『Nuclear Symmetry Energy』
Giant Resonances, EoS , Symmetry Energy
(July 24, 2013 at MSU Japan)

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1. Incompressibility and Giant Monopole Resonances
2. Isospin dependence of GMR
3. Mass model and symmetry energy
4. Summary

- Giant Resonances Study
- Which and Why?

1. GR: Giant Monopole → Incompressibility, Isospin dependence IV EOS, symmetry energy
   +
   GQR → Effective mass
   Gamow-Teller → Landau parameters G'_0
   T=0 pairing, △-h coupling
   IS and IV M1 → Landau parameters G_0 G'_0
   Spin-Dipole → tensor correlations, neutron skin
   GDR → Polarizability, symmetry energy term L

2. Low energy collective excitations
   First 2^+ → Super Fluidity(T=1 Pairing), shell structure, deformation
   --

- Where and How?

RIKEN SAMURAI - Inverse Kinematics and Missing Mass Techniques
RCNP with (p,p'),(α、α'),(p,n),(^{3}He,t)
Texas A&M (α、α')
MAYA, Ganil (d,d')
MSU

Well-known basics on EDF's

$$E = \langle \Psi | \hat{H} | \Psi \rangle = \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}\,]$$

$|\Phi\rangle$ **Slater determinant** $\Leftrightarrow$ $\hat{\rho}$ **1-body density matrix**

Calculating the parameters from a more fundamental theory (RBHF or Chiral theory --)

Setting the structure by means of symmetries (spin, isospin --) and fitting the parameters

$$E[\rho]$$

Allows calculating nuclear matter and finite nuclei (even complex states), by disentangling physical parameters.

HF/HFB for g.s., RPA/QRPA for excited states. Possible both in non-relativistic and in covariant form.

Nuclear Matter EOS → Supernova Explosion

イメージを表示できません。メモリ不足のためにイメージを開くことができないか、イメージが破損している可能性があります。コンピューターを再起動して再度ファイルを開いてください。それでも赤い x が表示される場合は、イメージを削除して挿入してください。

Isoscalar Giant Monopole Resonances

Isoscalar Compressional Dipole Resonances

Incompressibility K

$$E_{ISGMR} = \sqrt{\frac{\hbar^2 K_A}{m < r^2 >_m}},$$

$$K_A = K_\infty + K_{surf} A^{-1/3} + K_\tau \delta^2 + K_{Coul} \frac{Z^2}{A^{4/3}},$$

Self consistent HF+RPA calculations

Self consistent RMF+RPA calculations

(α, α') experimtent

The nuclear incompressibility from ISGMR

We can give credit to the idea that the link should be provided microscopically through the Energy Functional E[ρ].

IT PROVIDES AT THE SAME TIME

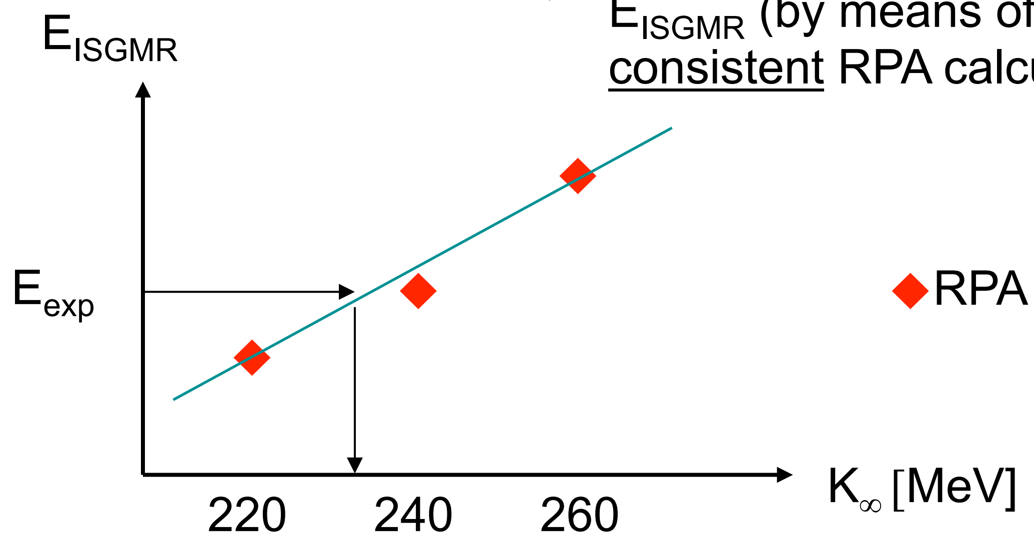
K_∞ in nuclear matter (analytic)

E_{ISGMR} (by means of <u>self-consistent</u> RPA calculations)

Skyrme

Gogny

RMF



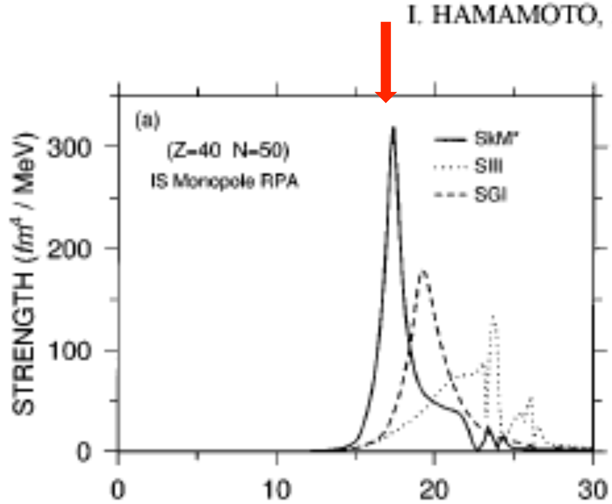
Extracted value of K_∞

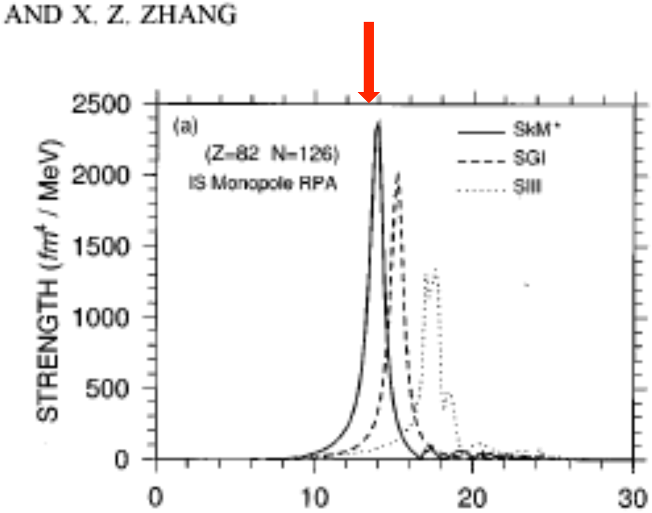
J.P. Blaizot, Phys. Rep. 64 (1980) 171

TABLE II. Peak energies, widths, and EWSR fractions for the ISGMAR and ISGDR. The errors in fitting the $L=0$ and $L=1$ strengths with the Breit-Wigner functions are included.

	ISGMR			LE ISGDR			HE ISGDR		
	E_{ISGMR} (MeV)	Γ (MeV)	EWSR (%)	E_{ISGDR} (MeV)	Γ (MeV)	EWSR (%)	E_{ISGDR} (MeV)	Γ (MeV)	EWSR (%)
^{90}Zr	16.6±0.1	4.9±0.2	101±3	17.8±0.5	3.7±1.2	7.9±2.9	26.9±0.7	12.0±1.5	67±8
^{116}Sn	15.4±0.1	5.5±0.3	95±4	15.6±0.5	2.3±1.0	4.9±2.2	25.4±0.5	15.7±2.3	68±9
^{144}Sm [21]	$15.3^{+0.11}_{-0.12}$	$3.70^{+0.12}_{-0.63}$	84^{+4}_{-25}	14.2±0.2	4.8±0.8	23^{+4}_{-10}	$25.0^{+1.7}_{-0.3}$	19.9±1.4	91^{+25}_{-17}
^{208}Pb	13.4±0.2	4.0±0.4	104±9	13.0±0.1	1.1±0.4	7.0±0.4	22.7±0.2	11.9±0.4	111±6

