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Low-lying charge-exchange modes of excitation relevant to beta decay

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Recent progress in microscopic description of beta-decay rate

proton-neutron (Q)RPA based on nuclear density-functional theory

"no-core" "no adjustable parameters"

spherical

HFB

Engel et al., PRC60(1999)014302: A

Bai et al., PRC90(2014)054335

Niu, Colò et al, PRC94(2016)064328: A + phonon-coupling effect

HF-BCS

Fracasso, Colò, PRC72(2005)064310

RHB, RHFB

Paar, Nikšić et al., PRC69(2004)054303; Nikšić, Marketin et al., PRC71(2005)014308: A

Marketin et al., PRC93(2016)025805: A+FF

Niu, Niu et al., PLB723(2013)172; PRC95(2017)044301: A

Recent progress in microscopic description of beta-decay rate

proton-neutron (Q)RPA based on nuclear density-functional theory

"no-core" "no adjustable parameters"

deformed

HFB

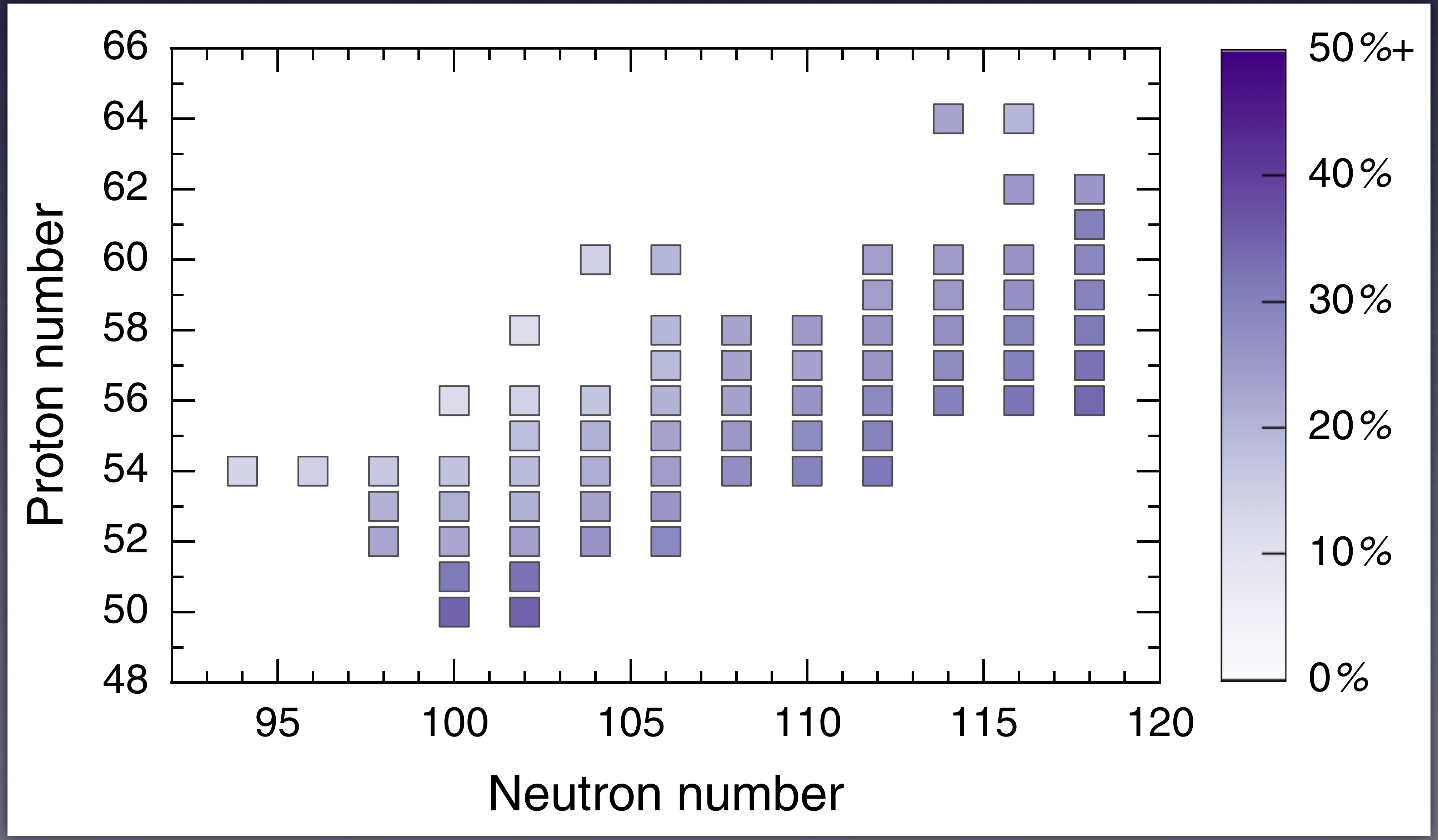
Mustonen, Engel, PRC87(2013)064302: A

Yoshida, PTEP2013(2013)113D02: A

Martini et al., PRC89(2014)044306: A

Shafer, Engel et al., PRC94(2016)055802: A+FF

contribution of FF transitions

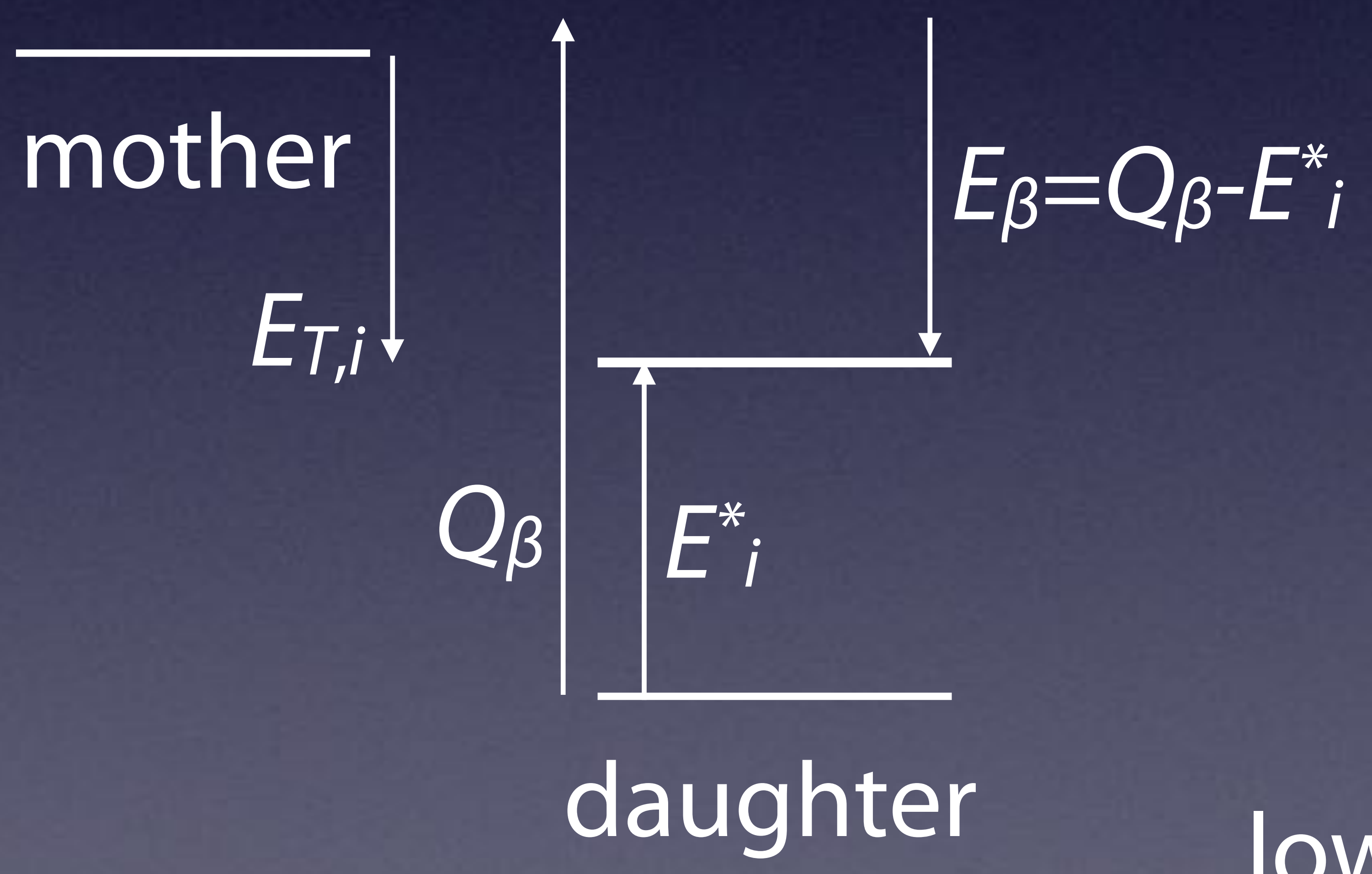


Microscopic description of the nuclear β-decay

charge-exchange mode of excitation
= superposition of 2qp excitations of a proton and a neutron

$$\hat{O}_i^\dagger = \sum_{\alpha\beta} X^i_{\alpha\beta}\hat{a}^\dagger_{\alpha,\nu}\hat{a}^\dagger_{\beta,\pi} - Y^i_{\alpha\beta}\hat{a}_{\bar{\beta},\pi}\hat{a}_{\bar{\alpha},\nu}$$

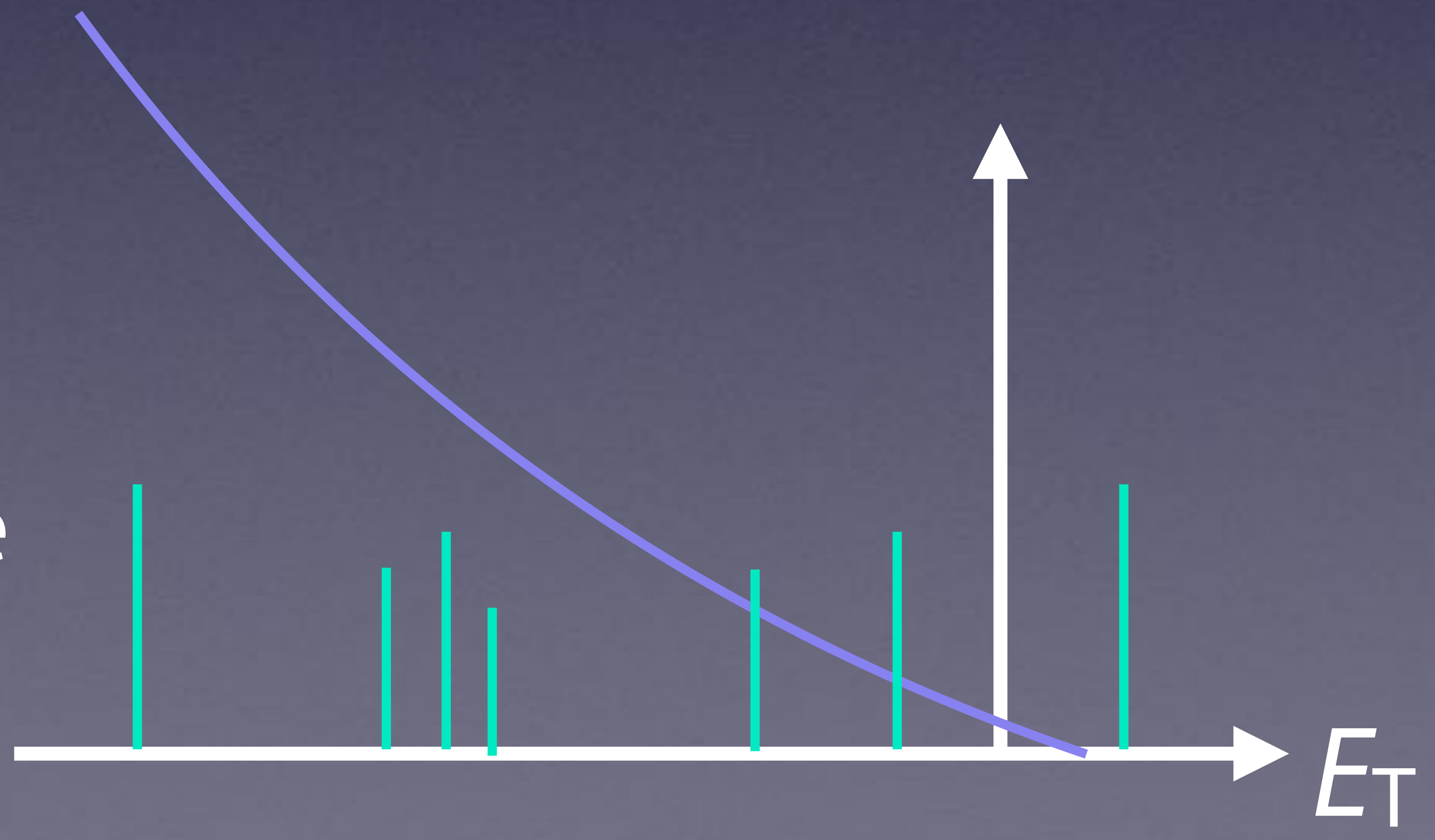
$$\frac{1}{T_{1/2}} = \frac{(g_A/g_V)^2_{\text{eff}}}{D}\sum_K \sum_{E_i^*<Q_\beta} f(Z, Q_\beta - E_i^*)\underline{|\langle i|\hat{F}_K^-|0\rangle|^2}$$



