Spin-Dipole Excitations and Neutron Matter EOS

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H. Sagawa, University of Aizu

1. Introduction
2. Neutron Matter EOS and Neutron Skin Thickness
3. Spin-Dipole Excitations and Neutron Skin Thickness
4. Summary

Nuclear Matter EOS → Supernova Explosion

Isoscalar Monopole Giant Resonances

Isoscalar Compressional Dipole Resonances

→ Incompressibility K

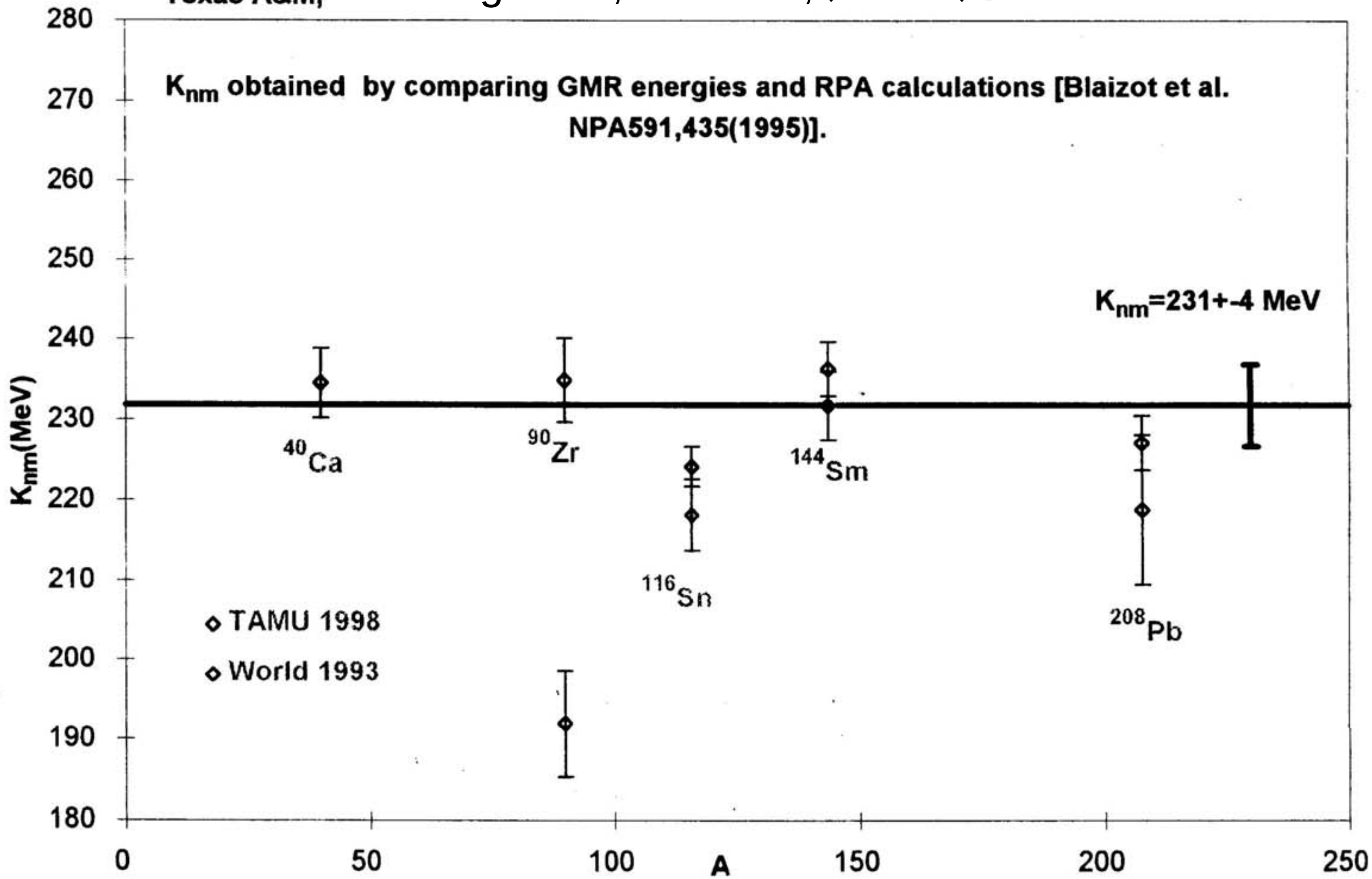
How much ?

Self consistent HF+RPA calculations

Self consistent RMF+RPA (TDHF) calculations

(α,α) experiment

Texas A&M, Youngblood, Lui et al.,(2002)



Nuclear Matter EOS

Isoscalar Monopole Giant Resonances

Isoscalar Compressional Dipole Resonances

Incompressibility K

$K \approx (220 \pm 10)$ MeV for Skyrme

$\approx (230 \pm 10)$ MeV for Gogny

$\approx (260 \pm 10)$ MeV for RMF

What can we learn about neutron EOS from nuclear physics?