Phys. Rev. C 56, 3121 – Published 1 December 1997



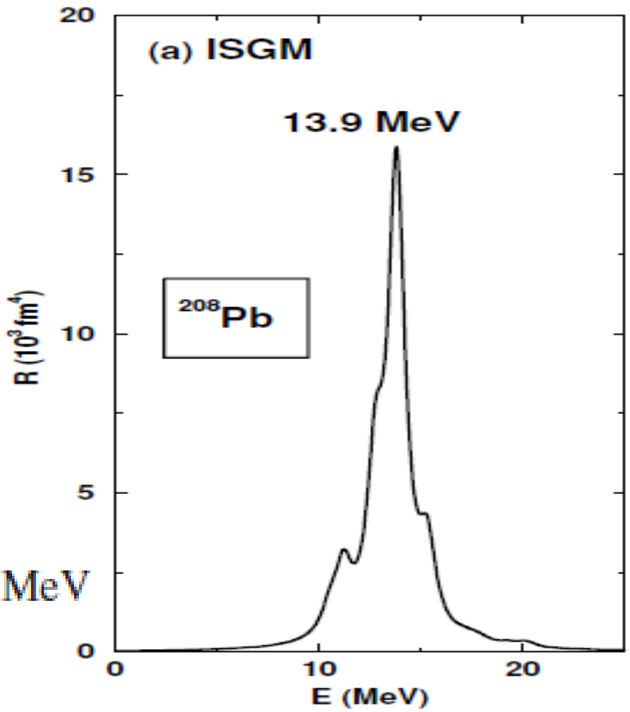


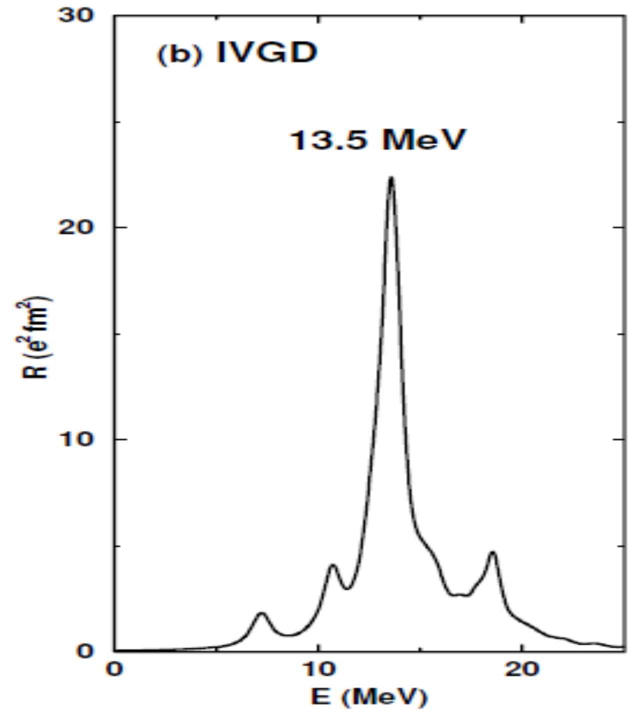
K=217MeV for SkM*

K=256MeV for SGI

K=355MeV for SIII

RRPA





EXP

14.1 ± 0.3 MeV

EXP

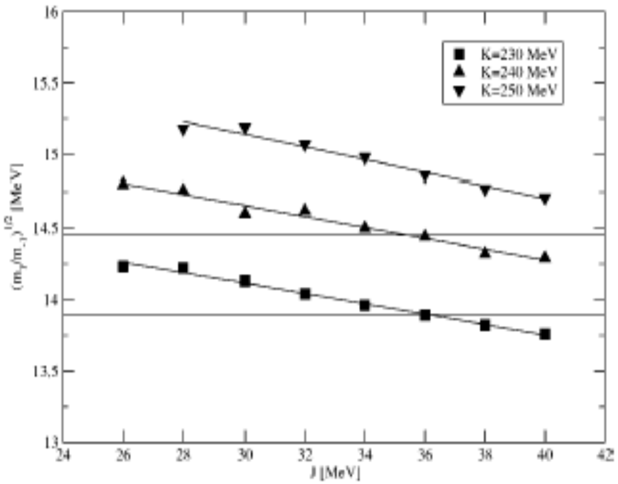
13.3 ± 0.1 MeV

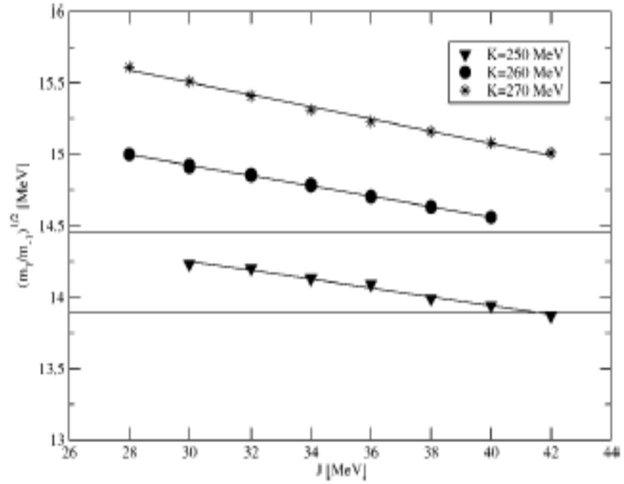
	DD-ME2	DD-ME1
ρ_{sat} (fm^{-3})	0.152	0.152
E/A (MeV)	−16.14	−16.20
K_0 (MeV)	250.89	244.5
m^*	0.572	0.578
a_4 (MeV)	32.3	33.1

PHYSICAL REVIEW C **71**, 024312 (2005)

New relativistic mean-field interaction with density-dependent meson-nucleon couplings

G. A. Lalazissis T. Nikšić and D. Vretenar P. Ring





α = 1/6 implies K around 230-240 MeV

α = 1/3 implies K around 250 MeV

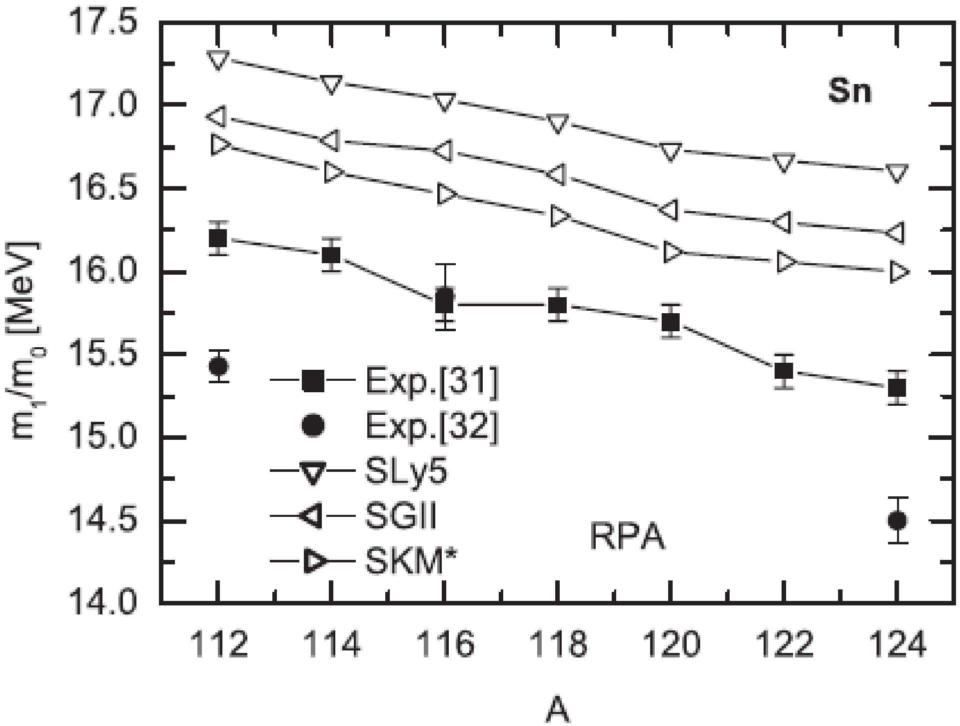
G.Colo, N. Van Giai, J. Meyer, K. Bennaceur, P. Bonche, *Phys. Rev.* C70, 024307 (2004)

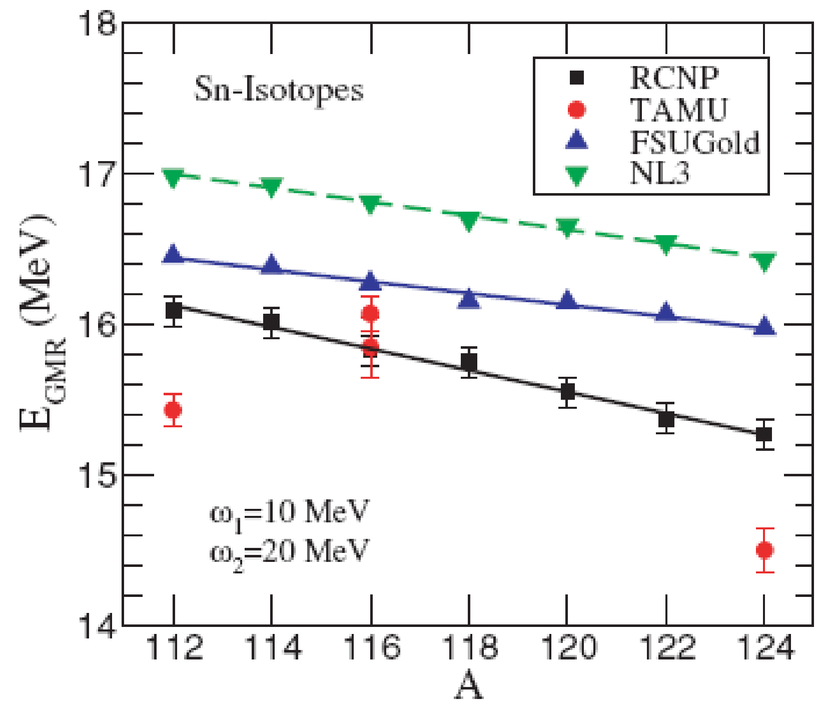
<u>Constraint from the ISGMR in ^{208}Pb</u> :

E_{GMR} constrains K_∞ = 240 ± 10 MeV. The error comes from the choice of the density dependence

New problem is appeared.

Phys. Rev. Lett. 99, 162503 (2007).



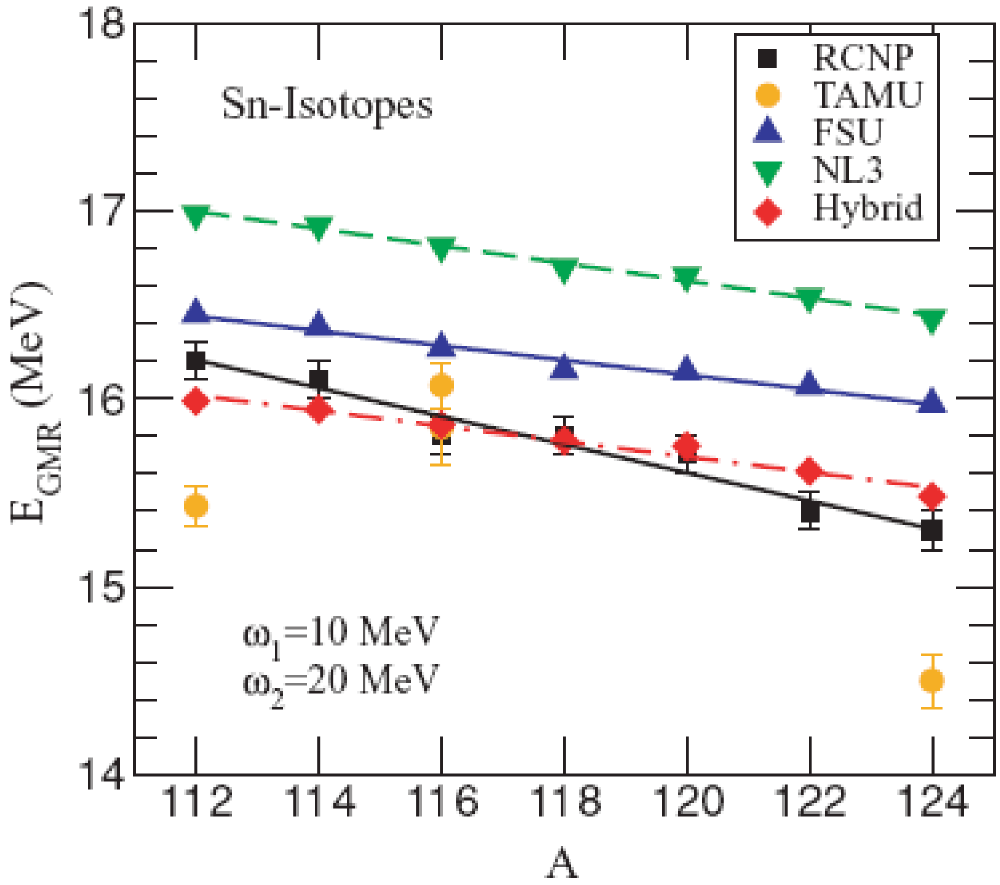


Why Tin is so soft?

Or

Why Pb is so hard?

A trial to solve this problem by introducing an isospin dependent Incompressibility, they can get better description in Sn isotopes, but fails in Pb208.   J. Piekarewicz, PRC79, 054311 (2009)



Based on the HFB+QRPA calculation, the ISGMR energies in Sn Isotopes are obtained using different Skyrme interaction, but There is No satisfied conclusion according to those calculation Because the calculations are not fully self-consistent, such as The two-body spin-orbit interaction is dropped .
J. Li et.al.,PRC78,064304(2008)

Or the HF+BCS+QRPA(QTBA). The spin-orbit interaction is dropped. V. Tselyaev, PRC 79, 034309 (2009)

T. Sil, et.al., Phys. Rev. C73, 034316 (2006). The spin-orbit residual interaction in HF+RPA produces an attractive effect on the ISGMR strength, the energies are pushed down by about 0.6MeV.
No pairing.

