Neutron-proton asymmetry in nuclear matter and finite nuclei

Dao Tien Khoa

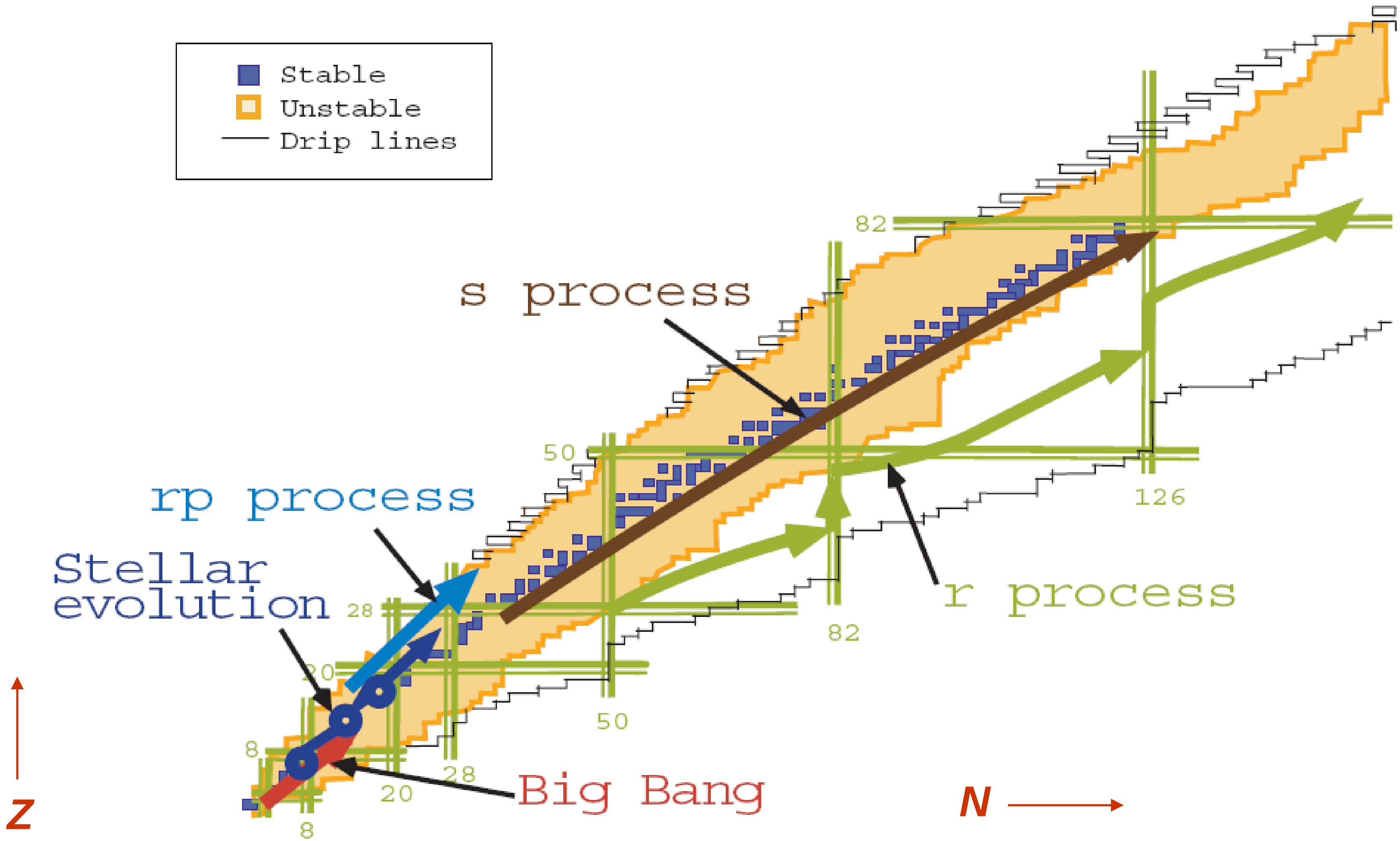
Institute for Nuclear Science & Technology
Vietnam Atomic Energy Commission (VAEC)

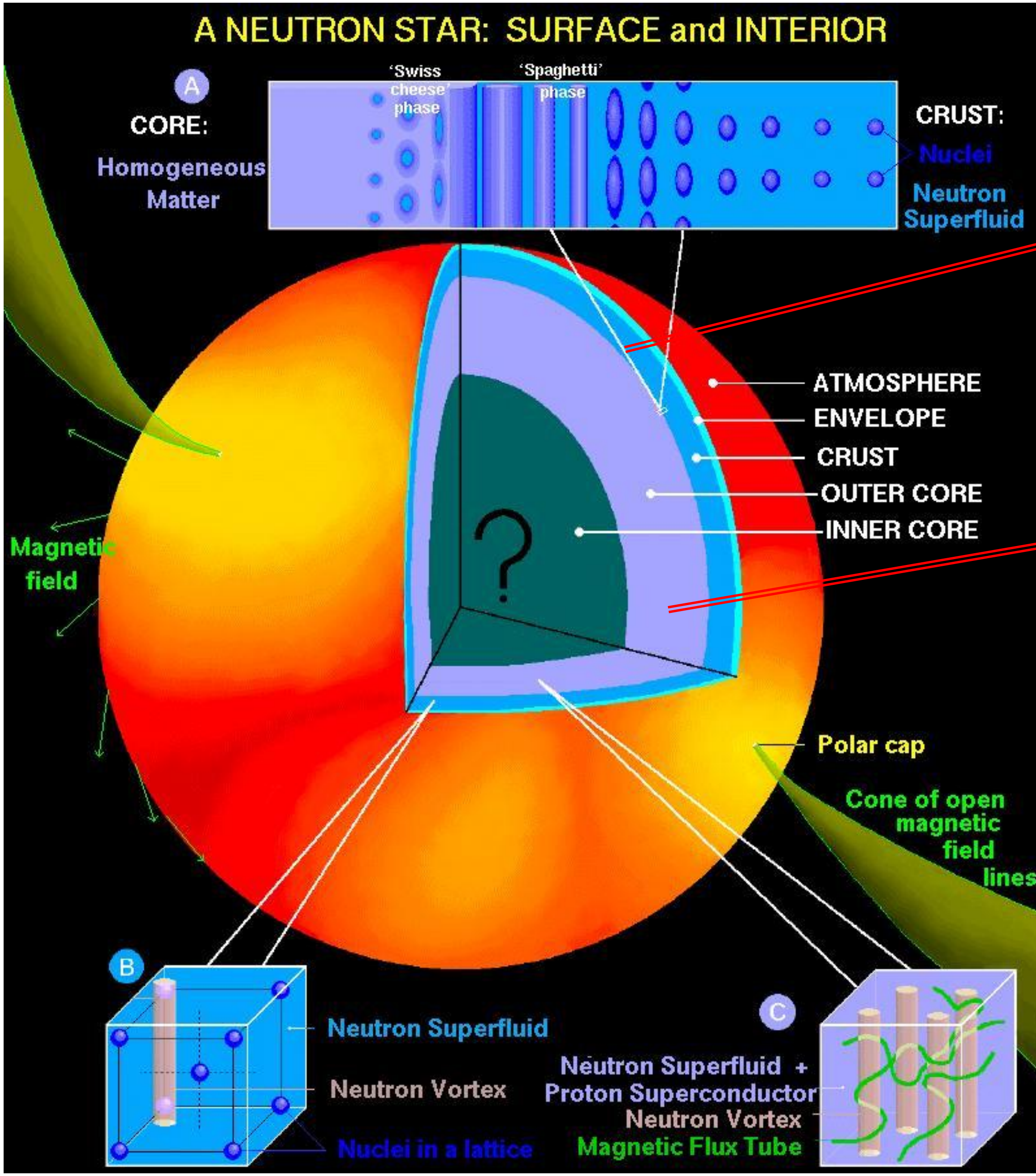
- ***Equation of state for asymmetric nuclear matter***
- ***Charge-exchange (p,n)IAS reaction*** ⟺ ***Nuclear symmetry energy***
- ***(p,p') scattering on Oxygens*** ⟺ ***Impurity of isospin symmetry ?***

Author's participation at NuSYM10 is supported by National Foundation for Scientific and Technological Development (NAFOSTED)

Neutron-proton asymmetry in finite nuclei $\delta = (N\text{-}Z)/A$

δ is large in neutron-rich nuclei, with δ_{max}=0.5 for ^{8}He !





Proton fraction

$x = \rho_p / \rho = 0.5*(1-\delta)$

$\rho = (0.5 \sim 1)\rho_0$
$\delta = 0.94 \sim 0.90$
$x = 0.03 \sim 0.05$

$\rho_0 \sim 0.17$ nucleon/fm^{-3}

$\rho = (2 \sim 6)\rho_0$
$\delta = 0.86 \sim 0.80$
$x = 0.07 \sim 0.10$

Sly EOS by Douchin & Haensel
Astronomy & Astrophysics
380 (2001) 151

Experimentally

δ <=> Symmetry Energy
still unknown at large ρ !

Microscopic calculation of nuclear matter

BHF or DBHF

Talks by Schulze & Lombardo

NN scattering data → Free NN interaction

$$G[\omega;\rho] = V + \sum_{k_a,k_b>k_F} V \frac{|k_a k_b\rangle\langle k_a k_b|}{\omega - e(k_a) - e(k_b) + i\epsilon} G[\omega;\rho]$$

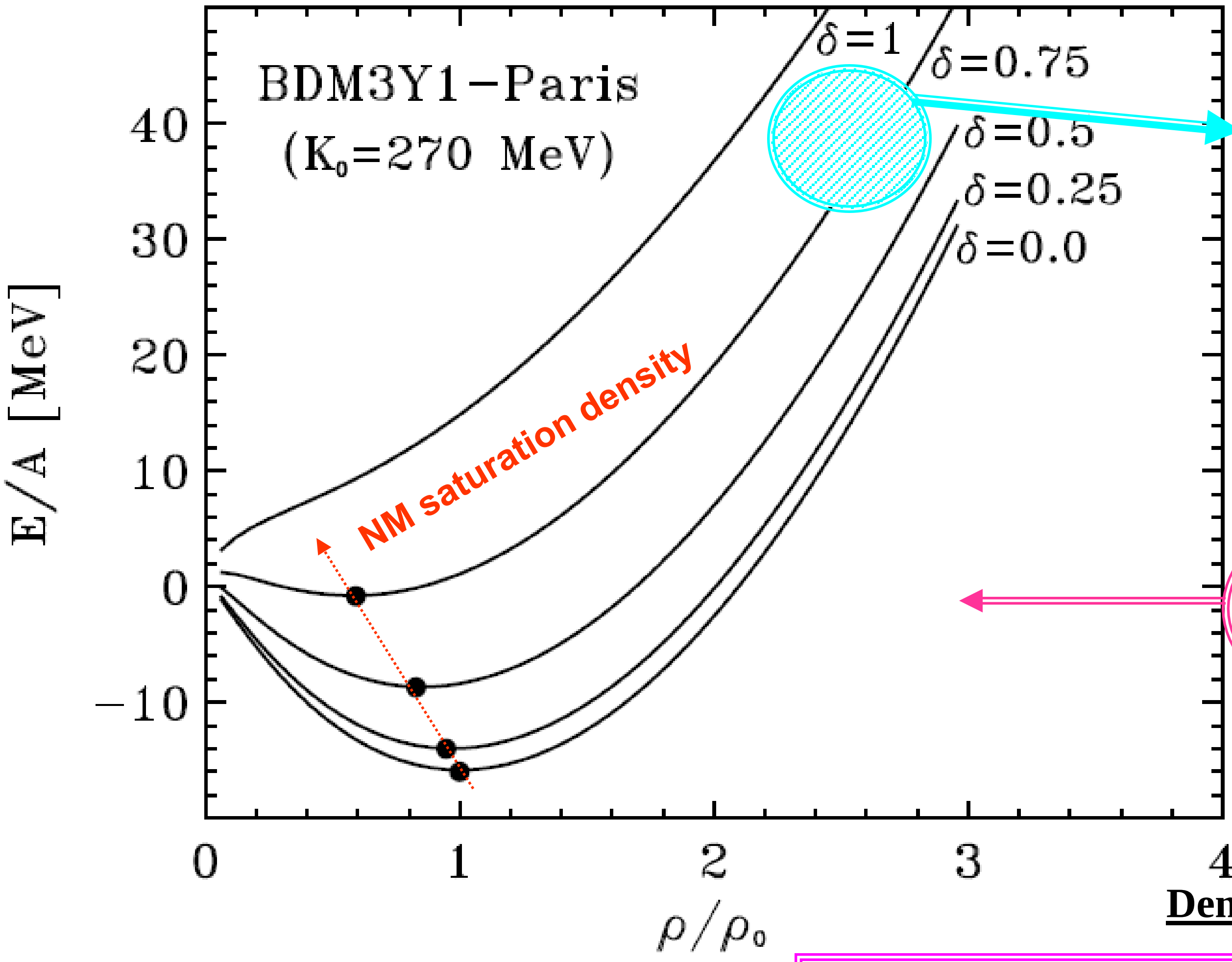
$$\frac{B}{A} = \frac{3}{5}\frac{k_F^2}{2m} + \frac{1}{2\rho}\mathrm{Re}\sum_{k,k'\leqslant k_F} \langle kk'|G[e(k)+e(k');\rho]|kk'\rangle_a$$