Neutron surface thickness ⟷ Pressure of neutron EOS

Size ~10fm

Neutron star ~10km

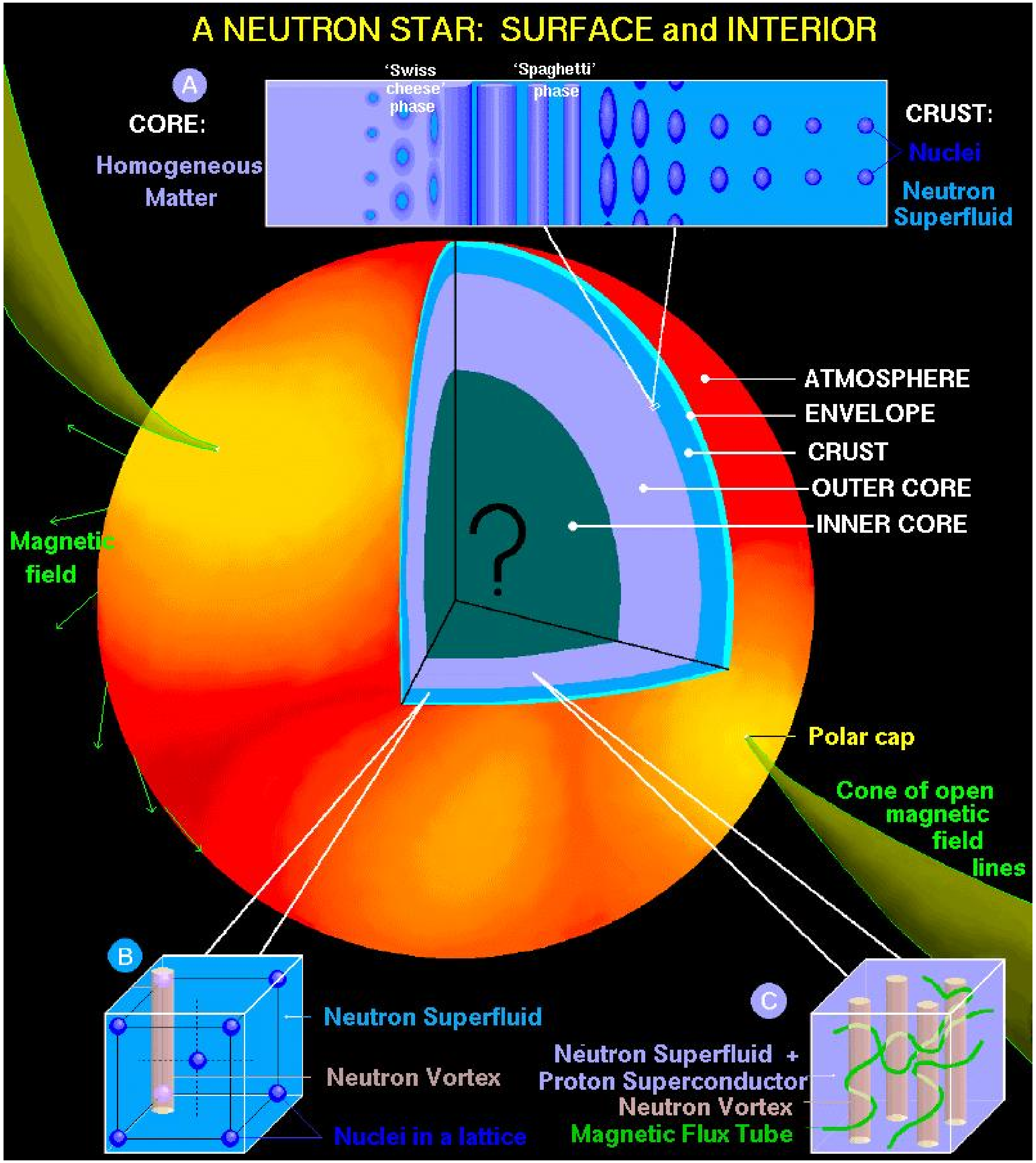
size difference ~ 10^{18}

Neutron star vs. Aizu

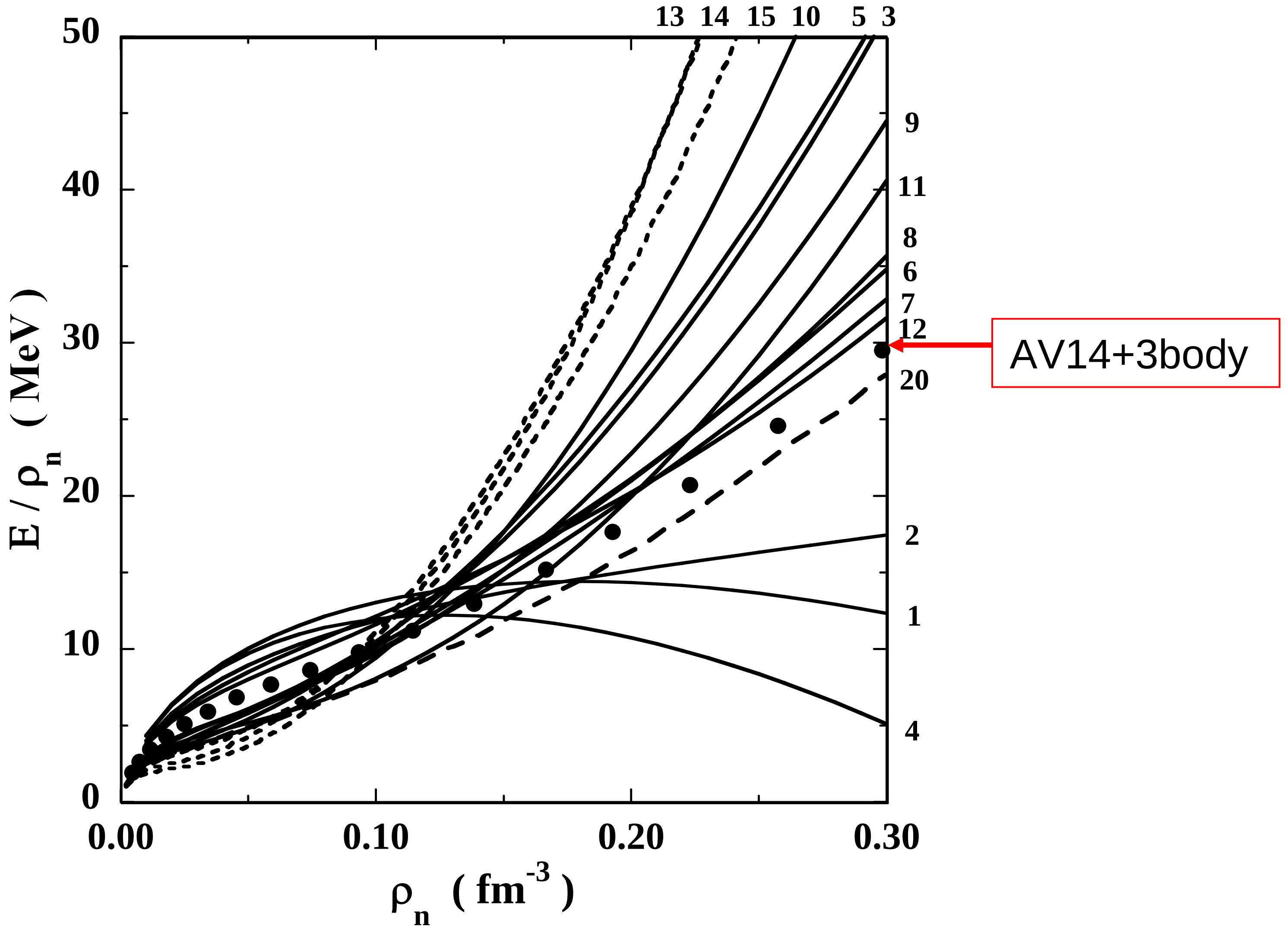
Mass=1.4 M_{sun}, Radius=10 km

Spin rate up to 38,000 rpm

Density~10^{14} g/cc, Magnetic field~10^{12} Gauss



J.M. Lattimer and M. Prakash, Sience 304 (2004)



interactions: 1 for SI, 2 for SIII, 3 for SIV, 4 for SVI, 5 for Skya, 6 for SkM, 7 for SkM*, 8 for SLy4, 9 for MSkA, 10 for SkI3, 11 for SkI4, 12 for SkX, 13 for NLSH, 14 for NL3, 15 for NLC, 16 for SII, 17 for SV, 18 for Skyb, 19 for SGI, 20 for SGII, 21 for SLy10, 22 for NL1, and 23 for NL2.

Parameter sets of SHF and relativistic mean field (RMF) model

Notation for the Skyrme interactions

1	SI	2	SIII	3	SIV
4	SVI	5	Skya	6	SkM
7	SkM*	8	SLy4	9	MSkA
10	SkI3	11	SkI4	12	SkX
13	SGII				

Notation for the RMF parameter sets

14	NL3	15	NLC
16	NLSH	17	TM1
18	TM2	19	DD-ME1
20	DD-ME2		

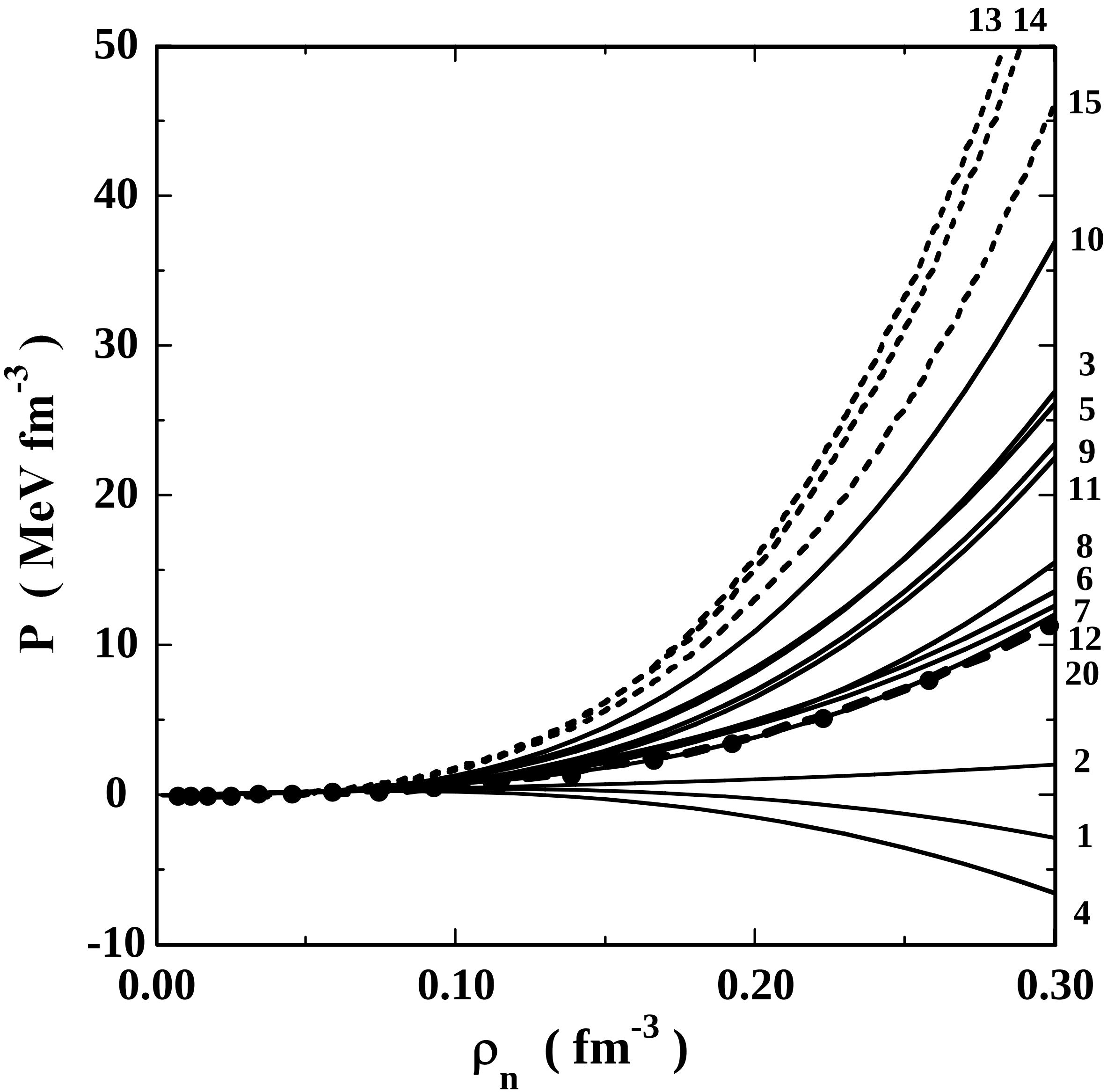

P (MeV fm-3)
ρn (fm-3)
50
40
30
20
10
0
-10
0.00
0.10
0.20
0.30
13 14
15
10
3
5
9
11
8
6
7
12
20
2
1
4

Fig. 4

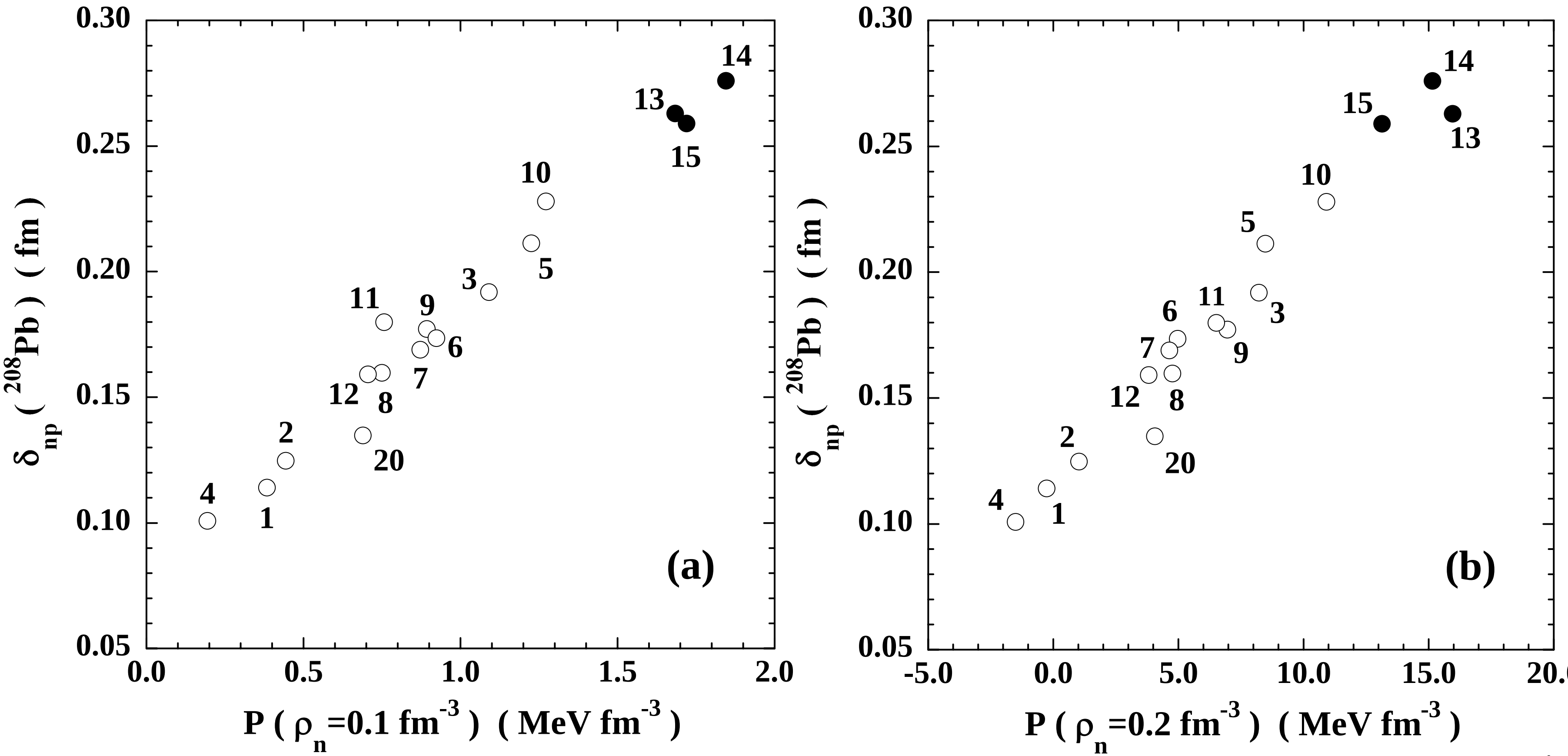

(a)
(b)
δnp (208Pb) (fm)
P (ρn=0.1 fm-3) (MeV fm-3)
P (ρn=0.2 fm-3) (MeV fm-3)
0.05
0.10
0.15
0.20
0.25
0.30
0.0
0.5
1.0
1.5
2.0
-5.0
5.0
10.0
15.0
20.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
20