The strength function of QRPA is obtained by

Residual interaction： full Skyrme force, two-body spin-orbit, two-body Coulomb, and also the pairing in particle-particle channel

$$S(E) = \sum_n \left| \langle 0 | \hat{F} | n \rangle \right|^2 \delta(E - E_n)$$

The various moments are defined as

$$m_k = \int E^k S(E) dE$$

And various energies are defined as

$$E_{con} = \sqrt{\frac{m_1}{m_{-1}}}, \quad E_{cen} = \frac{m_1}{m_0}, \quad E_s = \sqrt{\frac{m_3}{m_1}}$$

$$V_{pair}(\vec{r}_1,\vec{r}_2) = V_0\left[1-\eta\left(\frac{\rho(r)}{\rho_0}\right)\right]\delta(\vec{r}_1-\vec{r}_2)$$

η equals to 1, 0.5,0 corresponding to surface, mixed, and volume Pairing.

TABLE I: The parameter V_0 for different Skyrme parameter sets and different pairing interactions. The units are in MeV.

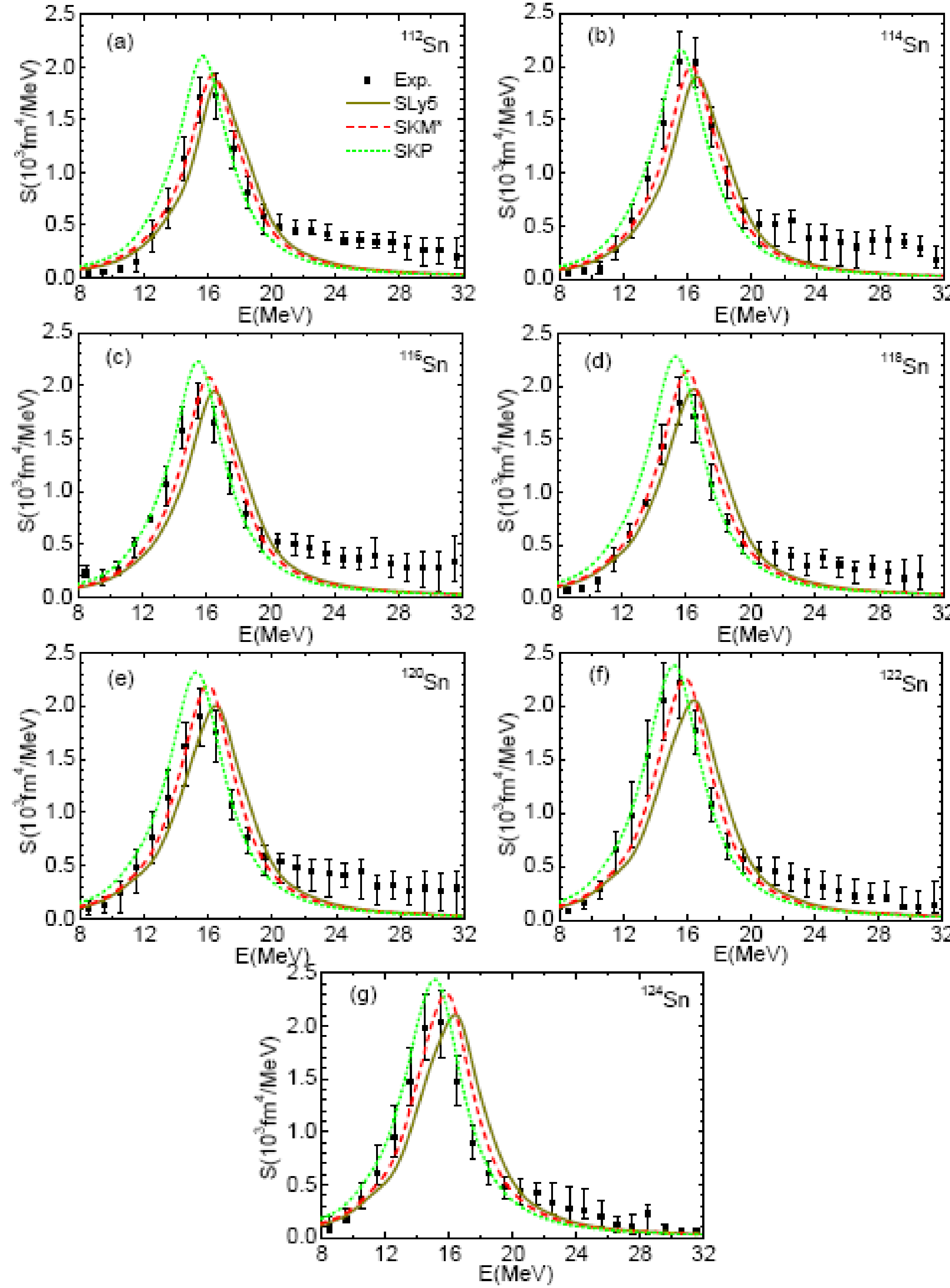
			Volume	surface	mixed
$\Delta_n = 1.334 MeV$	^{112}Cd	SLy5	261	738	388
		SKM*	230	675	342
		SKP	215	692	328
$\Delta_n = 1.321 MeV$	^{120}Sn	SLy5	218	645	325
		SKM*	255	725	381
		SKP	213	688	328
$\Delta_n = 0.841 MeV$	^{204}Pb	SLy5	265	875	409
		SKM*	255	863	392
		SKP	211	771	335