$$\begin{aligned} Q_\beta - E_i^* &\simeq \Delta M_{n-H} - \omega_i + \lambda_\nu - \lambda_\pi \\ &= \Delta M_{n-H} - E_{\mathrm{T},i} \end{aligned}$$

$$\hat{F}_K^- = \sum_{\sigma\sigma'}\int dr\hat{\psi}^\dagger_\pi(r\sigma')\langle\sigma'|\sigma_K|\sigma\rangle\hat{\psi}_\nu(r\sigma)$$

J. Engel et al., PRC60(1999)014302



low-lying GT states are decisive for the half-life

Spin-isospin response

$$\boxed{s_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r}t)=\sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma'\tau' t)\rangle\langle\sigma|\boldsymbol{\sigma}_{\mu_\sigma}|\sigma'\rangle\langle\tau|\boldsymbol{\tau}_{\mu_\tau}|\tau'\rangle}$$

$\rho(\boldsymbol{r})+[\delta s^\lambda_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})e^{-i\omega_\lambda t}+\mathrm{c.c}]$ in linear-response of TDDFT

physical observables in spin-isospin response

$$\left|\int d\boldsymbol{r}\, f(\boldsymbol{r})\delta s^\lambda_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})\right|^2$$

Gamow-Teller strength distribution: w/ isospin-change $\mu_\tau=\pm1$

$$S^{\mu_\tau}_{\mu_\sigma}(\omega)=\sum_\lambda\left|\int d\boldsymbol{r}\delta s^\lambda_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})\right|^2\delta(\omega-\omega_\lambda)$$

GT matrix element to low-lying states:
key quantity to beta-decay rate

Skyrme energy-density functional approach

Energy functional: $\mathcal{E} = \int d\boldsymbol{r} \mathcal{H}(\boldsymbol{r})$

Energy density: $\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{Skyrme}} + \mathcal{H}_{\mathrm{em}}$

Skyrme energy density: $\mathcal{H}_{\mathrm{Skyrme}} = \sum_{t=0,1} \sum_{t_3=-t}^{t} \left(\mathcal{H}_{tt_3}^{\mathrm{even}} + \mathcal{H}_{tt_3}^{\mathrm{odd}} \right)$

$$\mathcal{H}_{tt_3}^{\mathrm{even}} = C_t^{\rho}\, \rho_{tt_3}^2 + C_t^{\Delta\rho}\, \rho_{tt_3} \Delta \rho_{tt_3} + C_t^{\tau}\, \rho_{tt_3} \tau_{tt_3} + C_t^{\nabla J} \rho_{tt_3}\, \nabla \cdot \mathbf{J}_{tt_3} + C_t^{J} \overleftrightarrow{J}{}_{tt_3}^{2}$$

$$\mathcal{H}_{tt_3}^{\mathrm{odd}} = C_t^{s}\, \mathbf{s}_{tt_3}^2 + C_t^{\Delta s}\, \mathbf{s}_{tt_3} \cdot \Delta \mathbf{s}_{tt_3} + C_t^{T}\, \mathbf{s}_{tt_3} \cdot \mathbf{T}_{tt_3} + C_t^{\nabla s}\, (\nabla \cdot \mathbf{s}_{tt_3})^2 + C_t^{j}\, \mathbf{j}_{tt_3}^2 + C_t^{\nabla j}\, \mathbf{s}_{tt_3} \cdot \nabla \times \mathbf{j}_{tt_3}$$

Poorly known (poorly constrained):

- T-odd Skyrme energy density
  - vanishes for ground-state of even-even nuclei
- Isovector (t=1) coupling constants
  - less information on nuclei with neutron (proton) excess

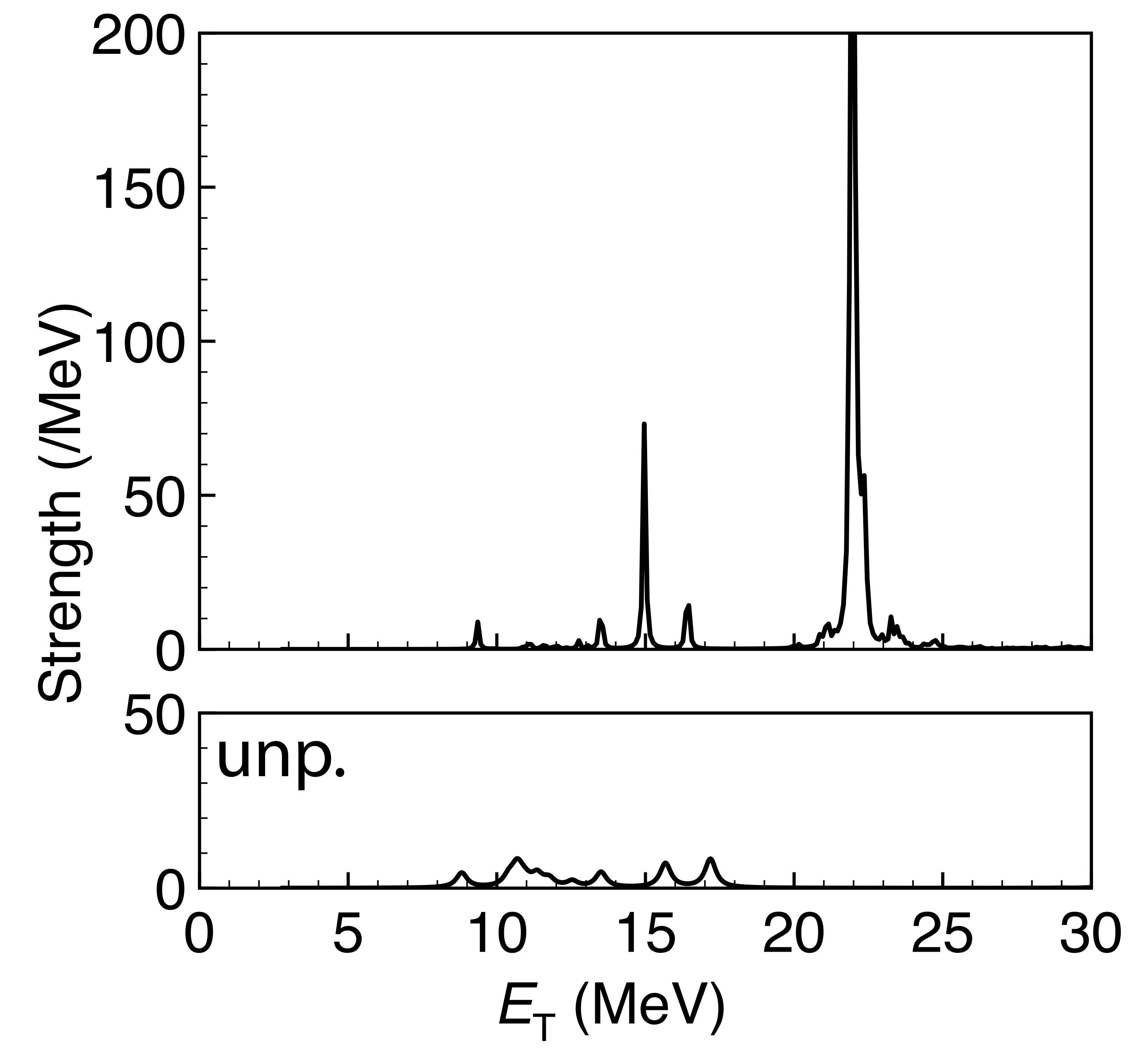
coupling constants for vector-isovector density