Fig. 5

Fig. 5

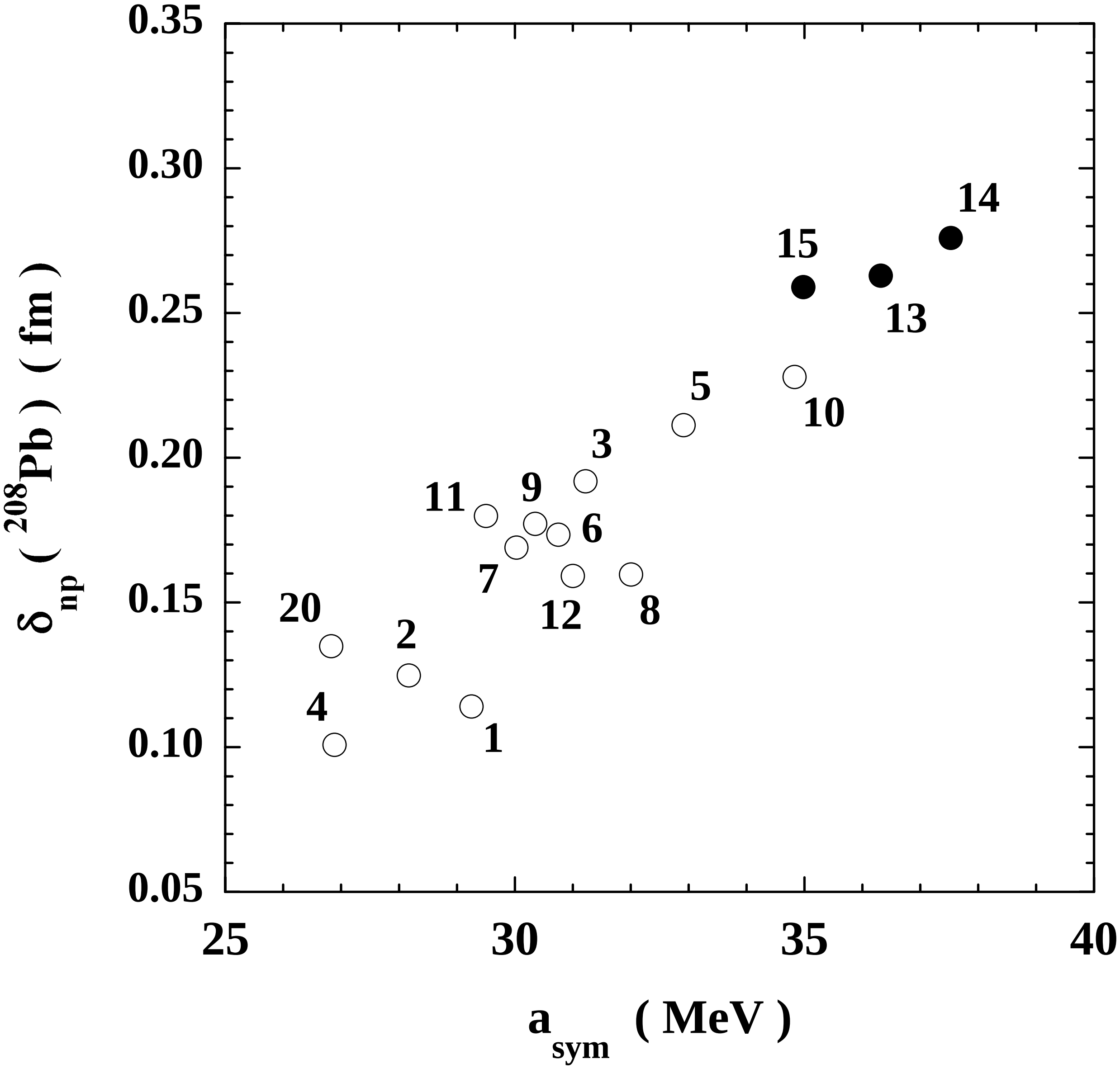

0.35
0.30
0.25
0.20
0.15
0.10
0.05
25
30
35
40
δnp (208Pb) (fm)
asym (MeV)
14
15
13
5
10
3
11
9
6
7
12
8
20
2
4
1

Fig. 8

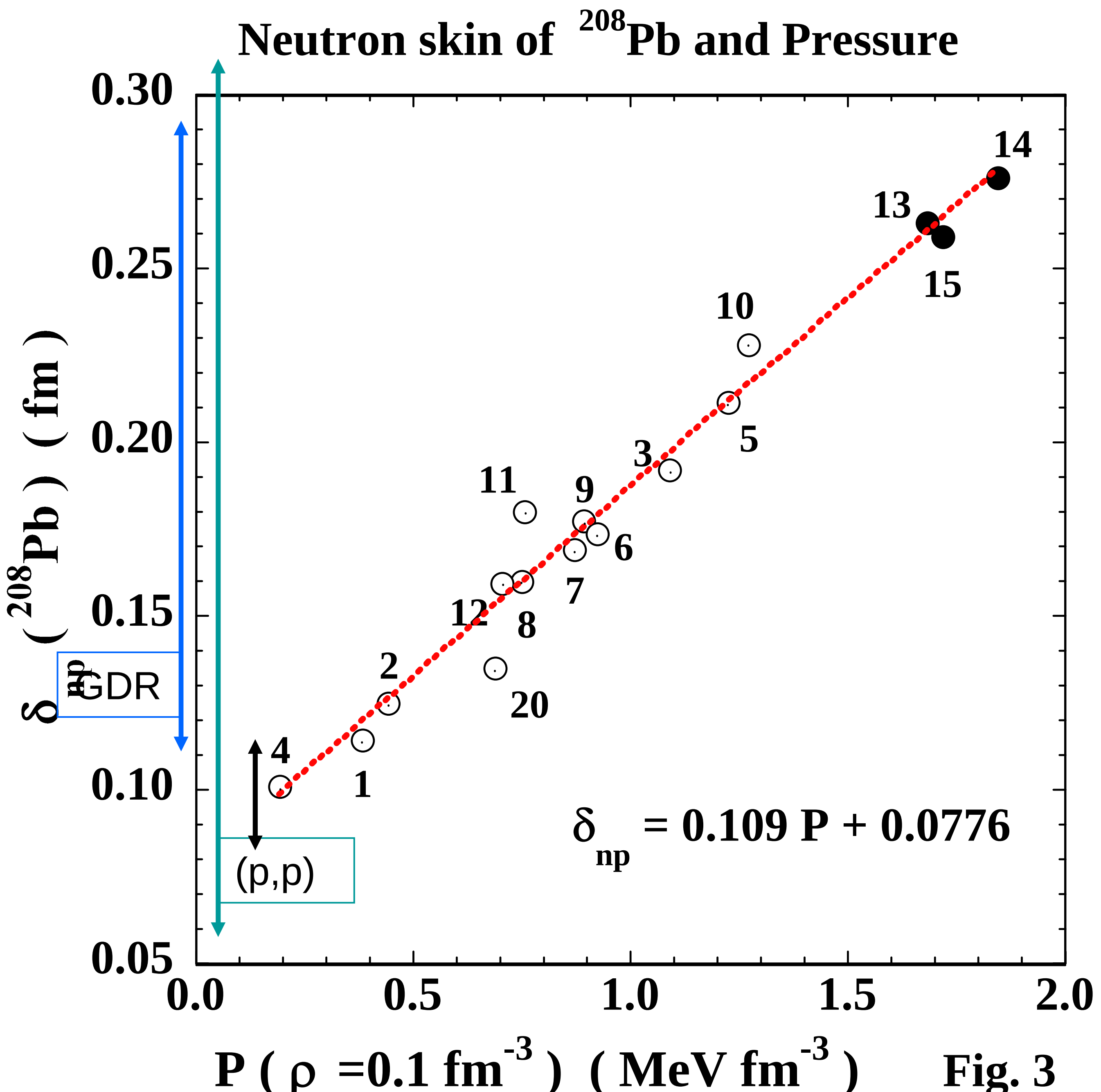

Neutron skin of ^{208}Pb and Pressure
δ_{np} (^{208}Pb) (fm)
P (ρ =0.1 fm^{-3}) (MeV fm^{-3})
0.05
0.10
0.15
0.20
0.25
0.30
0.0
0.5
1.0
1.5
2.0
GDR
(p,p)
δ_{np} = 0.109 P + 0.0776
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
20

Fig. 3

Model Independent observation of neutron skin

Electron scattering parity violation experiments

Polarized electron beam experiment at Jefferson Lab.