Antisymmetrization

$$\frac{B}{A} = \frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4) + \ldots$$

Nuclear matter symmetry energy (E_{sym})

EOS of asymmetric nuclear matter



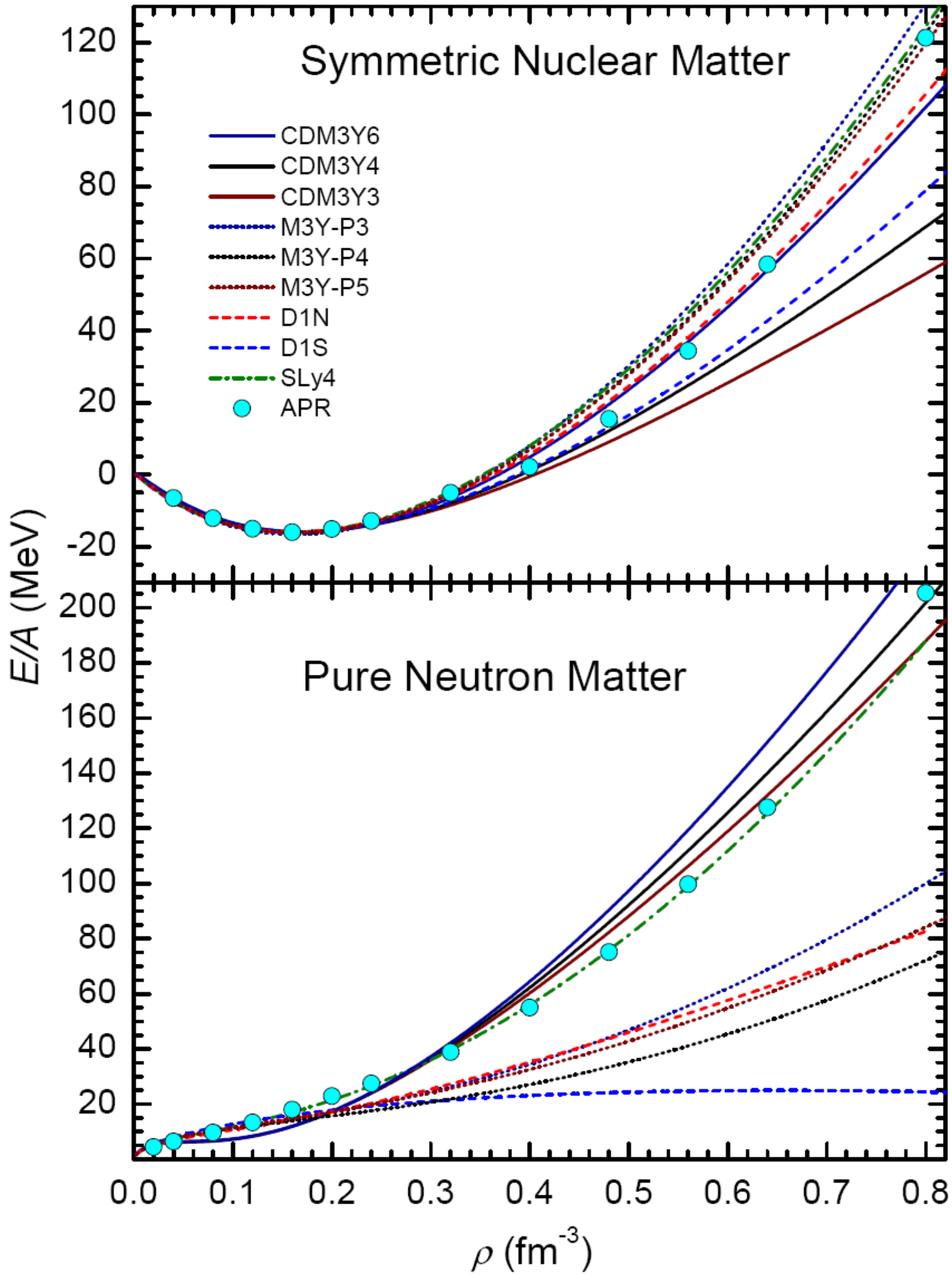
Determined by the isospin dependence of in-medium NN interaction !

Exploratory HF study:

D.T. Khoa, W. von Oertzen A.A. Ogloblin, *Nucl. Phys.* **A602** (1996) 98

Density dependent M3Y interaction

$$\frac{B}{A} = \frac{3}{5}\frac{k_F^2}{2m} + \frac{1}{2\rho}\mathrm{Re}\sum_{k,k' \leqslant k_F} \langle kk'|G[e(k)+e(k');\rho]|kk'\rangle_a$$



$$\frac{E}{A}(\rho, \delta = 0) + S(\rho)\delta^2 + O(\delta^4) + \ldots$$

HF results given by some mean-field interaction

CDM3Y*n*: D.T. Khoa, G.R. Satchler, and W. von Oertzen, *Phys. Rev.* C **56**, 954 (1997); D.T. Khoa, H.S. Than, and D.C. Cuong, *Phys. Rev.* C **76**, 014603 (2007).

M3Y-P*n*: H. Nakada, *Phys. Rev.* C **78**, 054301 (2008).

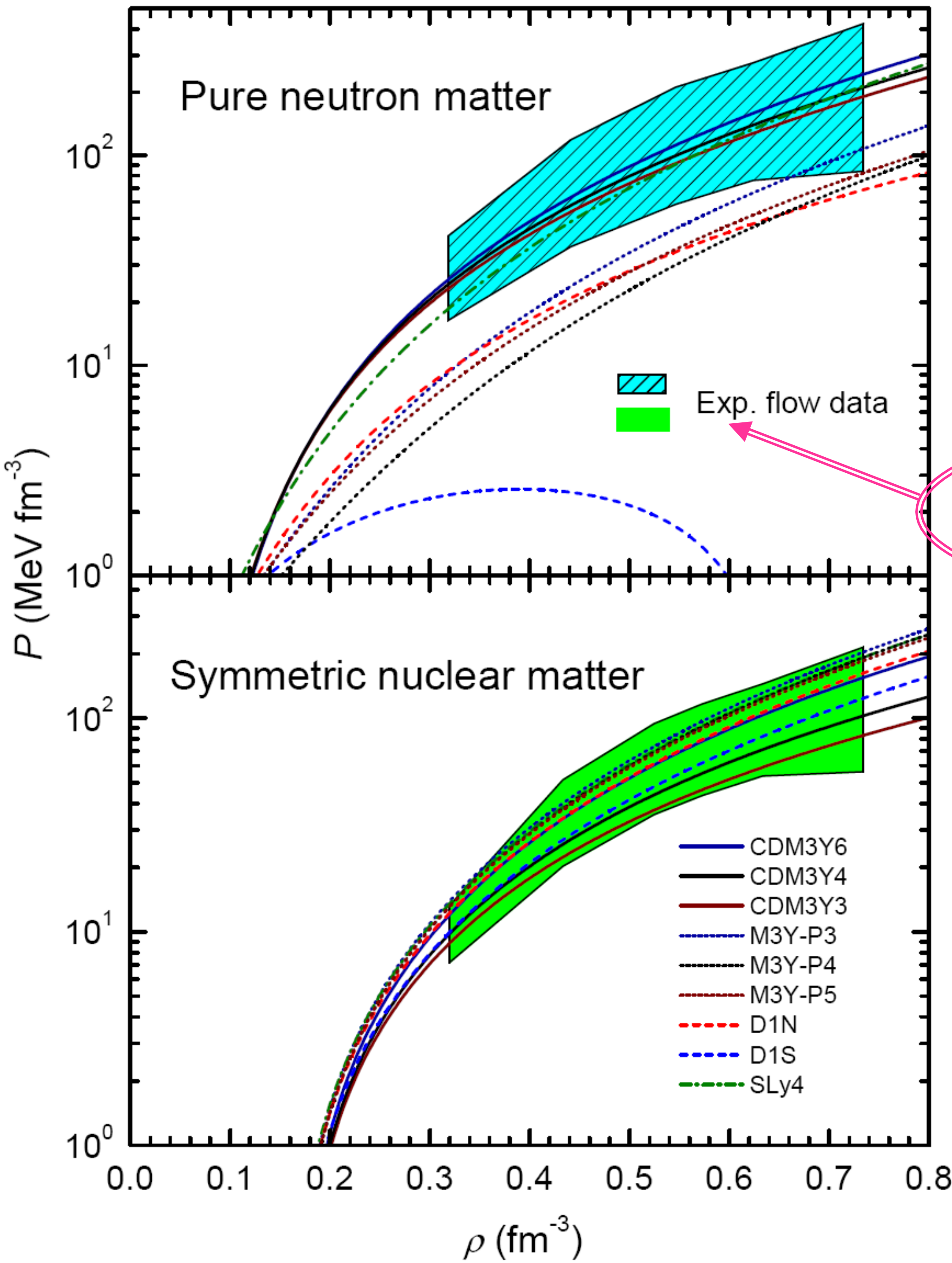
D1S: J.F. Berger, M. Girod, and D. Gogny, *Comp. Phys. Comm*. **63**, 365 (1991).

D1N: F. Chappert, M. Girod, and S. Hilaire, *Phys. Lett.* B **668**, 420 (2008).

SLy4: E. Chabanat *et al.*, *Nucl. Phys.* A **635**, 231 (1998)

Ab-initio variational calculation using Argon V18 NN + NNN inter.

APR: A. Akmal, V.R. Pandharipande, and D.G. Ravenhall, *Phys. Rev.* C **58**, 1804 (1998)



$$P(\rho, \delta) = \rho^2 \frac{\partial}{\partial \rho} \left[\frac{E}{A}(\rho, \delta) \right]$$

P. Danielewicz, R. Lacey and W.G. Lynch
Science **298**, 1592 (2002)

M3Y-Pn, D1S, D1N ***fail to reproduce empirical pressure of neutron matter !***

Two distinct scenarios for NM symmetry energy:
Asy-soft & Asy-stiff

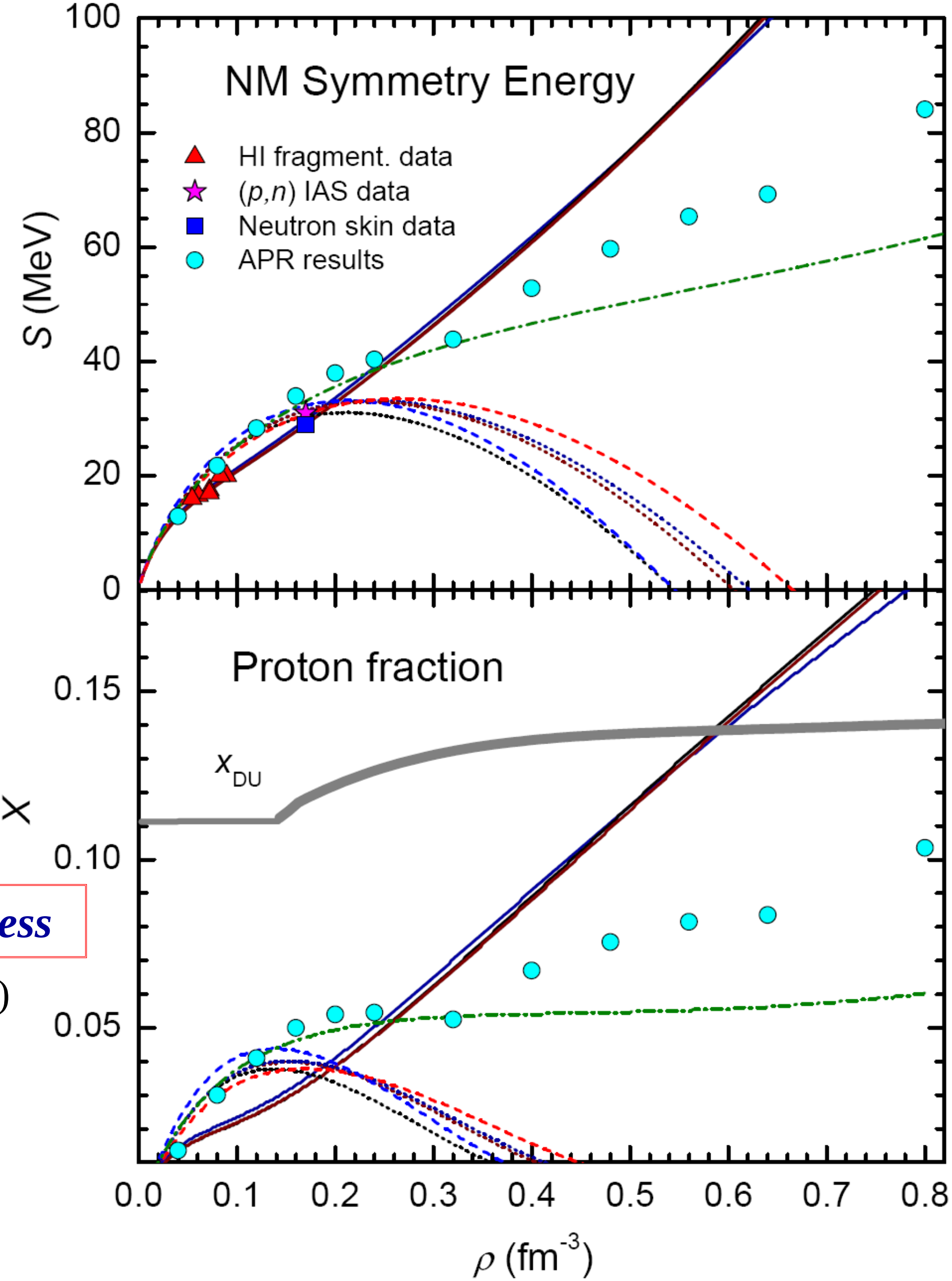
Neutron star cooling ?