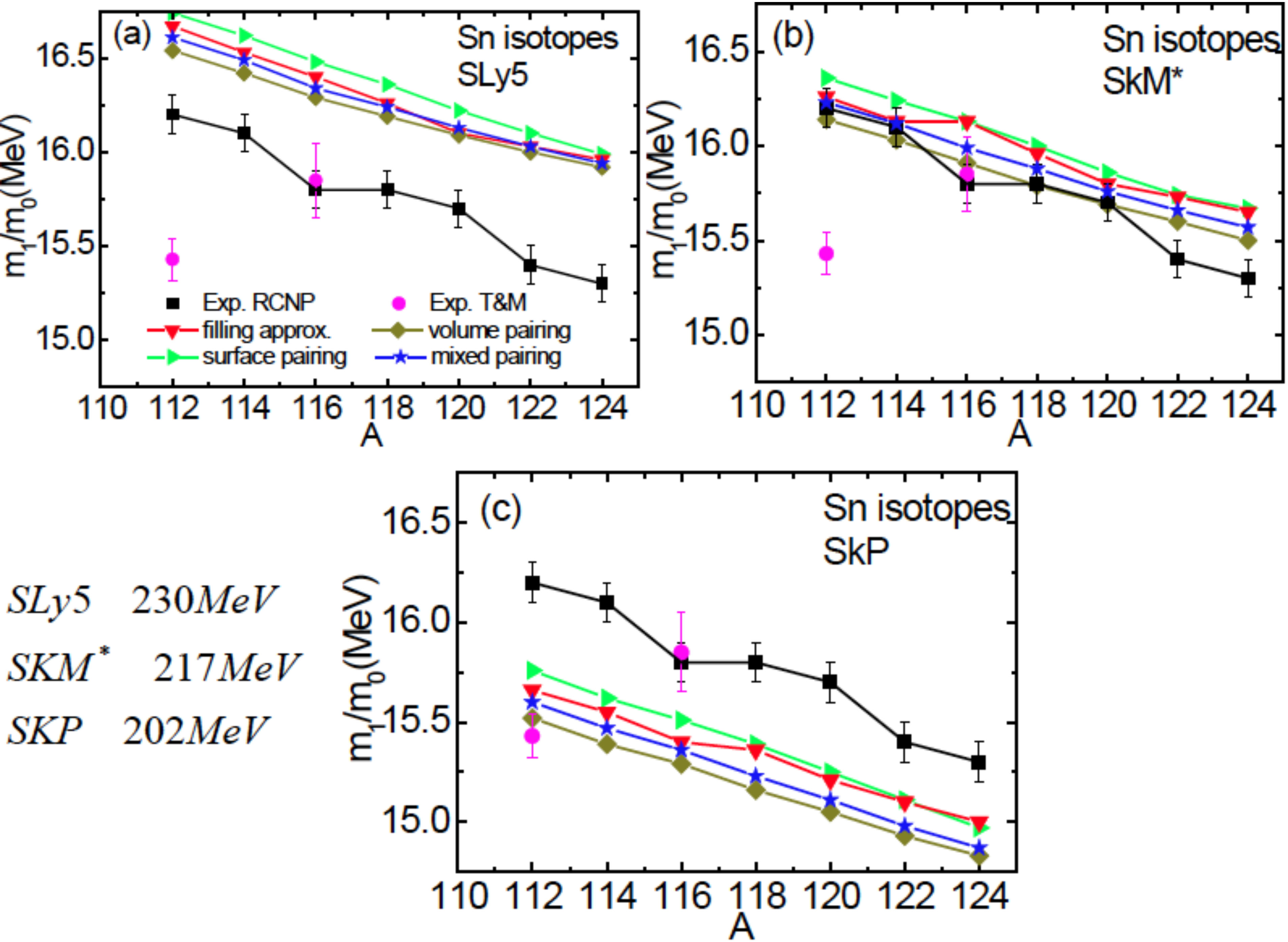
Results for Sn isotopes
Exp at RCNP

$SLy5 \quad 230MeV$

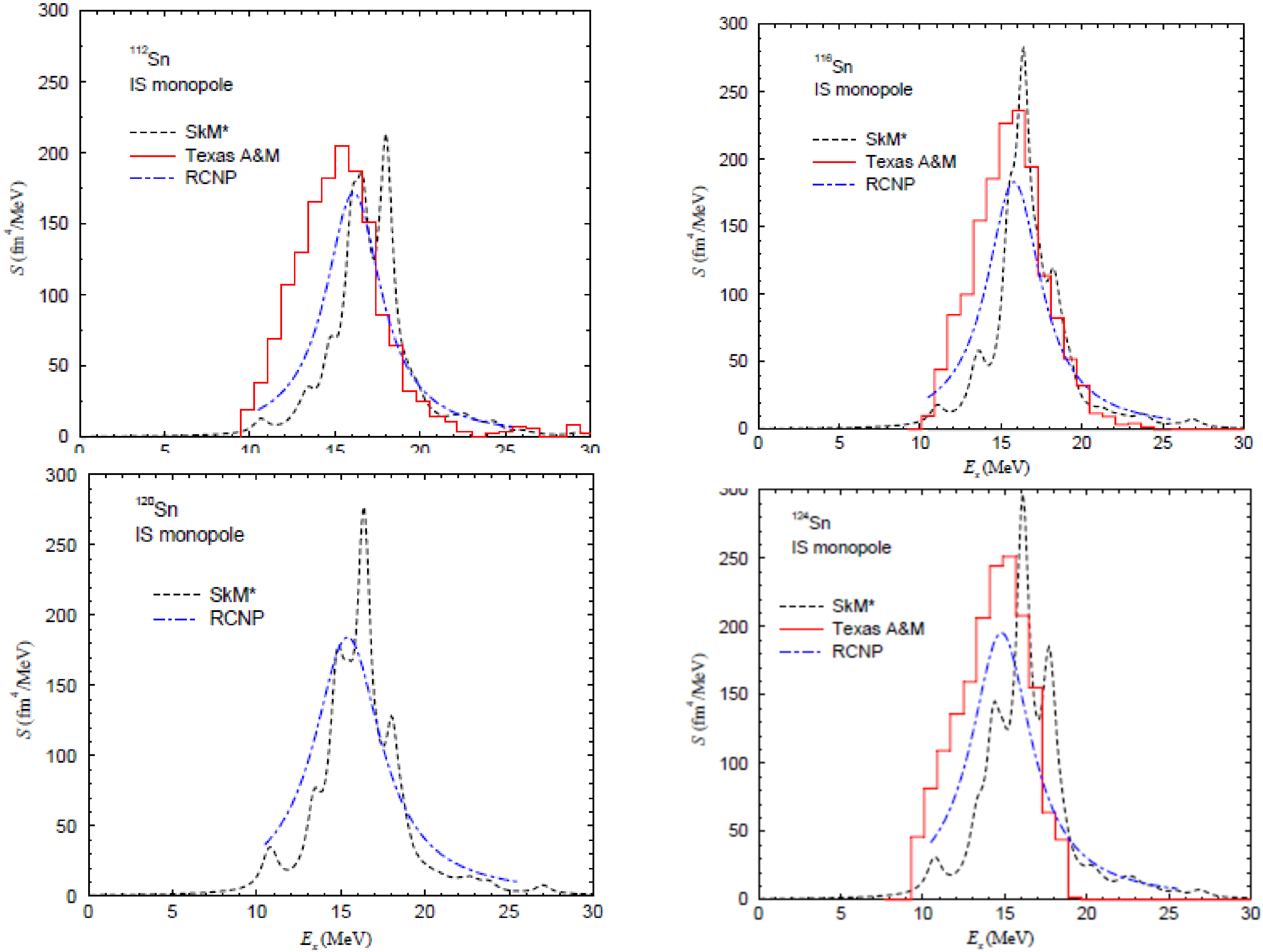
$SKM^* \quad 217MeV$

$SKP \quad 202MeV$



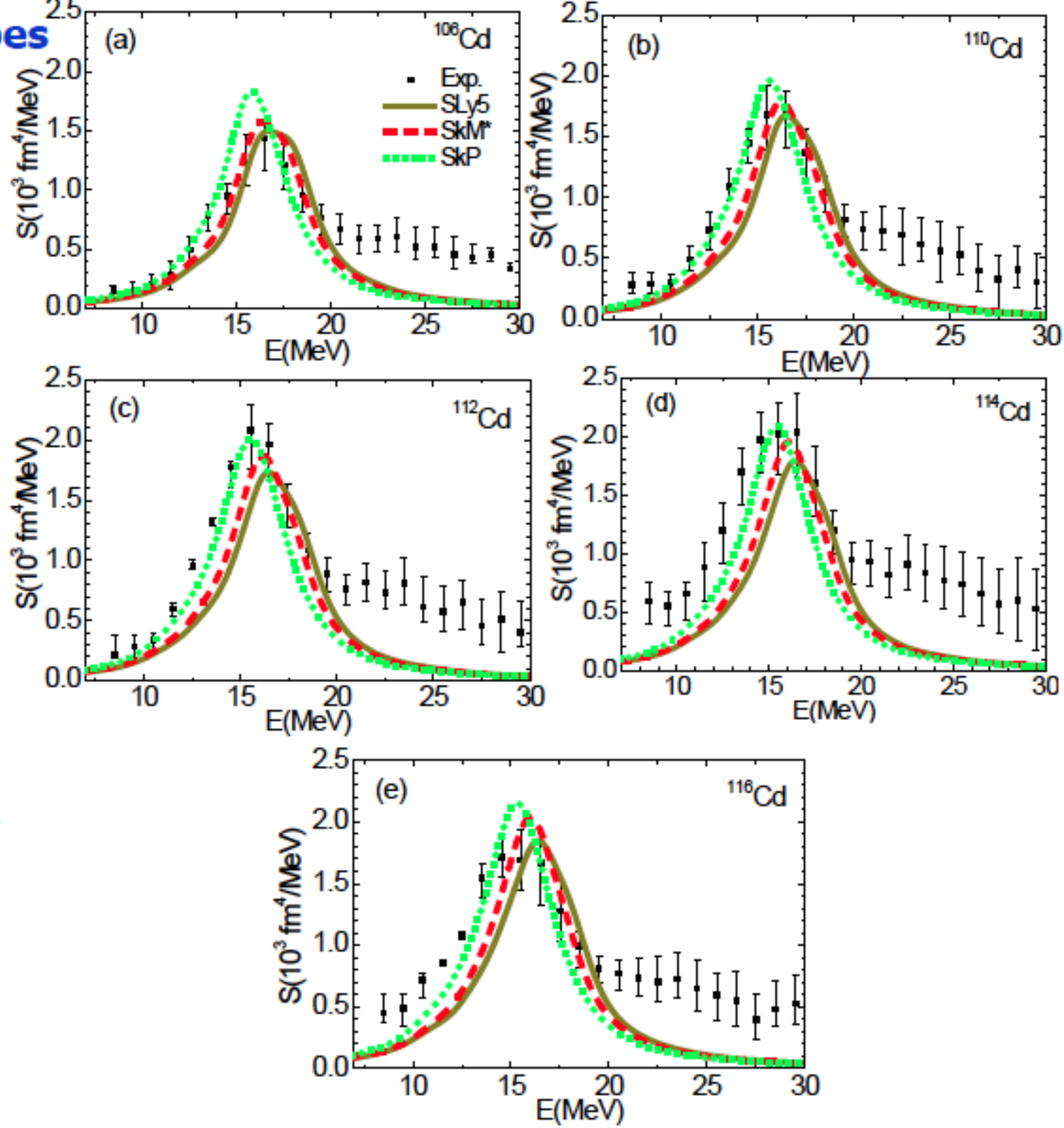


(a)
Sn isotopes
SLy5
(b)
Sn isotopes
SkM*
(c)
Sn isotopes
SkP
m1/m0(MeV)
A
16.5
16.0
15.5
15.0
110
112
114
116
118
120
122
124
Exp. RCNP
Exp. T&M
filling approx.
volume pairing
surface pairing
mixed pairing
SLy5 230MeV
SKM* 217MeV
SKP 202MeV



112Sn
IS monopole
SkM*
Texas A&M
RCNP
S (fm4/MeV)
116Sn
IS monopole
SkM*
Texas A&M
RCNP
S (fm4/MeV)
Ex (MeV)
120Sn
IS monopole
SkM*
RCNP
S (fm4/MeV)
Ex (MeV)
124Sn
IS monopole
SkM*
Texas A&M
RCNP
S (fm4/MeV)
Ex (MeV)

