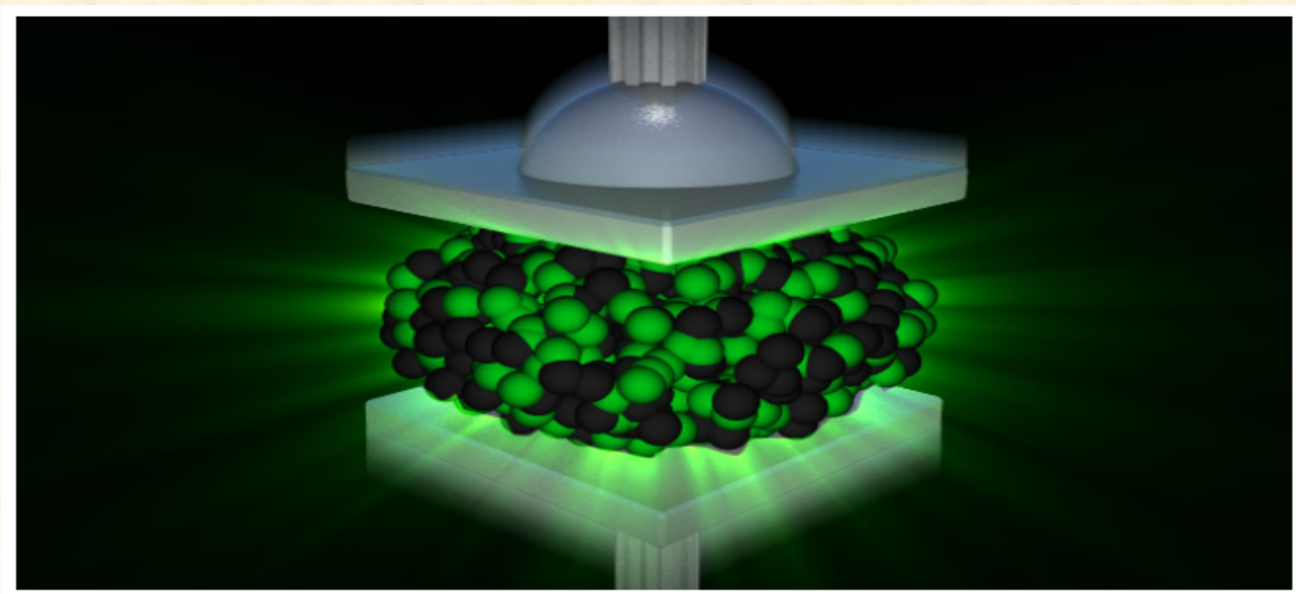
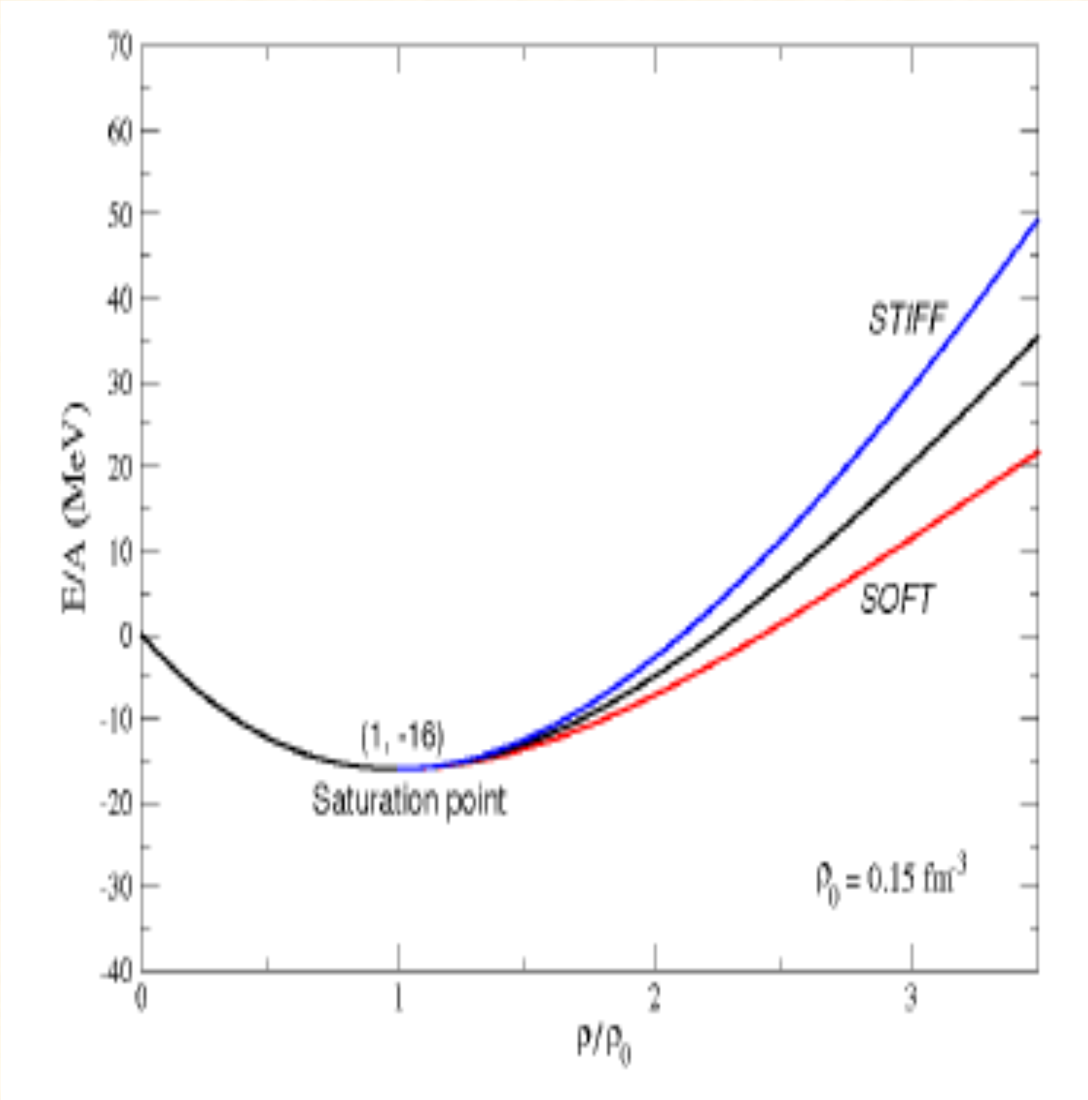
Nuclear Incompressibility: Does it depend on nuclear structure?



U. Garg
University of Notre Dame

Supported in part by the National Science Foundation

Ischia, May 17, 2022



$$K_\infty = K_F^2 \frac{\partial^2}{\partial K_F^2}\left(E_B / A \right) \qquad K_F = \left(\frac{3\pi^2}{2} \rho_0 \right)^{1/3}$$

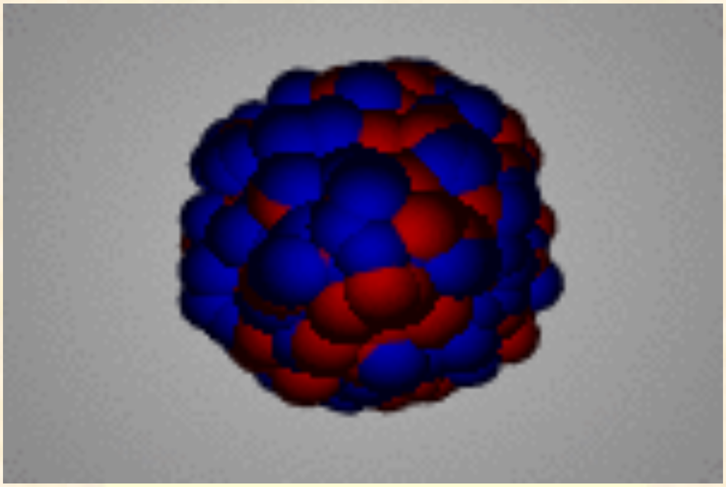
Nuclear Incompressibility

K_∞

- Nuclear Equation of State
  - Neutron Star
  - Stellar Collapse
  - Supernovae
- High-energy Heavy Ion Collisions

The Isoscalar Giant Monopole Resonance

l = 0



"Breathing Mode"

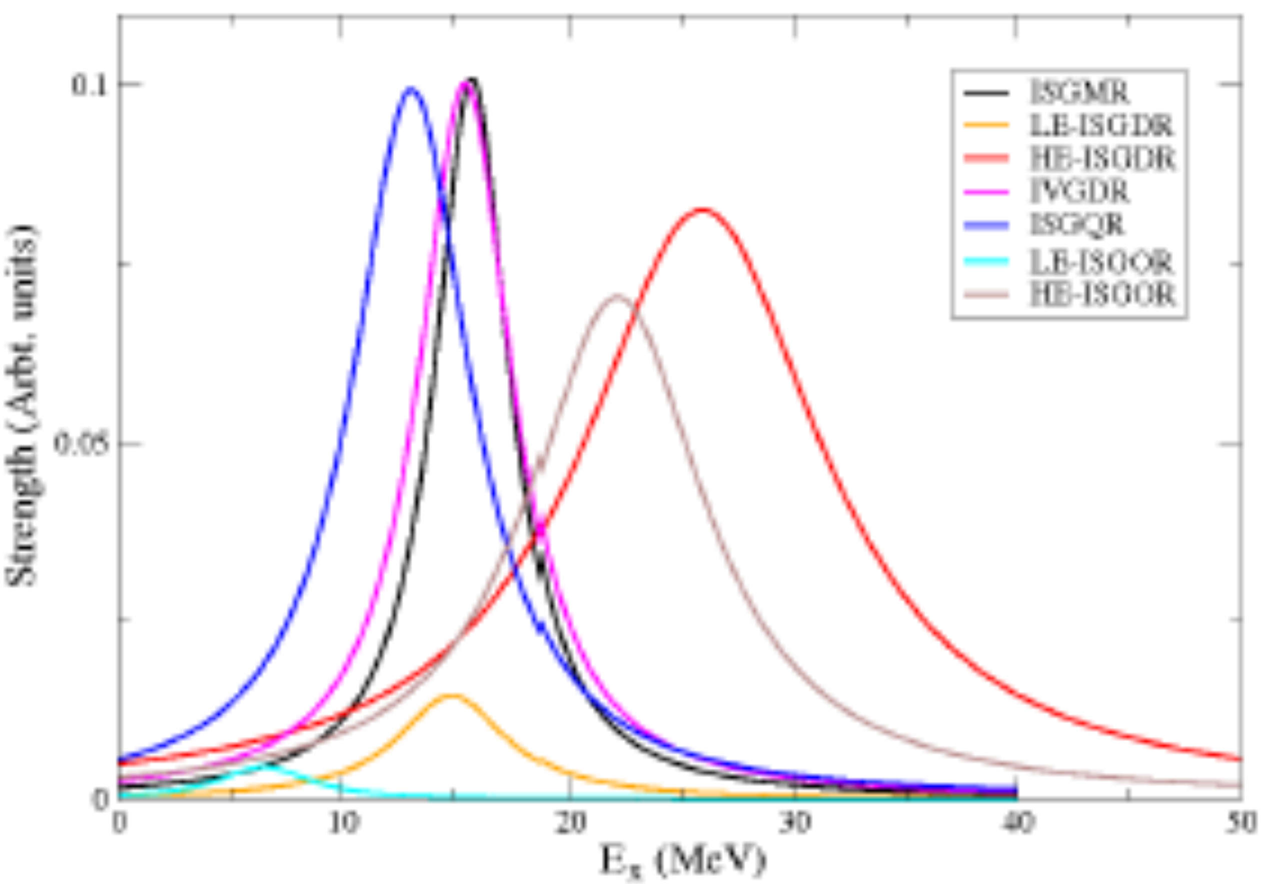
$$\sum r_i^2$$

$$2\hbar\omega$$

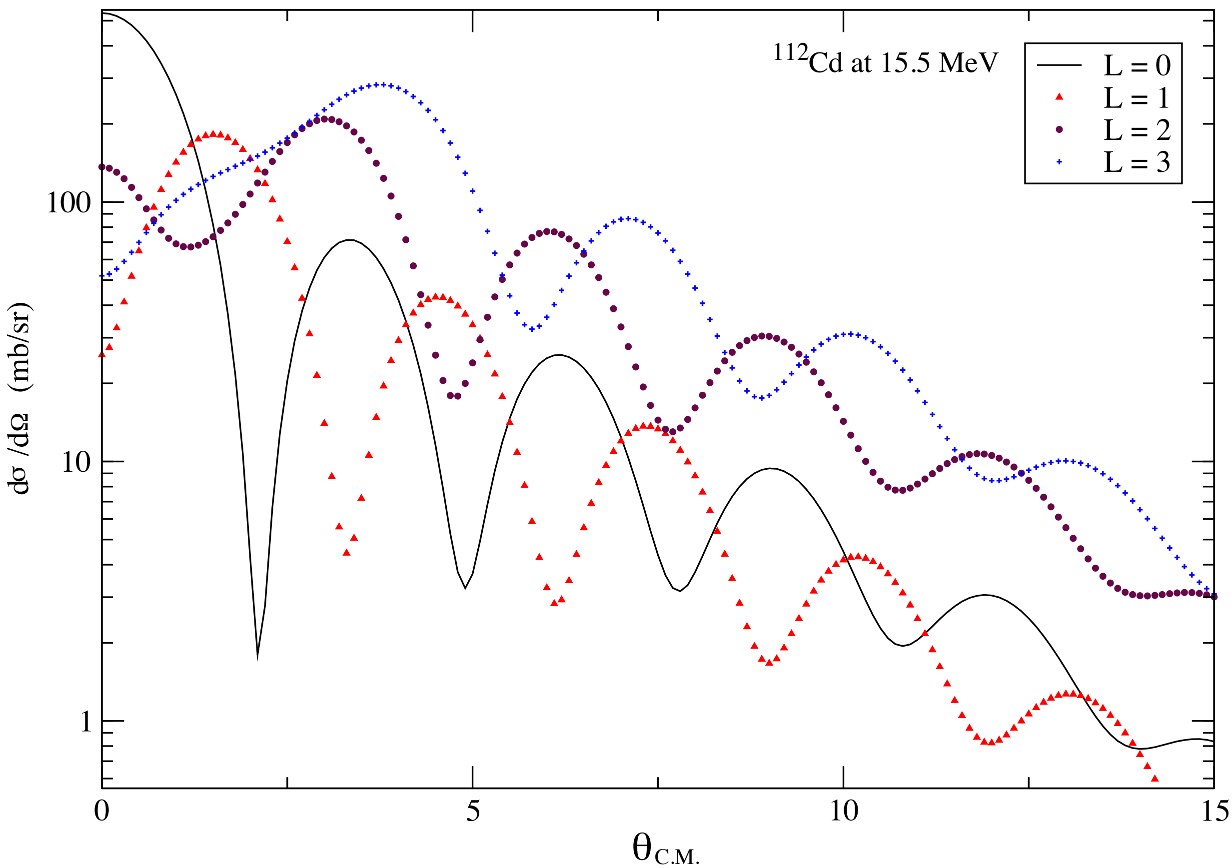
The energy of ISGMR may be directly related to the nuclear incompressibility