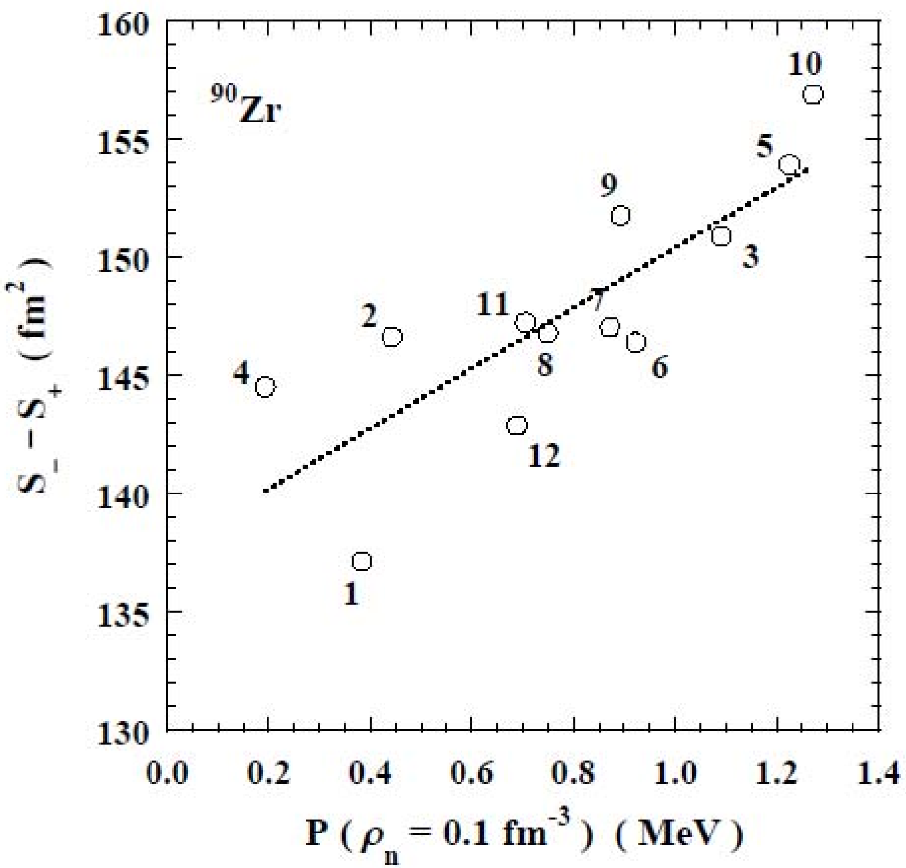
---- Approved but not yet scheduled! ----

Sum Rule of Spin Dipole Excitations

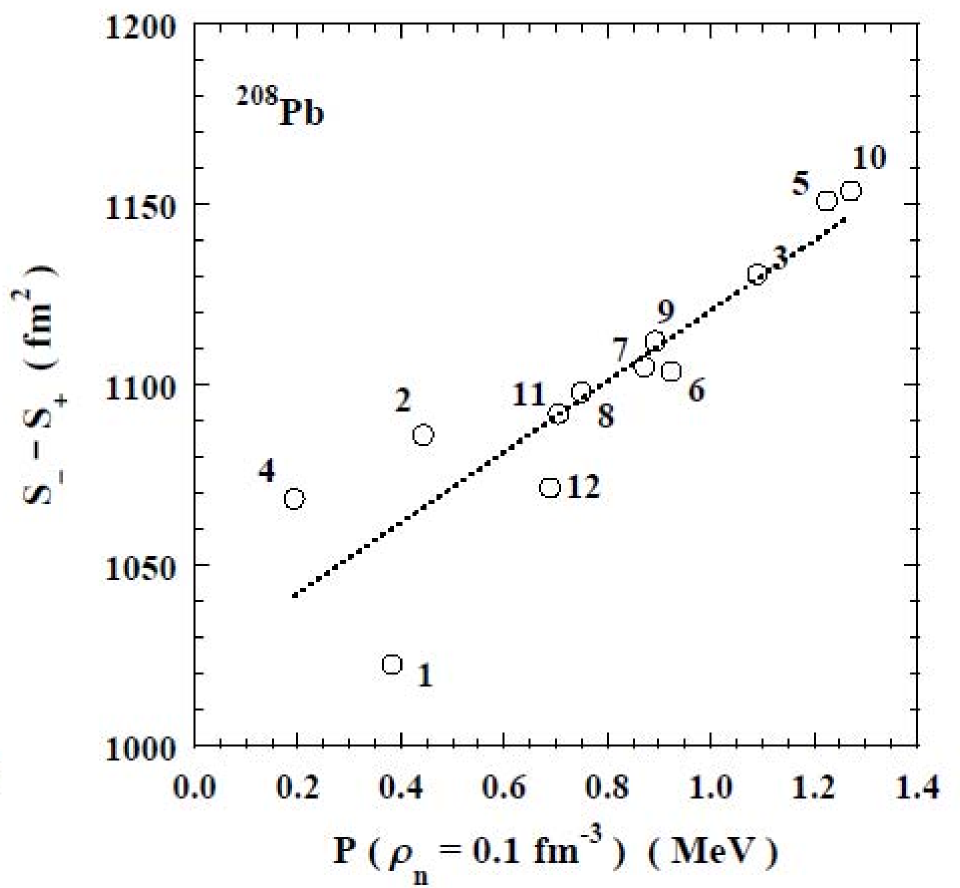
$$\hat{O}^{\lambda}_{\pm} = r[Y_{l=1} \times \sigma]^{\lambda} t_{\pm}$$

$$S_{-} - S_{+} = \sum_{f} \left| \left\langle f \mid \hat{O}^{\lambda}_{-} \mid i \right\rangle \right|^2 - \sum_{f} \left| \left\langle f \mid \hat{O}^{\lambda}_{+} \mid i \right\rangle \right|^2$$

$$= \frac{2\lambda + 1}{4\pi} \left(N \left\langle r^2 \right\rangle_n - Z \left\langle r^2 \right\rangle_p \right)$$



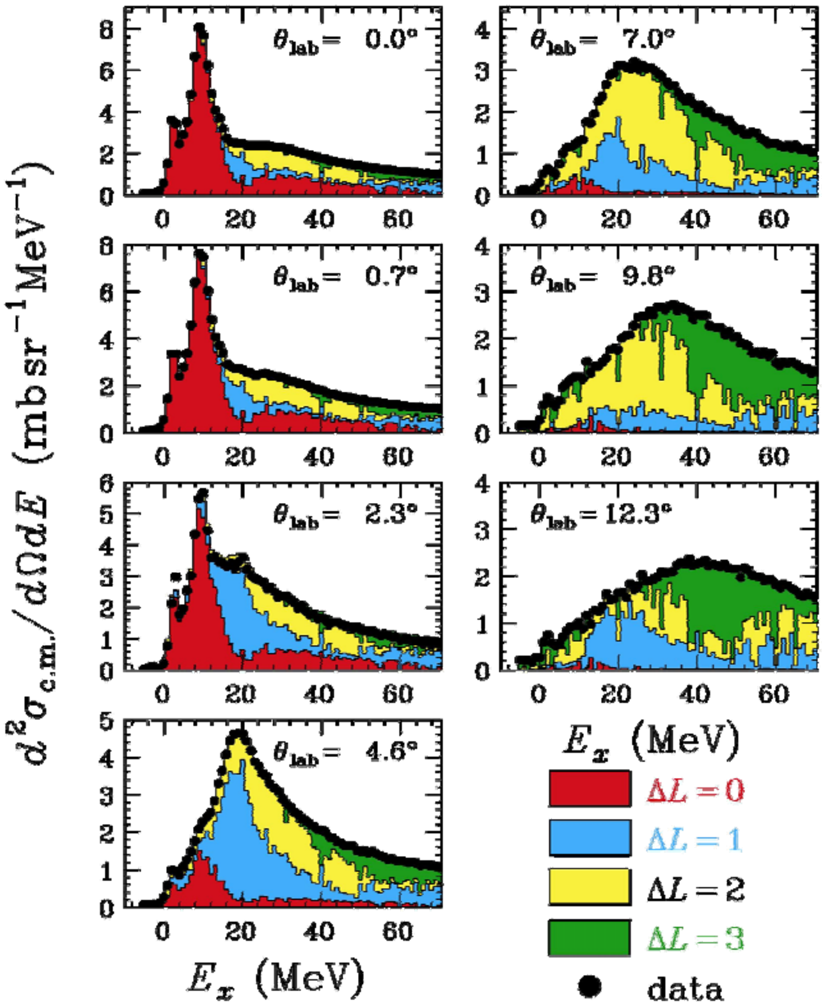
160
155
150
145
140
135
130
^{90}Zr
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$S_- - S_+$ (fm^2)
P (ρ_n = 0.1 fm^{-3}) (MeV)
1
2
3
4
5
6
7
8
9
10
11
12



1200
1150
1100
1050
1000
^{208}Pb
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$S_- - S_+$ (fm^2)
P (ρ_n = 0.1 fm^{-3}) (MeV)
1
2
3
4
5
6
7
8
9
10
11
12

Results of MDA

- MD analysis of $^{90}Zr(p,n)$ at 295 MeV
  - Almost L=0 for GTGR region (no background)
  - Fairly large L=0 (GT) strength up to 50 MeV excitation
- GT quenching problem
  - Configuration mixing (2p2h) plays major role
  - Δh^{-1} coupling plays minor role