Results for Cd isotopes



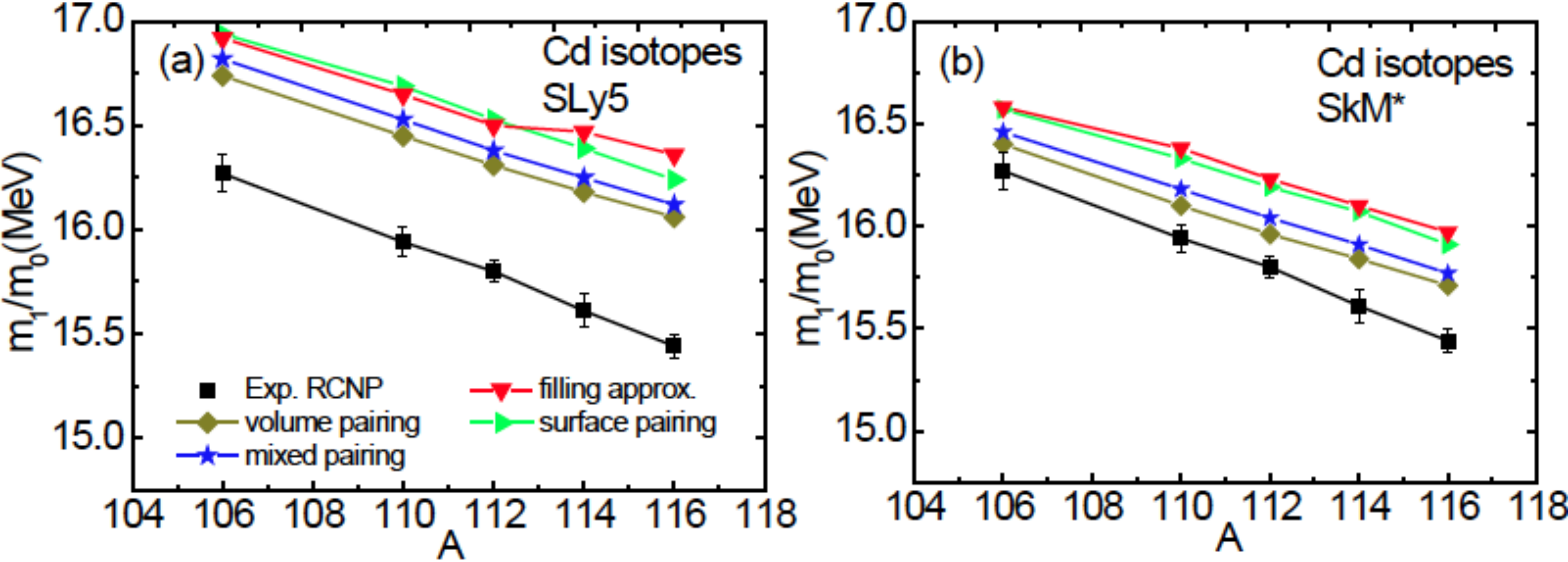
$SLy5 \quad 230 MeV$

$SKM^* \quad 217 MeV$

$SKP \quad 202 MeV$

$HFBCS + QRPA$

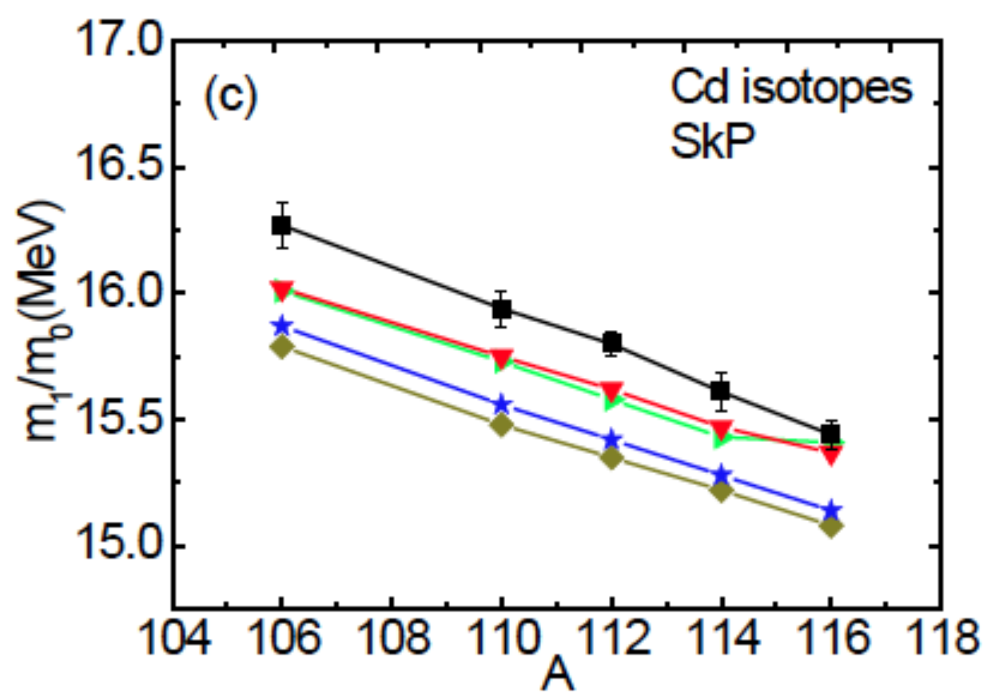
mixed pairing



$SLy5 \quad 230MeV$

$SKM^{*} \quad 217MeV$

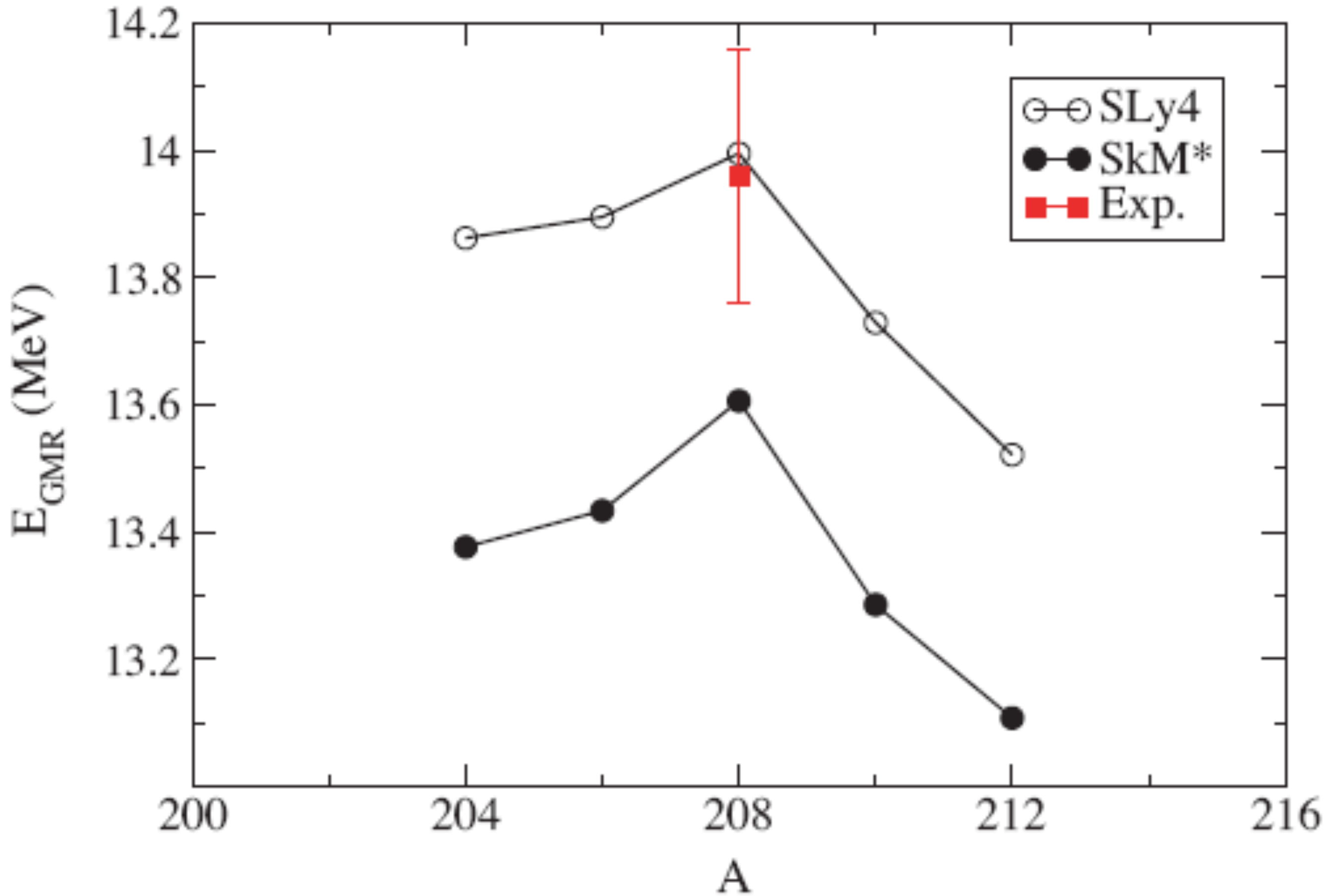
$SKP \quad 202MeV$



Summary for Incompressibility

- **We have studied the ISGMR in Cd, Sn and Pb isotopes based on the fully self-consistent HF+BCS plus QRPA calculations. The SLy5, SKM*, and SKP and different pairing interactions are used in our calculations.**
- **We found that the pairing plays a role in producing the ISGMR properties.**
- **The SLy5 interaction (K_∞=230MeV) together with the effect of pairing can give better description on ISGMR in Pb isotopes, but it has some discrepancies between experiments in Cd and Sn isotopes.**
- **SKM* (K_∞=217MeV) can produce the experimental data in Cd and Sn isotopes, but is not satisfactory to describe Pb isotopes.**
- **SKP(K_∞=202MeV) fails for all isotopes because the incompressibility is too low.**
- <u>K_∞=(225 +/- 10)MeV is consistent with Pb, Sn and Cd data.</u>

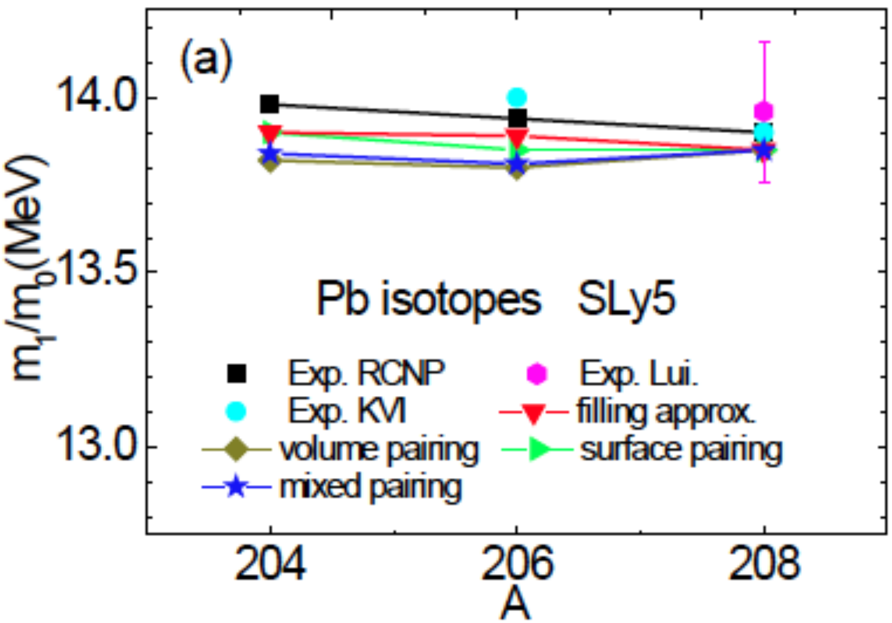
Results for Pb isotopes

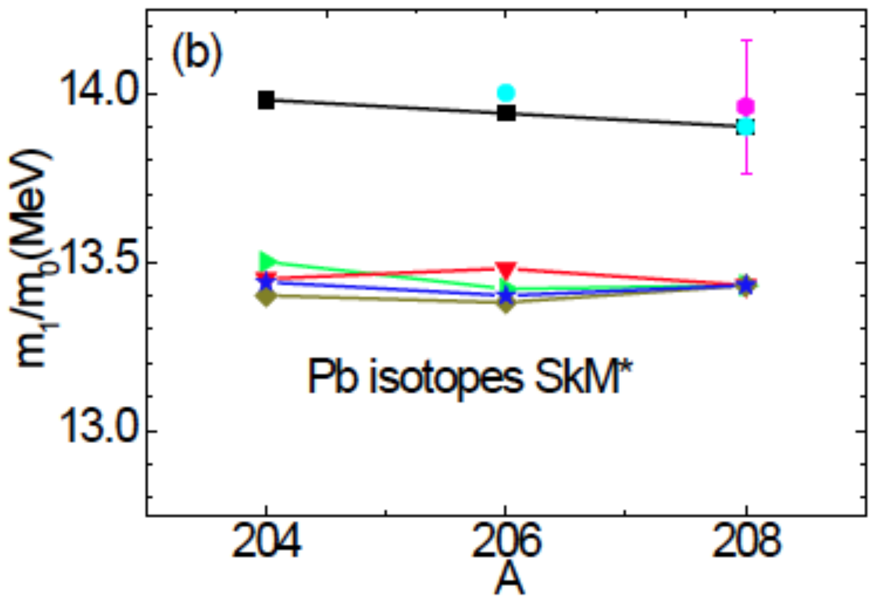


E. Khan, Phys. Rev. C80, 057302 (2009).

The so-called mutually-enhanced-magicity effect, which is proposed by Lunney and Zeldes.

Results for Pb isotopes





$SLy5 \quad 230MeV$

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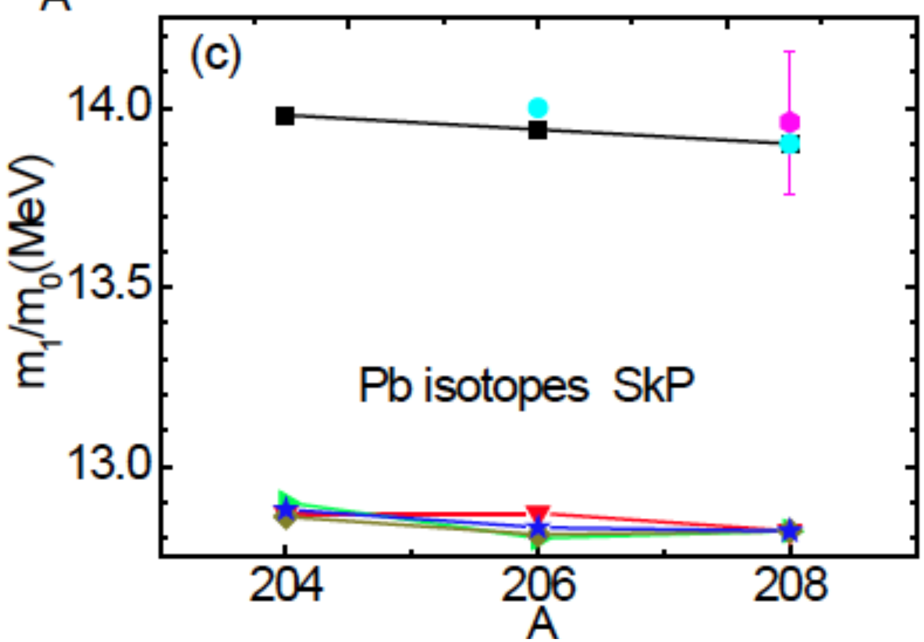


What can we learn about neutron EOS from Giant resonances and mass formulas?