$$E_{GMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

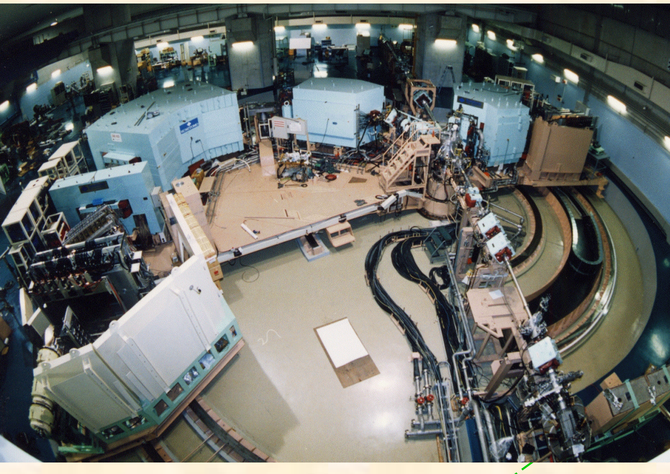
animation courtesy T. Aumann

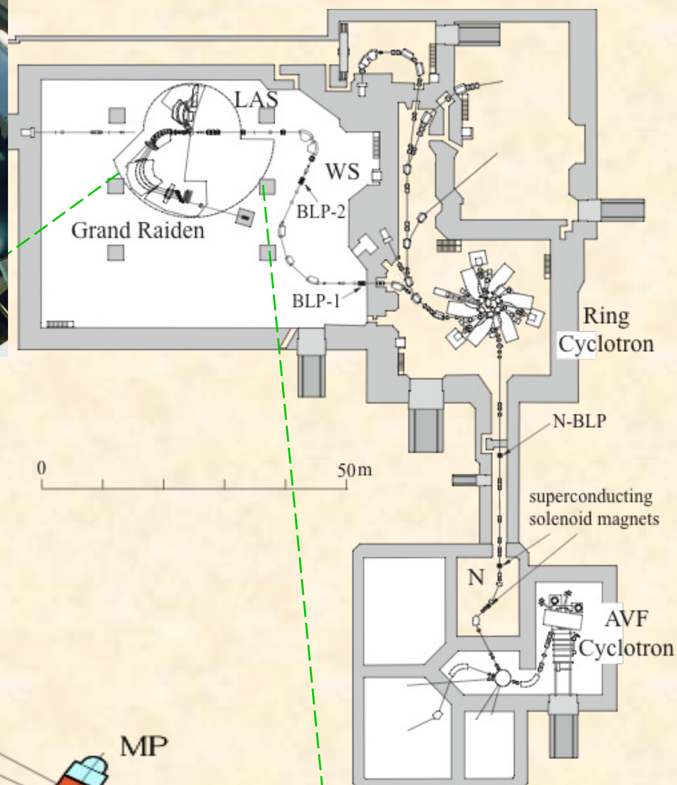


ISGMR
LE-ISGDR
HE-ISGDR
IVGDR
ISGQR
LE-ISOOR
HE-ISOOR
Strength (Arbt. units)
0.1
0.05
0
0
10
20
30
40
50
E_x (MeV)

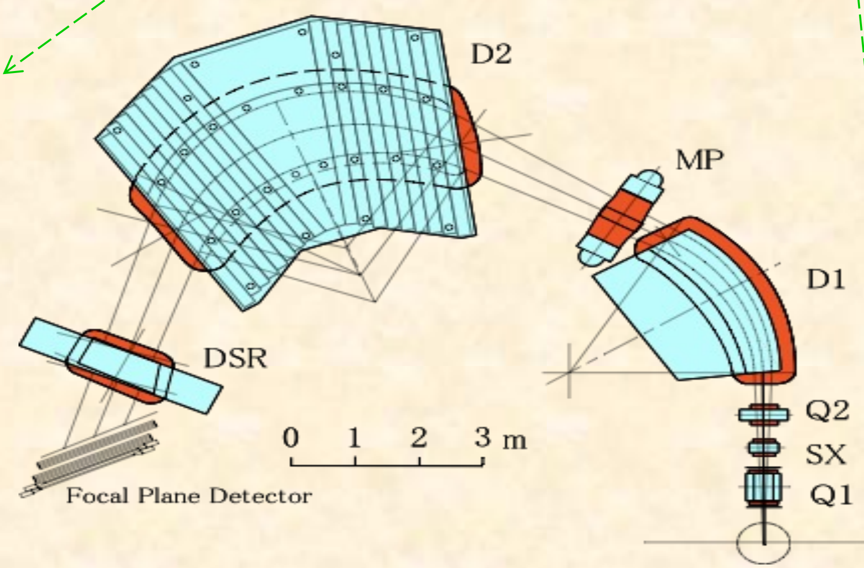


(α,α’) at 400 MeV

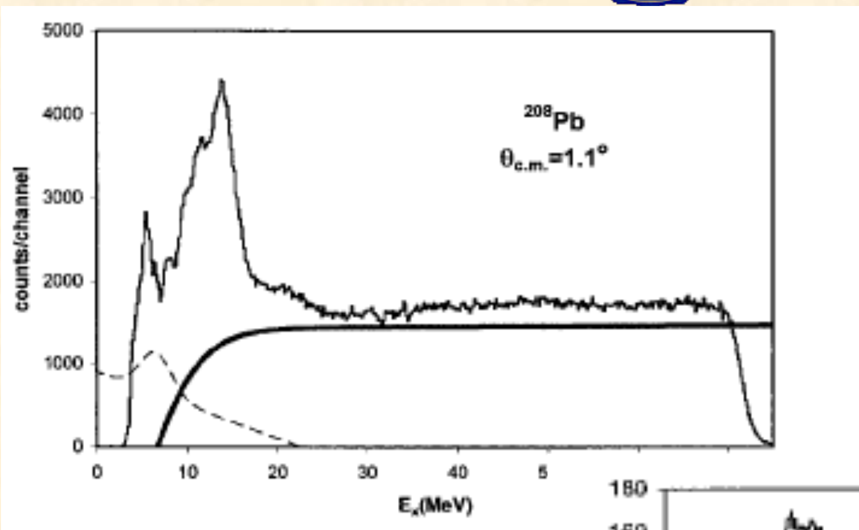


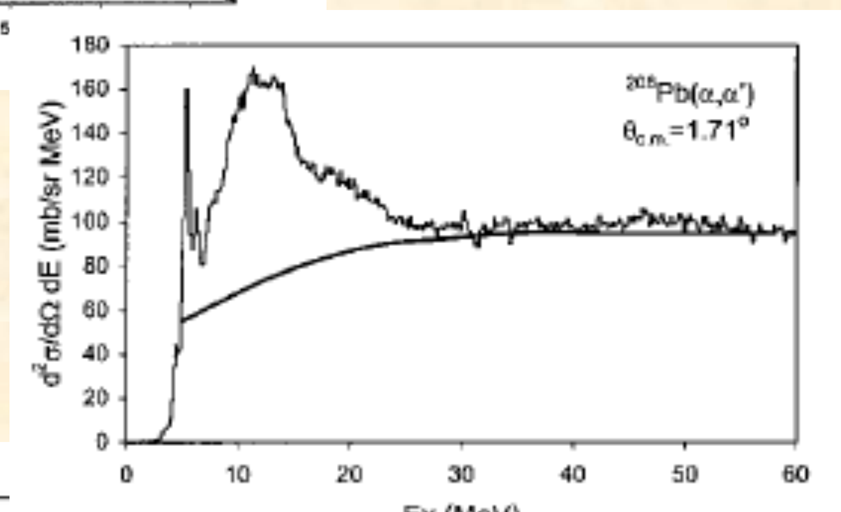


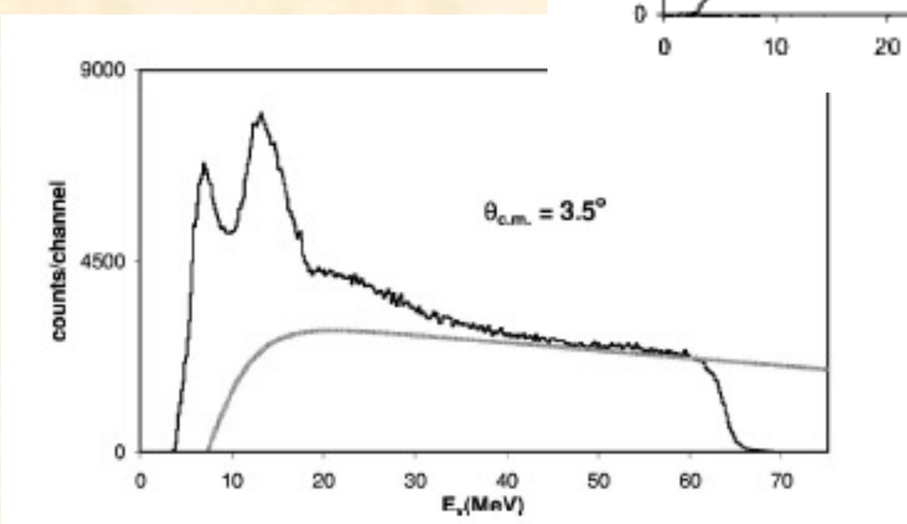
LAS
WS
BLP-2
Grand Raiden
BLP-1
Ring Cyclotron
N-BLP
0
50m
superconducting solenoid magnets
N
AVF Cyclotron



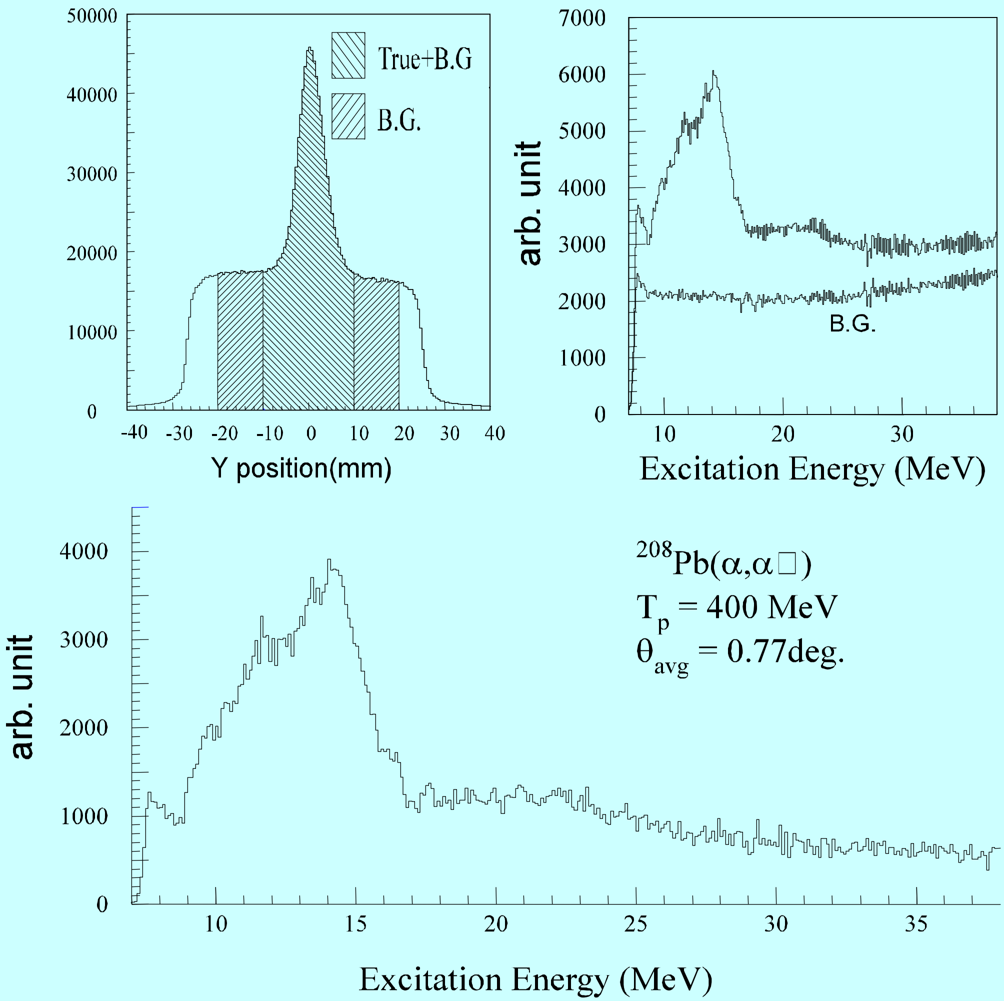
D2
MP
D1
DSR
Q2
SX
Q1
0 1 2 3 m
Focal Plane Detector