↕

Gamow-Teller ME

Many-body correlations essential in low energy

^{208}Pb, SGII

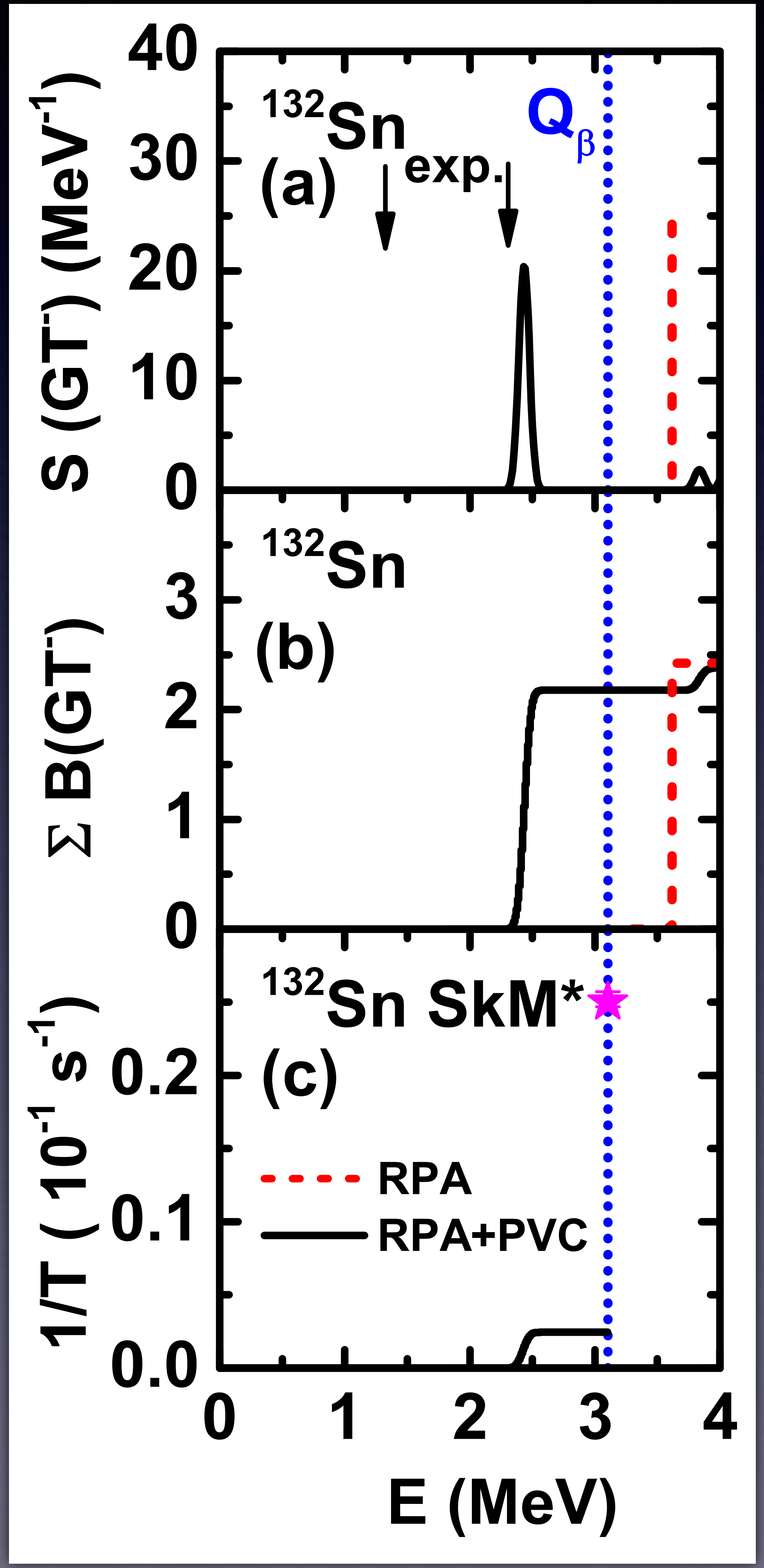


Most of the strengths are gathered in the high-energy giant resonance

Tiny low-lying strengths

^{132}Sn

spherical and normal-fluid nucleus



RPA

single peak

Phonon coupling

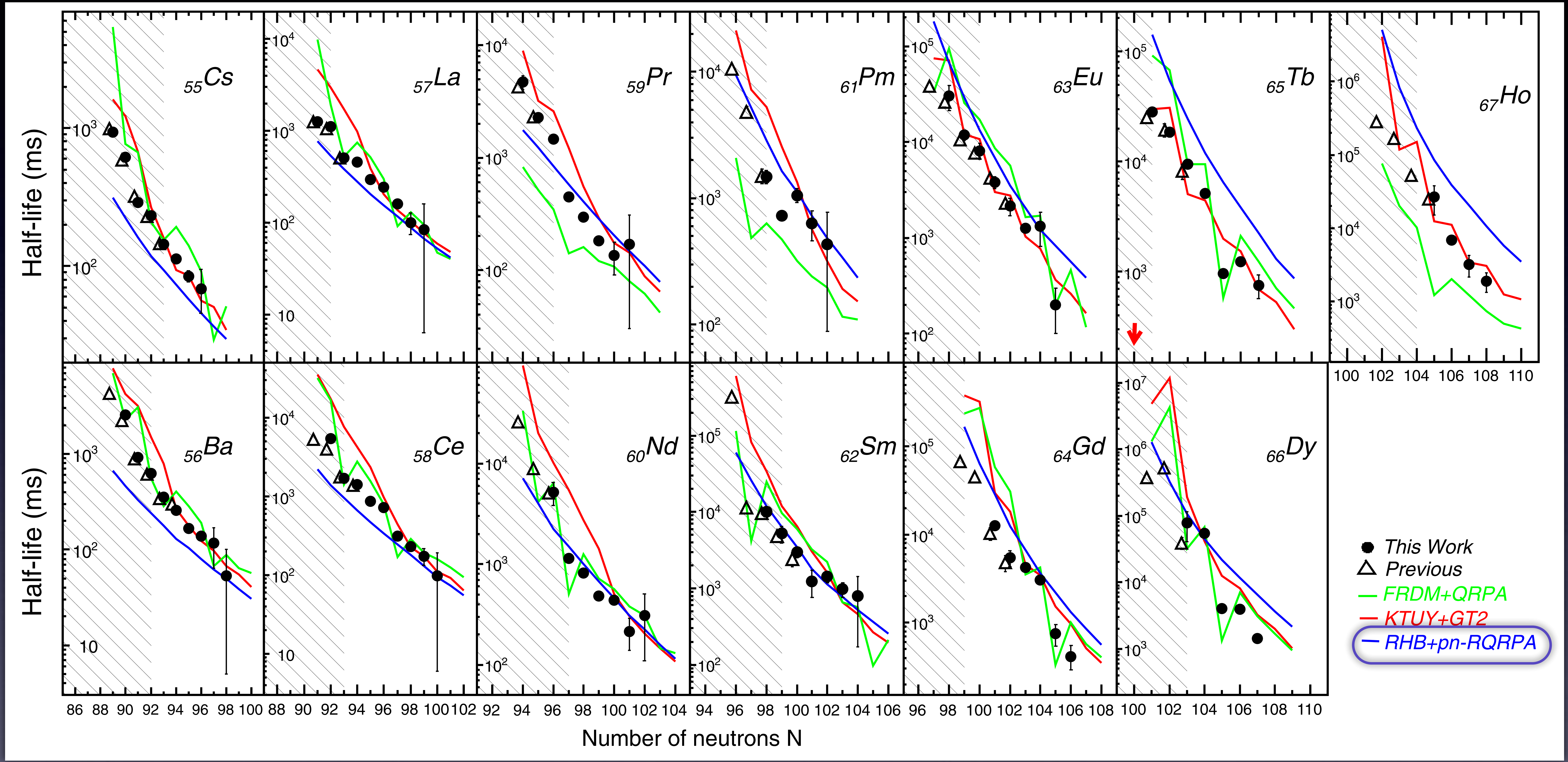
spreading
lowering

$T_{1/2}$: ∞ → finite

Y. F. Niu et al., PRL114(2015)142501

β-decay study at RIBF for the rare-earth elements production of the r-process

J. Wu, S. Nishimura et al., PRL118(2017)072701



Rare-earth nuclei

far from the magic numbers

strongly deformed in space/ gauge space

role of MB correlations?

Nuclear DFT cal.

assuming the spherical shape

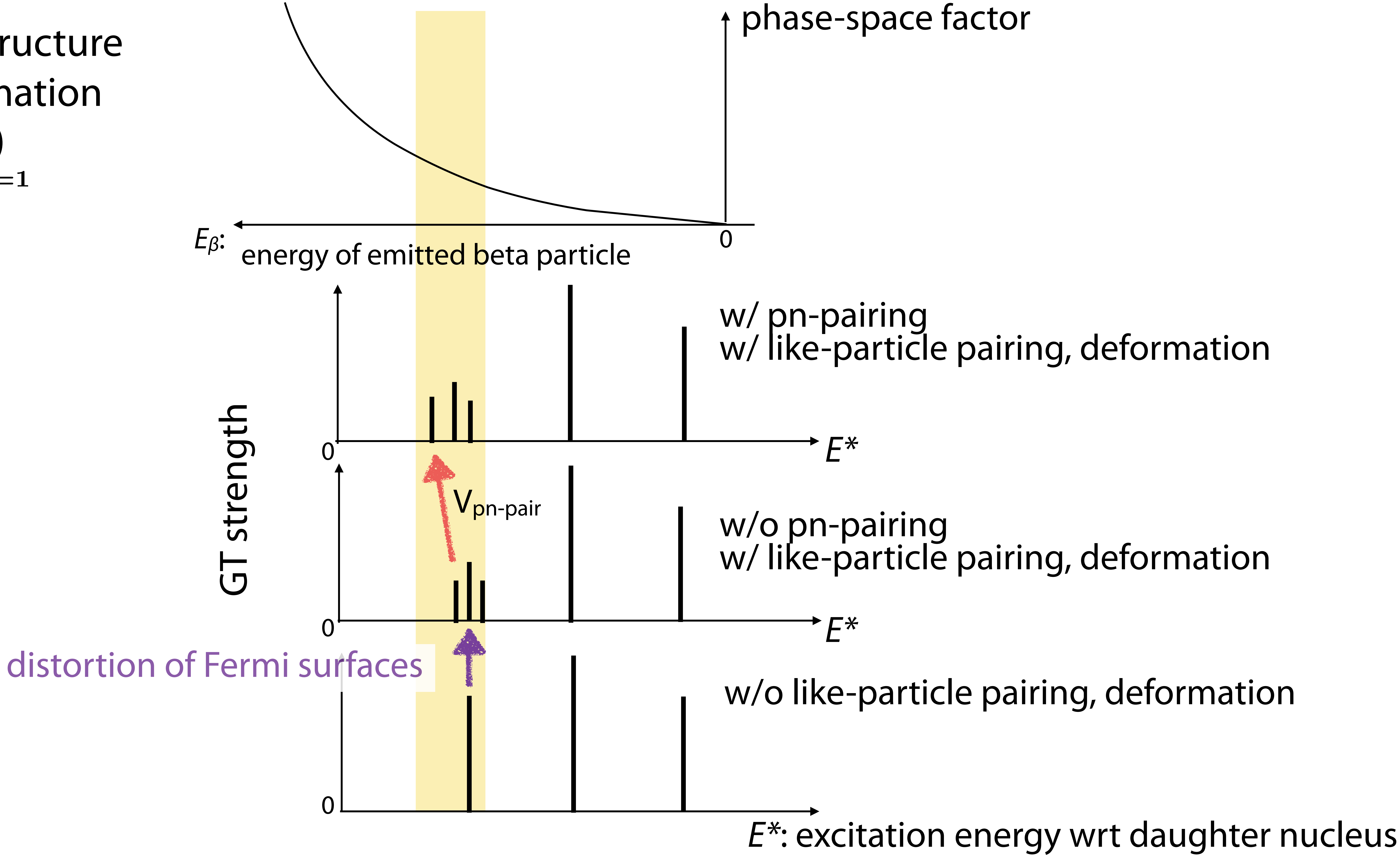
reasonably produces the obs.

Marketin et al., PRC93(2016)025805

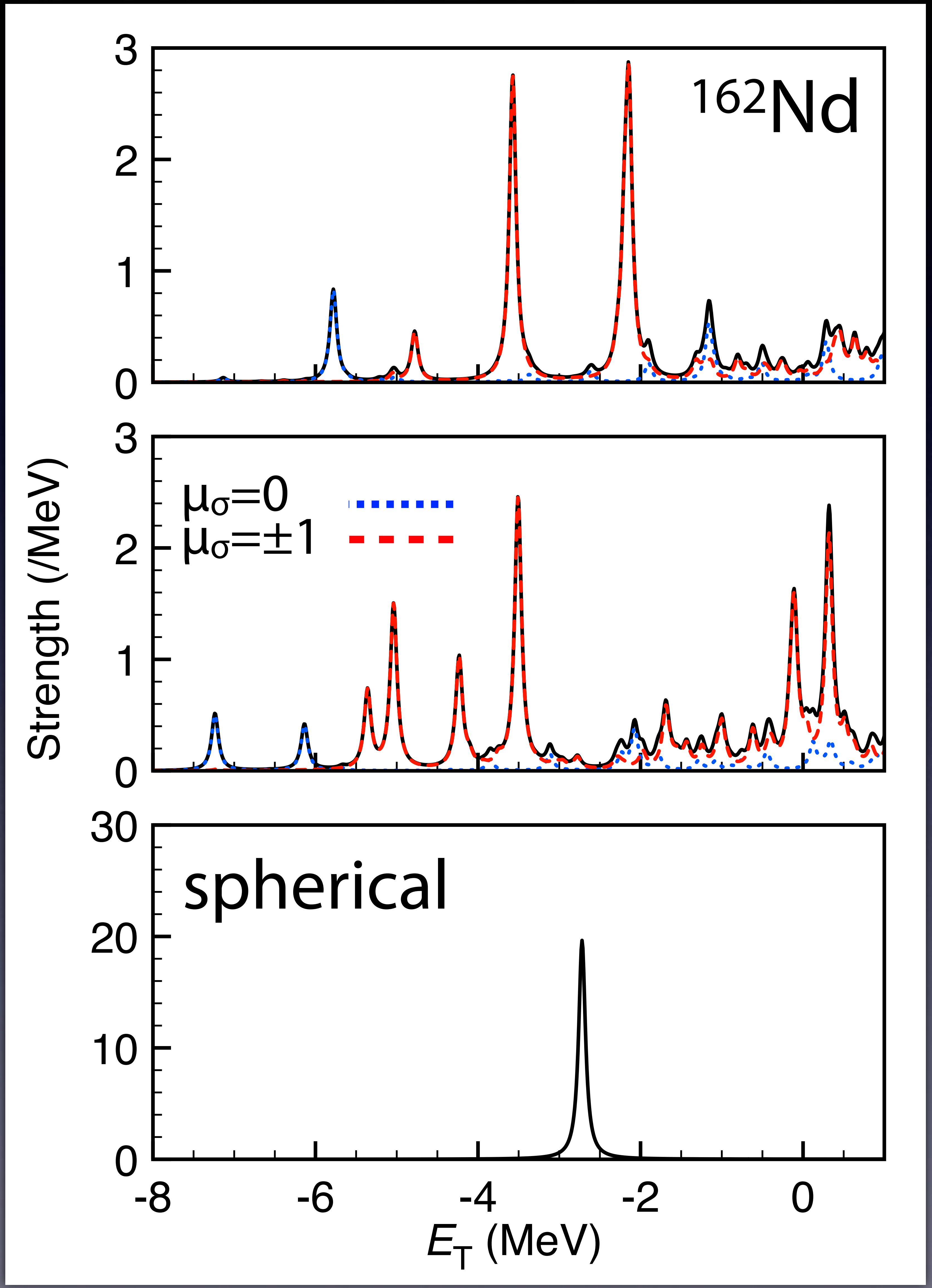
Roles of pairing and def. on beta-decay: naive picture

sensitive to shell structure
and pairing/deformation
(both T=0 and T=1)

$$\boldsymbol{V^{T=0} = f \cdot V^{T=1}}$$



Pairing and deformation for low-lying GT states



Exp.

