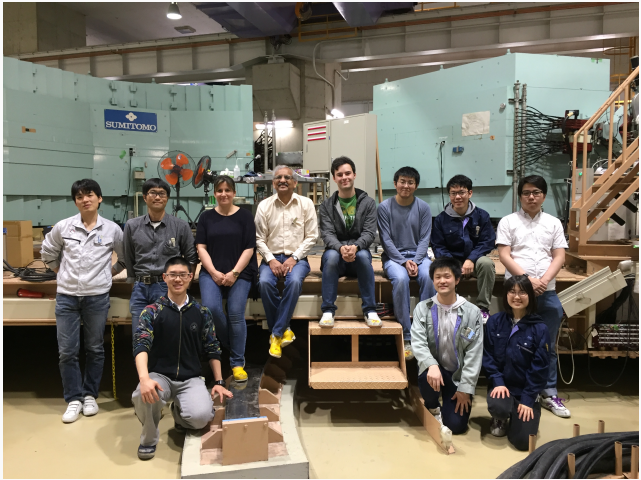
Total Fit = Low-Energy + High-Energy

We would argue: it does not appear so!



Experiment compared with FSUGarnet RPA

Acknowledgements



ANKARA UNIVERSITY

NSF

KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN

大阪大学 OSAKA UNIVERSITY

TOHOKU UNIVERSITY

東京大学 THE UNIVERSITY OF TOKYO

UNIVERSITY OF NOTRE DAME

LIU INSTITUTE FOR ASIA & ASIAN STUDIES

university of groningen