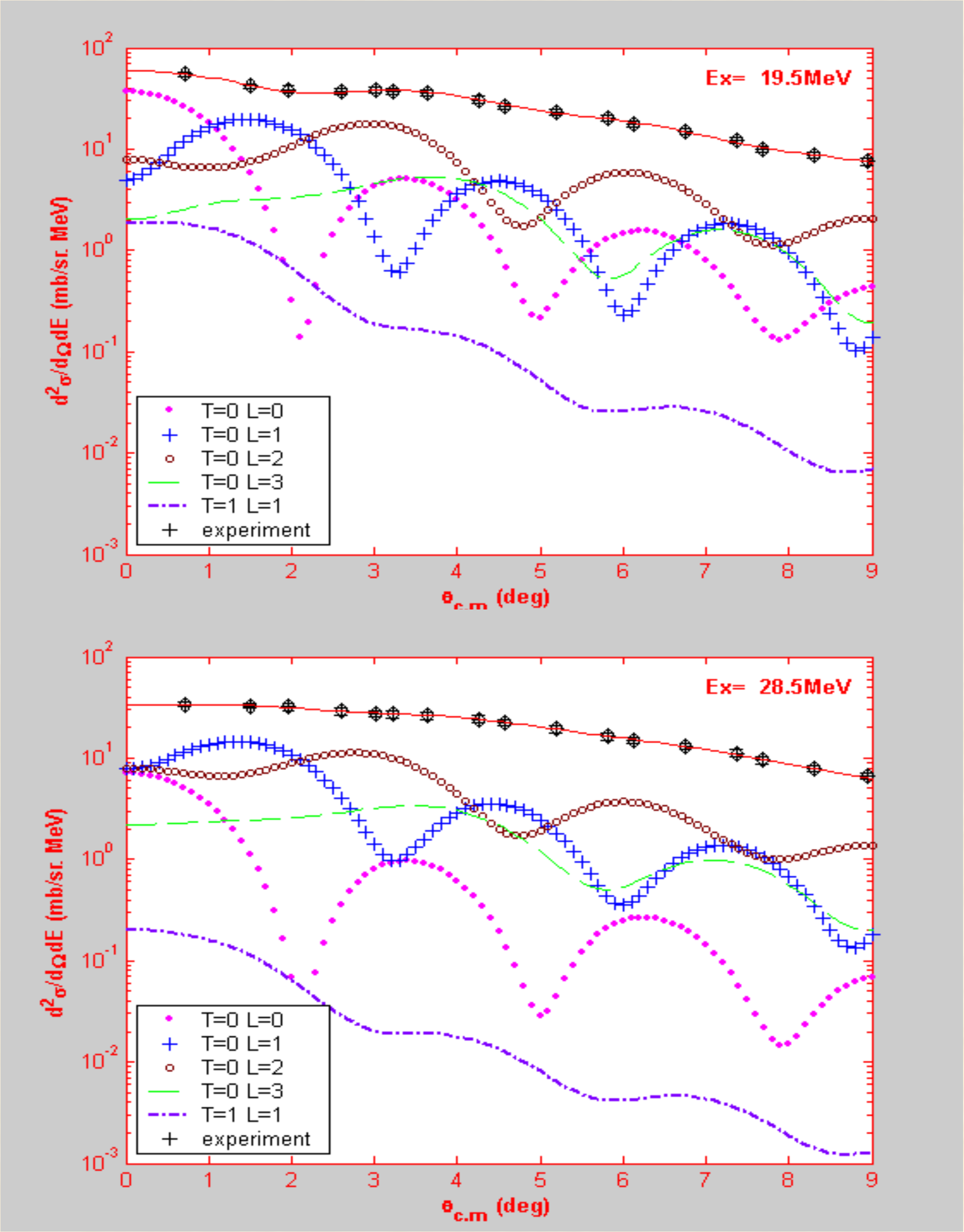


240 MeV (α,α') [Texas A & M]

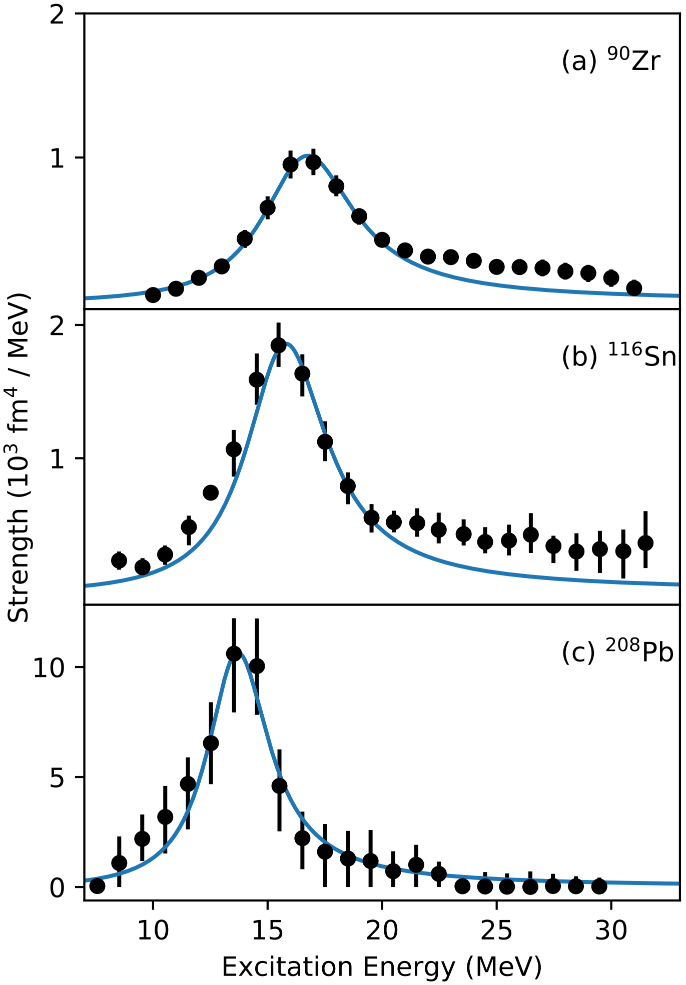


50000
40000
30000
20000
10000
0
-40 -30 -20 -10 0 10 20 30 40
Y position(mm)
True+B.G
B.G.
7000
6000
5000
4000
3000
2000
1000
0
10 20 30
arb. unit
Excitation Energy (MeV)
B.G.
4000
3000
2000
1000
0
10 15 20 25 30 35
arb. unit
^{208}Pb(α,α□)
T_p = 400 MeV
θ_{avg} = 0.77deg.
Excitation Energy (MeV)

^{112}Sn



Ex= 19.5MeV
$d^2\sigma/d\Omega dE$ (mb/sr. MeV)
$\theta_{c.m}$ (deg)
T=0 L=0
T=0 L=1
T=0 L=2
T=0 L=3
T=1 L=1
experiment
Ex= 28.5MeV
$d^2\sigma/d\Omega dE$ (mb/sr. MeV)
$\theta_{c.m}$ (deg)
T=0 L=0
T=0 L=1
T=0 L=2
T=0 L=3
T=1 L=1
experiment



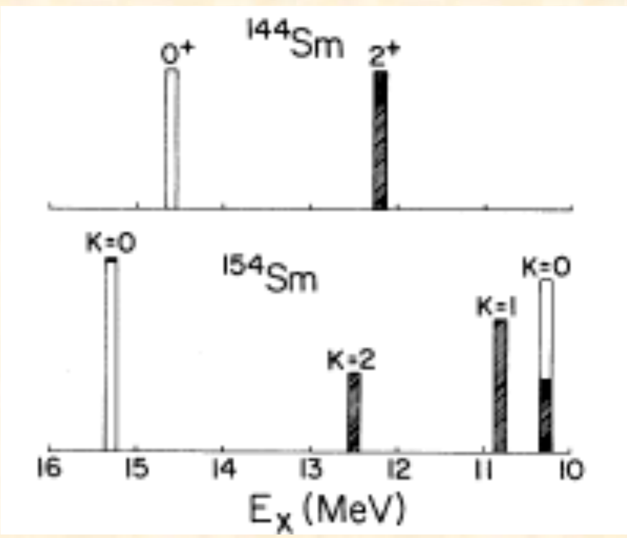
(a) 90Zr
(b) 116Sn
(c) 208Pb
Strength (10^3 fm^4 / MeV)
Excitation Energy (MeV)

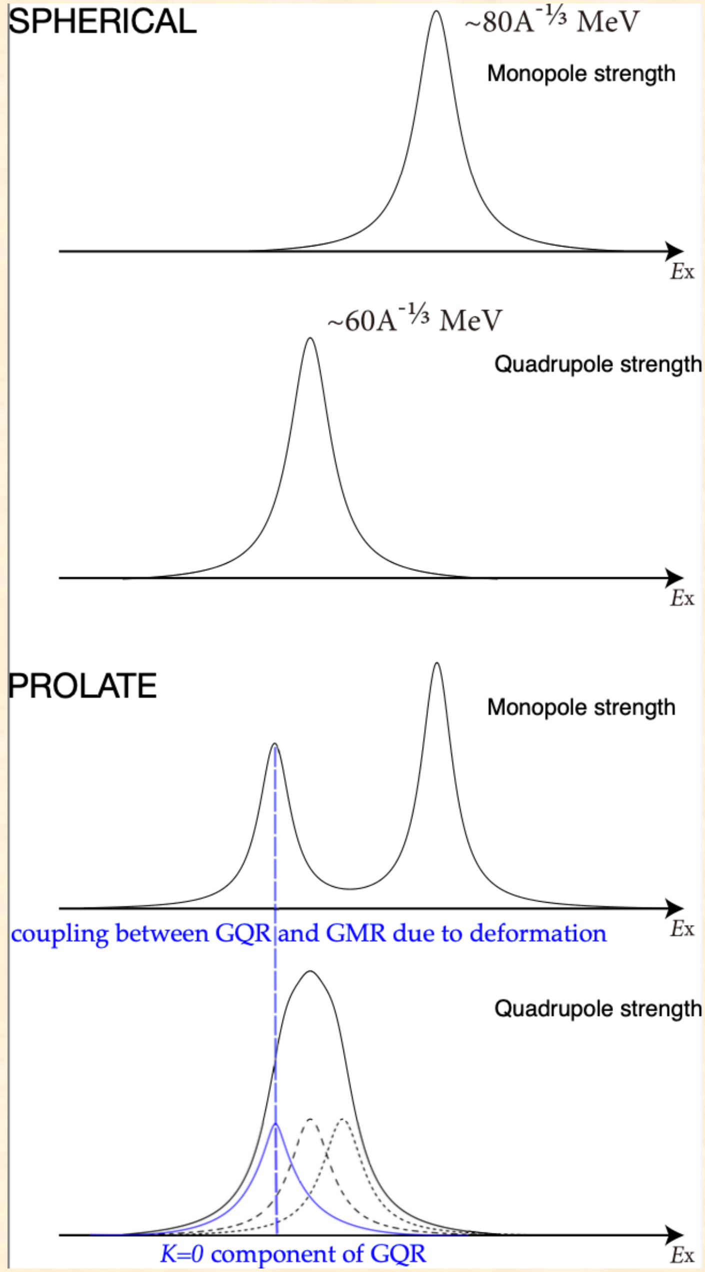
From GMR data on ^{208}Pb and ^{90}Zr

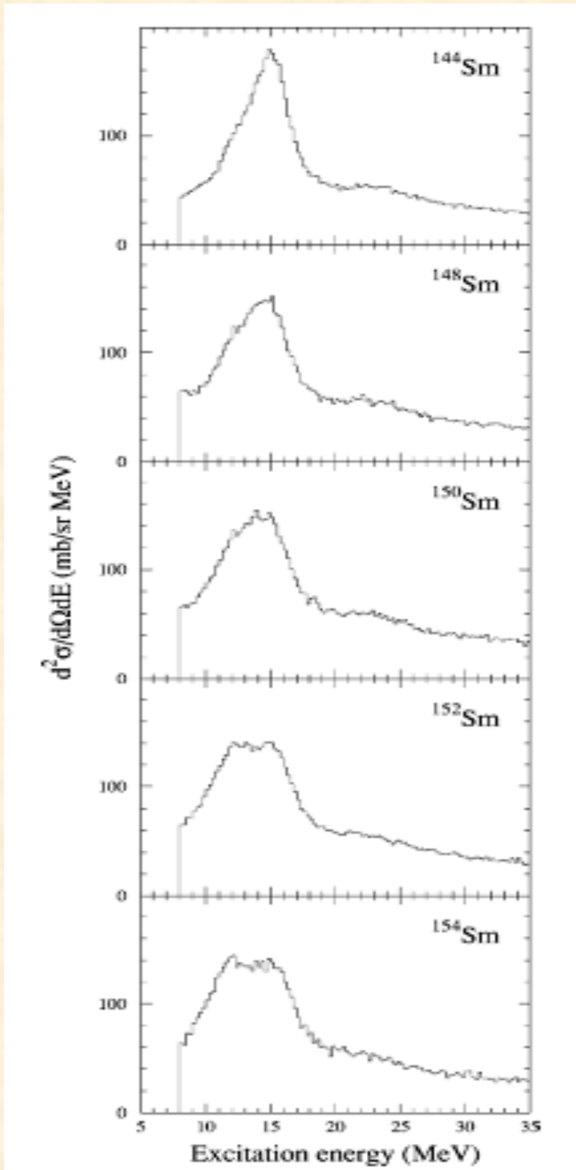
$K_{\infty} = 240 \pm 20$ MeV

This number is consistent with both GMR and ISGDR data and with non-relativistic and relativistic calculations