H.S. Than, D.T. Khoa, N.V. Giai, *Phys. Rev.* C **80**, 064312 (2009).

x_{DU} => threshold for the direct Urca process

T. Klahn *et al*., *Phys. Rev.* C **74**, 035802 (2006)

Talk by N.V. Giai !



(p,n) charge exchange "scattering" to IAS states and isospin dependence of the nucleon optical potential

Explicit IS and IV parts of the proton–nucleus potential

$$U(E,\boldsymbol{R}) = U_0(E,\boldsymbol{R}) - \varepsilon U_1(E,\boldsymbol{R}),\ \varepsilon = \frac{N-Z}{A} = \frac{2T_A}{A}$$

$$U_0(E,\boldsymbol{R}) = \int \{[\rho_p(\boldsymbol{r}) + \rho_n(\boldsymbol{r})] v_{00}^{D}(\rho,E,s) +$$
$$[\rho_p(\boldsymbol{R},\boldsymbol{r}) + \rho_n(\boldsymbol{R},\boldsymbol{r})] v_{00}^{EX}(\rho,E,s) j_0(k(E,R)s)\} d\boldsymbol{r},$$

$$U_1(E,\boldsymbol{R}) = \frac{1}{\varepsilon}\int \{[\rho_n(\boldsymbol{r}) - \rho_p(\boldsymbol{r})] v_{01}^{D}(\rho,E,s) +$$
$$[\rho_n(\boldsymbol{R},\boldsymbol{r}) - \rho_p(\boldsymbol{R},\boldsymbol{r})] v_{01}^{EX}(\rho,E,s) j_0(k(E,R)s)\} d\boldsymbol{r}.$$

$U_1 \Rightarrow$ ***microscopic description of Lane potential***

D.T. Khoa, E. Khan, G. Colo and N. van Giai, *Nucl. Phys.* **A706**, 61 (2002)

G. R. Satchler *et al.*, *Phys. Rev.* **136**, B637 (1964).

The explicit isospin coupling based on the total wave function

$$\Psi(\boldsymbol{R}) = \left| pA \right\rangle \chi_{pA}(\boldsymbol{R}) + \left| n\tilde{A}_{IAS} \right\rangle \chi_{n\tilde{A}_{IAS}}(\boldsymbol{R})$$

=> the coupled channels equations for quasi-elastic *(p,n)* scattering

$$\left[K_p + U_0(\boldsymbol{R}) - \frac{2T_A}{A}U_1(\boldsymbol{R}) + V_c(\boldsymbol{R}) - E_p\right]\chi_{pA}(\boldsymbol{R}) = -\frac{2\sqrt{2T_A}}{A}U_1(\boldsymbol{R})\chi_{n\tilde{A}_{IAS}}(\boldsymbol{R})$$

$$\left[K_n + U_0(\boldsymbol{R}) + \frac{2(T_A - 1)}{A}U_1(\boldsymbol{R}) - E_n\right]\chi_{n\tilde{A}_{IAS}}(\boldsymbol{R}) = -\frac{2\sqrt{2T_A}}{A}U_1(\boldsymbol{R})\chi_{pA}(\boldsymbol{R})$$

$\boldsymbol{F_{pn}(R)}$

$K_{p(n)}$ and $E_{p(n)}$ are the kinetic-energy operators and center-of-mass energies of the entrance-channel and the exit-channel

$$U_p(\boldsymbol{R}) = U_o(\boldsymbol{R}) - \frac{2T_A}{A}U_1(\boldsymbol{R}) \Longrightarrow$$ *Central OP in the entrance channel*

$$U_n(\boldsymbol{R}) = U_0(\boldsymbol{R}) + \frac{2(T_A - 1)}{A}U_1(\boldsymbol{R}) \Longrightarrow$$ *Central OP in the exit channel*

Folding model ← Density- and isospin dependent NN interaction

STEP I: ***Mapping the isovector density dependence of the CDM3Yn interactions to the BHF results by JLM group***

$v_0(\rho,E,r)=F_0(\rho,E)\, v_0(r)$ $v_1(\rho,E,r)=F_1(\rho,E)\, v_1(r)$

Hartree-Fock calculation

Complex nucleon optical potential (in nuclear matter limit)

$$U(\rho,E)=V_0(\rho,E)+i*W_0(\rho,E)\pm\delta*[V_1(\rho,E)+i*W_1(\rho,E)]$$

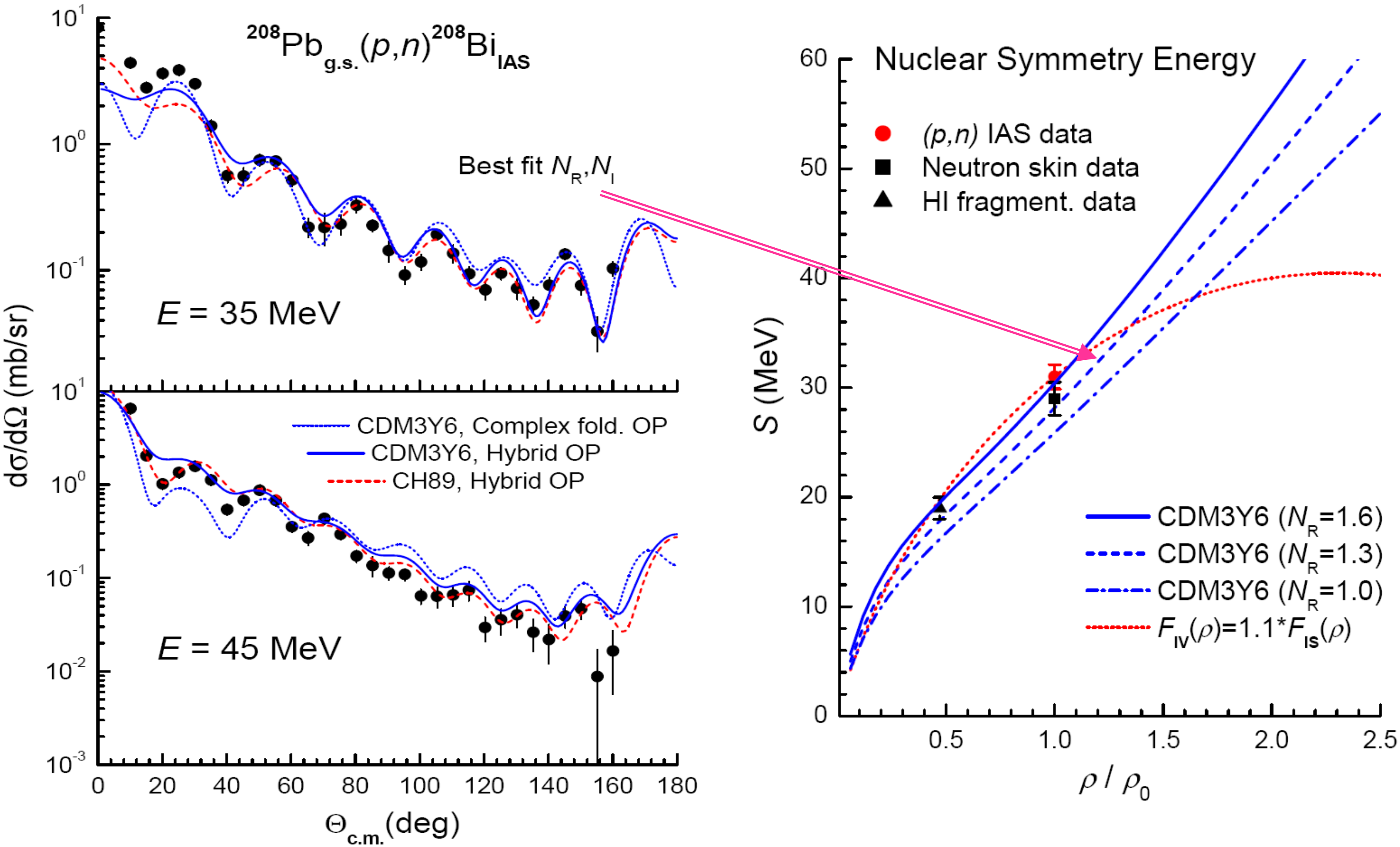
* Parameters of $Im[F_0(\rho,E)]$, $Re[F_1(\rho,E)]$ and $Im[F_1(\rho,E)]$ are adjusted to reproduce the BHF results by J.P. Jeukenne, A. Lejeune and C. Mahaux (JLM interaction)
Phys. Rev. C **16,** 80 (1977).

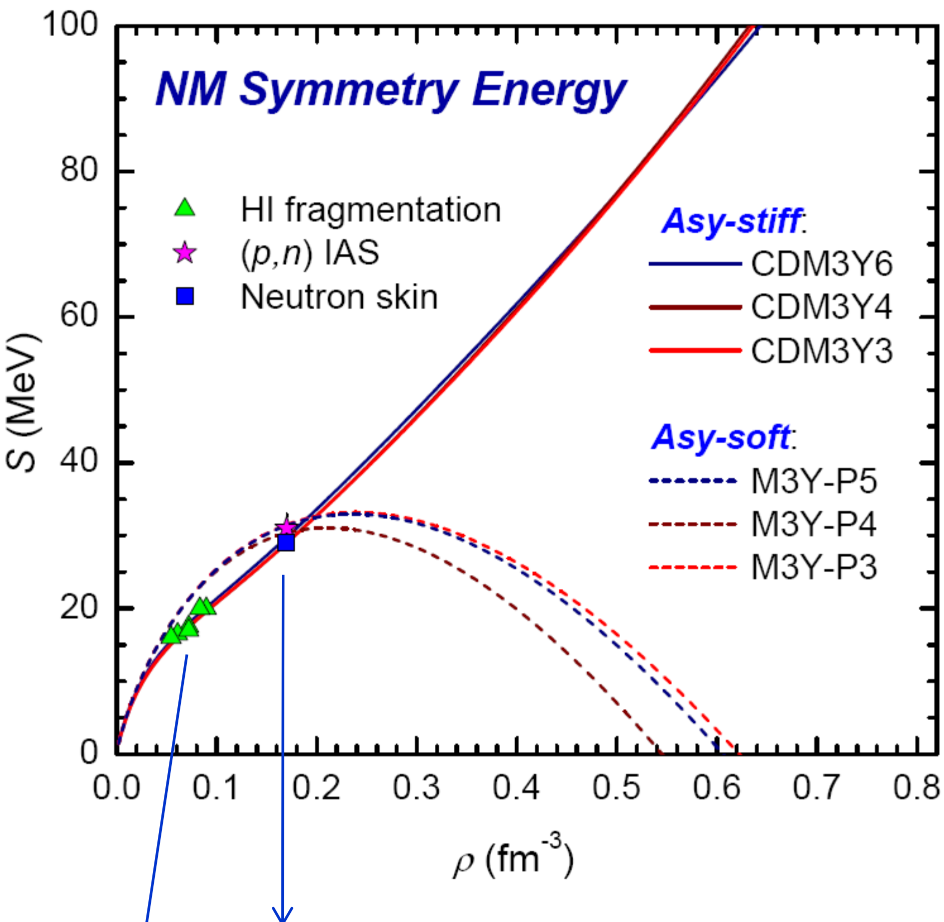
* $v_0(r)$ and $v_1(r)$ are the original M3Y - Paris interaction by N. Anantaraman et al.
Nucl. Phys. A398 (1983) 269.