$T_{1/2} = 0.31(20)$ s

$T_{1/2} = 0.27$ s

T=1 superfluidity

Energies are shifted higher

pairing gaps

Low-lying strengths are reduced

distortion of Fermi surfaces

$T_{1/2} = 0.14$ s

deformation

Quadrupole deformation ≃2^+ phonon condensation

non-perturbed phonon coupling

fragmentation and appearance of low-lying states

$T_{1/2} = 0.53$ s

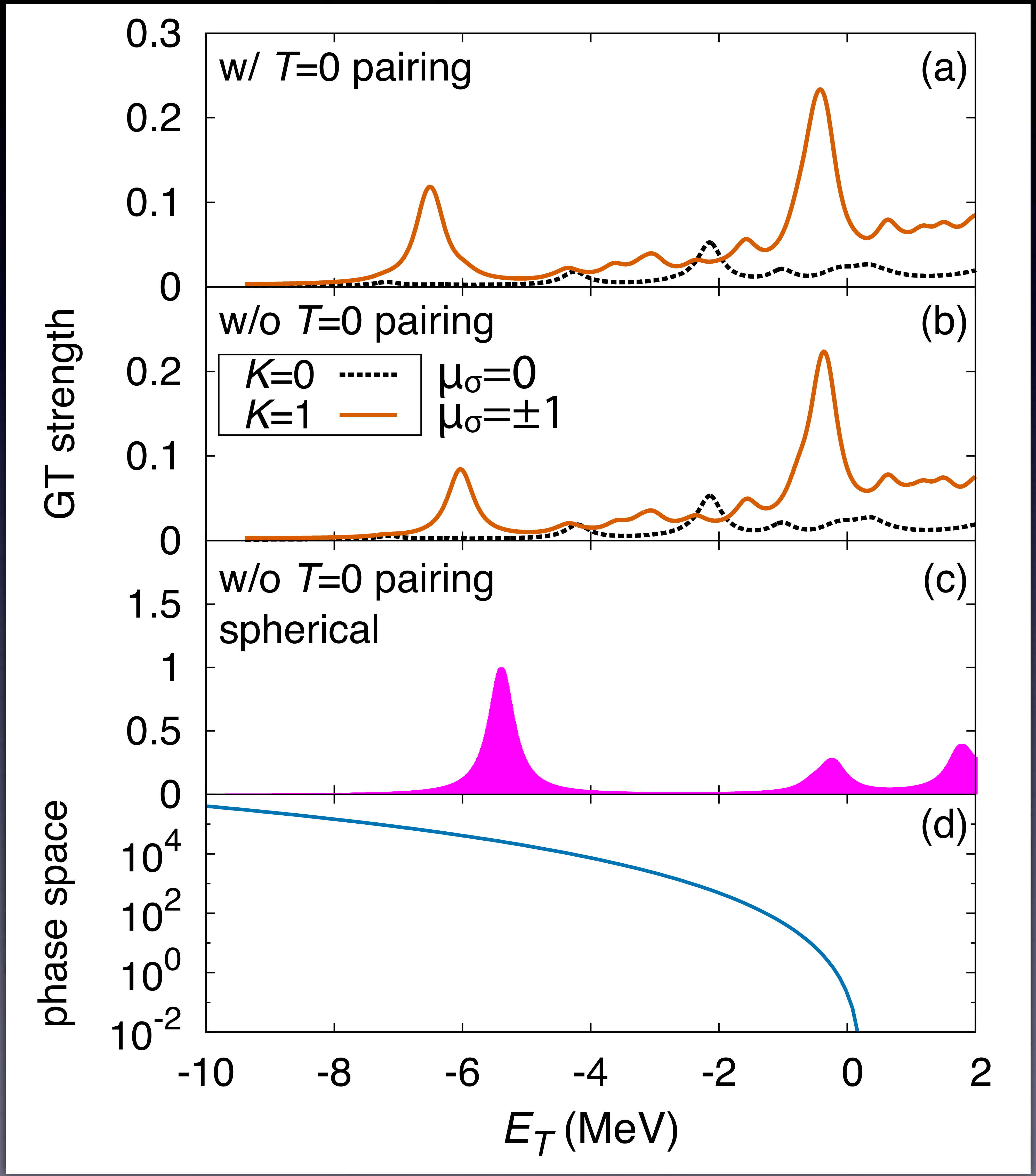
Strengths are concentrated on a single state w/ high energy

$\nu 1h_{9/2} \rightarrow \pi 1h_{11/2}$

SLy4 + pairing functional of M. Yamagami et al., PRC80(2009)064301

Pairing and deformation for low-lying GT states

^{106}Zr



KY, JPS Conf. Proc. 6(2015)020017

SLy4

$T_{1/2} = 0.21$ s

T=0 pairing

$T_{1/2} = 0.41$ s

deformation

T=1 superfluidity

$T_{1/2} = 0.07$ s

S. Nishimura et al., PRL106(2011)052502

Exp.

$T_{1/2} = 0.186(11)$ s

Effect of MB correlations on β-decay rate depends very much on the nuclide (shell structure)

Summary (I)

TDDFT gives an intuitive picture of nuclear dynamics by looking at the density distributions

Linear response is a powerful method to investigate vibration of densities

allowing the breaking of symmetries: rotational symmetry in space/gauge space, we can include the many-body correlations in a simple way

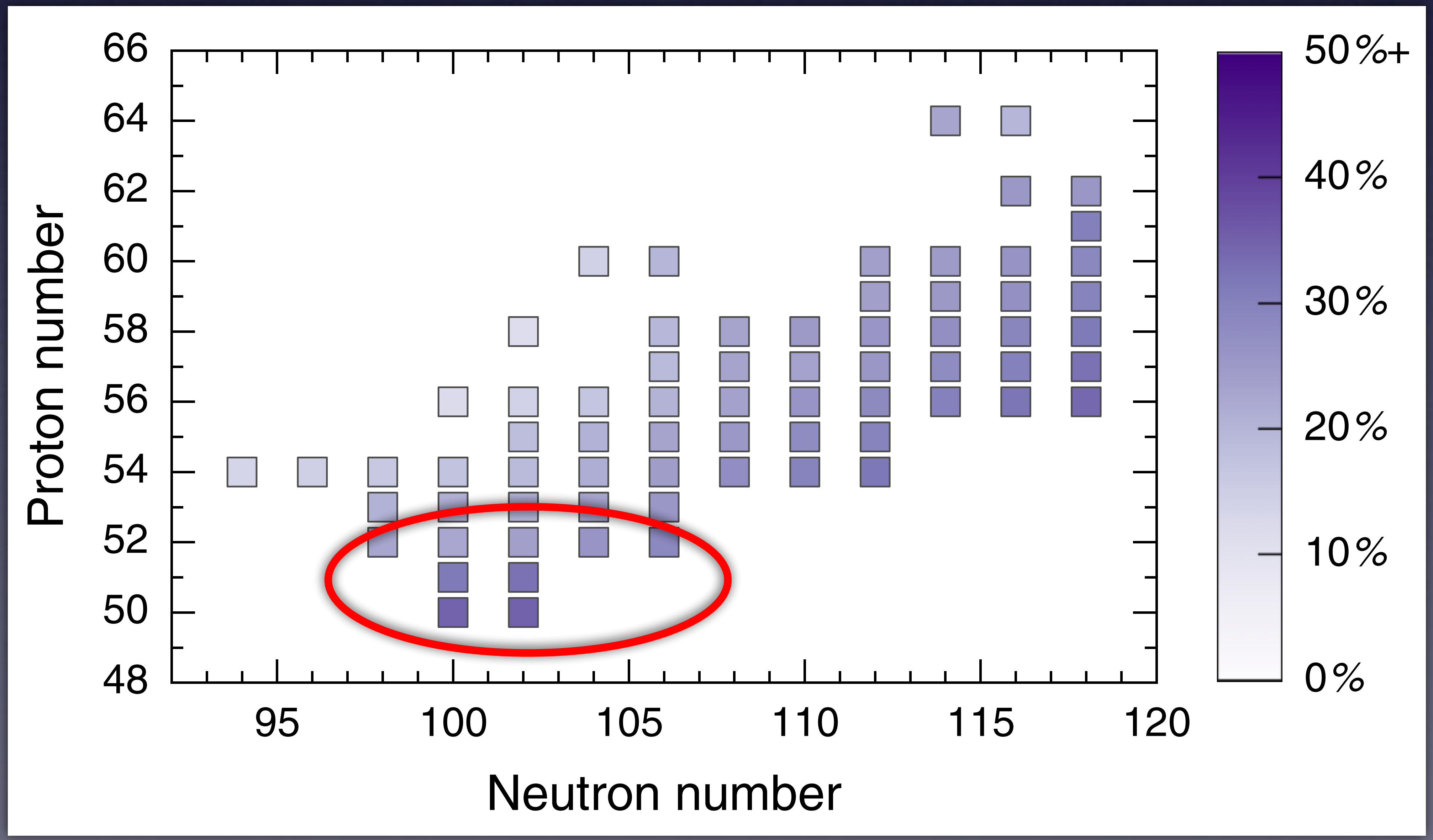
(Q)RPA on top of the deformed state includes (partly) the non-perturbed phonon coupling effect