Effect of deformation on ISGMR



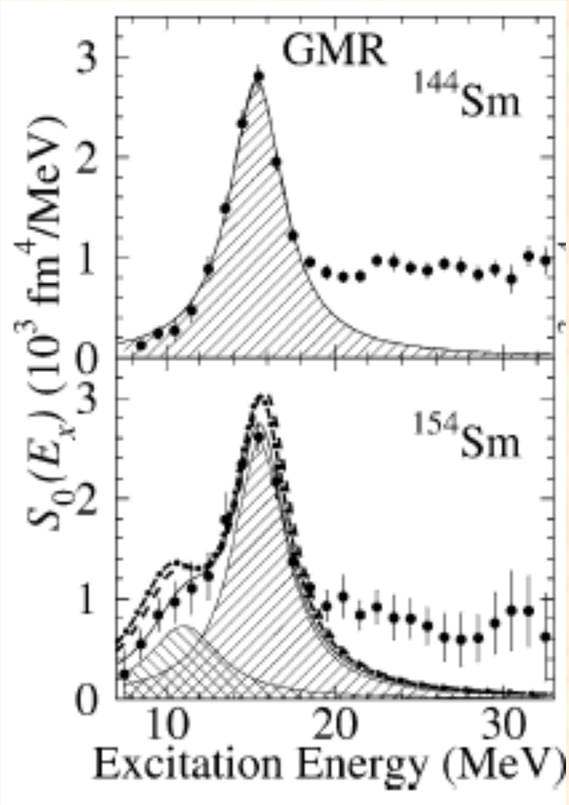




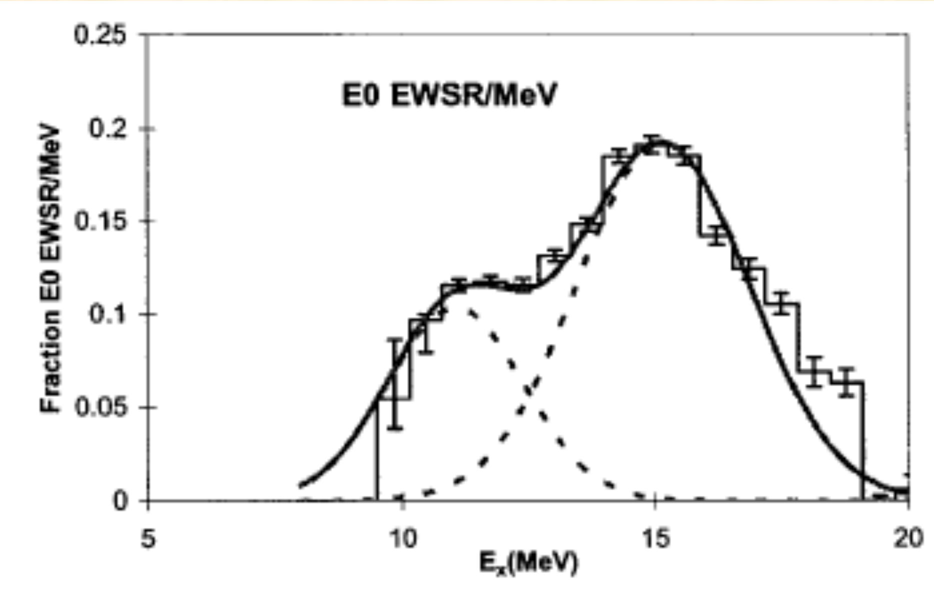
β2
0.0881
0.142
0.193
0.308
0.339

Well understood in terms of K=0 mixing of ISGMR and ISGQR

M. Itoh et al., Phys. Rev. C 68, 064602 (2003)



RCNP Data



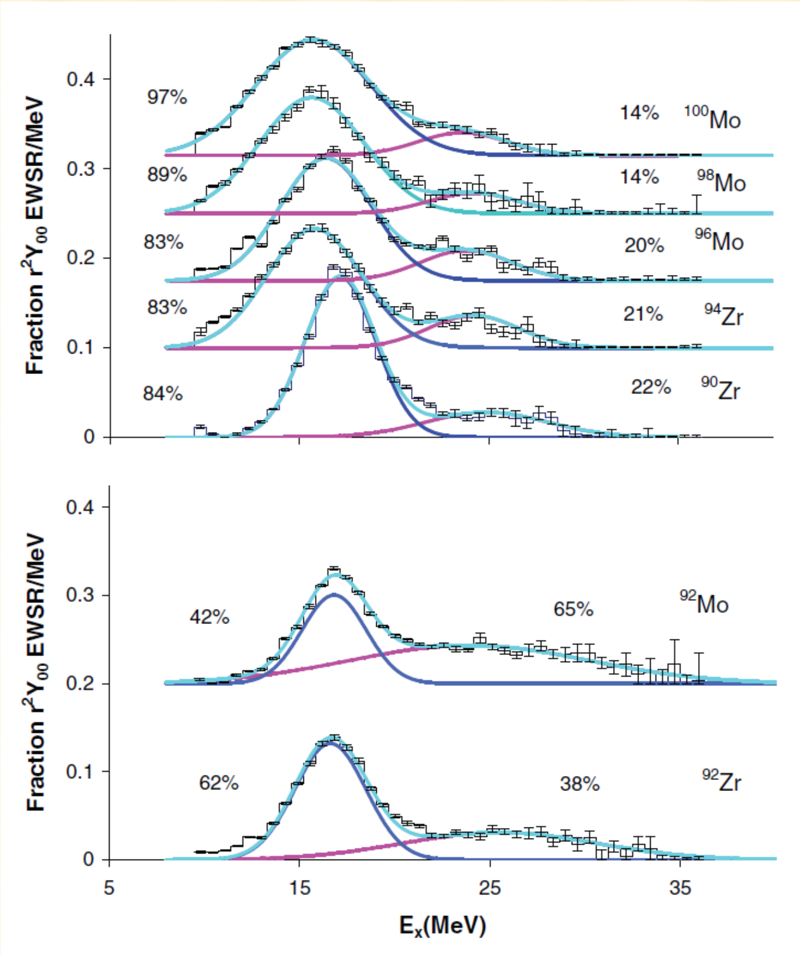
A&M Data

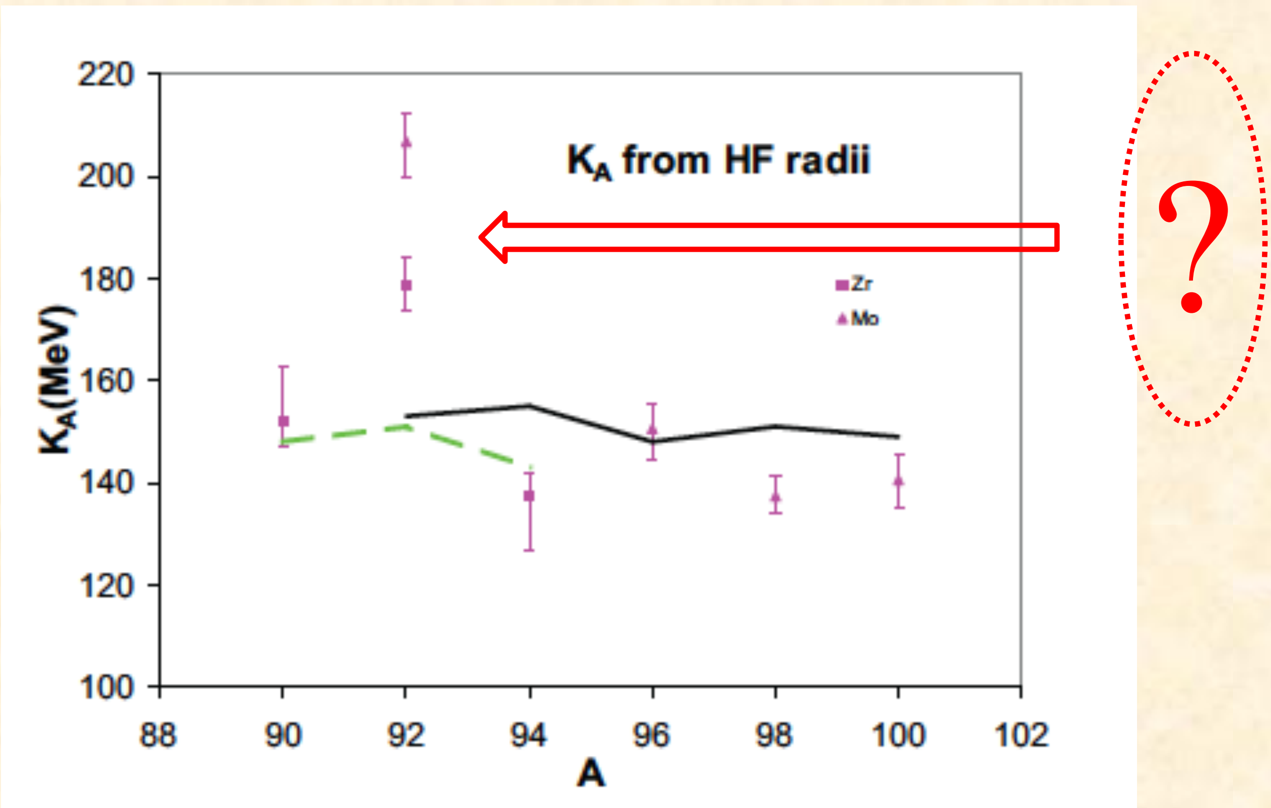
RAPID COMMUNICATIONS

PHYSICAL REVIEW C **88**, 021301(R) (2013)

Unexpected characteristics of the isoscalar monopole resonance in the $A \approx 90$ region: Implications for nuclear incompressibility

D. H. Youngblood,[1] Y.-W. Lui,[1] Krishichayan,[1,2] J. Button,[1] M. R. Anders,[1] M. L. Gorelik,[3] M. H. Urin,[3] and S. Shlomo[1]
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*



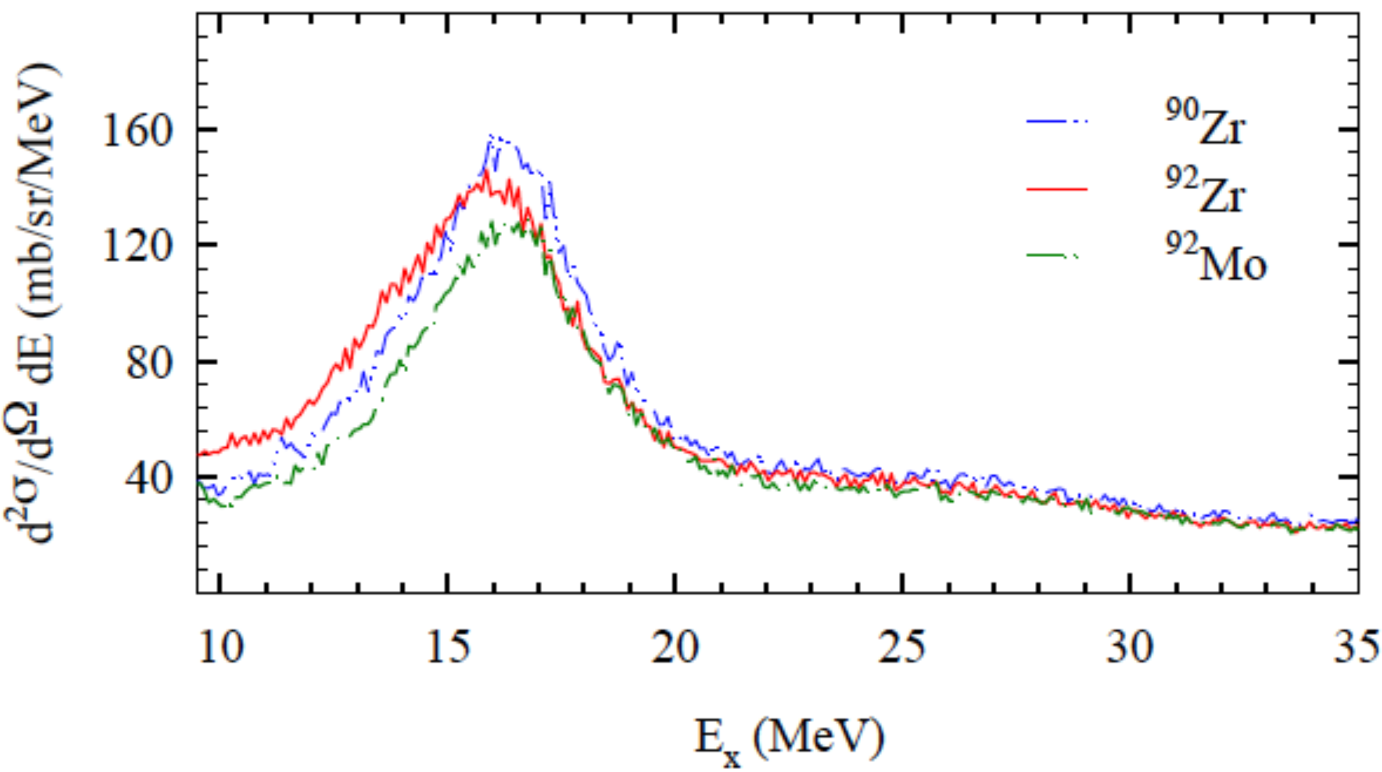

K_A from HF radii
Zr
Mo
K_A(MeV)
A
220
200
180
160
140
120
100
88
90
92
94
96
98
100
102
?