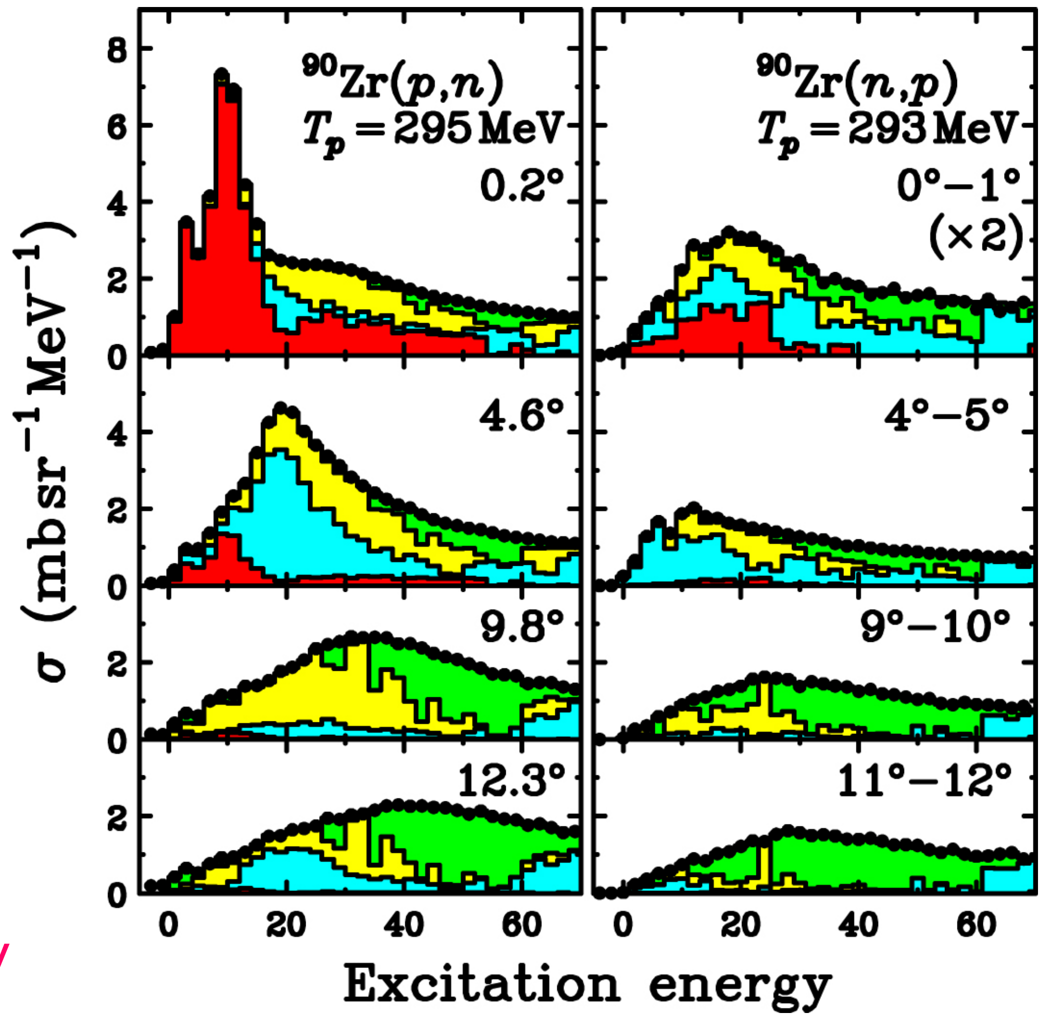


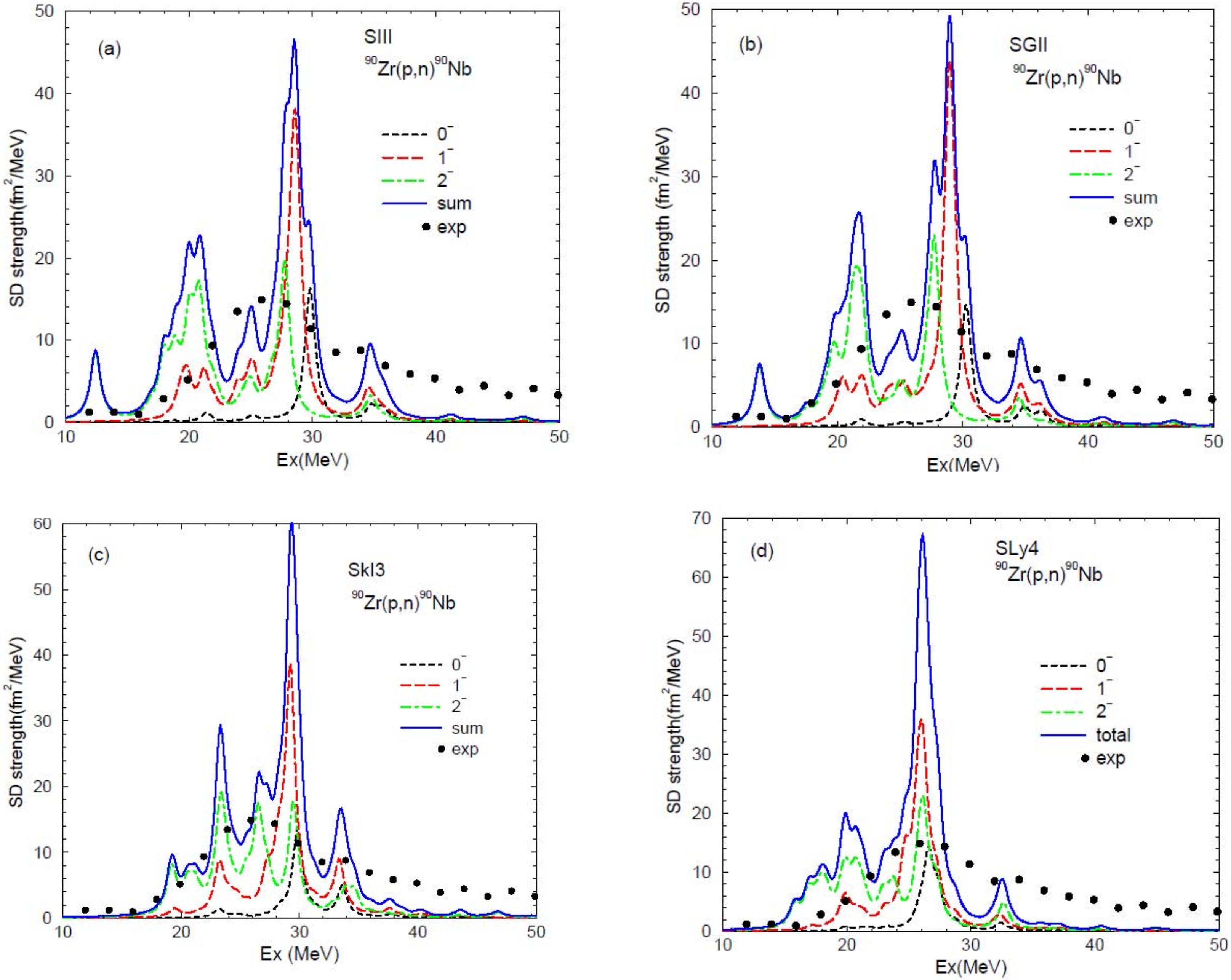
T.Wakasa et al.,Phys.Rev.C55, 2909(1997)

Results of MDA for ^{90}Zr(p,n) & (n,p) at 300 MeV

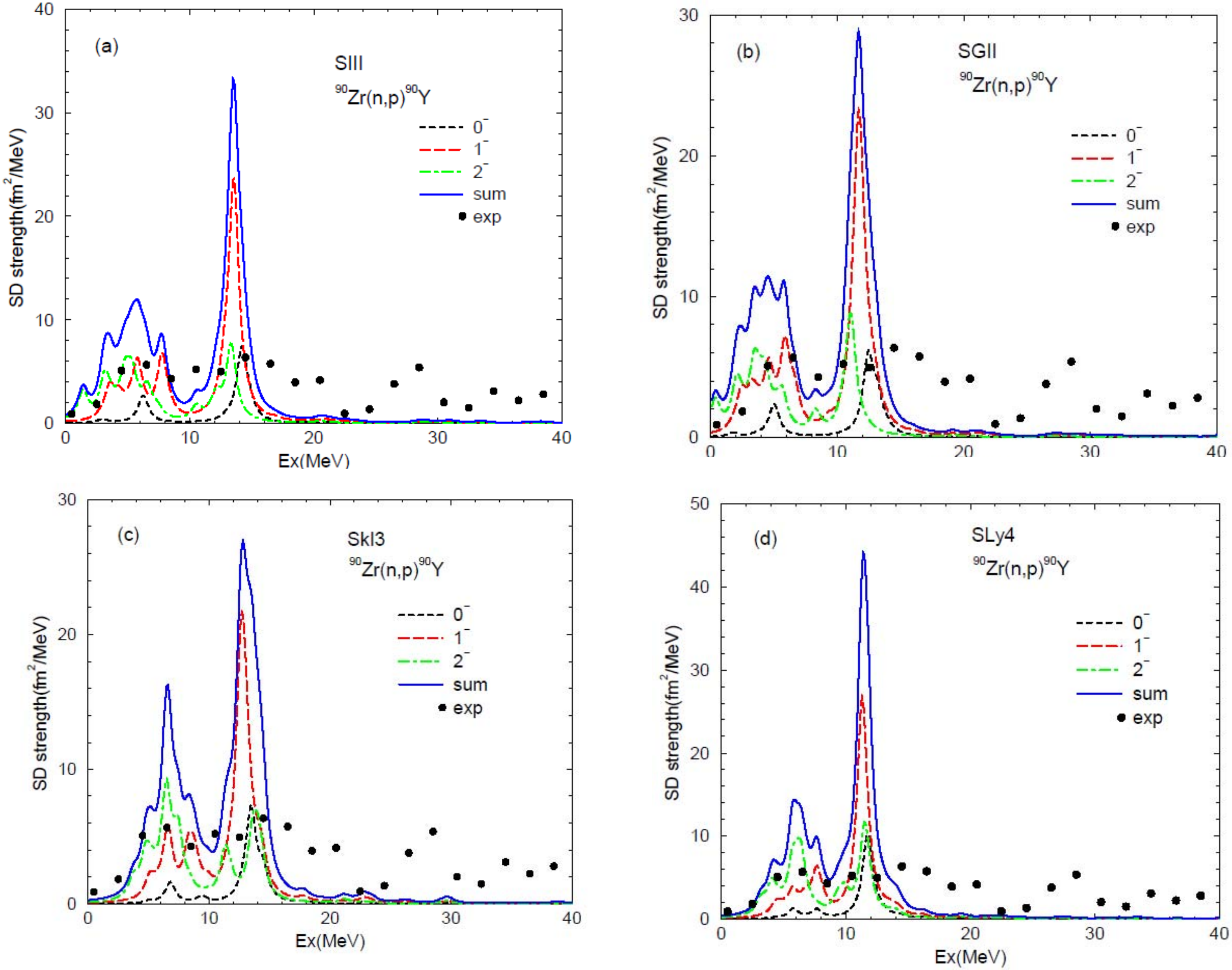
(K.Yako et al.,PLB 615, 193 (2005))