β-decay rates are sensitive to the details of the strengths in low-energy

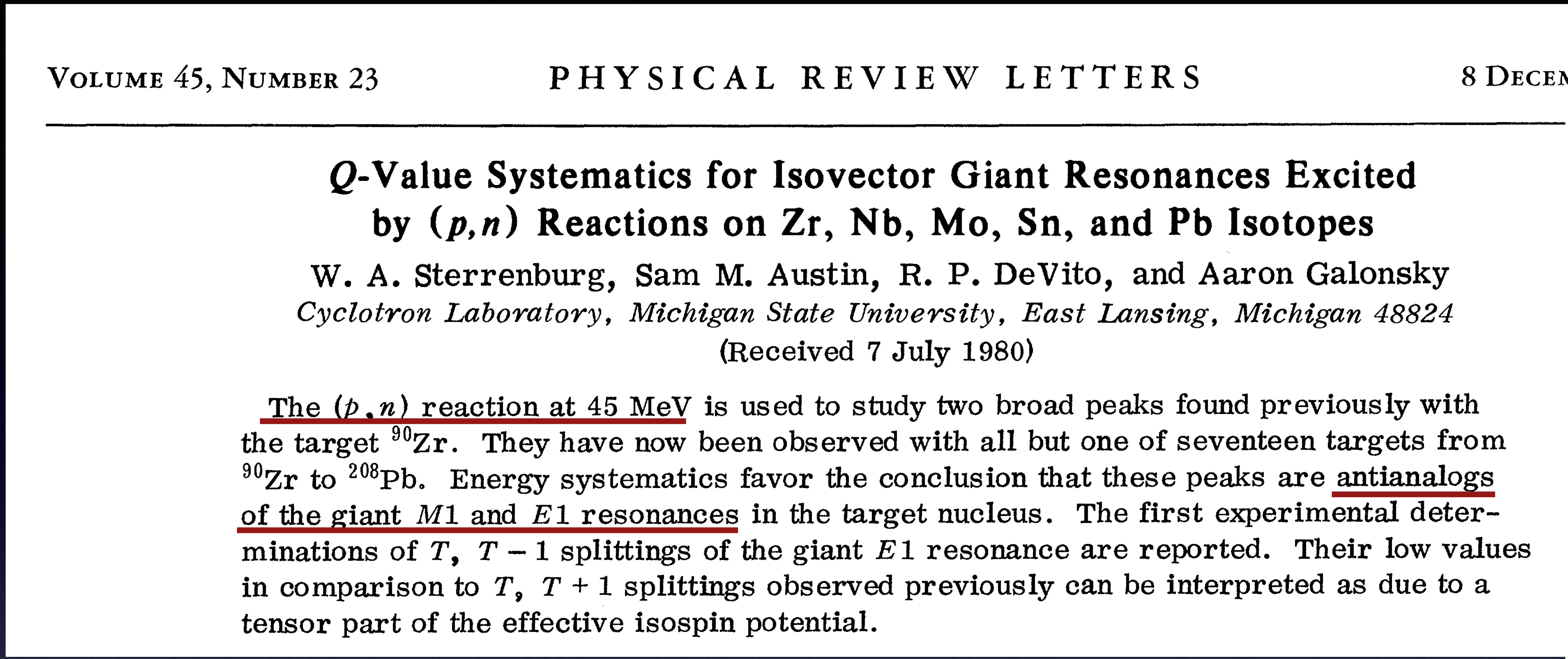
nuclear deformation and superfluidity

Low-lying charge-exchange dipole modes in very-neutron rich nuclei

(spherical systems for simplicity)



Shafer, Engel et al., PRC94(2016)055802



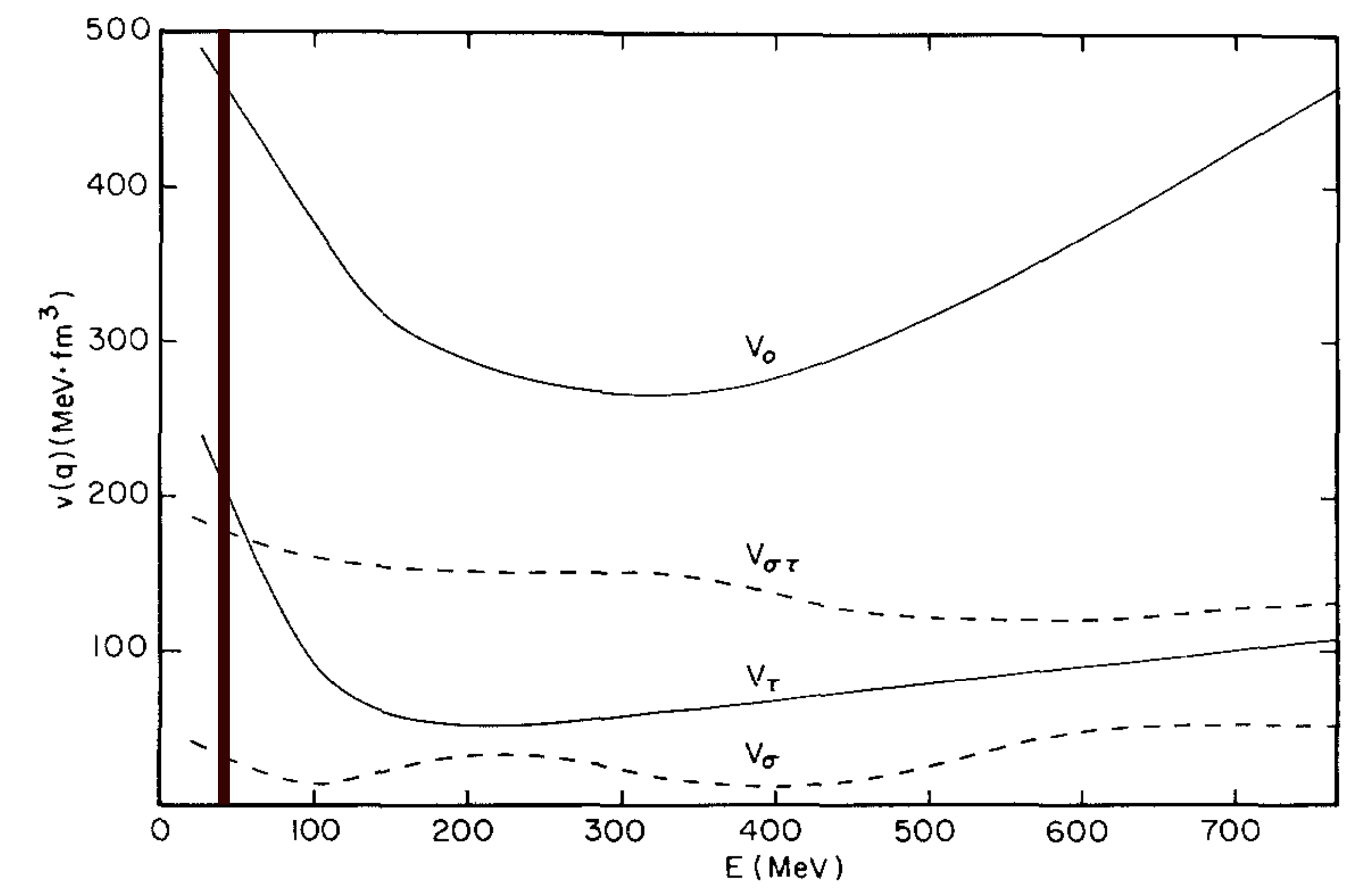
VOLUME 45, NUMBER 23 PHYSICAL REVIEW LETTERS 8 DECEMBER 1980

Q-Value Systematics for Isovector Giant Resonances Excited by (p,n) Reactions on Zr, Nb, Mo, Sn, and Pb Isotopes

W. A. Sterrenburg, Sam M. Austin, R. P. DeVito, and Aaron Galonsky
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

(Received 7 July 1980)

The (p,n) reaction at 45 MeV is used to study two broad peaks found previously with the target ^{90}Zr. They have now been observed with all but one of seventeen targets from ^{90}Zr to ^{208}Pb. Energy systematics favor the conclusion that these peaks are antianalogs of the giant $M1$ and $E1$ resonances in the target nucleus. The first experimental determinations of T, $T-1$ splittings of the giant $E1$ resonance are reported. Their low values in comparison to T, $T+1$ splittings observed previously can be interpreted as due to a tensor part of the effective isospin potential.