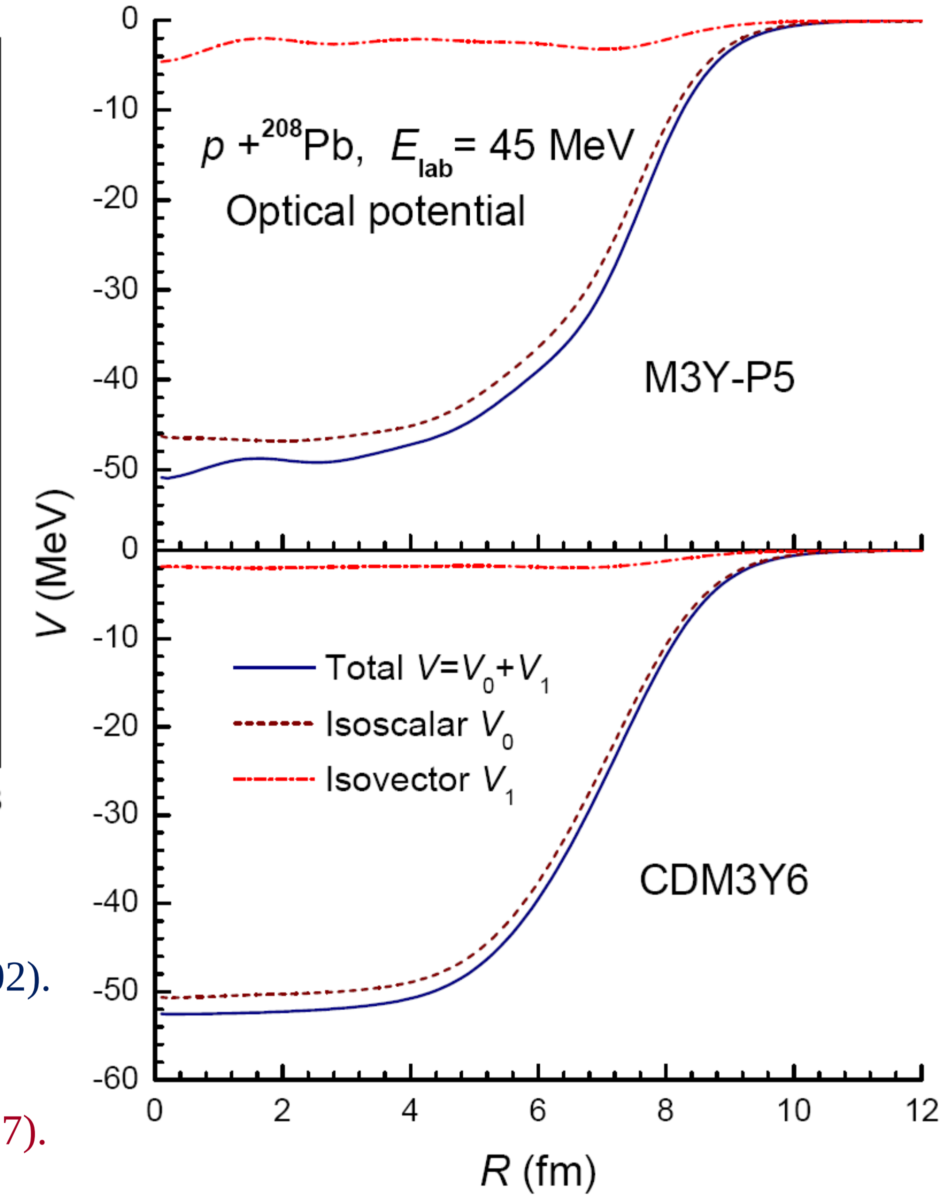
STEP II: ***Adjusting the isospin dependence of the CDM3Yn interaction to (p,n) data for IAS excitation !***

D.T. Khoa, H.S. Than, and D.C. Cuong, *Phys. Rev.* C **76**, 014603 (2007).

MSU Data: R.R. Doering et al. *Phys. Rev.* C **12,** 378 (1975).

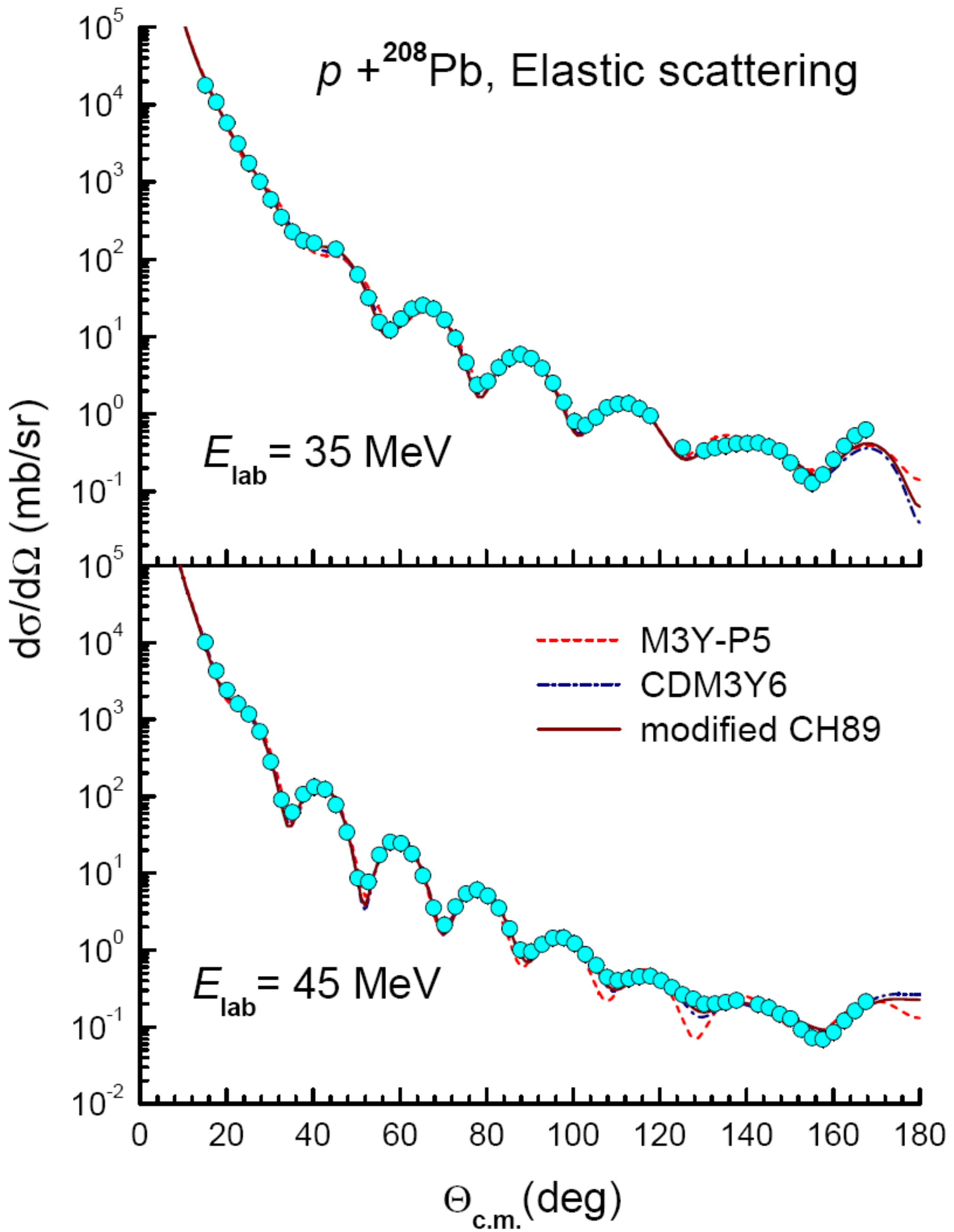






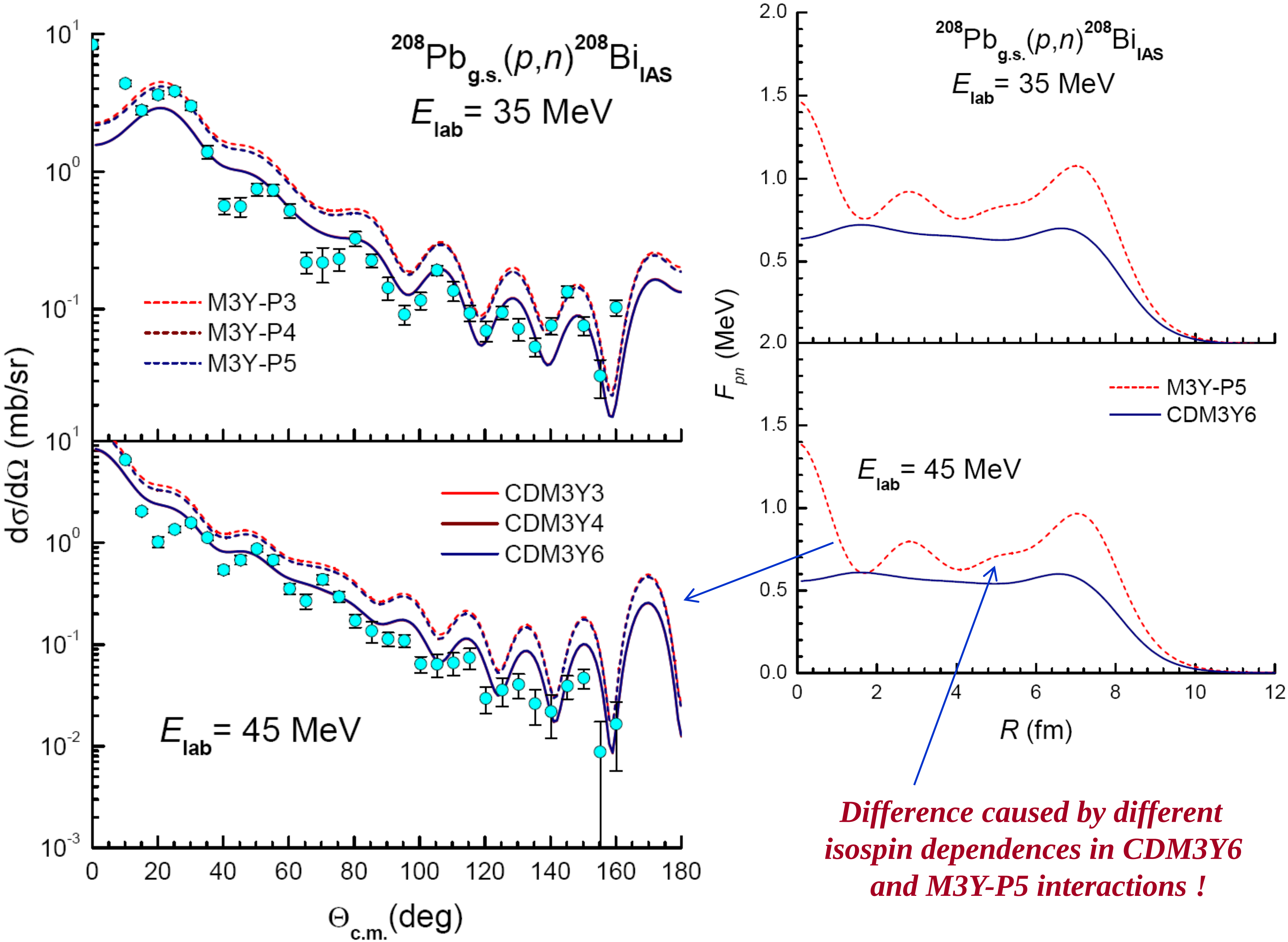
R. J. Furnstahl, *Nucl. Phys*. A**706**, 85 (2002).

A. Ono *et al., Phys. Rev*. C **68**, 051601(R) (2003),
D. V. Shetty *et al.*, *Phys. Rev.* C **76**, 024606 (2007);
D. V. Shetty *et al.*, *NIM Phys. Res***.** B **261**, 990 (2007).