^{92}Zr and ^{92}Mo

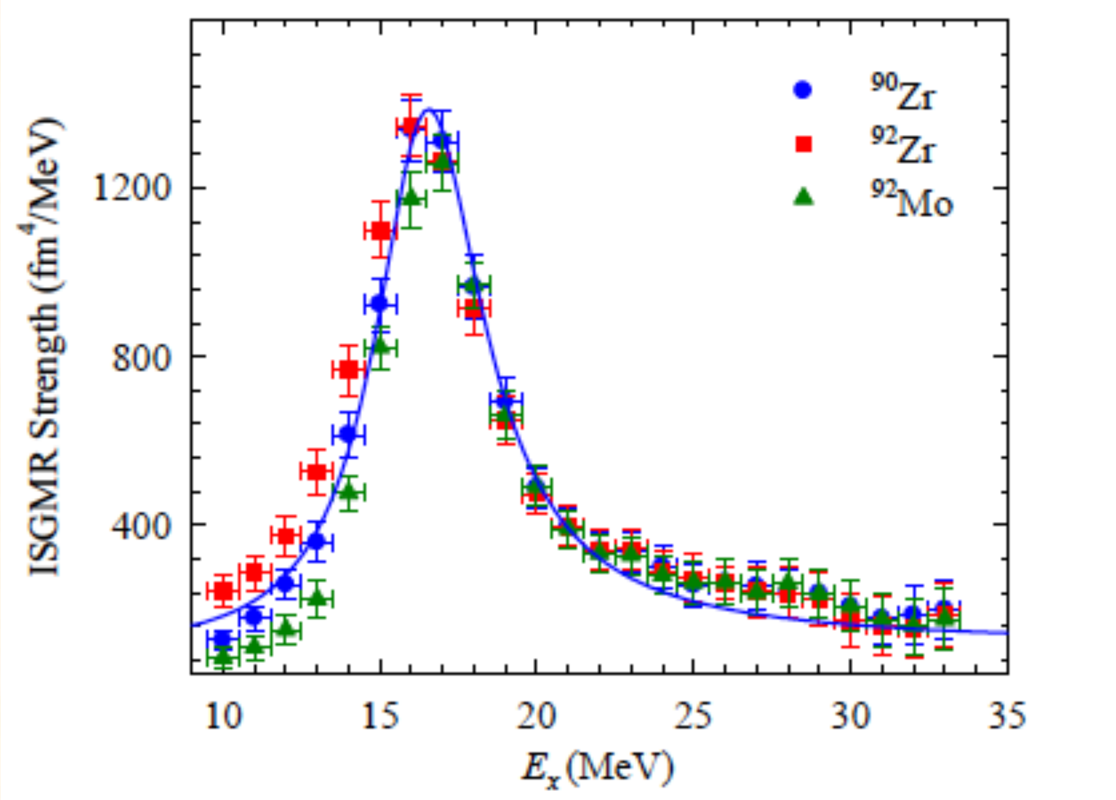
E_{ISGMR}: Centroids 1.2 MeV and 2.8 MeV higher than ^{90}Zr

EWSR in second peak: 62% and 42%

- **K_A for ^{92}Zr and ^{92}Mo is higher than that for ^{90}Zr by 27 and 56 MeV, respectively!**
- **Significant nuclear structure contributions to the nuclear compressibility !**
- **These are the first observations of this kind since first identification of ISGMR in 1970s !**

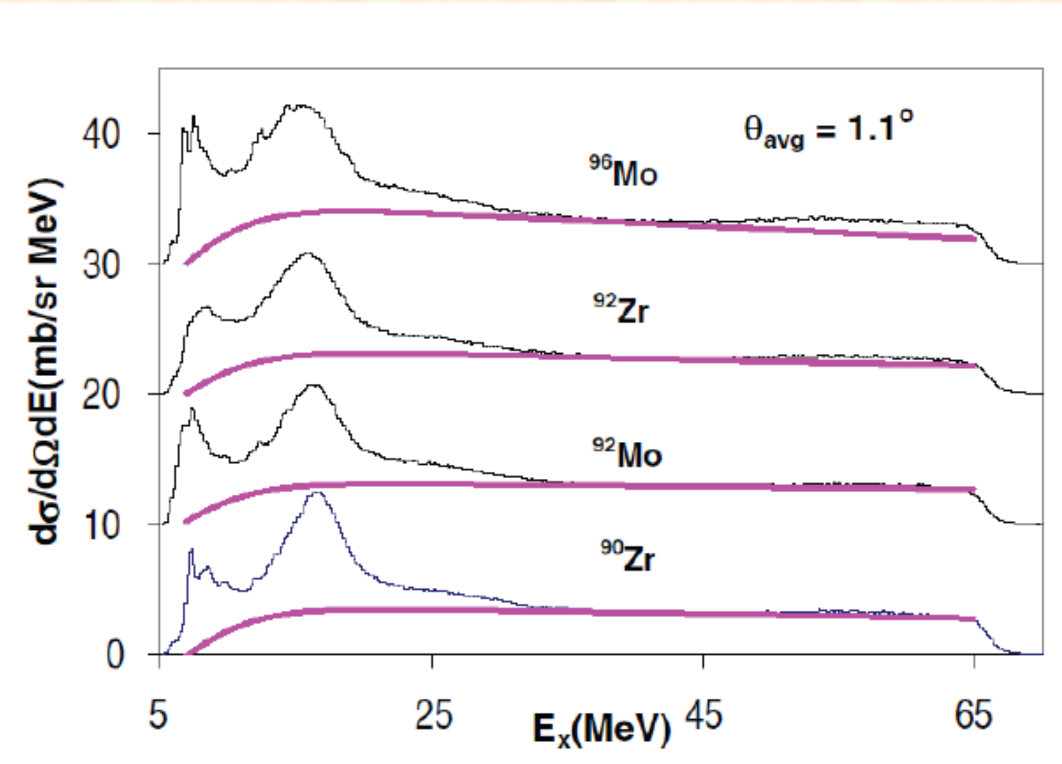


Zero Deg Spectra

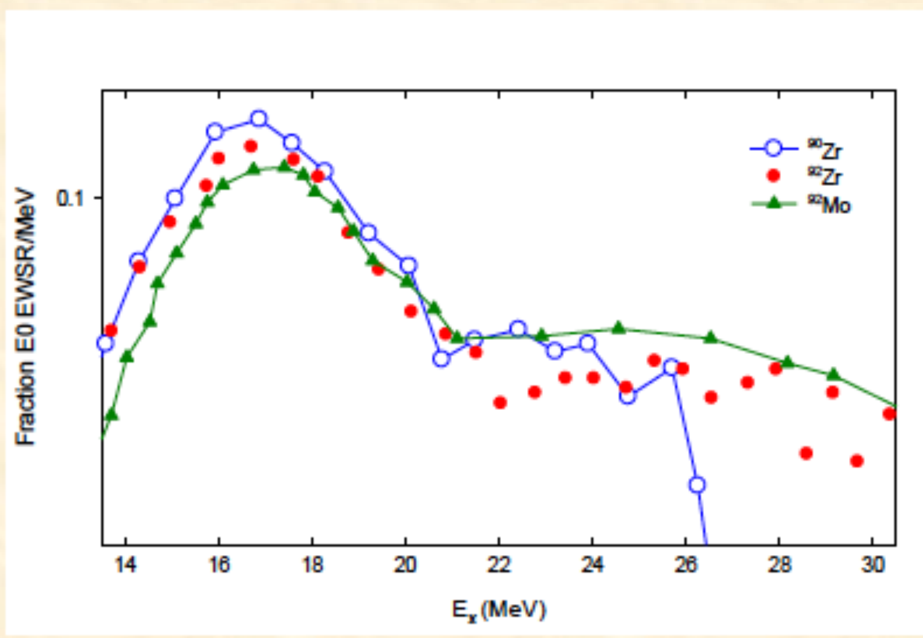


Nucleus	E_m (MeV)	Γ (MeV)
^{90}Zr	16.55 ± 0.08	4.2 ± 0.3
^{92}Zr	16.12 ± 0.04	4.5 ± 0.2
^{92}Mo	16.79 ± 0.11	4.2 ± 0.4

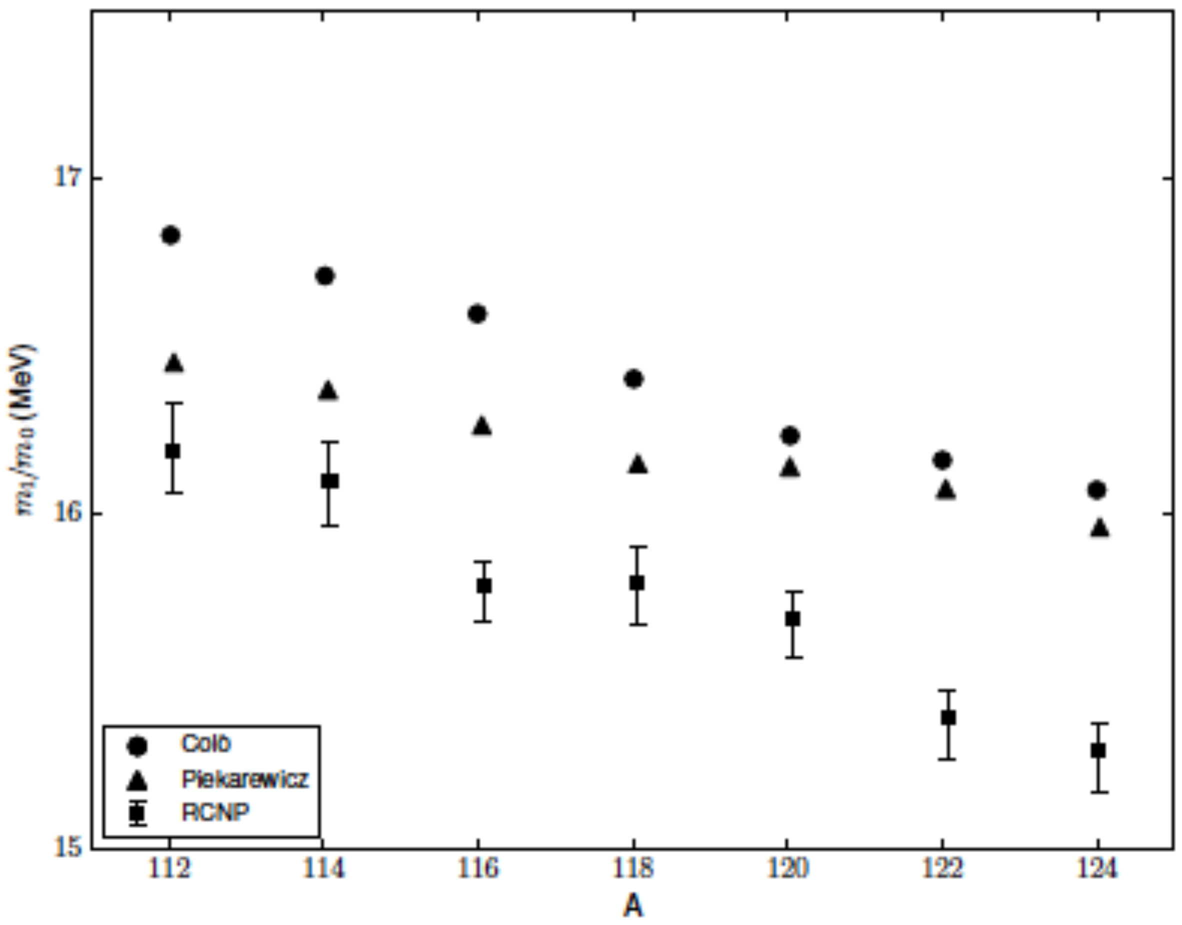
Y. K. Gupta *et al.*, Phys. Lett. B **760**, 482 (2016)



dσ/dΩdE(mb/sr MeV)
E_x(MeV)
θ_avg = 1.1°
96Mo
92Zr
92Mo
90Zr
0
10
20
30
40
5
25
45
65



Fraction E0 EWSR/MeV
E_x (MeV)
0.1
14
16
18
20
22
24
26
28
30
90Zr
92Zr
92Mo



Why are tins so "Fluffy"?