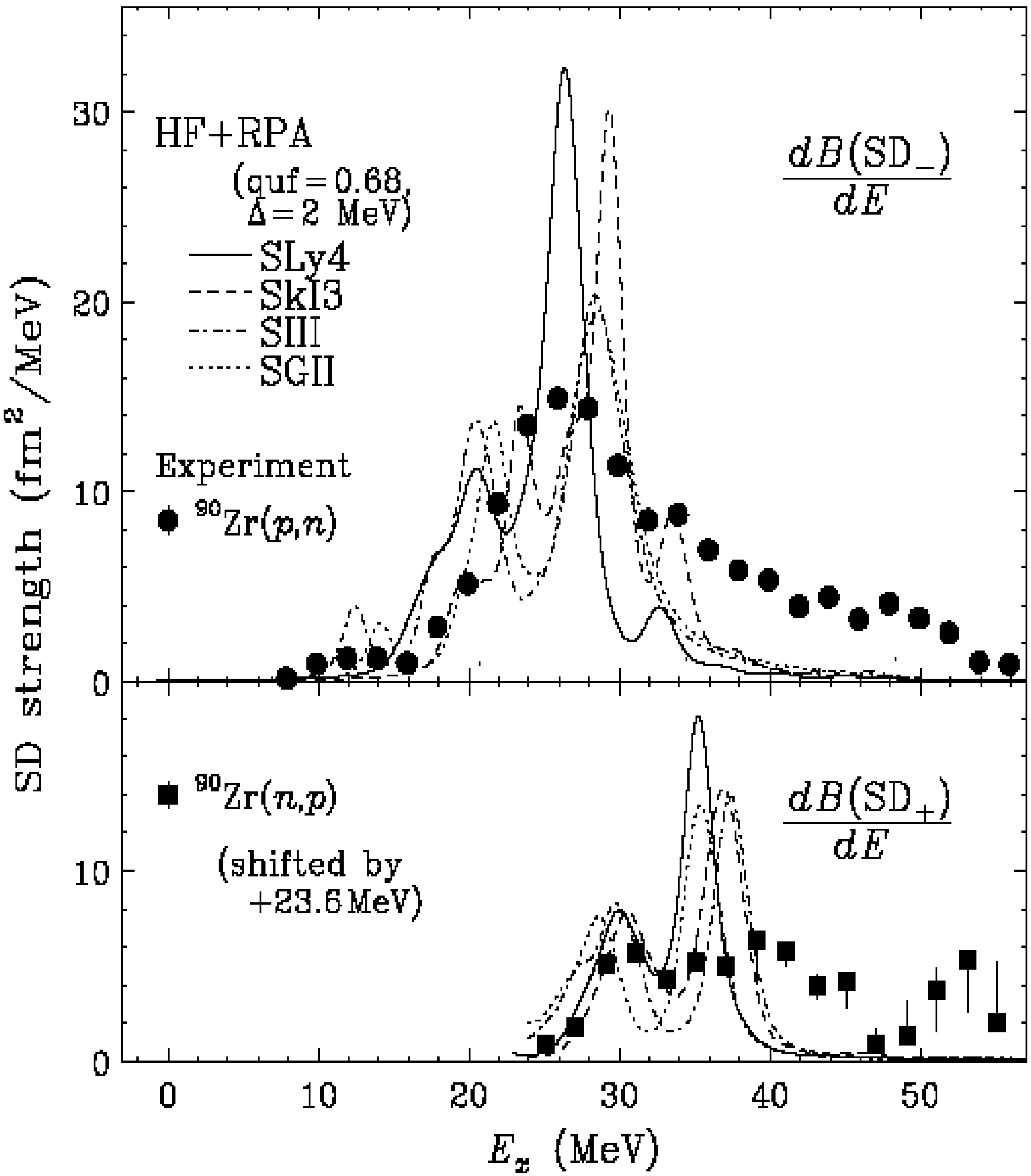
- Multipole Decomposition (MD) Analyses
  - (p,n)/(n,p) data have been analyzed with the same MD technique
  - (p,n) data have been re-analyzed up to 70 MeV
- Results
  - (p,n)
    - Almost L=0 for GTGR region (No Background)
    - Fairly large L=0 (GT) strength up to 50 MeV excitation
  - (n,p)
    - L=0 strength up to 30MeV

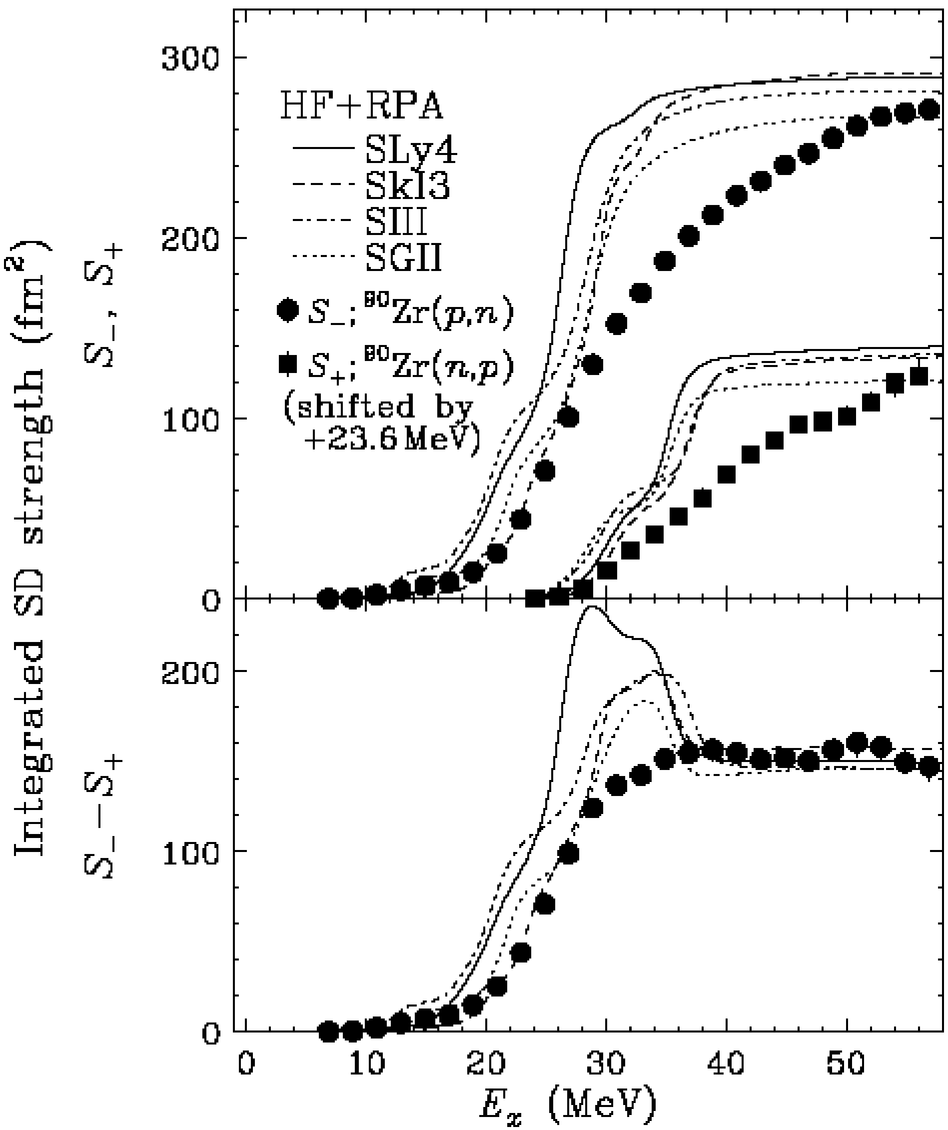




(a)
SIII
^{90}Zr(p,n)^{90}Nb
0^{-}
1^{-}
2^{-}
sum
exp
SD strength(fm^2/MeV)
Ex(MeV)
(b)
SGII
^{90}Zr(p,n)^{90}Nb
0^{-}
1^{-}
2^{-}
sum
exp
SD strength (fm^2/MeV)
Ex(MeV)
(c)
SkI3
^{90}Zr(p,n)^{90}Nb
0^{-}
1^{-}
2^{-}
sum
exp
SD strength(fm^2/MeV)
Ex (MeV)
(d)
SLy4
^{90}Zr(p,n)^{90}Nb
0^{-}
1^{-}
2^{-}
total
exp
SD strength(fm^2/MeV)
Ex(MeV)


(a)
SIII
90Zr(n,p)90Y
0-
1-
2-
sum
exp
SD strength(fm2/MeV)
Ex(MeV)
(b)
SGII
90Zr(n,p)90Y
0-
1-
2-
sum
exp
SD strength(fm2/MeV)
Ex(MeV)
(c)
SkI3
90Zr(n,p)90Y
0-
1-
2-
sum
exp
SD strength(fm2/MeV)
Ex(MeV)
(d)
SLy4
90Zr(n,p)90Y
0-
1-
2-
sum
exp
SD strength(fm2/MeV)
Ex(MeV)


HF+RPA
(quf = 0.68,
Δ = 2 MeV)
SLy4
SkI3
SIII
SGII
Experiment
90Zr(p,n)
90Zr(n,p)
(shifted by
+23.6 MeV)
dB(SD−)/dE
dB(SD+)/dE
SD strength (fm2/MeV)
Ex (MeV)
0
10
20
30
40
50


HF+RPA
SLy4
SkI3
SIII
SGII
S−; 90Zr(p,n)
S+; 90Zr(n,p)
(shifted by +23.6 MeV)
Integrated SD strength (fm2)
S−, S+
S− − S+
300
200
100
0
200
100
0
0
10
20
30
40
50
Ex (MeV)