In infinite matter,

$$\mathcal{E}(\rho, \delta \equiv \frac{\rho_n - \rho_p}{\rho}) = \mathcal{E}_0(\rho, \delta = 0) + \mathcal{E}_{\mathrm{sym}}(\rho)\delta^2.$$

Symmetry Energy

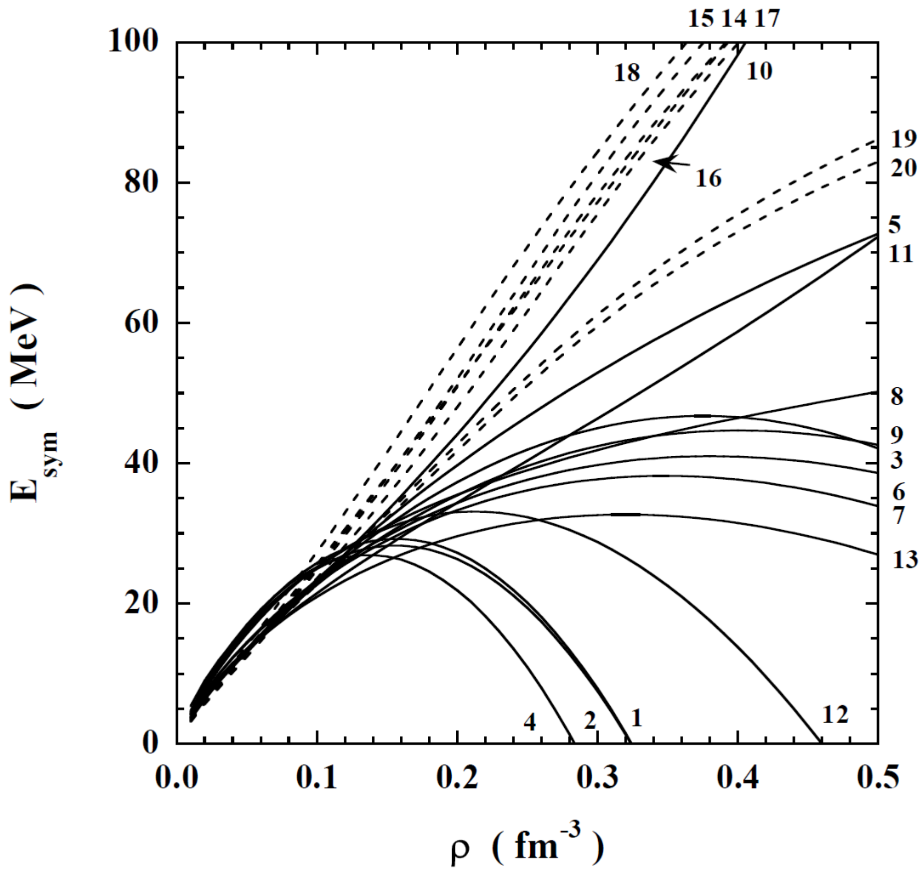
$$S(\rho)\ (=E_{sym}(\rho)) = \frac{1}{2}\frac{\partial^2(\varepsilon/\rho)}{\partial\delta^2} \text{ where } \delta=(\rho_n-\rho_p)/\rho$$

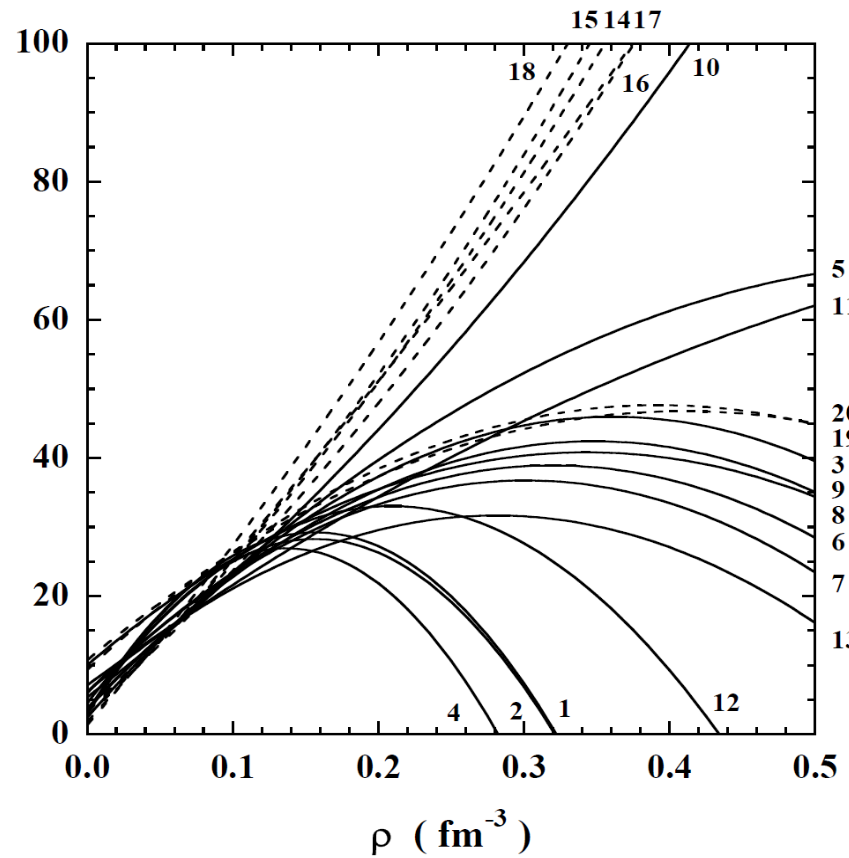
$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{sym}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2$$

$$\text{where } J=S(\rho_0),\ L=3\rho_0\left.\frac{\partial S}{\partial\rho}\right|_{\rho_0},\ K_{sym}=9\rho_0^2\left.\frac{\partial^2 S}{\partial\rho^2}\right|_{\rho_0}$$

$$\varepsilon_\delta(\rho) = \frac{1}{2} \lim_{I \to 0} \frac{\partial^2}{\partial I^2} \left(\frac{H_{nm}}{\rho} \right)$$

$$\varepsilon_\delta(\rho) = J + \frac{L}{3}\frac{\rho - \rho_{nm}}{\rho_{nm}} + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_{nm}}{\rho_{nm}}\right)^2.$$





Isospin dependence of GMR

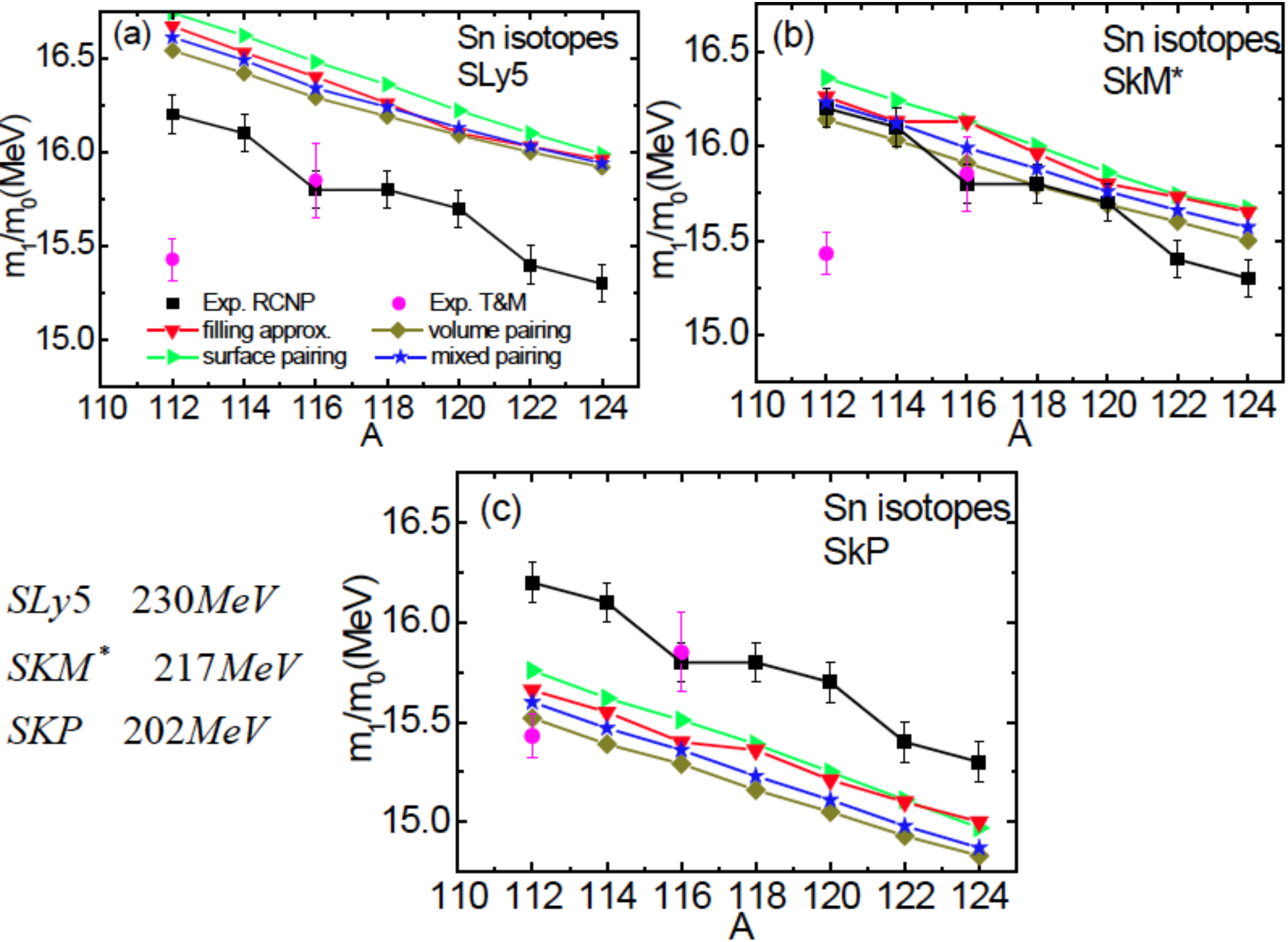
$$E_{ISGMR} = \sqrt{\frac{\hbar^2 K_A}{m < r^2 >_m}},$$

$$K_A = K_\infty + K_{surf} A^{-1/3} + K_\tau \delta^2 + K_{Coul} \frac{Z^2}{A^{4/3}},$$

$$K_{surf} = 4\pi\ {r_0}^2 \left[4\sigma(\rho_{nm}) + 9\rho_{nm} \left.\frac{d^2\sigma}{d\rho^2}\right|_{\rho=\rho_{nm}} + \frac{54\sigma(\rho_{nm})\rho_{nm}^2}{K_\infty} \left.\frac{d^3 h}{d\rho^3}\right|_{\rho=\rho_{nm}} \right]$$

$$K_{Coul} = \frac{3}{5}\frac{e^2}{r_0}\left(1 - \frac{27\rho_{nm}^2}{K_\infty}\left.\frac{d^3 h}{d\rho^3}\right|_{\rho=\rho_{nm}}\right),$$

$$K_\tau = K_{sym} + 3L - \frac{27 L \rho_{nm}^2}{K_\infty}\left.\frac{d^3 h}{d\rho^3}\right|_{\rho=\rho_{nm}}$$