P. Petrovich and W. G. Love, NPA354(1981)499c

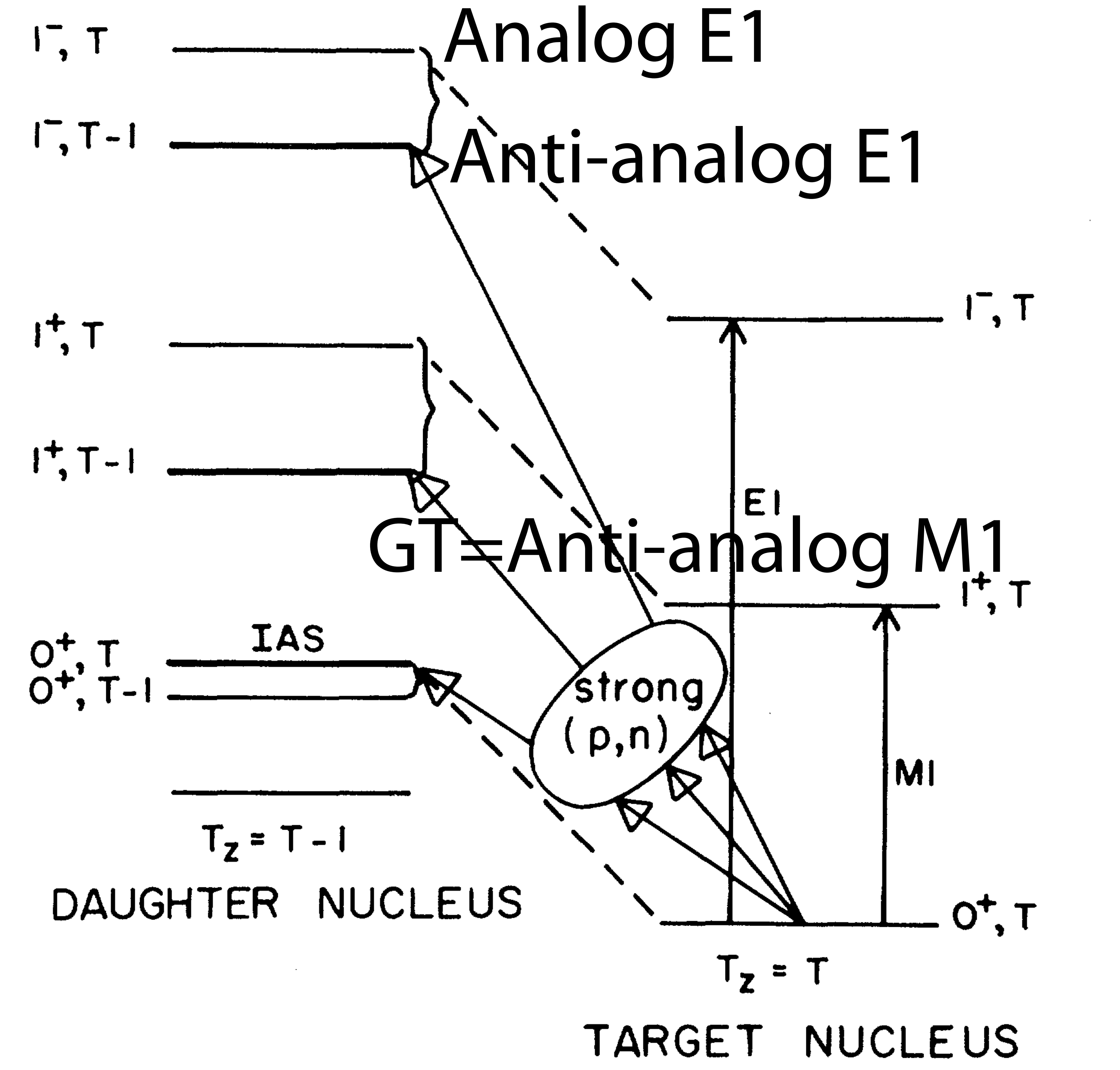
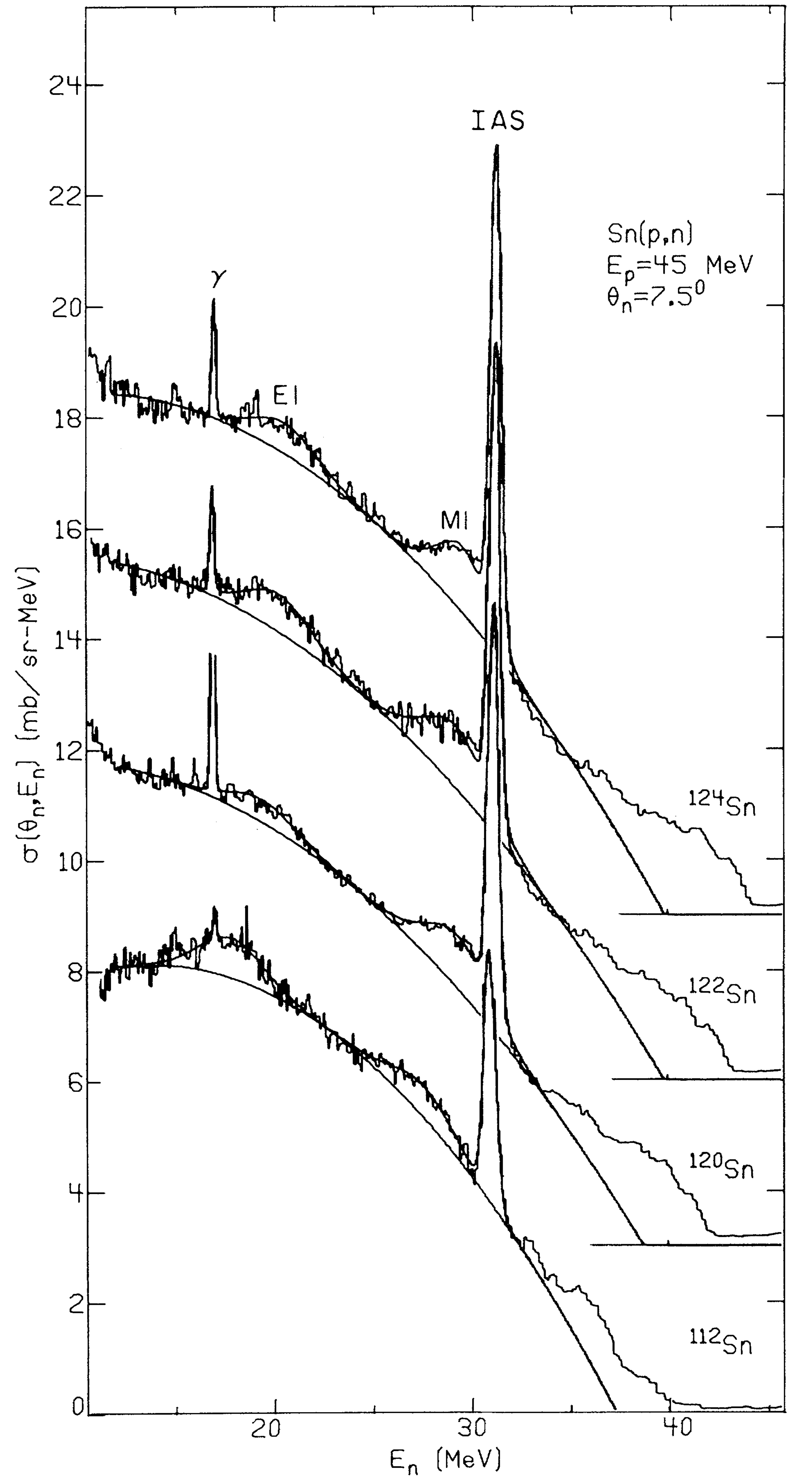
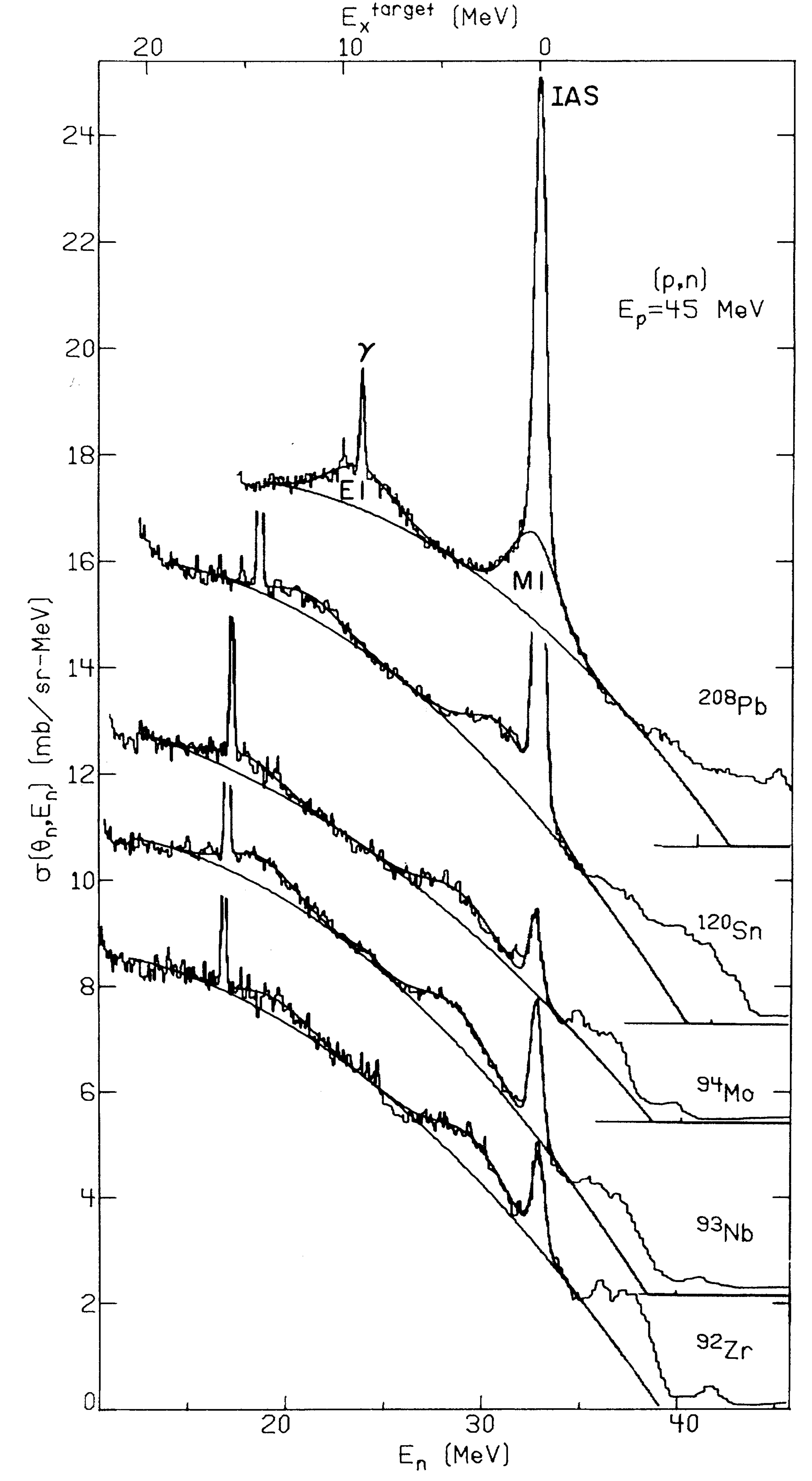
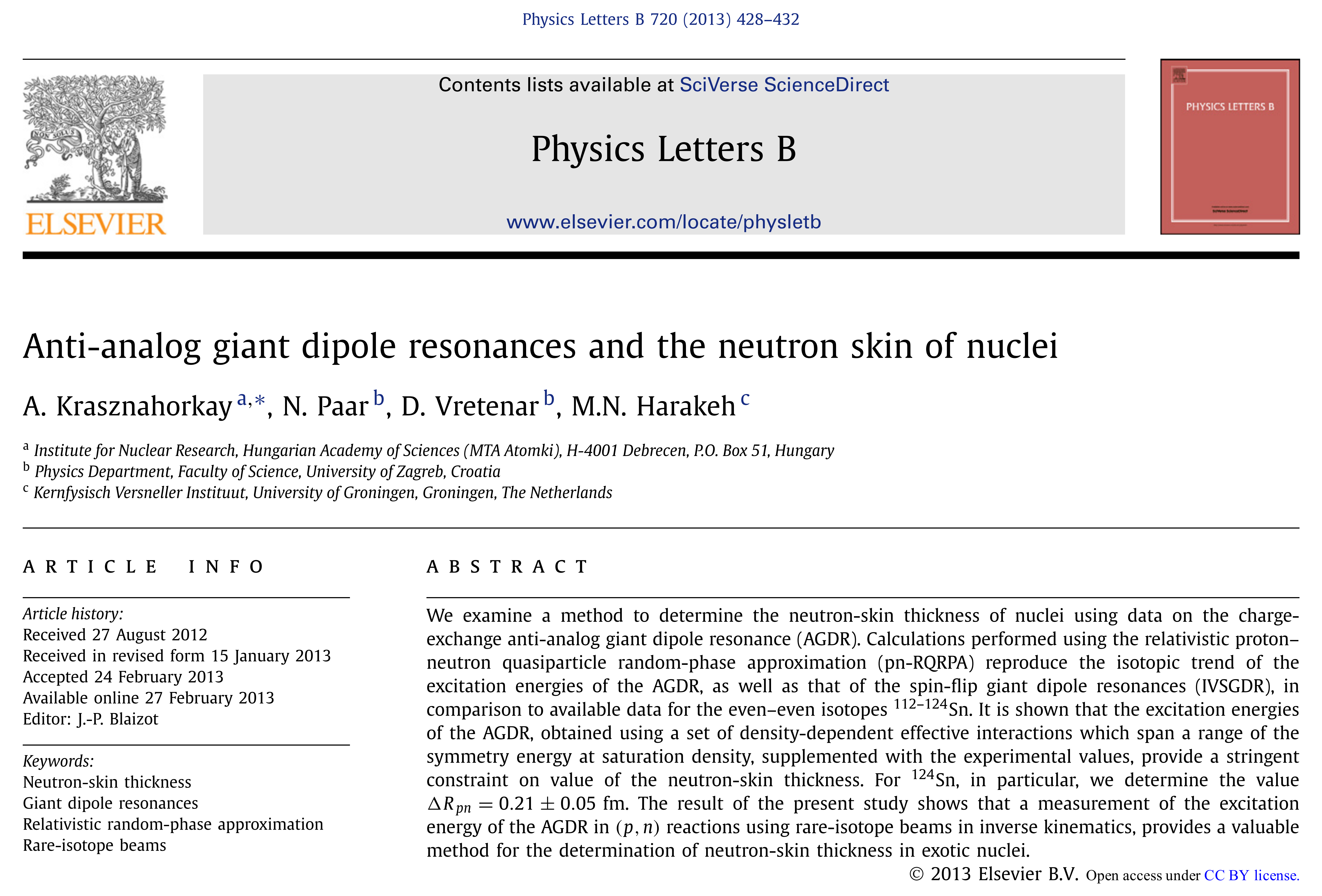


FIG. 1. Some states of the target nucleus ($T_z = T$) and their analogs (isospin $= T$) and antianalogs (isospin $= T-1$) in the $T_z = T-1$ nucleus resulting from a (p,n) reaction. The target states are the ground state and the $M1$ and $E1$ giant resonant states. Isospin geometry strongly favors the three transitions indicated.