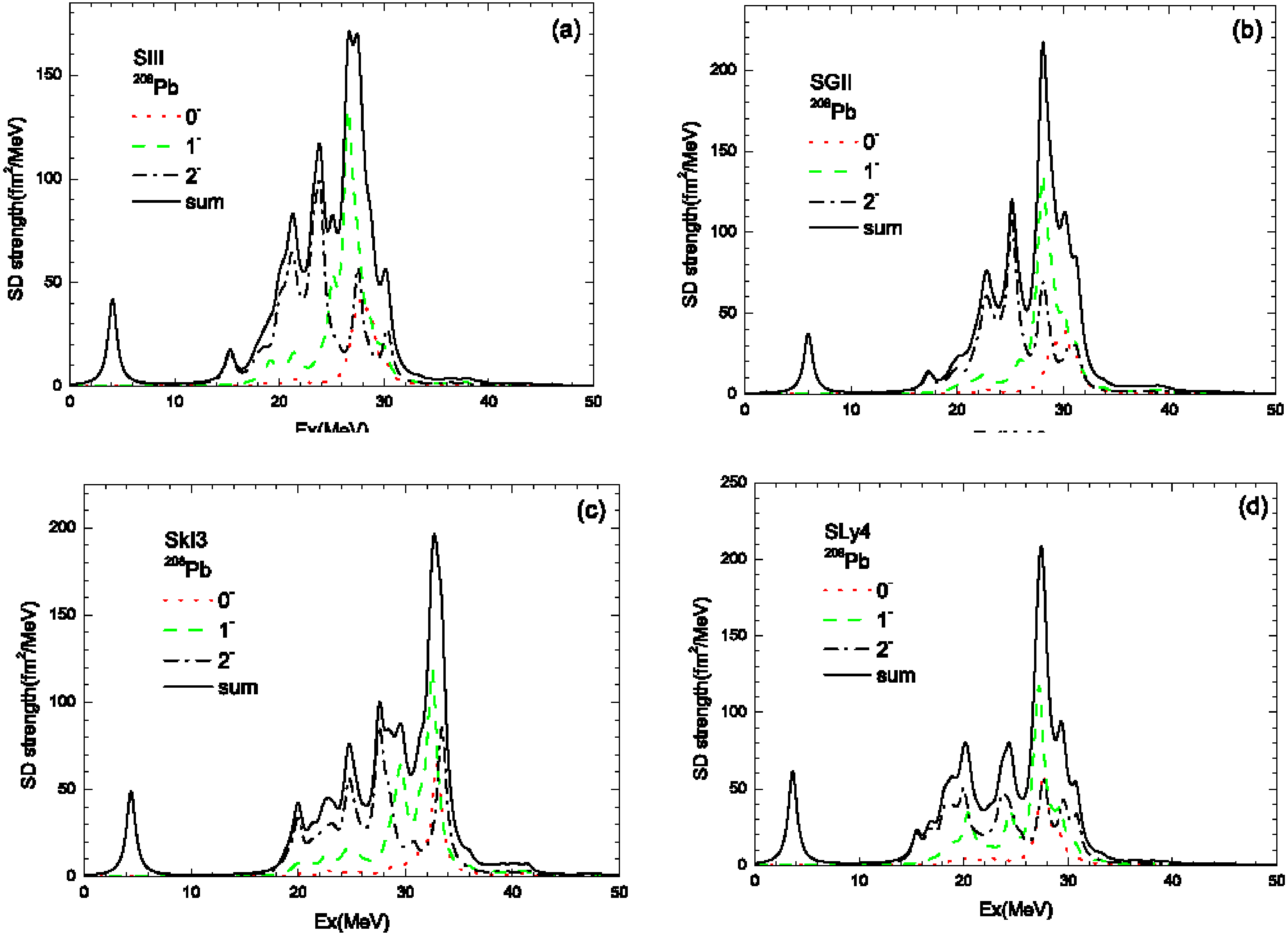
Hartree-Fock results

	SIII	SGII	SkI3	exp
r(p)	4.257	4.198	4.174	
r(ch)	4.321	4.263	4.24	4.258+/−0.008
r(n)	4.312	4.253	4.28	
r(n)−r(p)	0.055	0.055	0.106	0.09+/−0.07
S(−)−S(+)	146.7	144	156.9	147+/−13

Spin-Dipole sum rule value

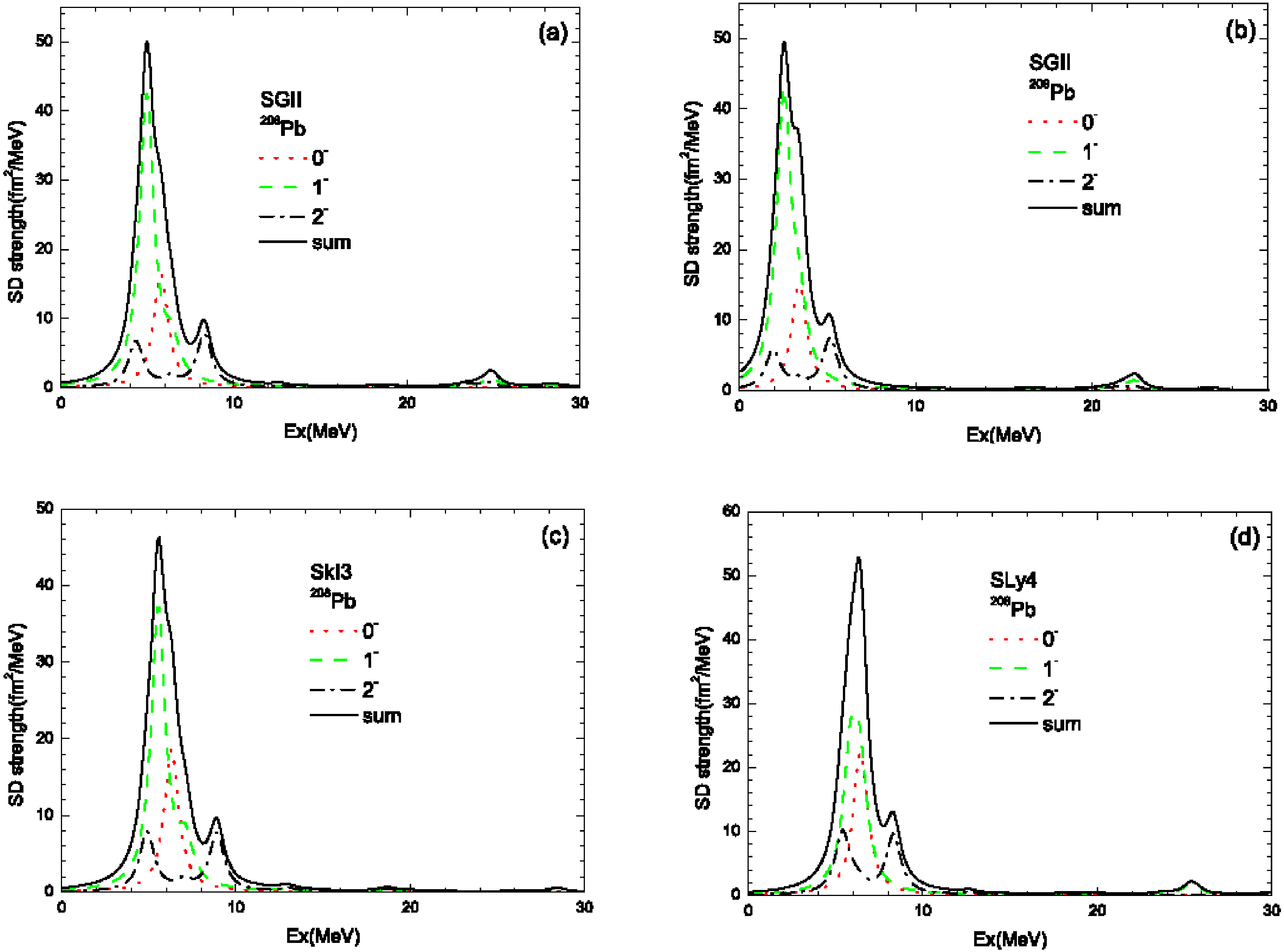
	SIII			SGII			SkI3			exp		
	S(-)	S(+)	S(-)-S(+)	S(−)	S(+)	S(−)−S(+)	S(−)	S(+)	S(−)−S(+)	S(−)	S(+)	S(−)−S(+)
0−	38. 76	22. 78	15. 98	38	22	15.86	36.6	19.1	17.48			
1−	104. 3	56. 51	47. 79	104	56	47.77	121	68.2	52.64			
2−	141. 4	55. 07	86. 33	129	49	79.23	139	51.1	87.93			
sum	284. 5	134. 4	150. 1	271	128	142.9	296	138	158	271	124	147(13)

t_- channel

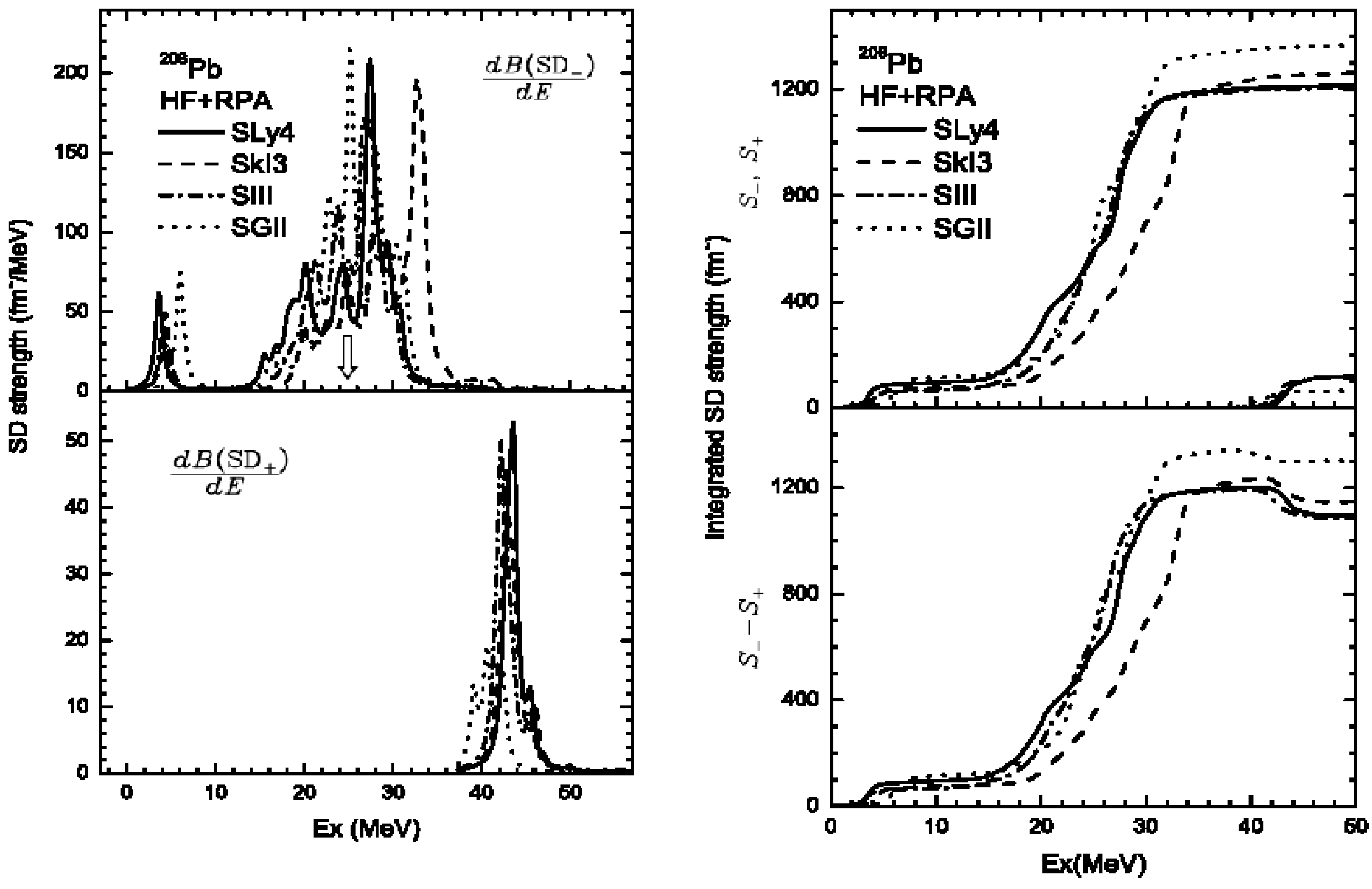


(a)
SIII
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
(b)
SGII
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
(c)
SkI3
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)
(d)
SLy4
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)