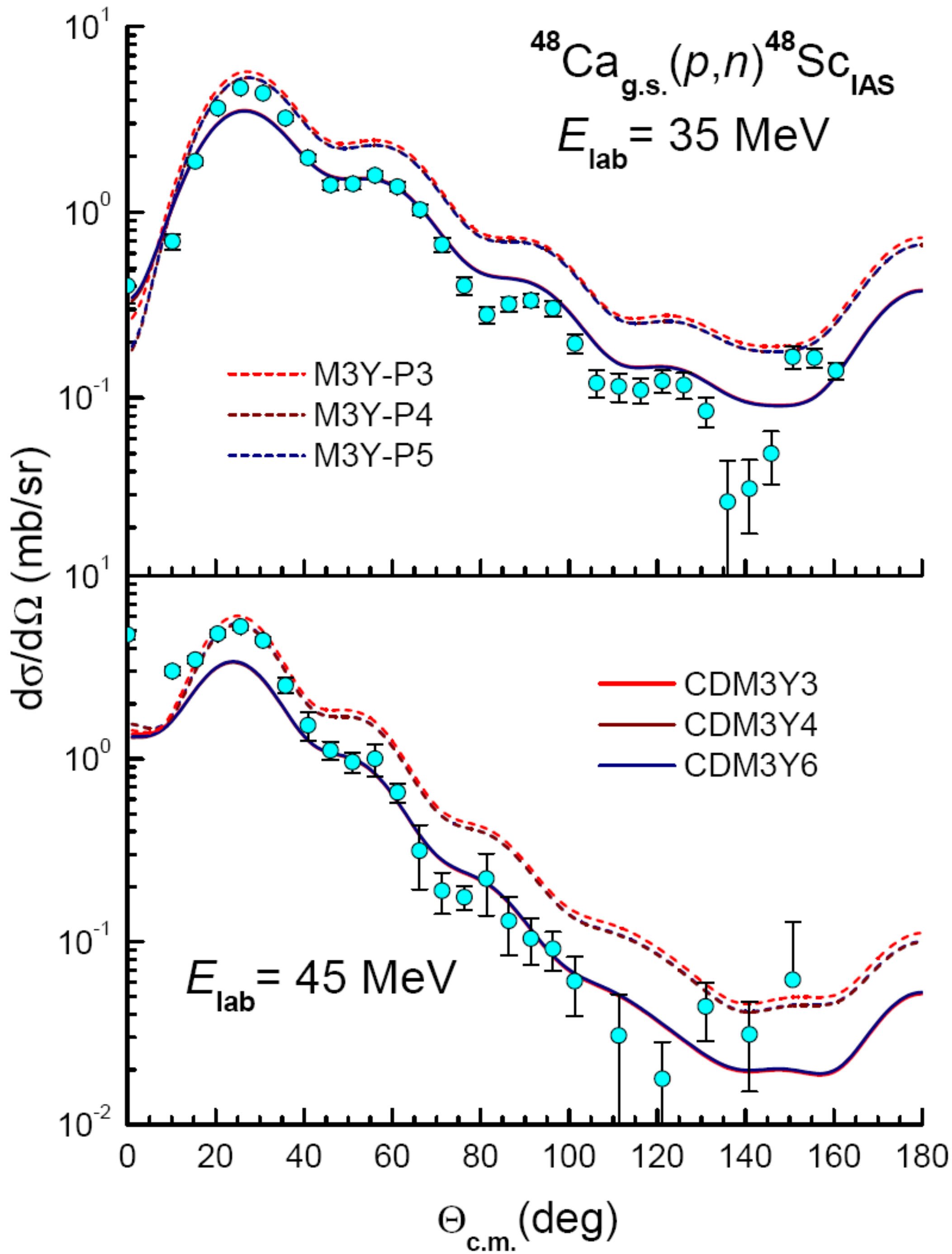


Data: W.T.H. van Oers *et al.*, *Phys. Rev.* C **10**, 307 (1974)

CH89 OP: R. L. Varner *et al.*, Phys. Rep. **201**, 57 (1991)

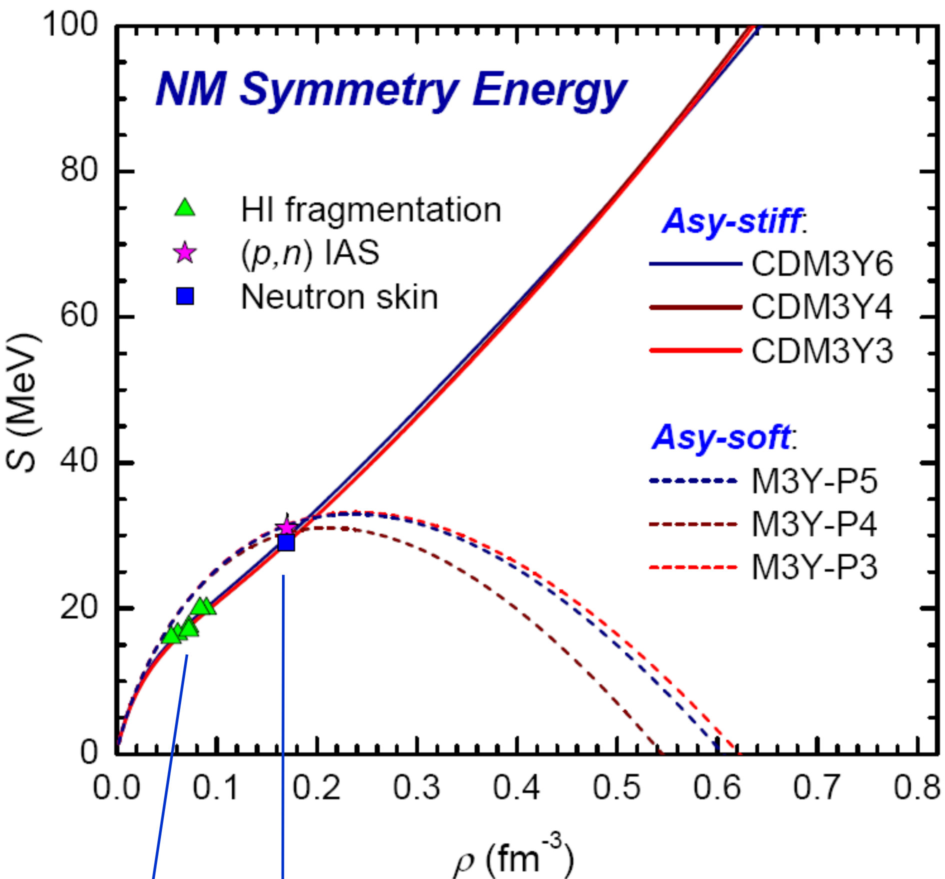


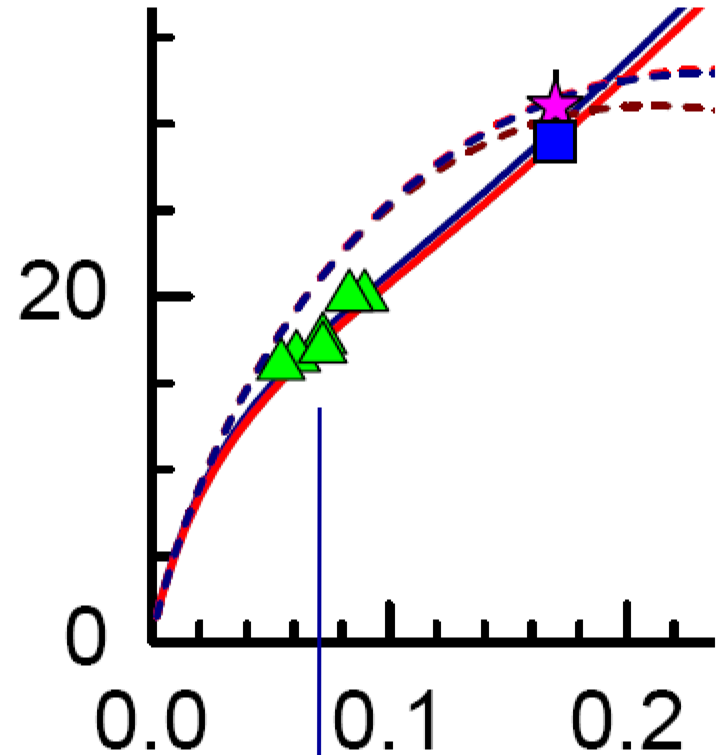
Difference caused by different isospin dependences in CDM3Y6 and M3Y-P5 interactions !



MSU Data: R.R. Doering *et al.* *Phys. Rev.* C **12,** 378 (1975).

Stiffness of the Sym. Energy at low barion densities can be probed by (p,n) IAS data !



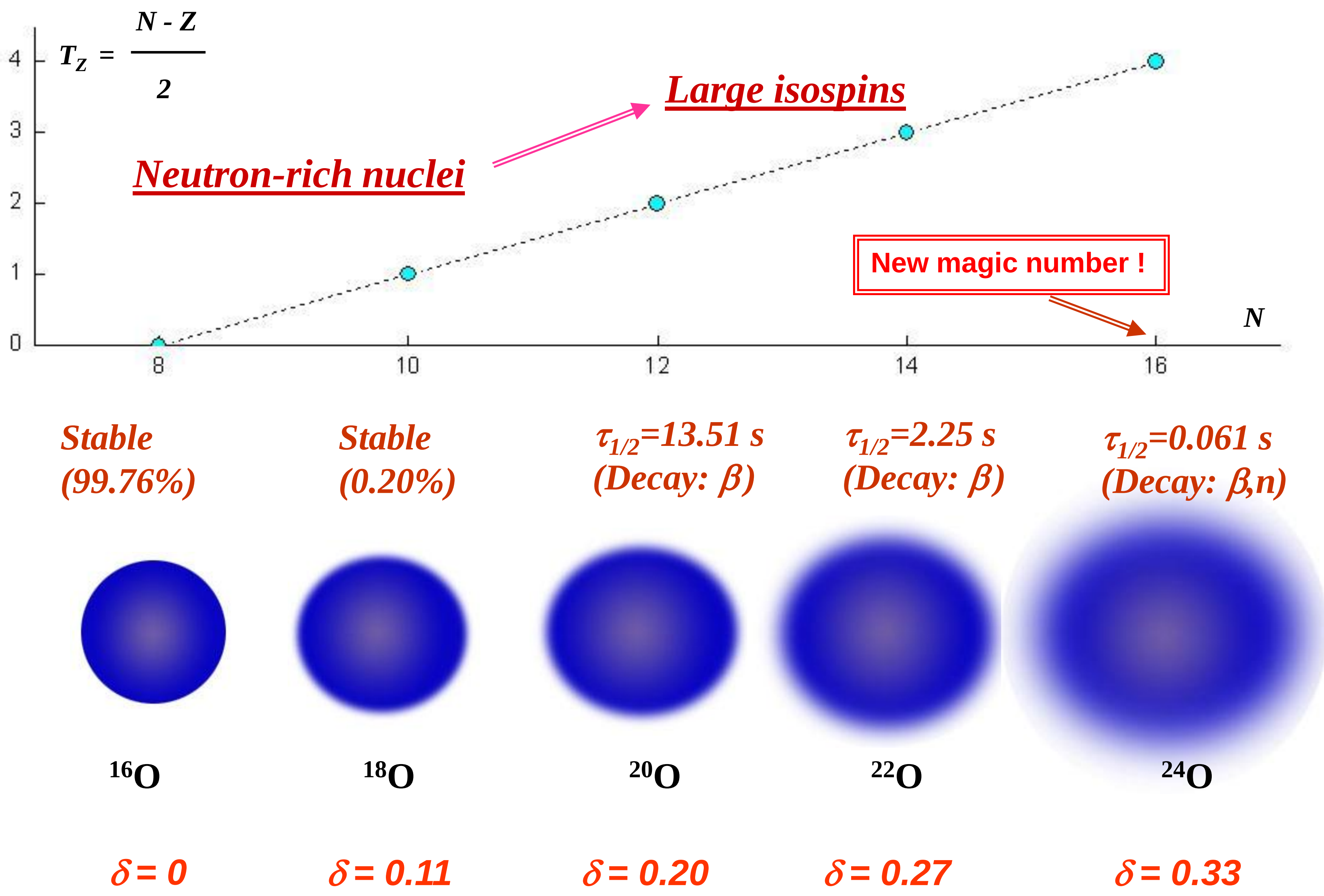


Crust - core interface
(1st-order phase transition from the NS crust to its uniform liquid core)

R. J. Furnstahl, *Nucl. Phys*. A**706**, 85 (2002).

A. Ono *et al., Phys. Rev*. C **68**, 051601(R) (2003),
D. V. Shetty *et al.*, *Phys. Rev.* C **76**, 024606 (2007);
D. V. Shetty *et al.*, *NIM Phys. Res***.** B **261**, 990 (2007).

Douchin & Haensel,
Astronomy & Astrophysics **380,** 151 (2001).