IAS
γ
E1
M1
Sn(p,n)
E_p=45 MeV
θ_n=7.5°
^{124}Sn
^{122}Sn
^{120}Sn
^{112}Sn
σ(θ$_n$,E$_n$) (mb/sr-MeV)
0
2
4
6
8
10
12
14
16
18
20
22
24
20
30
40
E$_n$ (MeV)


E$_x$^{target} (MeV)
20
10
0
IAS
γ
E1
M1
(p,n)
E_p=45 MeV
^{208}Pb
^{120}Sn
^{94}Mo
^{93}Nb
^{92}Zr
σ(θ$_n$,E$_n$) (mb/sr-MeV)
0
2
4
6
8
10
12
14
16
18
20
22
24
20
30
40
E$_n$ (MeV)



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Anti-analog giant dipole resonances and the neutron skin of nuclei

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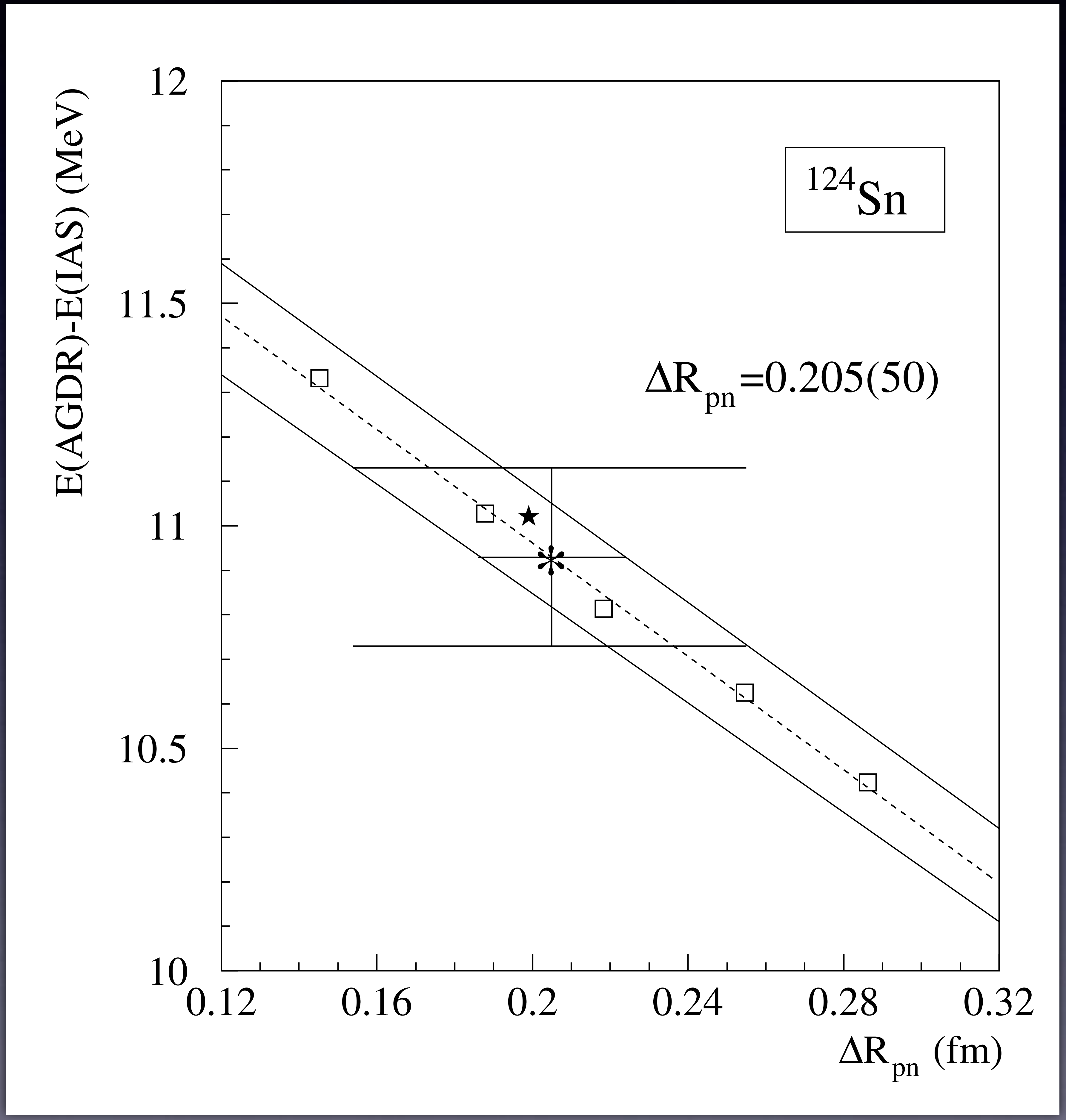
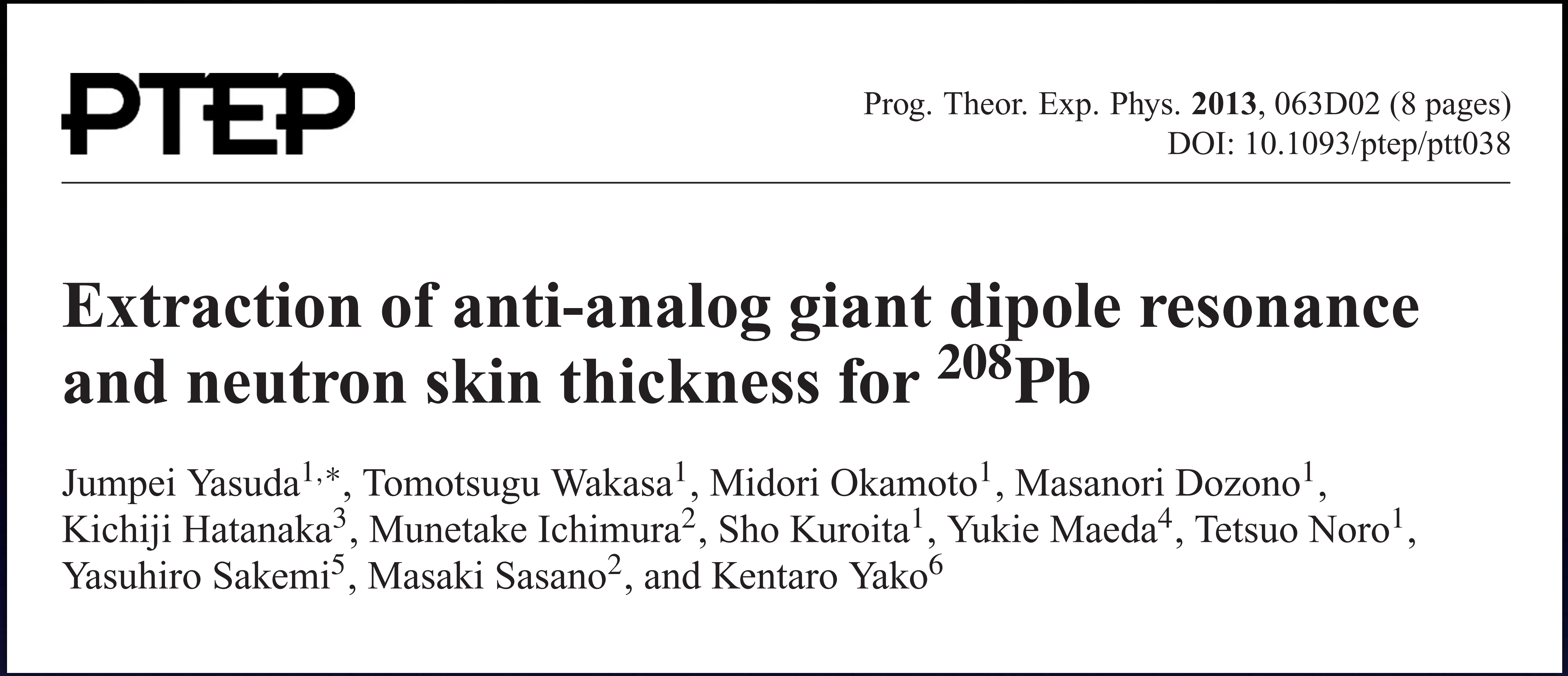
ABSTRACT

We examine a method to determine the neutron-skin thickness of nuclei using data on the charge-exchange anti-analog giant dipole resonance (AGDR). Calculations performed using the relativistic proton–neutron quasiparticle random-phase approximation (pn-RQRPA) reproduce the isotopic trend of the excitation energies of the AGDR, as well as that of the spin-flip giant dipole resonances (IVSGDR), in comparison to available data for the even–even isotopes $^{112-124}$Sn. It is shown that the excitation energies of the AGDR, obtained using a set of density-dependent effective interactions which span a range of the symmetry energy at saturation density, supplemented with the experimental values, provide a stringent constraint on value of the neutron-skin thickness. For ^{124}Sn, in particular, we determine the value $\Delta R_{pn} = 0.21 \pm 0.05$ fm. The result of the present study shows that a measurement of the excitation energy of the AGDR in (p, n) reactions using rare-isotope beams in inverse kinematics, provides a valuable method for the determination of neutron-skin thickness in exotic nuclei.

pnRQRPA
□ :J=30,32,34,36,38
★:DD-ME2



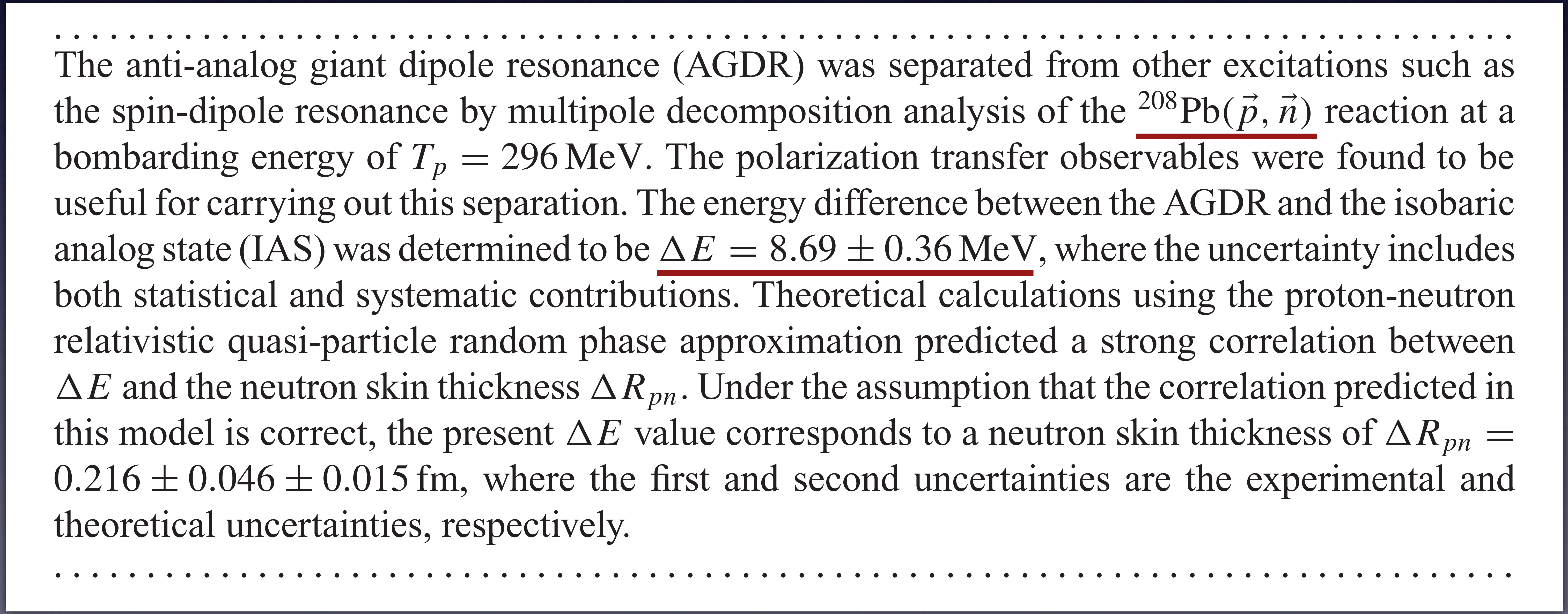


PTEP

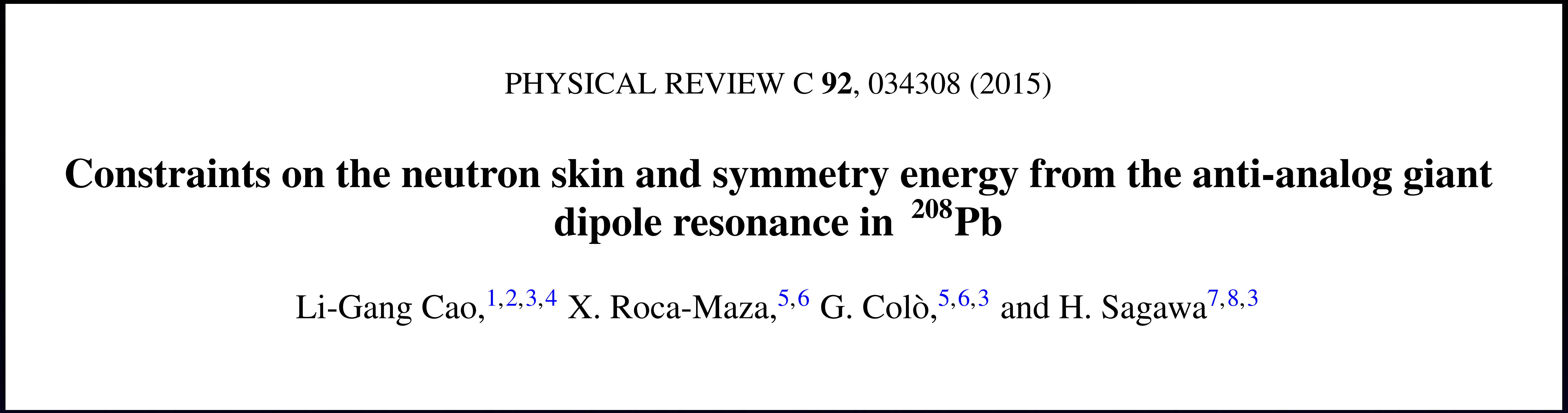
Prog. Theor. Exp. Phys. **2013**, 063D02 (8 pages)
DOI: 10.1093/ptep/ptt038