(a)
Sn isotopes
SLy5
(b)
Sn isotopes
SkM*
(c)
Sn isotopes
SkP
m_1/m_0(MeV)
A
Exp. RCNP
Exp. T&M
filling approx.
volume pairing
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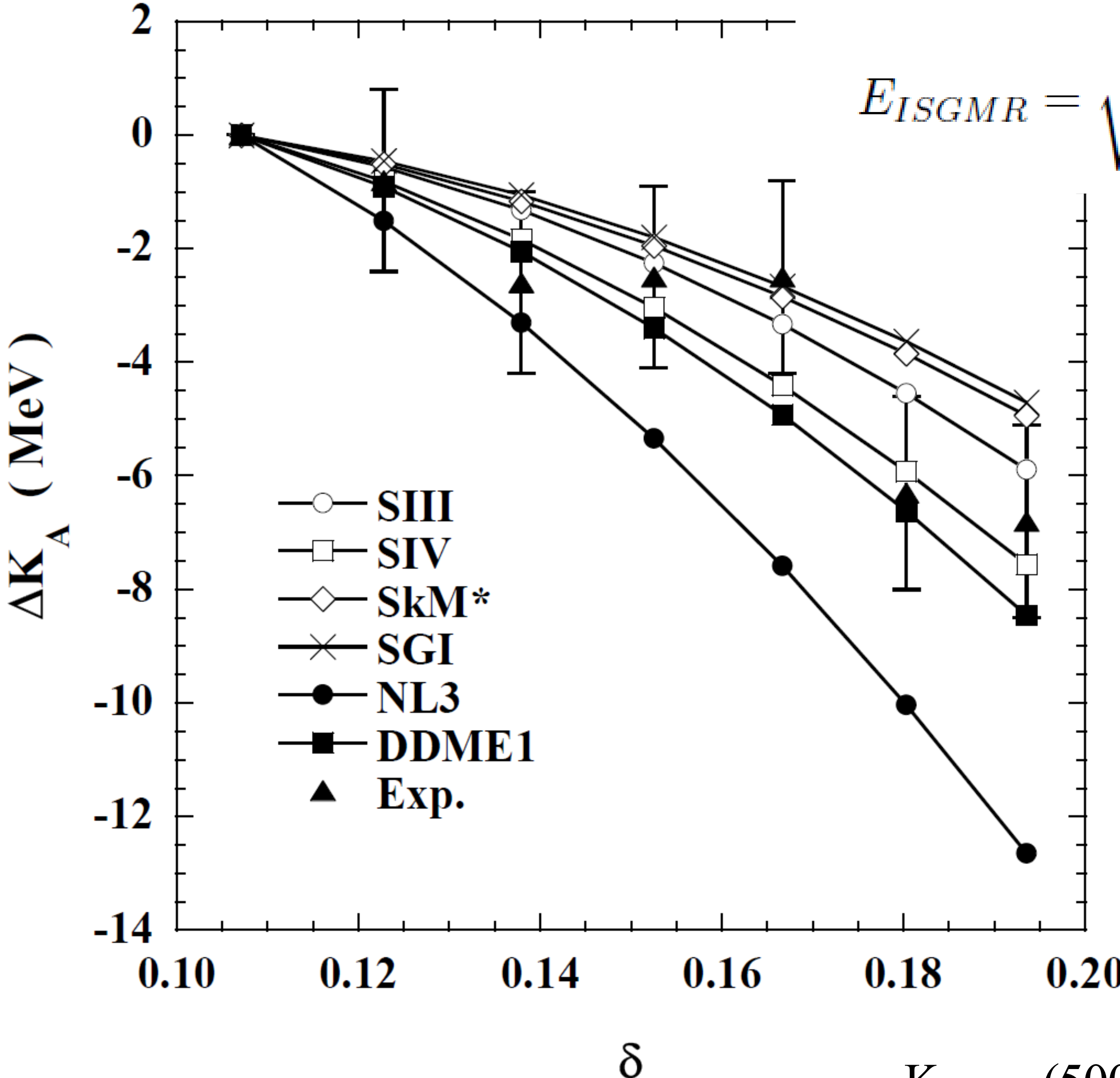
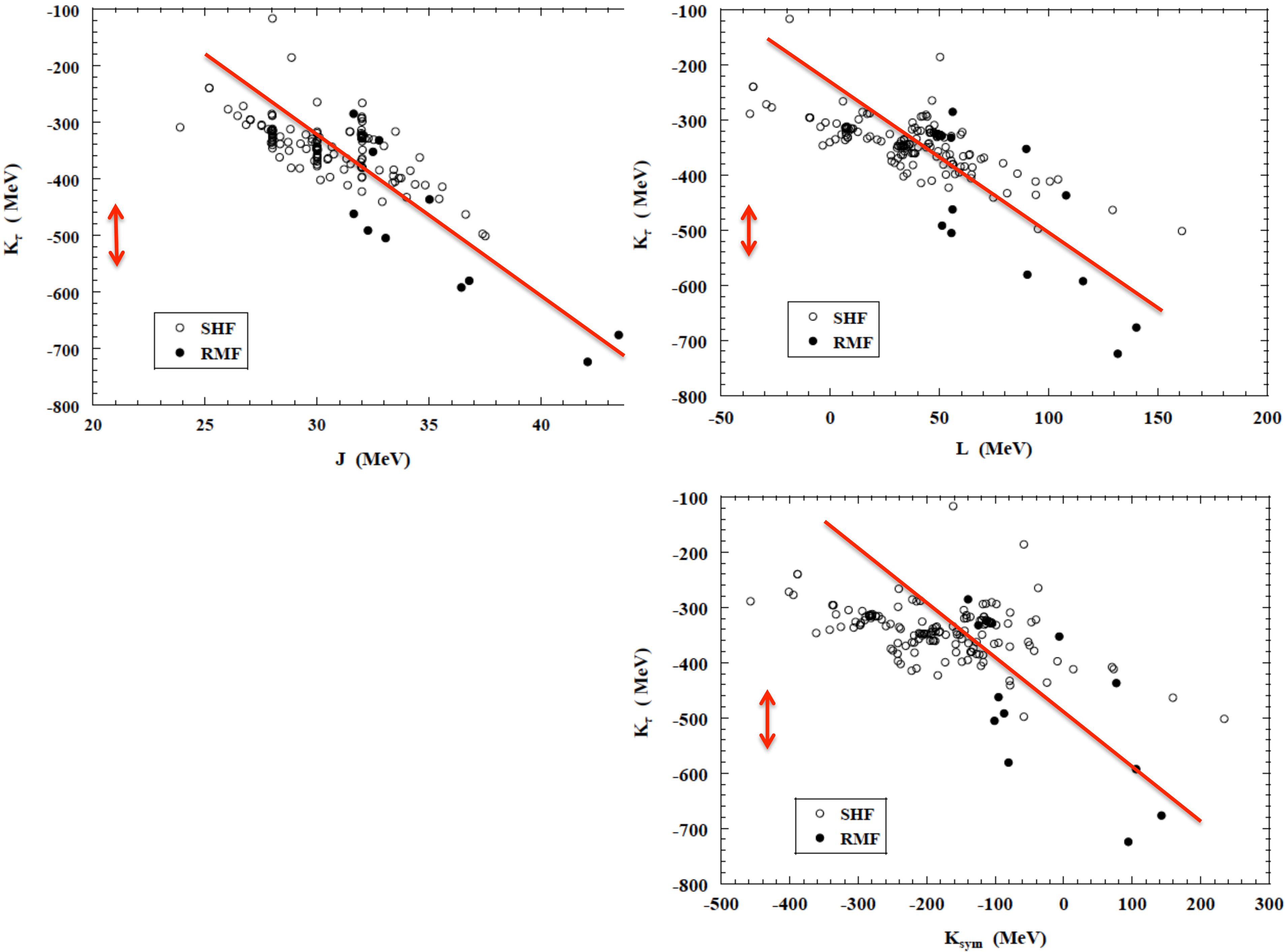


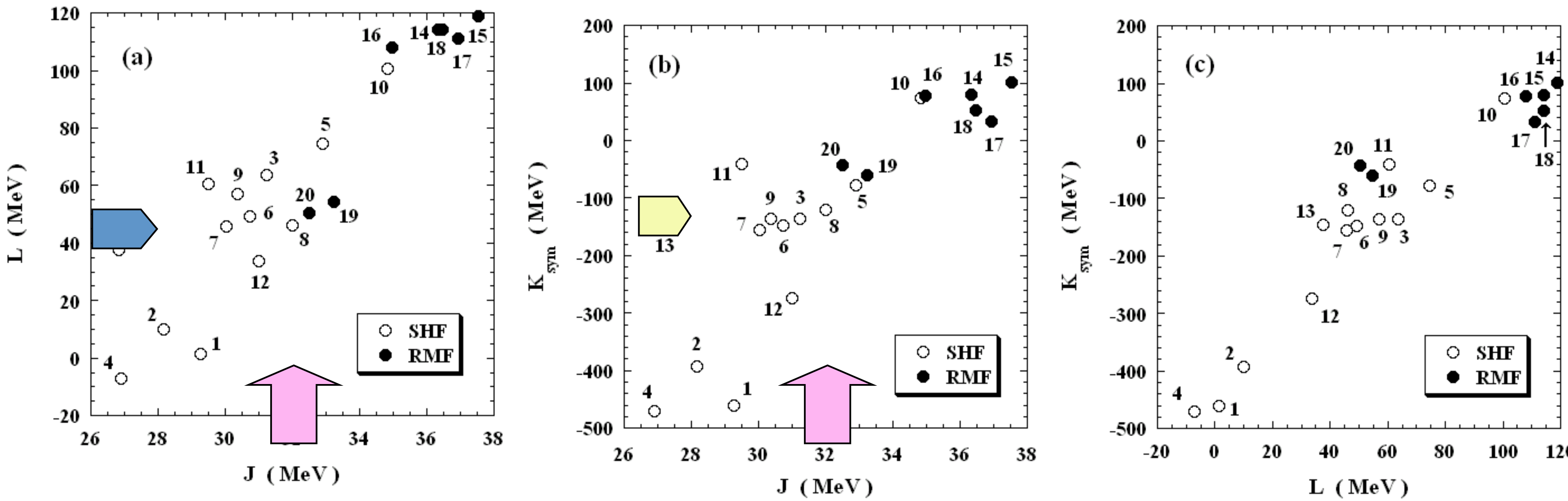
$$E_{ISGMR} = \sqrt{\frac{\hbar^2 K_A}{m < r^2 >_m}},$$

$K_\tau = -(500 \pm 50)\text{MeV}$



K_τ (MeV)
J (MeV)
SHF
RMF
K_τ (MeV)
L (MeV)
SHF
RMF
K_τ (MeV)
K_sym (MeV)
SHF
RMF

Correlation among nuclear matter properties



1.Nuclear incompressibility K is determined empirically with the ISGMR in ^{208}Pb to be

K~230MeV(Skyrme,Gogny), K~250MeV(RMF).