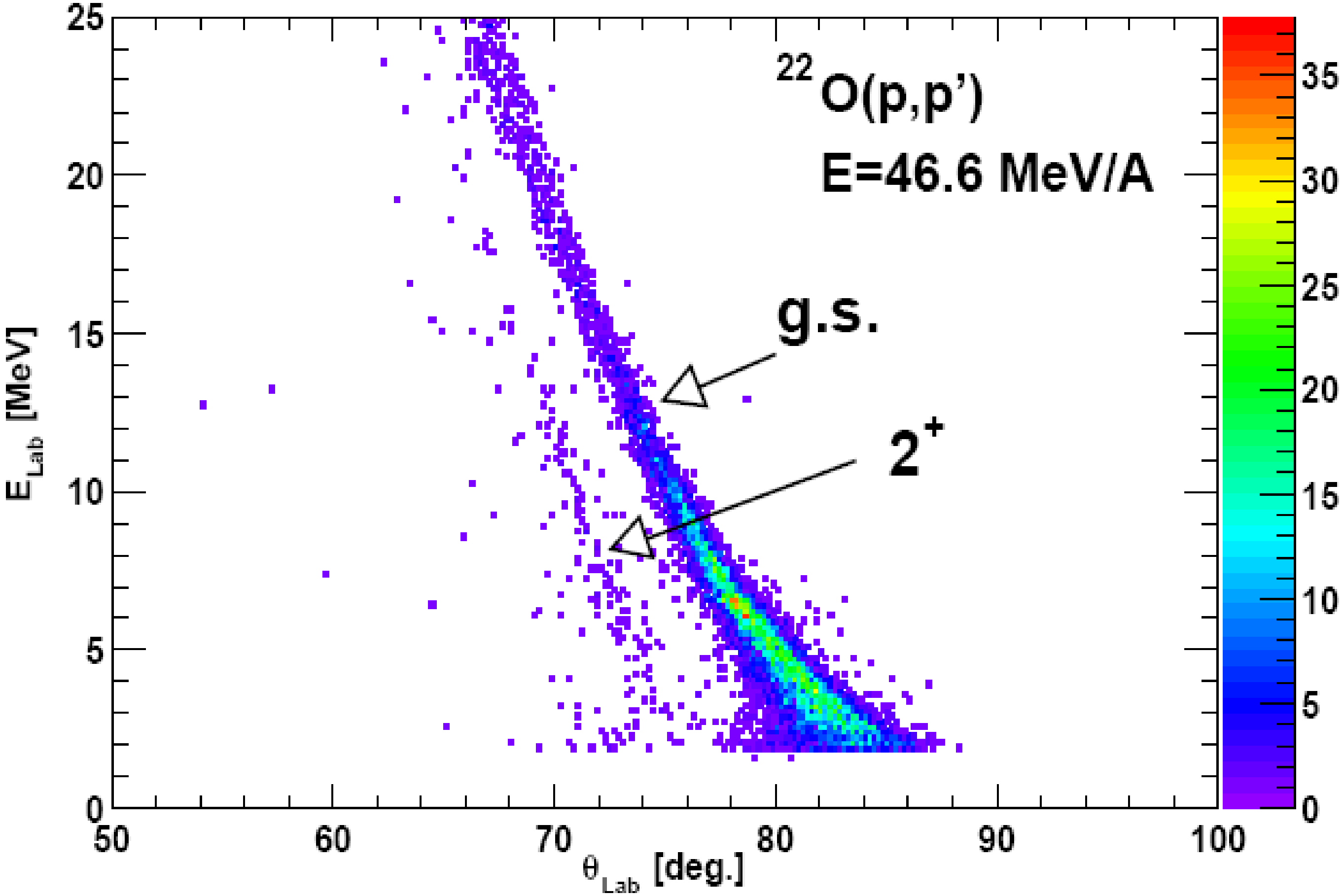


$T_Z = \dfrac{N - Z}{2}$
Large isospins
Neutron-rich nuclei
New magic number !
N
0
1
2
3
4
8
10
12
14
16
Stable (99.76%)
Stable (0.20%)
$\tau_{1/2}$=13.51 s (Decay: β)
$\tau_{1/2}$=2.25 s (Decay: β)
$\tau_{1/2}$=0.061 s (Decay: β,n)
^{16}O
^{18}O
^{20}O
^{22}O
^{24}O
$\delta = 0$
$\delta = 0.11$
$\delta = 0.20$
$\delta = 0.27$
$\delta = 0.33$

^{36}S primary beam (3*10^{12} pps) fragmented in the ^{12}C target located in SISSI device

⇒ In-flight production of ^{22}O secondary beam (~10^{3} pps) => Hydrogen target.

⇒ (p,p') events from the detected recoiling protons



E. Becheva et al., *Phys. Rev. Lett.* **96** (2006) 012501

Bohr–Mottelson prescription for the nuclear transition density ($\lambda \geq 2$)

$$\rho_{\lambda}^{\tau}(r) = -\delta_{\tau}\,\frac{d\rho_{g.s.}^{\tau}(r)}{dr}, \;\text{ with } \tau = p, n.$$

$\rho_{g.s.}^{\tau}(r)$ => proton and neutron ground state (g.s.) densities

δ_{τ} => the proton and neutron deformation lengths

IS and IV transition densities

$$\rho_{\lambda}^{0(1)}(r) = -\delta_{0(1)}\,\frac{d[\rho_{\text{g.s.}}^{n}(r) \pm \rho_{\text{g.s.}}^{n}(r)]}{dr}.$$

$\rho_{g.s.}$ calculated in the HFB formalism by Orsay group

M. Grasso, N. Sandulescu, N. Van Giai and R.J. Liotta, *Phys. Rev*. C **64,** 064321 (2001).

IS limit => neutron (ρ^n_λ) and proton (ρ^p_λ) transition densities have the same shape (total g.s. density scaled by *N*/*A* and Z/A)

$$\Rightarrow \delta_n = \delta_p = \delta_0 = \delta_1$$

$$\frac{M_n}{M_p} = \frac{N}{Z} \quad \text{and} \quad \frac{M_1}{M_0} = \frac{N-Z}{A} = \varepsilon.$$

IV mixing effect **=>** Difference between M_n/M_p and N/Z (or between M_1/M_0 and ε)

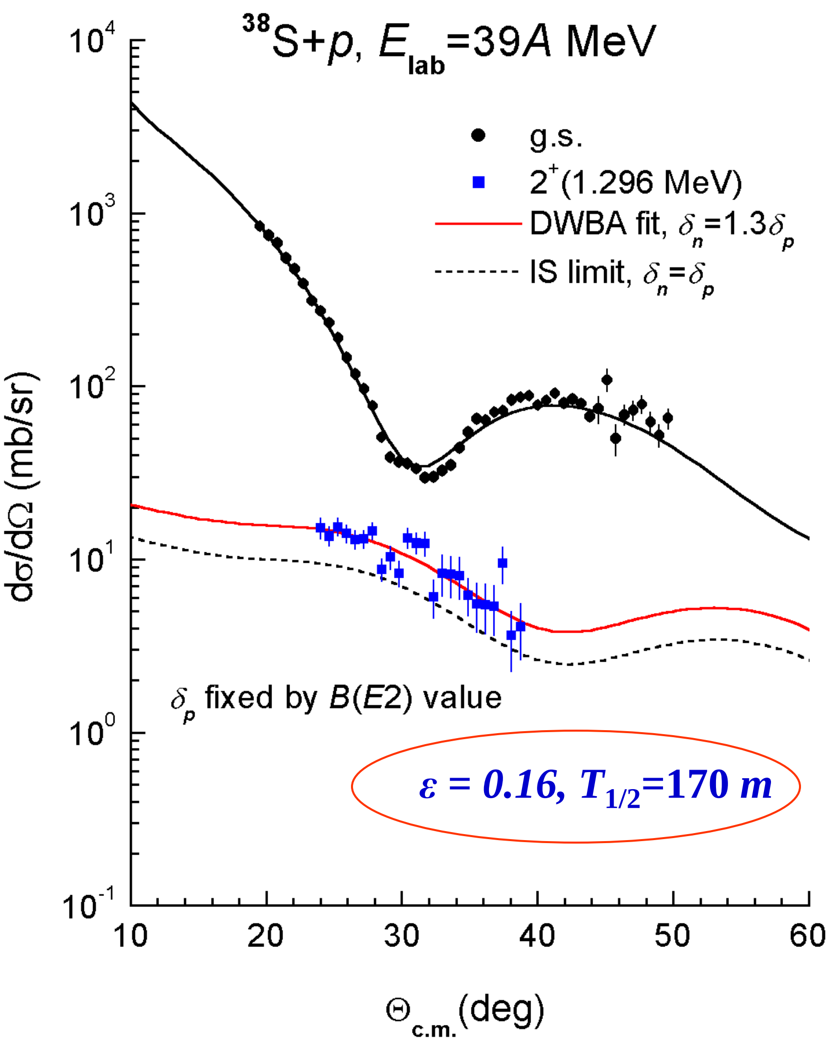
$B(E\lambda\uparrow)_{\text{exp}} = e^2|M_p|^2$ => δ_p; *neutron deformation length* δ_n is the only parameter *determined* from DWBA fit to the (*p*,*p'*) data.

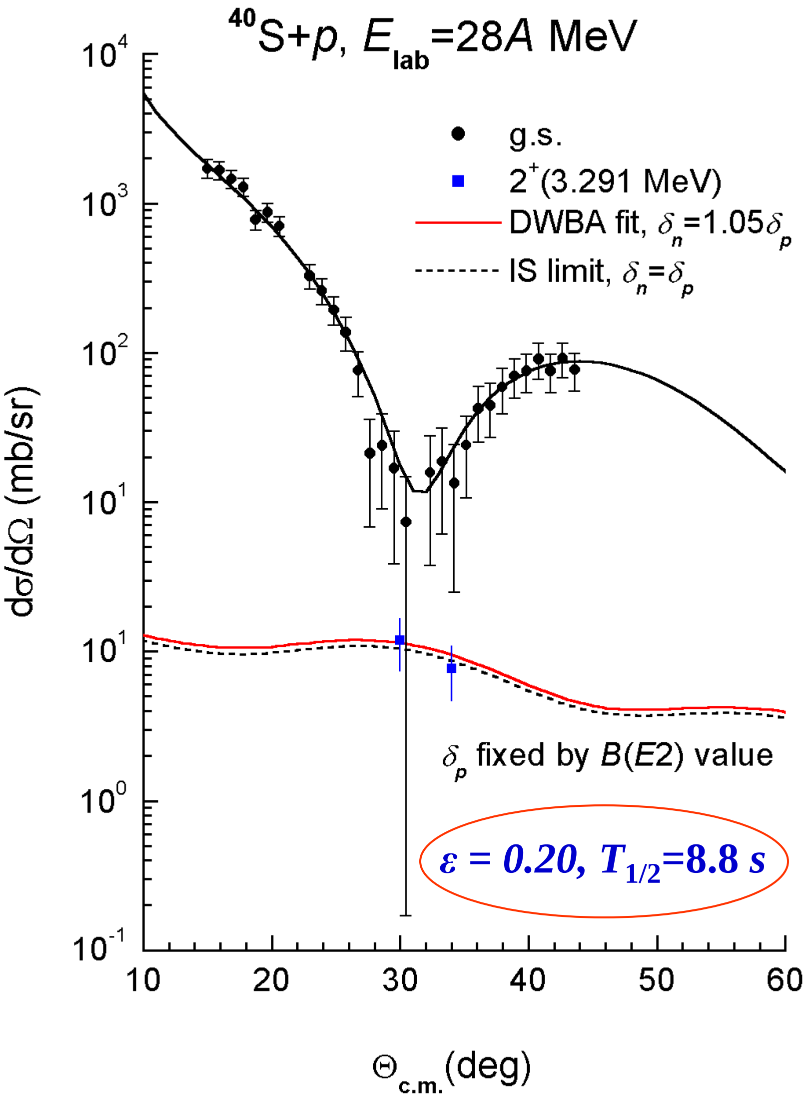
δ_n, δ_p, M_n, M_p <= one-to-one correspondence => δ_0, δ_1, M_0, M_1

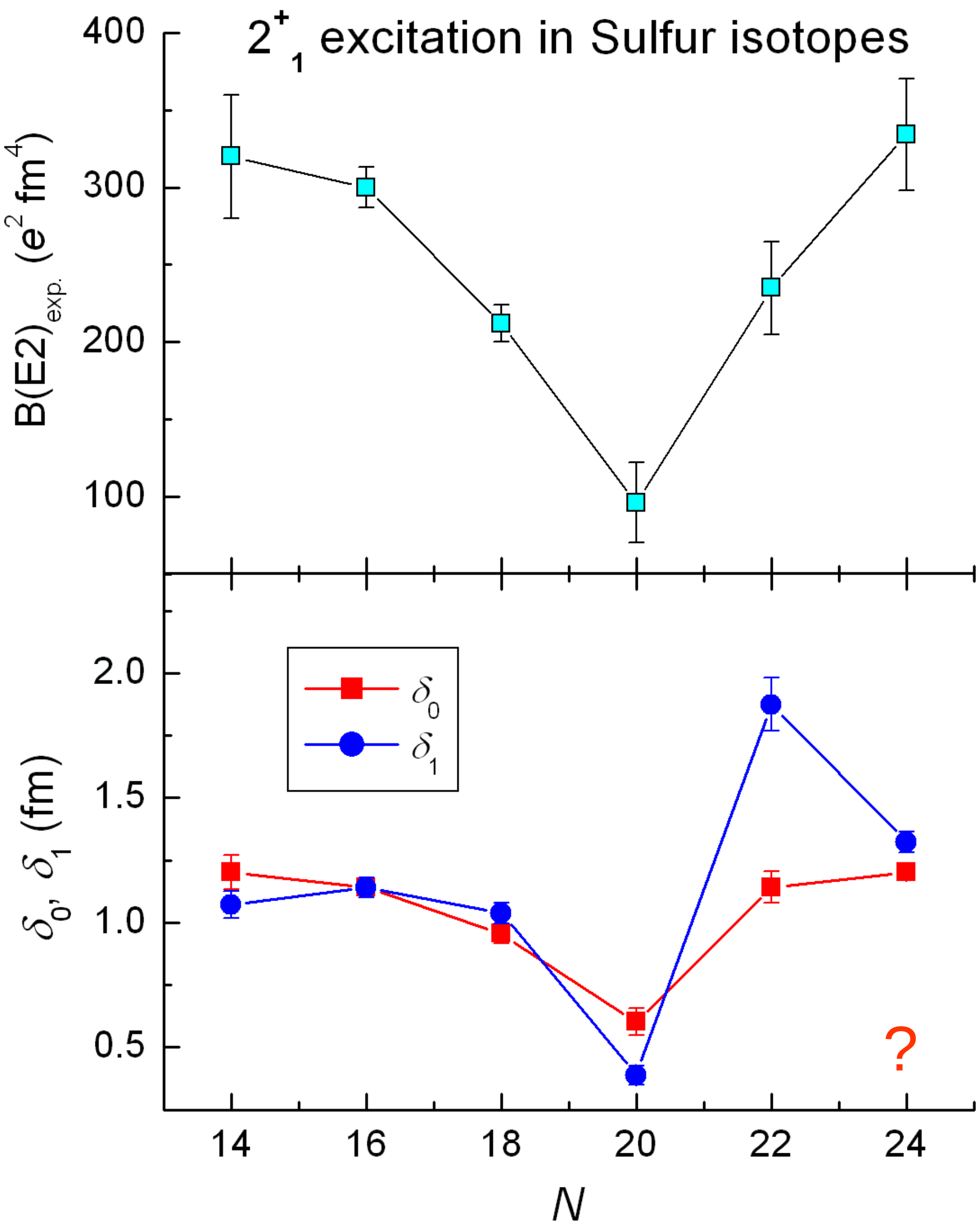
D.T. Khoa, *Phys. Rev.* C **68** (2003) 011601(R)

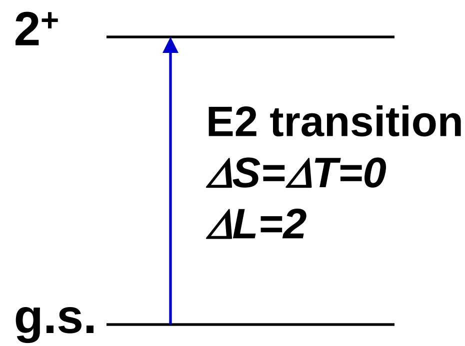
Data: J. H. Kelley et al., *Phys. Rev.* **C56** (1997) R1206
and F. Maréchal et al., *Phys Rev.* **C60** (1999) 034615.