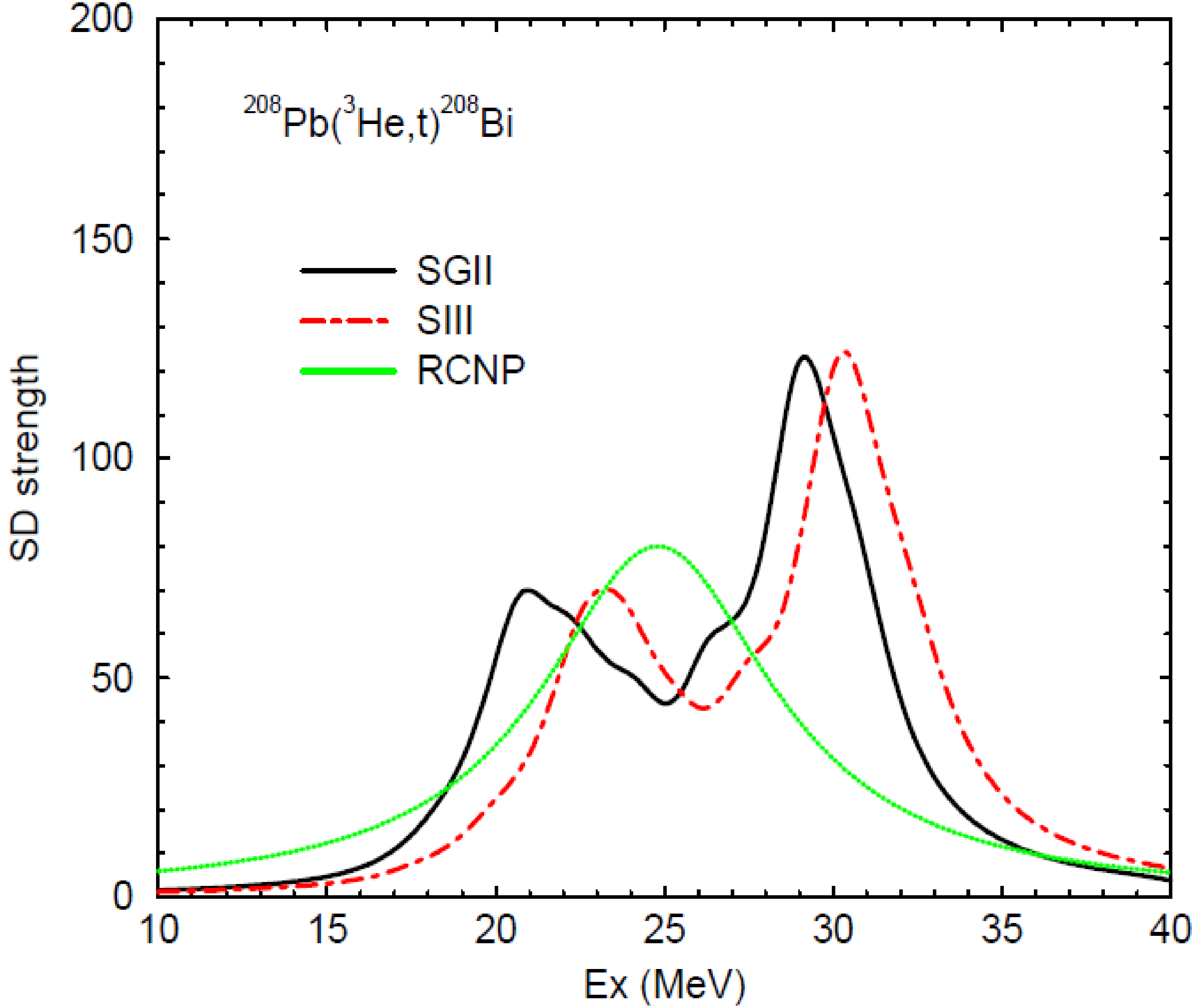
t_+ channel



(a)
SGII
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)
(b)
SGII
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)
(c)
SkI3
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)
(d)
SLy4
208Pb
0-
1-
2-
sum
SD strength(fm2/MeV)
Ex(MeV)



208Pb
HF+RPA
SLy4
SkI3
SIII
SGII
$\frac{dB(\mathrm{SD}_-)}{dE}$
$\frac{dB(\mathrm{SD}_+)}{dE}$
SD strength (fm²/MeV)
Ex (MeV)
Integrated SD strength (fm²)
S_-, S_+
$S_- - S_+$
Ex(MeV)



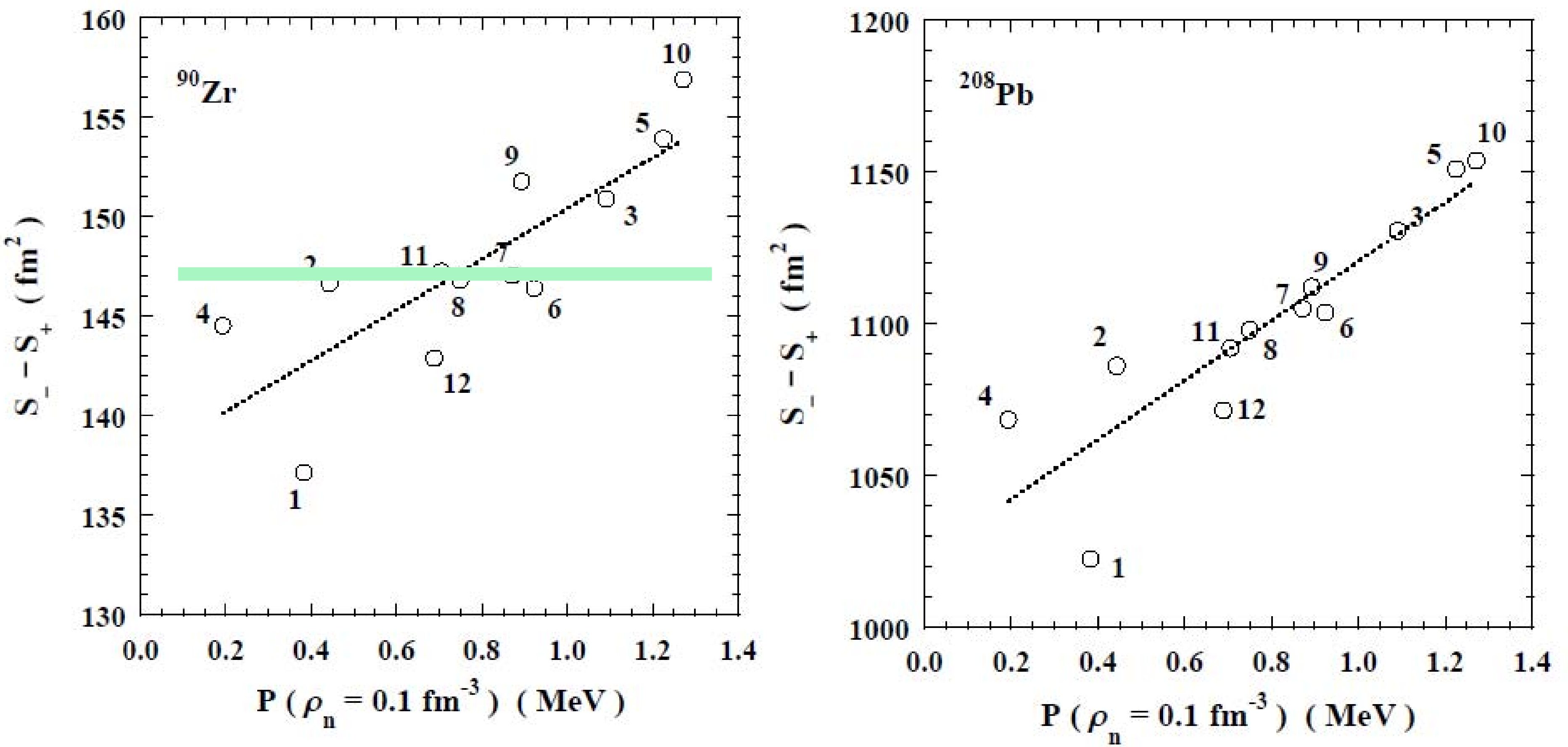
$^{208}Pb(^{3}He,t)^{208}Bi$
SGII
SIII
RCNP
SD strength
Ex (MeV)
0
50
100
150
200
10
15
20
25
30
35
40

Summary I

1. Nuclear incompressibility K is determined empirically to be K~230MeV
2. A clear correlation between neutron skin thickness and neutron matter EOS
3. Neutron skin thickness is large in neutron-rich unstable nuclei, but the correlation is weak.
4. There is also a clear correlation between the neutron skin thickness and the symmetry energy coefficient.
5. The pressure of RMF is higher than that of SHF in general.
6. The SD strength gives a critical information both on the neutron EOS and mean field models.

S. Yoshida and HS, Phys. Rev. C69, 024318 (2004), C73,024318(2006).

K. Yako, H. Sakai and HS, Phys. Rev. C74, 051303(2006)



90Zr
208Pb
S− − S+ (fm2)
P (ρn = 0.1 fm-3) (MeV)
1
2
3
4
5
6
7
8
9
10
11
12

Summary II

1. Correlation between spin-dipole excitations and pressure of neutron EOS is pointed out.
2. Spin-dipole strength are studied by RPA calculations and compared with (p,n) and (n,p) inelastic scattering data on ^{90}Zr.
3. Calculated results show a strong 1^- peak at high excitation energy, but it is missing in the experimental data of (p,n) reaction. → (2p-2h correlations ?).
4. Experimental study of spin-dipole strength of Zr and Pb probe soft neutron matter EOS.
5. Need more works!