K=(240 +/-10 +/- 10)MeV

2. Combining ISGMR data of Sn and Cd isotopes(RCNP)

K=(225 +/-10)MeV

3. $K_\tau = -(500 \pm 50)\mathrm{MeV}$ is extracted from isotope dependence of ISGMR.

4. This value provides further the isovector properties

J=(32+/-1)MeV, L=(60+/-5)MeV, Ksym= -(100+/-40)MeV

by using the mean field correlations

5. How much we can trust to extract K_{tau} by a single set od data Ni isotopes (Maya/ Ganil/Orsay) (E. Khan)

Mass model and EoS

PRL 108, 052501 (2012) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2012

New Finite-Range Droplet Mass Model and Equation-of-State Parameters

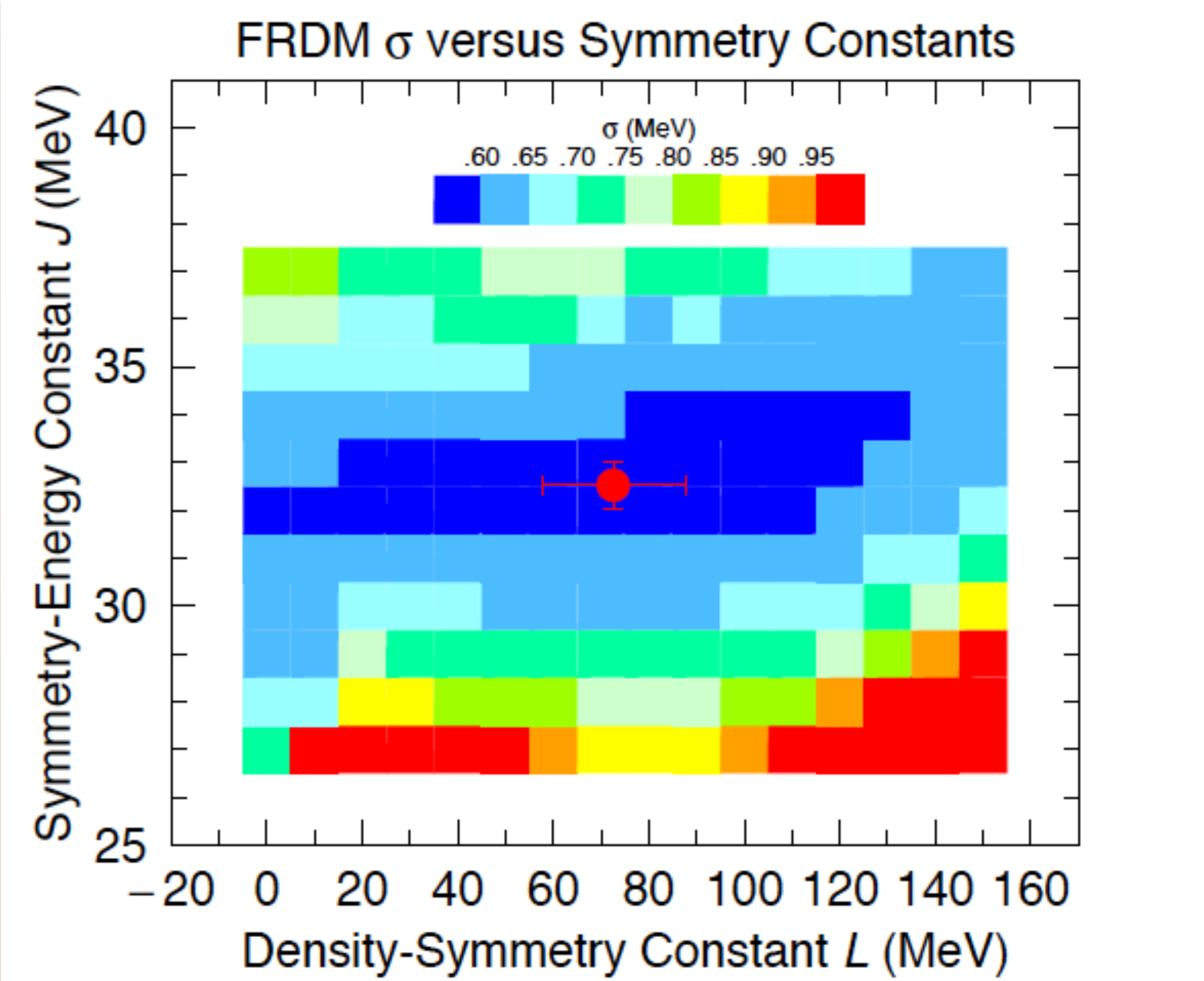
Peter Möller,[1,*] William D. Myers,[1] Hiroyuki Sagawa,[2] and Satoshi Yoshida[3]

Symmetry Energy

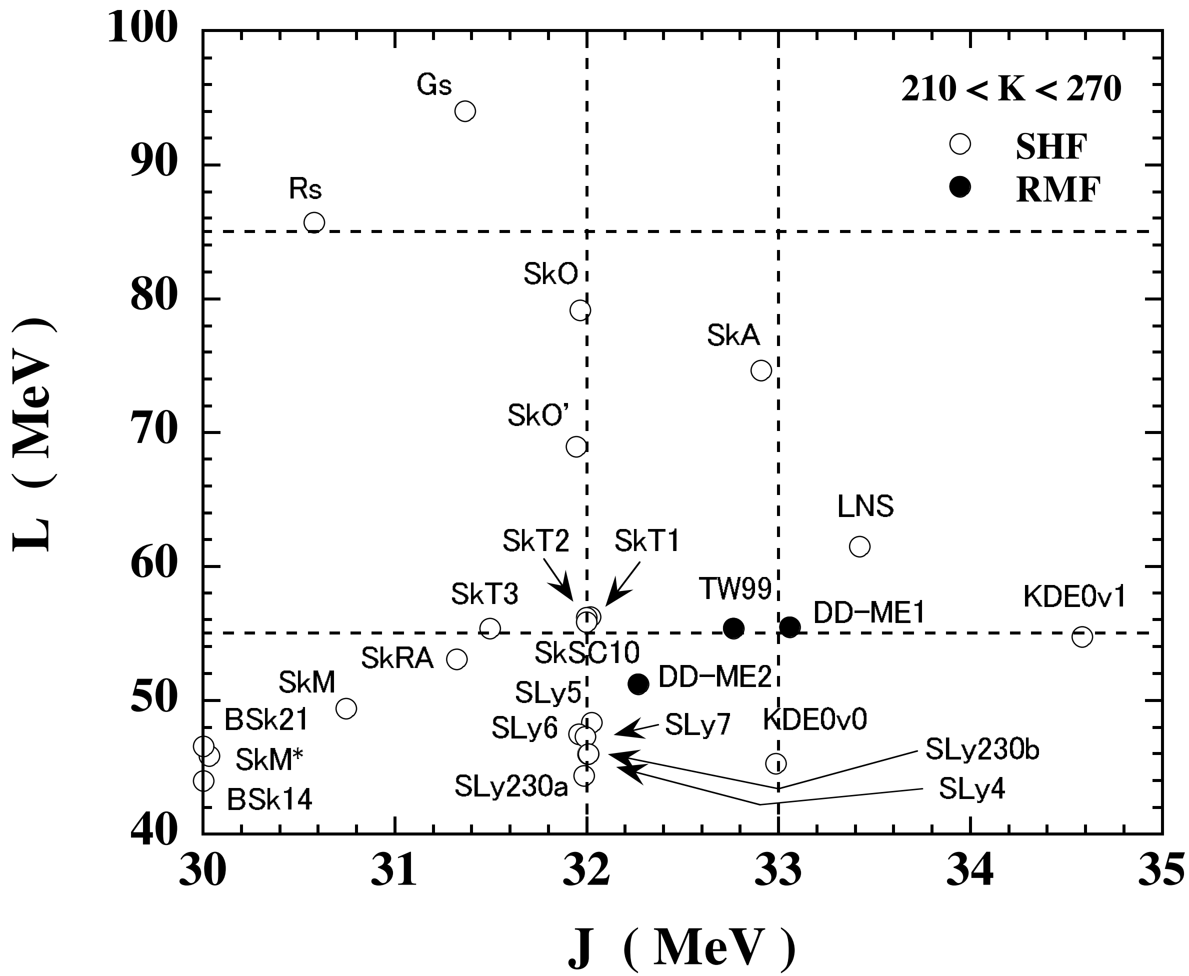
$$S(\rho) = \frac{1}{2}\frac{\partial^2(\varepsilon/\rho)}{\partial\delta^2} \quad \text{where } \delta=(\rho_n-\rho_p)/\rho$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{sym}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2$$

$$\text{where } J=S(\rho_0),\; L=3\rho_0 \left.\frac{\partial S}{\partial\rho}\right|_{\rho_0}, K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 S}{\partial\rho^2}\right|_{\rho_0}$$



J=32.5+/-0.5MeV L=70+/-15MeV
(L=54+/-15MeV:zero point fluctuation)



J=32.5+/-0.5MeV   L=70+/-15MeV (L=54+/-15MeV)

$K_{infinity}$=240+/-30MeV (94 Skyrme interactions and 7RMF Lagrangians)

Summary

1. Micro-macroscopic model (FRDM) is further improved taking into account the optimization of symmetry energy coefficients J and L:

   J=32.5 +/-0.5 MeV

   L=70 +/-15 MeV (55+/-15 MeV)

2. The importance of hyperon effect on EoS is pointed out to obtain the mass and radius of neutron stars in RMF and RMHF models which can be compatible with recent measurements of neutron stars (2012).

PHYSICAL REVIEW C **85**, 025806 (2012)

Hyperon effects in covariant density functional theory and recent astrophysical observations

Wen Hui Long (龙文辉),[1,2,*] Bao Yuan Sun (孙保元),[1] Kouichi Hagino,[2] and Hiroyuki Sagawa[3]