DWBA analysis: D.T. Khoa, *EPJ* Special Topics **150**, 31 (2007).







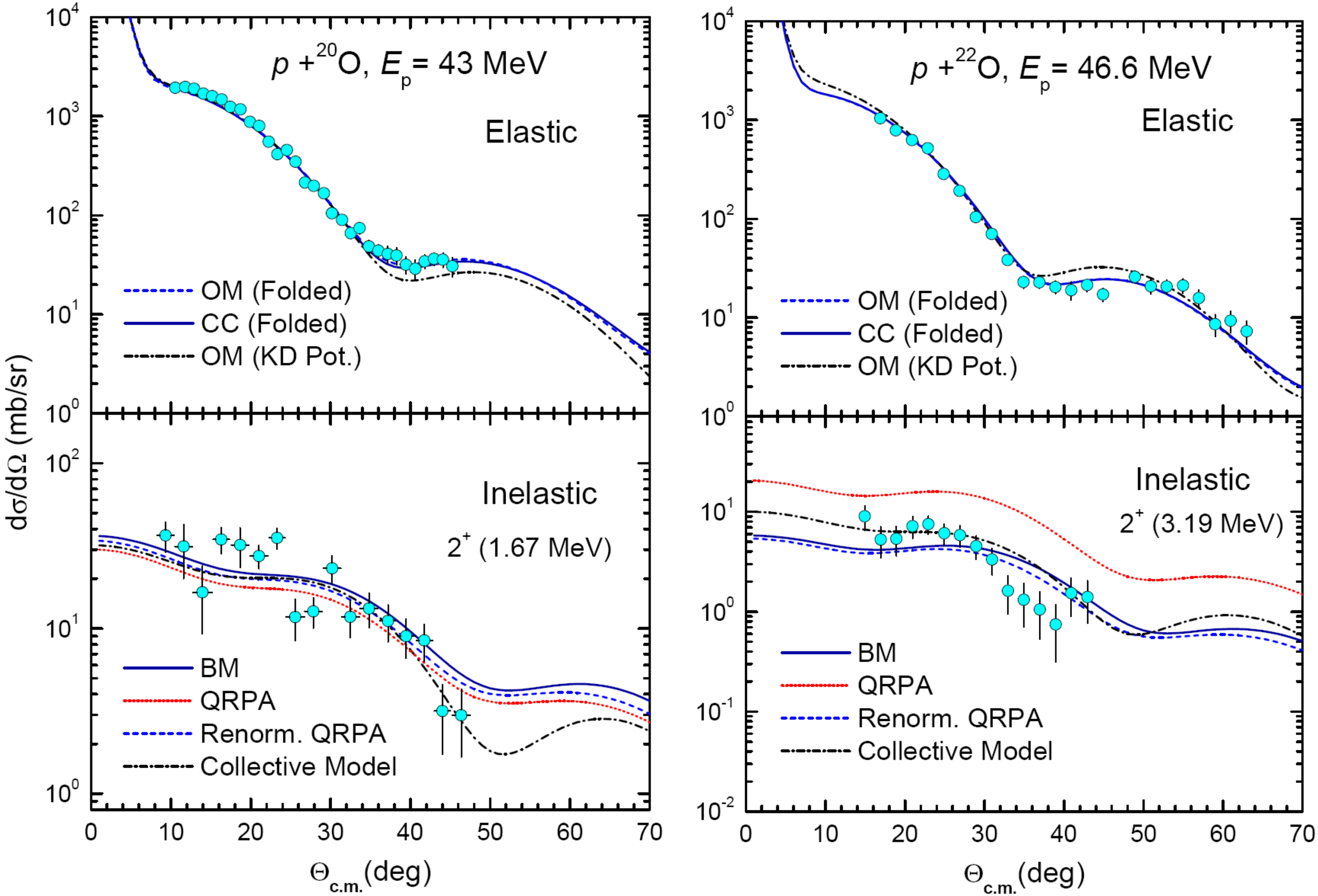


IS limit => $\delta_1=\delta_0$

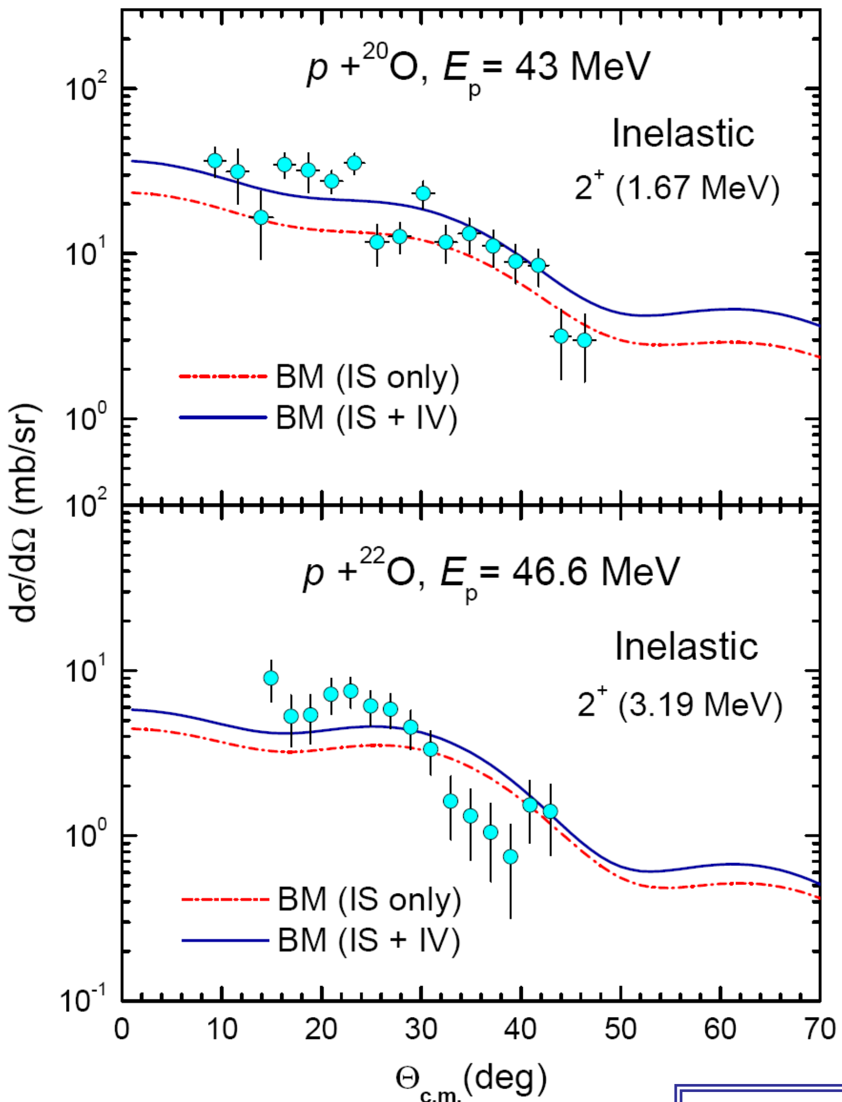
Neutron shell closure at N = 20

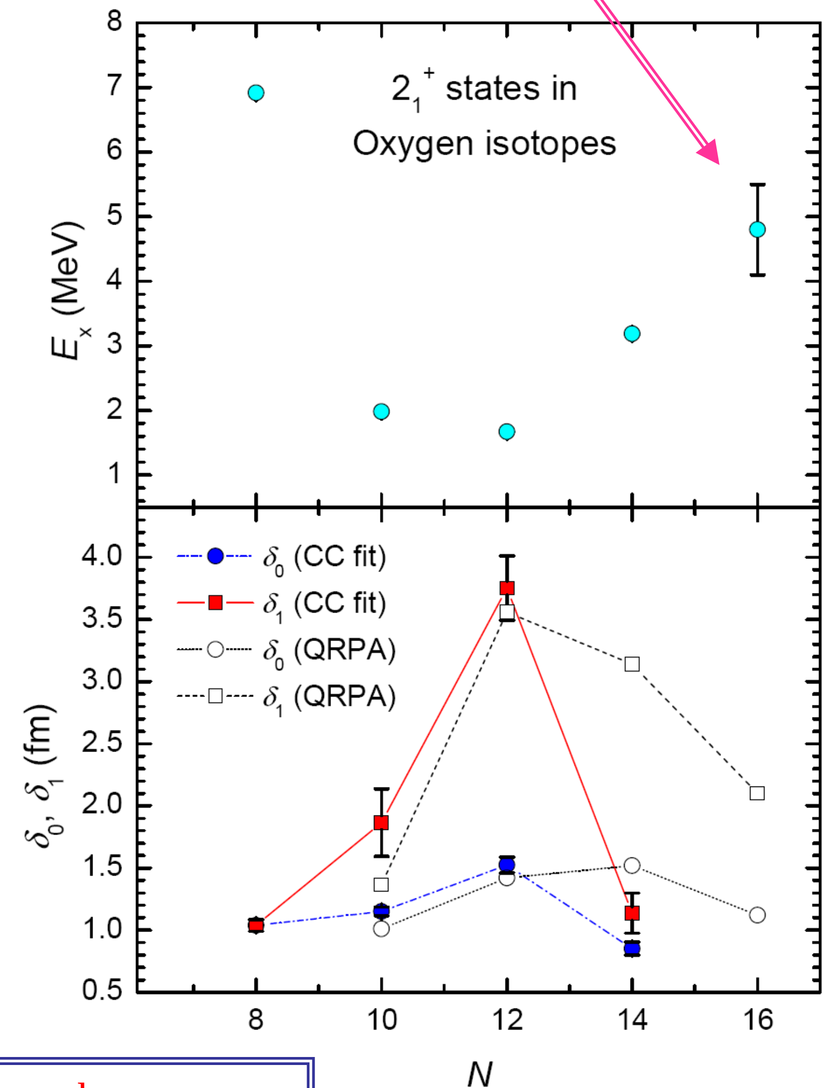
⇒ ***weak isovector deformation*** ($\delta_1 < \delta_0$)

Data: E. Khan et al., *Phys. Lett.* B **490** (2000) 45; E. Becheva et al., *Phys. Rev. Lett.* **96** (2006) 012501.
Complex folding + CC analysis: N.D. Chien & D.T. Khoa, *Phys. Rev.* C **79** (2009) 034314.