T. Li *et al.*, Phys. Rev. Lett. **99**, 162503 (2007)

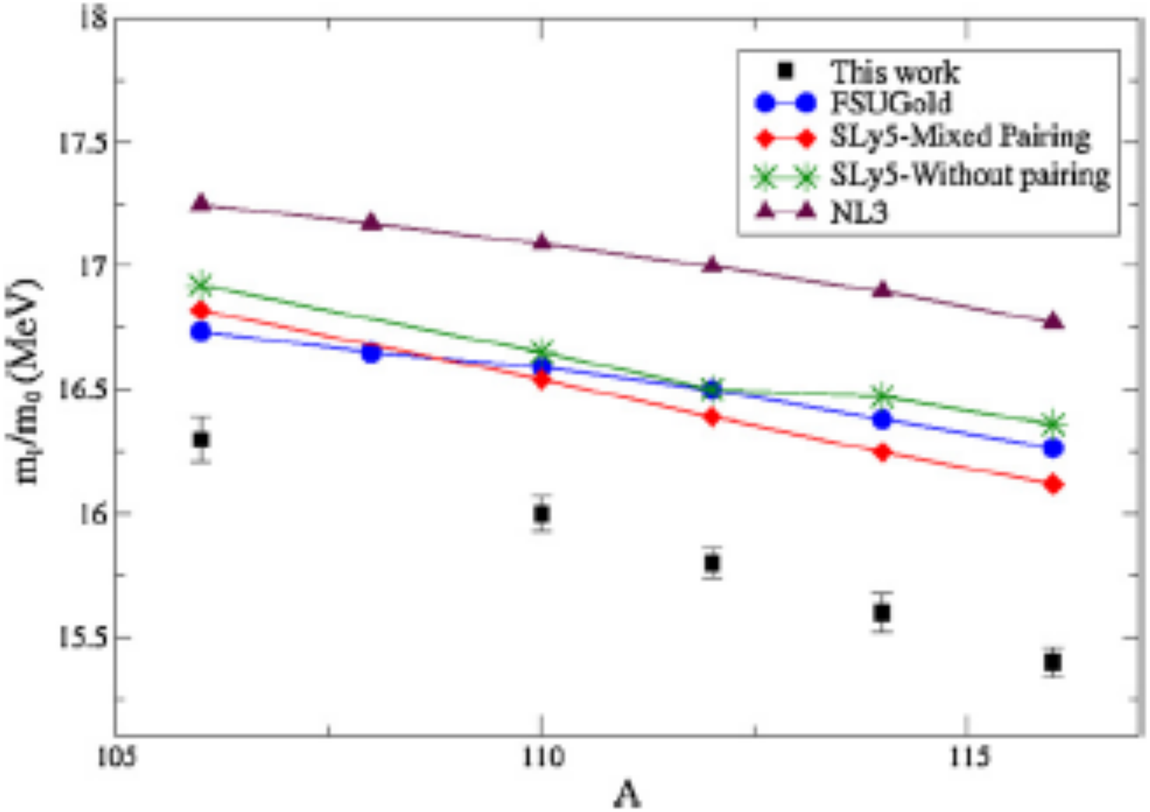
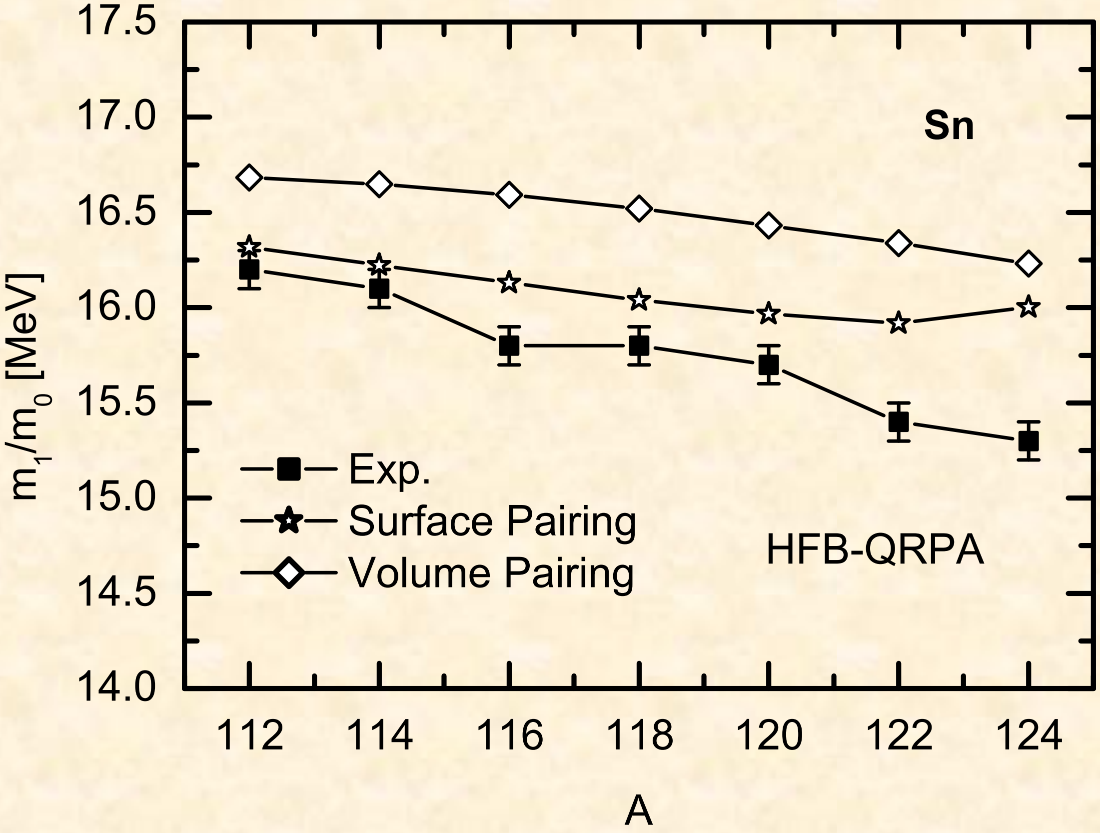


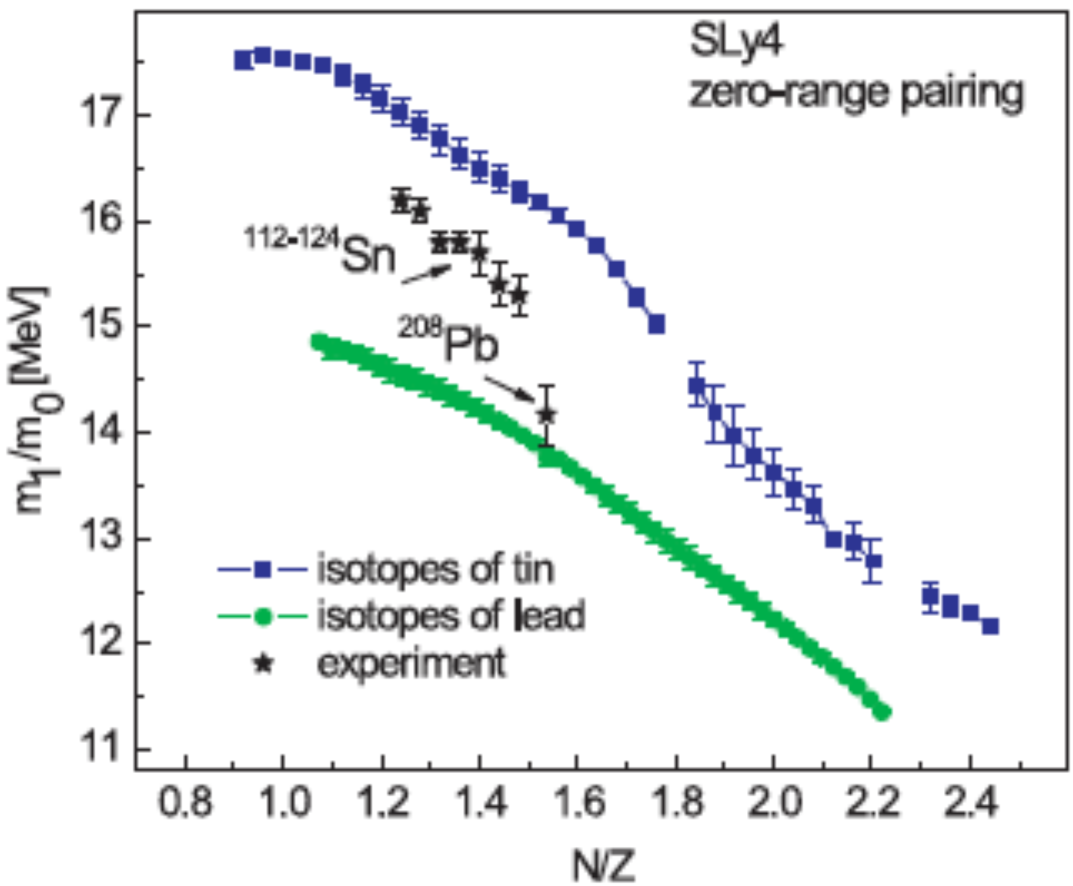
Fig. 3. (Color online.) Systematics of the moment ratio, m_1/m_0 for the ISGMR strength distributions in the Cd isotopes investigated in this work. The experimental results (squares) are compared with relativistic calculations performed using the FSUGold (circles) and NL3 (triangles) effective interactions. Also presented are results from non-relativistic calculations performed using the Sly5 parameter set in the HF-BCS + QRPA formalism with and without the mixed pairing interaction (diamonds and stars, respectively) [36]. The solid lines are to guide the eye.

D. Patel *et al.*, Phys. Lett. B **718**, 447 (2012)

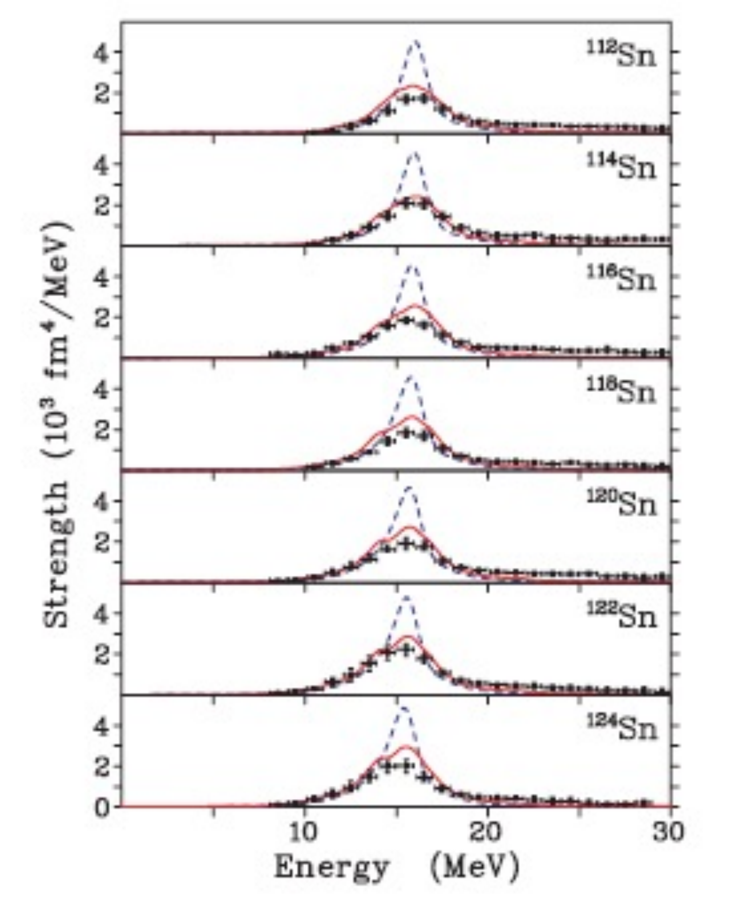


SkM* (K_∞ ~ 215 MeV)

Jun Li *et al.*, Phys. Rev. C 78, 064304 (2008)



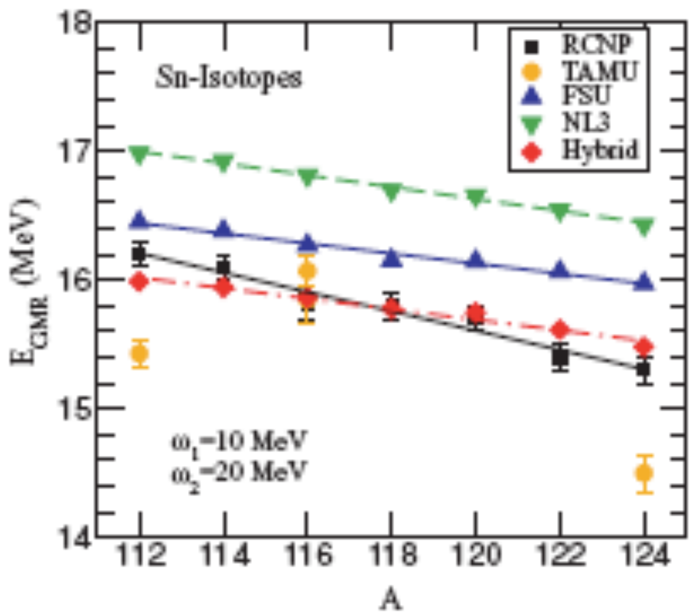
P. Vesely *et al.*, Phys. Rev. C 86, 024303 (2012)



V. Tselyaev *et al.*,
Phys. Rev. C **79**, 034309 (2009)

Self-consistent HF+BCS with T5 Skyrme Interaction;
K_∞ = 202 MeV

the experiment. On the whole, these results do not allow us to decrease the ambiguity in the value of K_∞ as compared with the previous known estimates. Note, however, that the main goal of our work is not to solve the problem of the nuclear matter incompressibility but to find under which conditions one can obtain reasonable description of the experimental data for the considered tin isotopes within the framework of the self-consistent approach including correlations beyond the QRPA.



$K_\infty \sim 230$ MeV; $K_\tau = -532$ MeV

although the improvement in the case of the Sn isotopes is significant and unquestionable, an important problem remains: the hybrid model underestimates the GMR centroid energy in ^{208}Pb—the heaviest doubly magic nucleus—by almost 1 MeV. This suggests that the rapid softening with neutron excess predicted by the hybrid model may be unrealistic.

Thus, where does theory stand with respect to experiment? One possibility, given that FSUGold reproduces the centroid energy in both ^{90}Zr (with $\alpha = 0.11$) and ^{208}Pb (with $\alpha = 0.21$), is that its predictions for K_0 and K_τ are reliable, but that its failure to reproduce the GMR energies in tin is due to missing physics unrelated to the incompressibility of neutron-rich matter. We feel inclined to favor this possibility for two