Neutron decay data: C.R. Hoffman et al., *Phys. Lett.* B **672** (2009) 17





Weaker IV mixing in ^{22}O

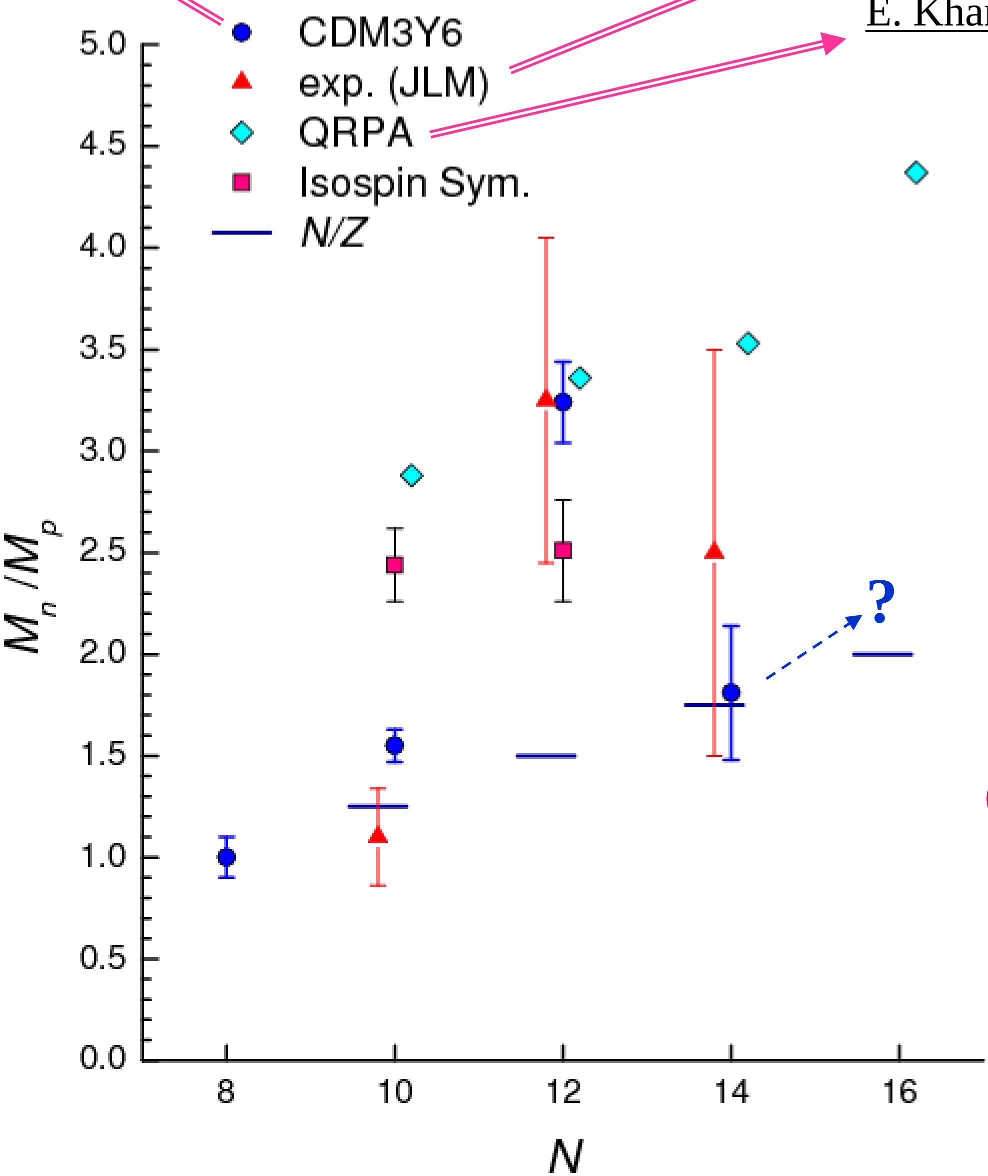
~ 4 MeV gap between 2*s*1/2 and 1*d*3/2 subshells

⟹ ***New magic number N=16 !***

N.D. Chien & D.T. Khoa,
Phys. Rev. C **79** (2009) 034314

E. Khan et al., *Phys. Lett.* B **490** (2000) 45;
Becheva et al., *Phys. Rev. Lett.* **96** (2006) 012501

E. Khan et al., *Phys. Rev.* C **66** (2002) 024309



Isospin symmetry

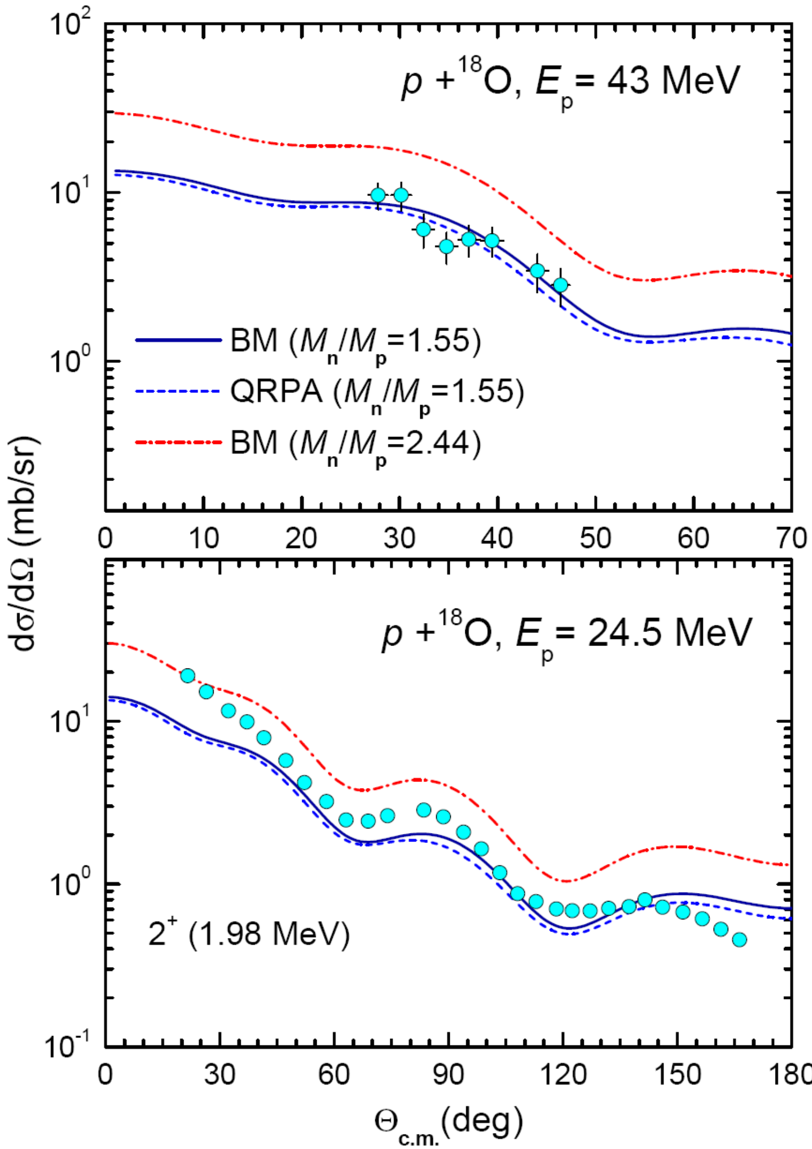
Charge independence of 2⁺ excitation in members of the T-isospin multiplet

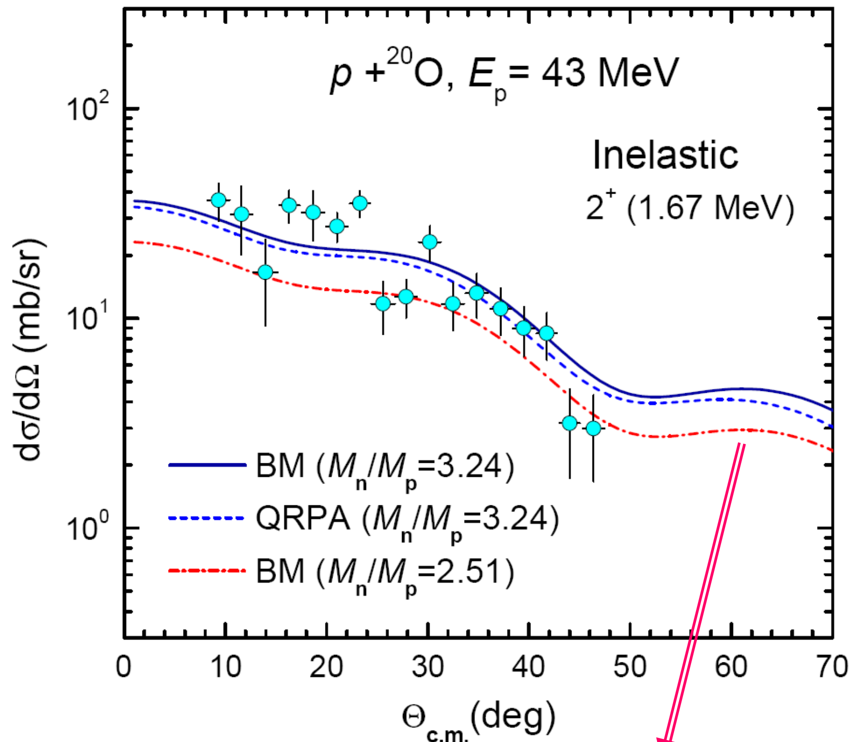
$M_p(-T_z)=M_n(T_z)$

A.M. Bernstein, V.R. Brown, and V.A. Madsen,
Phys. Rev. Lett. **42** (1979) 425.

$B(E2)_{exp}$ => M_p for ^{18}Ne and ^{20}Mg
=> M_n for ^{18}O and ^{20}O and vice verse

RIKEN experiment with unstable ^{20}Mg beam
N. Iwasa et al., *Phys. Rev.* C **78** (2008) 024306

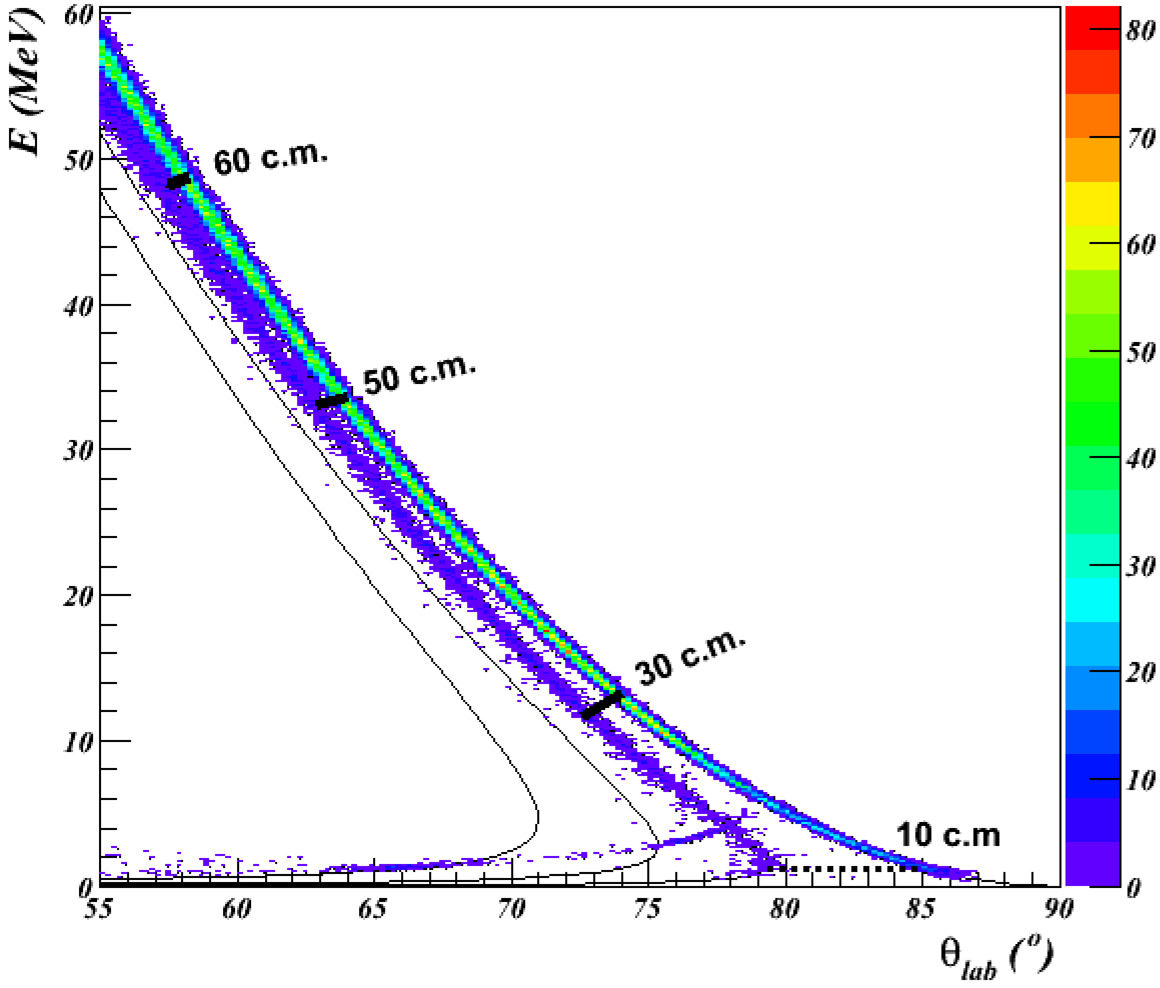




Mirror symmetry in the first 2^+ excitation of $A = 18$; $T = 1$ and $A = 20$; $T = 2$ isobars

More (p,p') experiments needed !

^{20}Mg(p,p') at 50 MeV, simulation of recoiled proton spectrum for elastic and inelastic (to 2^{+} state at 1.6 MeV in ^{20}Mg) scattering based on efficiency of MUST2 detector
by Valerie Lapoux in September 2009. *Not yet measured !!!*



Thank you !

Arigato gozaimasu !

Cám ơn !