J. Piekarewicz and M. Centelles, Phys. Rev. C **79**, 054311 (2009)

Nuclear Physics A399 (1983) 11–50

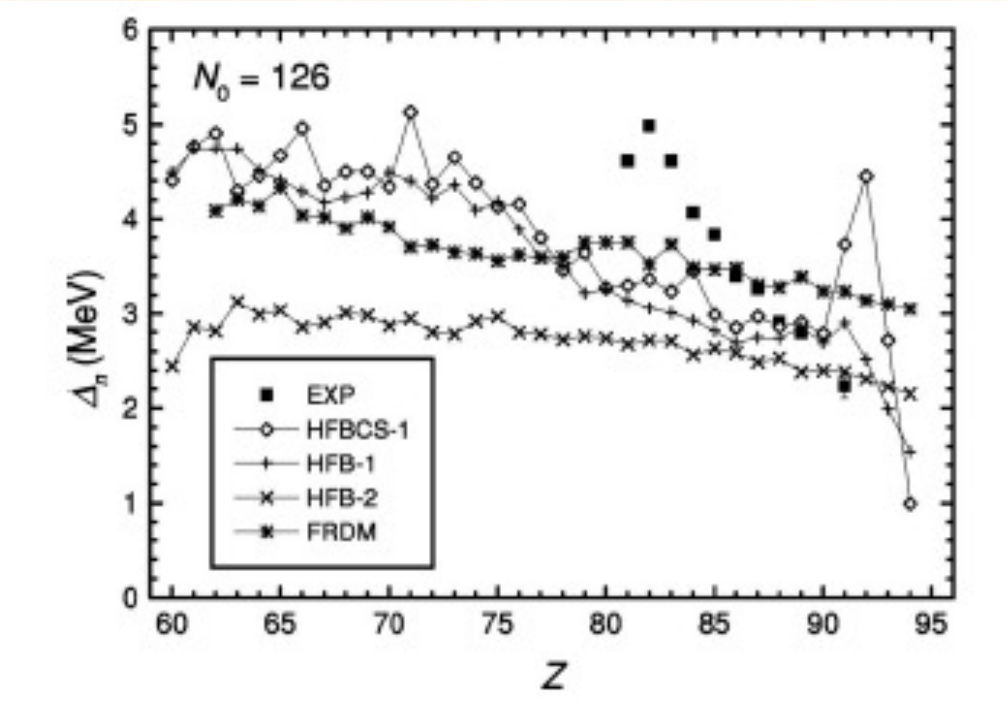
MUTUAL SUPPORT OF MAGICITIES AND RESIDUAL EFFECTIVE INTERACTIONS NEAR ^{208}Pb

N. ZELDES[†], T. S. DUMITRESCU[††] and H. S. KÖHLER[†††]

Niels Bohr Institute and Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

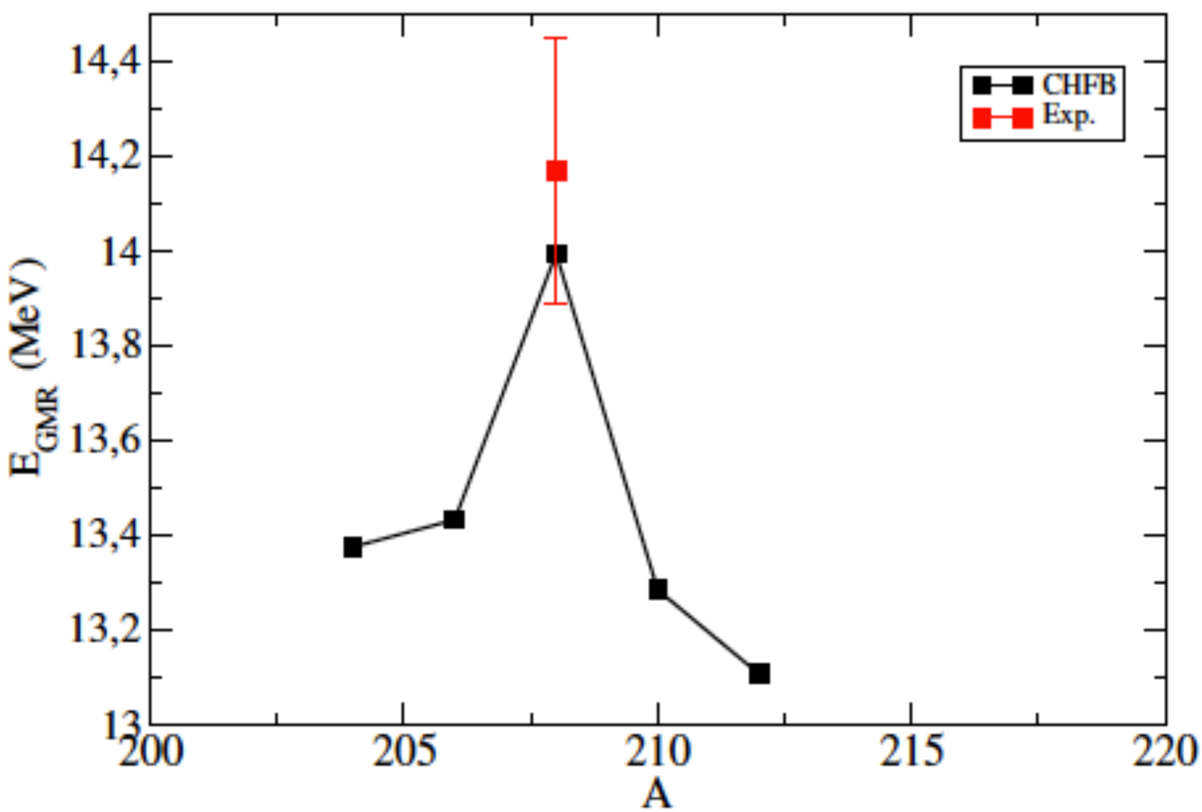
Received 1 November 1982

Abstract: We summarize experimental evidence in the lead region on the increased stability associated with neutron magic number when the proton number is magic, and vice versa. The effect is interpreted in the framework of the nuclear shell model with empirical effective interactions. Its relation to spherical Hartree-Fock calculations is pointed out and used to test Skyrme-type forces. None of the considered Skyrme interactions reproduce the effect.

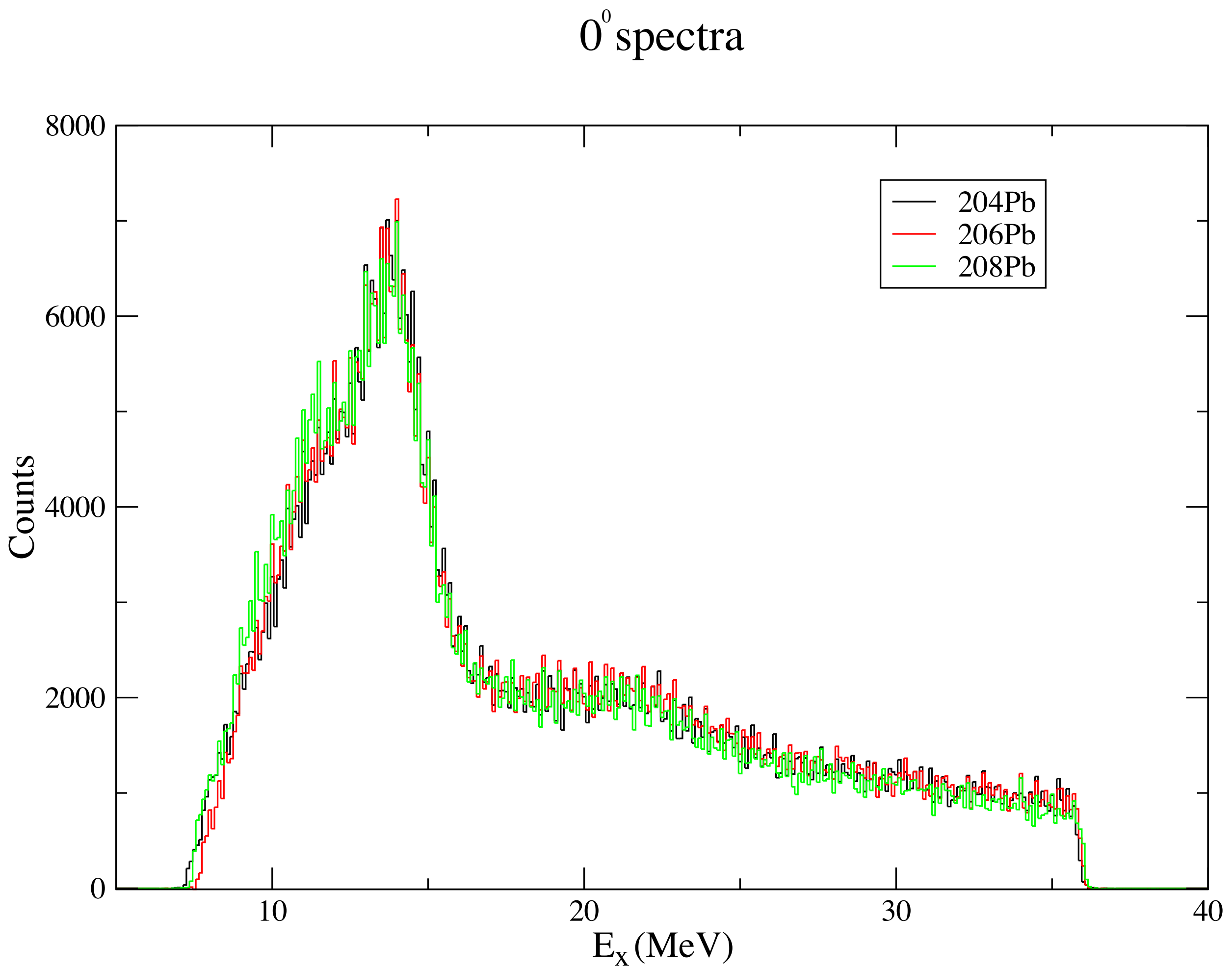


term). There are 27 such nuclei, and in the case of both HFB formulas their mean error (experiment −calculated) is −1.31 MeV, as compared to 0.040 MeV for the complete set of 1768 data points in the case of HFB-1 and 0.000 MeV (to three decimals) for the 2135 data points in the case of HFB-2. For HFBCS-1 the effect is smaller but still significant, the mean error for the 27 nuclei being −0.731 MeV, to be compared with 0.102 MeV for the complete fit.

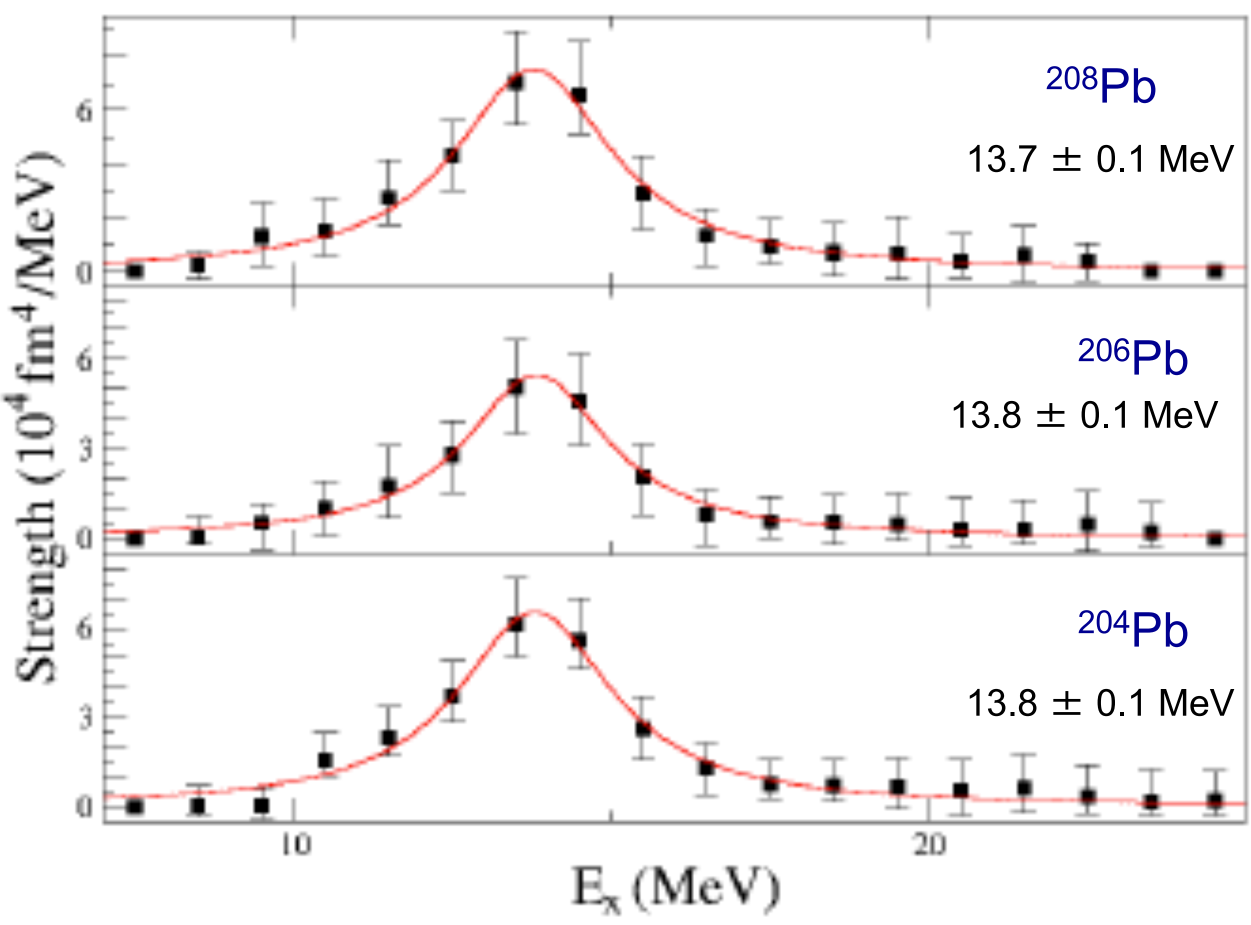
D. Lunney *et al.*, Rev. Mod. Phys. **75**, 1021 (2003)



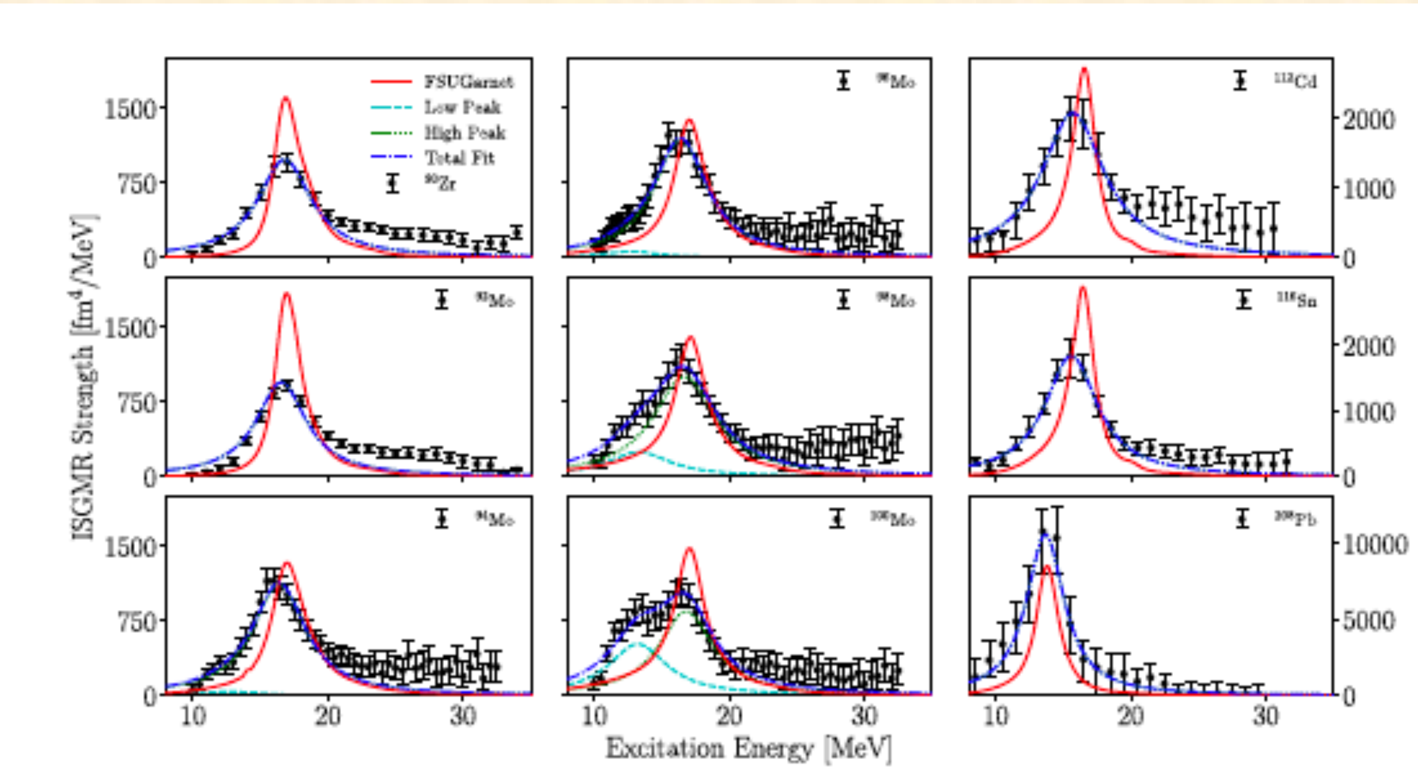
E. Khan, Phys. Rev. C **80**, 053702 (2009)



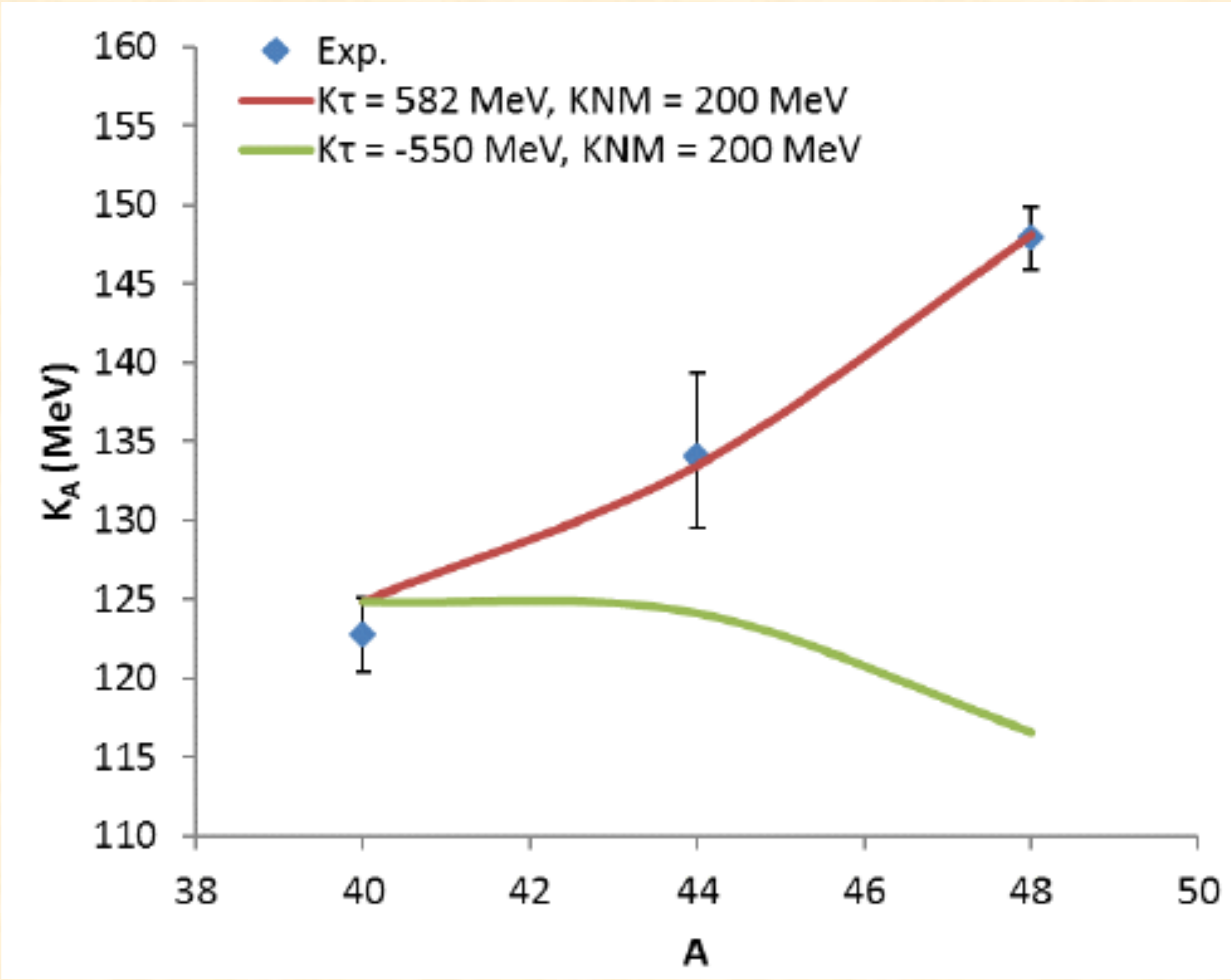
0^0 spectra
8000
6000
4000
2000
0
Counts
10
20
30
40
E_x (MeV)
204Pb
206Pb
208Pb



D. Patel *et al.*, Phys. Lett. B, **726**, 178 (2013)



K.B. Howard *et al.*, Phys. Lett. B **807**, 135608 (2020)



J. Button et al., Phys. Rev. C **96**, 054330 (2017)

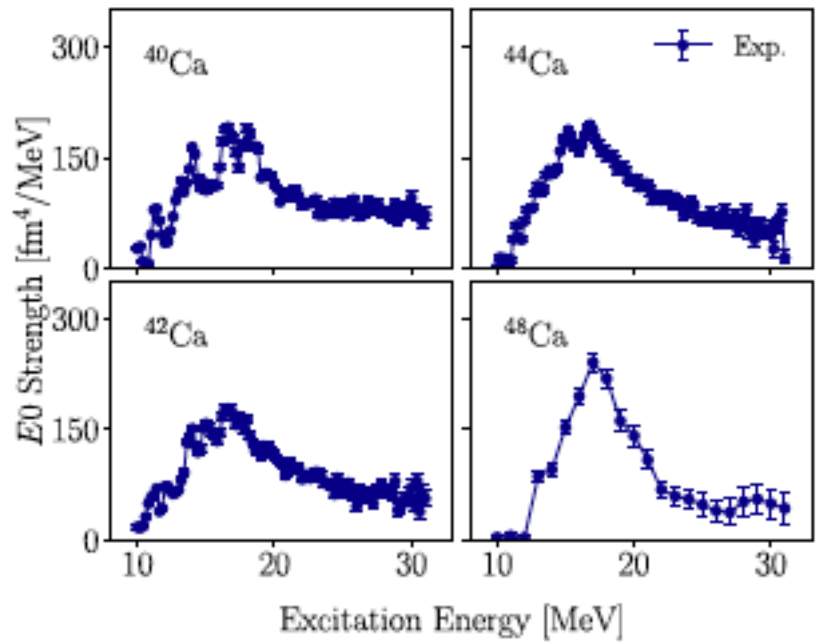
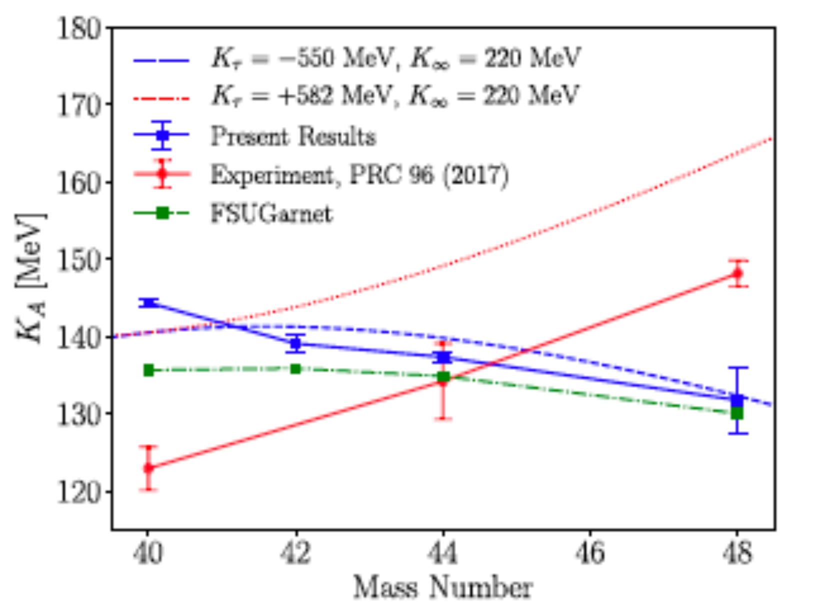


Fig. 3. Extracted isoscalar monopole strength distributions for ^{40,42,44,48}Ca.



K.B. Howard *et al.*, Phys. Lett. B **801**, 135185 (2020)

- We have investigated “structure effects” on the ISGMR (the “breathing mode”) : deformation, open-shell nuclei, direct shell structure effects, via inelastic scattering of 386-MeV α particles at extremely forward angles (including 0^{o}).
- In deformed nuclei, the ISGMR shows a splitting of strength into two components. This splitting is attributed to coupling with the K=0 component of the ISGQR.
- In the Cd and Sn isotopes, the ISGMR energy is significantly lower than that expected from the accepted value of K_{∞}. As of now, there is no satisfactory theoretical explanation of this “fuzziness” of open-shell nuclei. This effect appears to start manifesting in Mo nuclei even.
- The ISGMR response of $^{90,92}Zr$ and ^{92}Mo is practically identical, in contrast with a recent report claiming significant shell structure contribution to nuclear incompressibility.

U. Garg, G.P.A. Berg, Y.K. Gupta, J. Hoffman, K. Howard, M. Koss, T. Li, Y. Liu, R. Marks, E. Martis, J.T. Matta, B.K. Nayak, D. Patel, P.V. Madhusudhana Rao, K. Sault, K. Schlax, M. Sengiyit, R. Talwar, S. Weyhmiller, M. White

University of Notre Dame

S. Ando, T. Aoki, M. Ichikawa, M. Itoh, R. Matsuo, T. Terazono, A. Uchiyama, H.P. Yoshida

Tohuku University

S. Adachi, C. Iwamoto, M. Fujiwara, H. Hashimoto, K. Kawase, K. Nakanishi, S. Okumura, A. Tamii, M. Yosoi

RCNP, Osaka University

T. Furuno, Y. Iwao, T. Kawabata, T. Murakami, H. Sakaguchi, S. Terashima, M. Tsumura, M. Uchida, Y. Yasuda, J. Zenihiro

Kyoto University

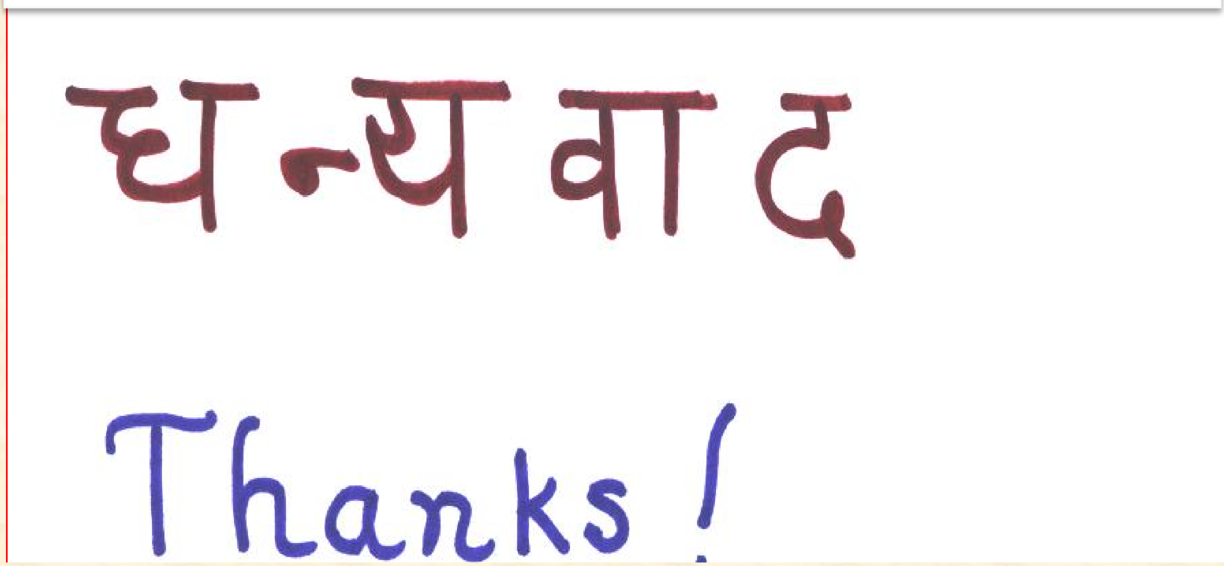
H. Akimune, C. Kadano, Y. Matsuda, T. Nakahara, A. Okamoto

Konan University

M.N. Harakeh, N. Kalantar-Nayestanaki

KVI, Groningen

Grazie!



The Question Kitten