Extraction of anti-analog giant dipole resonance and neutron skin thickness for ^{208}Pb

Jumpei Yasuda[1,*], Tomotsugu Wakasa[1], Midori Okamoto[1], Masanori Dozono[1], Kichiji Hatanaka[3], Munetake Ichimura[2], Sho Kuroita[1], Yukie Maeda[4], Tetsuo Noro[1], Yasuhiro Sakemi[5], Masaki Sasano[2], and Kentaro Yako[6]



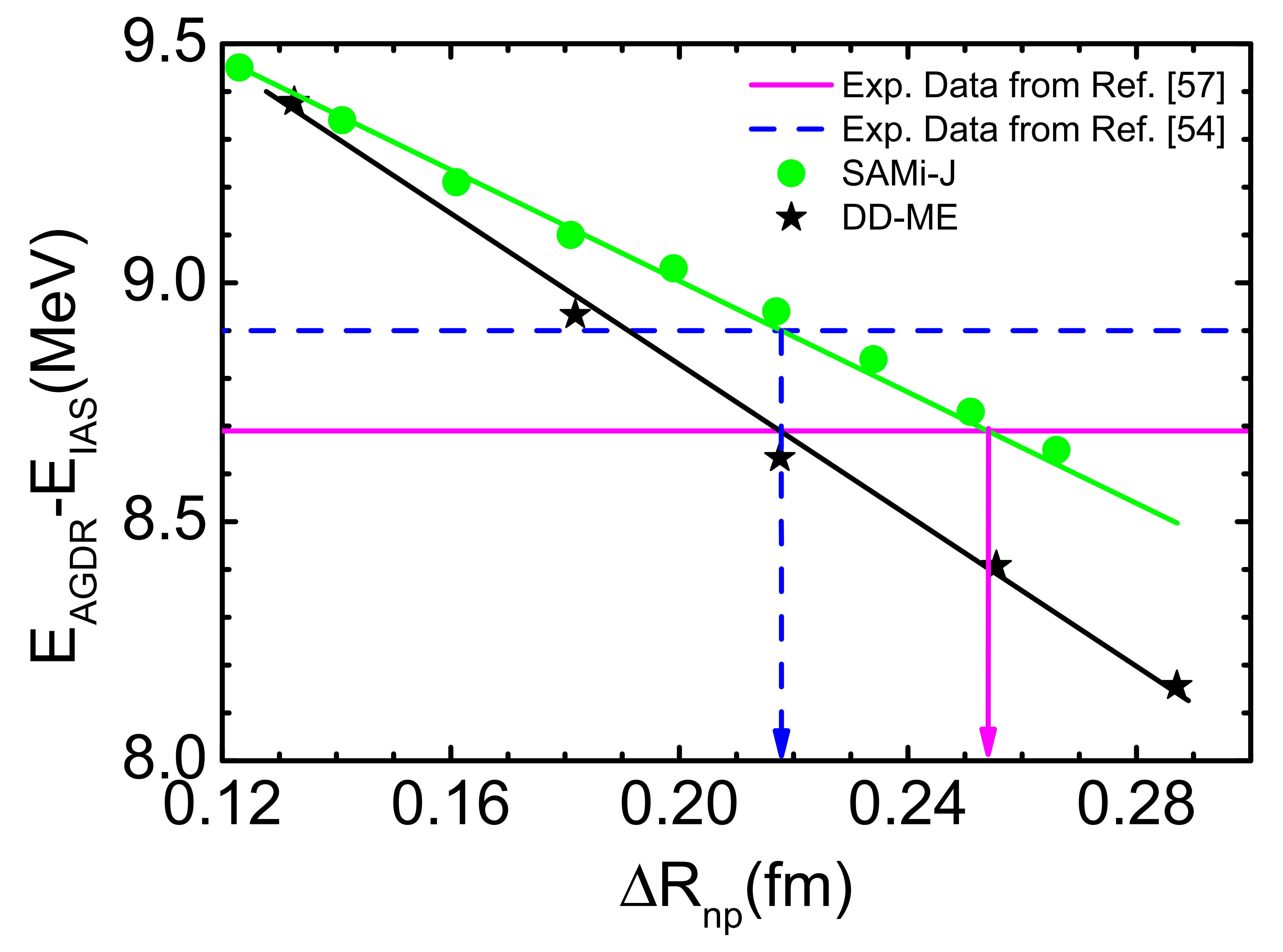
The anti-analog giant dipole resonance (AGDR) was separated from other excitations such as the spin-dipole resonance by multipole decomposition analysis of the $^{208}\mathrm{Pb}(\vec{p}, \vec{n})$ reaction at a bombarding energy of $T_p = 296$ MeV. The polarization transfer observables were found to be useful for carrying out this separation. The energy difference between the AGDR and the isobaric analog state (IAS) was determined to be $\Delta E = 8.69 \pm 0.36$ MeV, where the uncertainty includes both statistical and systematic contributions. Theoretical calculations using the proton-neutron relativistic quasi-particle random phase approximation predicted a strong correlation between ΔE and the neutron skin thickness ΔR_{pn}. Under the assumption that the correlation predicted in this model is correct, the present ΔE value corresponds to a neutron skin thickness of $\Delta R_{pn} = 0.216 \pm 0.046 \pm 0.015$ fm, where the first and second uncertainties are the experimental and theoretical uncertainties, respectively.



PHYSICAL REVIEW C **92**, 034308 (2015)

Constraints on the neutron skin and symmetry energy from the anti-analog giant dipole resonance in ^{208}Pb

Li-Gang Cao,[1,2,3,4] X. Roca-Maza,[5,6] G. Colò,[5,6,3] and H. Sagawa[7,8,3]



First-forbidden vector (FFV) modes
= charge-exchange dipole ~ anti-analog dipole

effect of isospin mixing(?) not discussed

$$\hat{O}_{K\mu} = \int d\boldsymbol{r} \sum_{\sigma\sigma'} \sum_{\tau\tau'} r Y_{1K} \delta_{\sigma,\sigma'} \langle\tau|\tau_\mu|\tau'\rangle \hat{\psi}^\dagger(\boldsymbol{r}\sigma\tau)\hat{\psi}(\boldsymbol{r}\sigma'\tau')$$

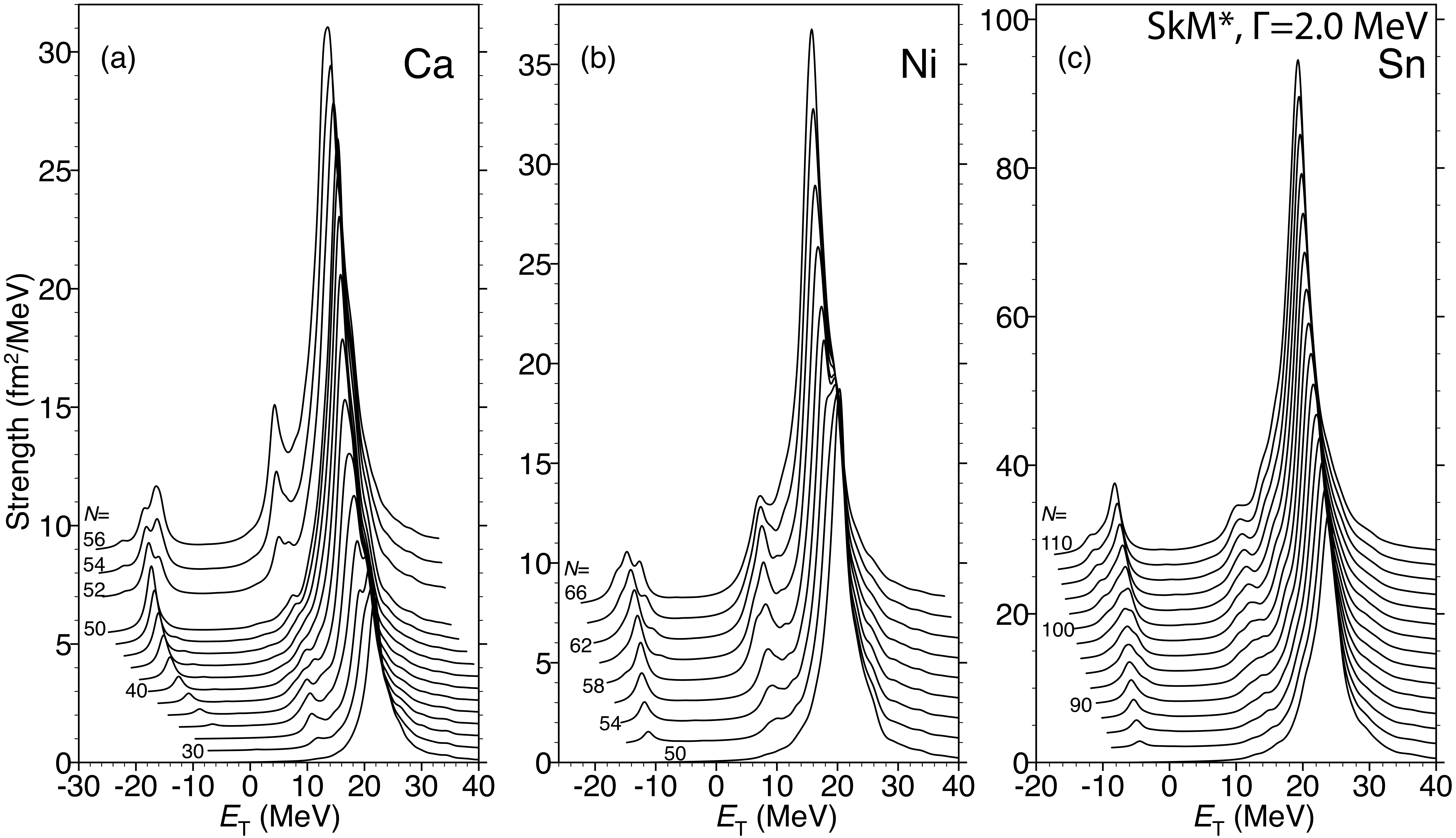
focus on μ=-1 excitations in neutron-rich nuclei

(anti-)analog of pygmy dipole (Low-energy dipole) mode??

understanding of PDR (LED) in terms of iso-triplet states

general mechanism for emergence of the PDR

appearance of the low-lying mode and its effect on FF transitions?


SkM*, Γ=2.0 MeV
(a)
Ca
(b)
Ni
(c)
Sn
Strength (fm²/MeV)
N=
56
54
52
50
40
30
N=
66
62
58
54
50
N=
110
100
90
0
5
10
15
20
25
30
35
40
60
80
100
-30
-20
-10
0
10
20
30
40
E_T (MeV)
E_T (MeV)
E_T (MeV)

Mechanism for the occurrence of the low-lying FFV mode

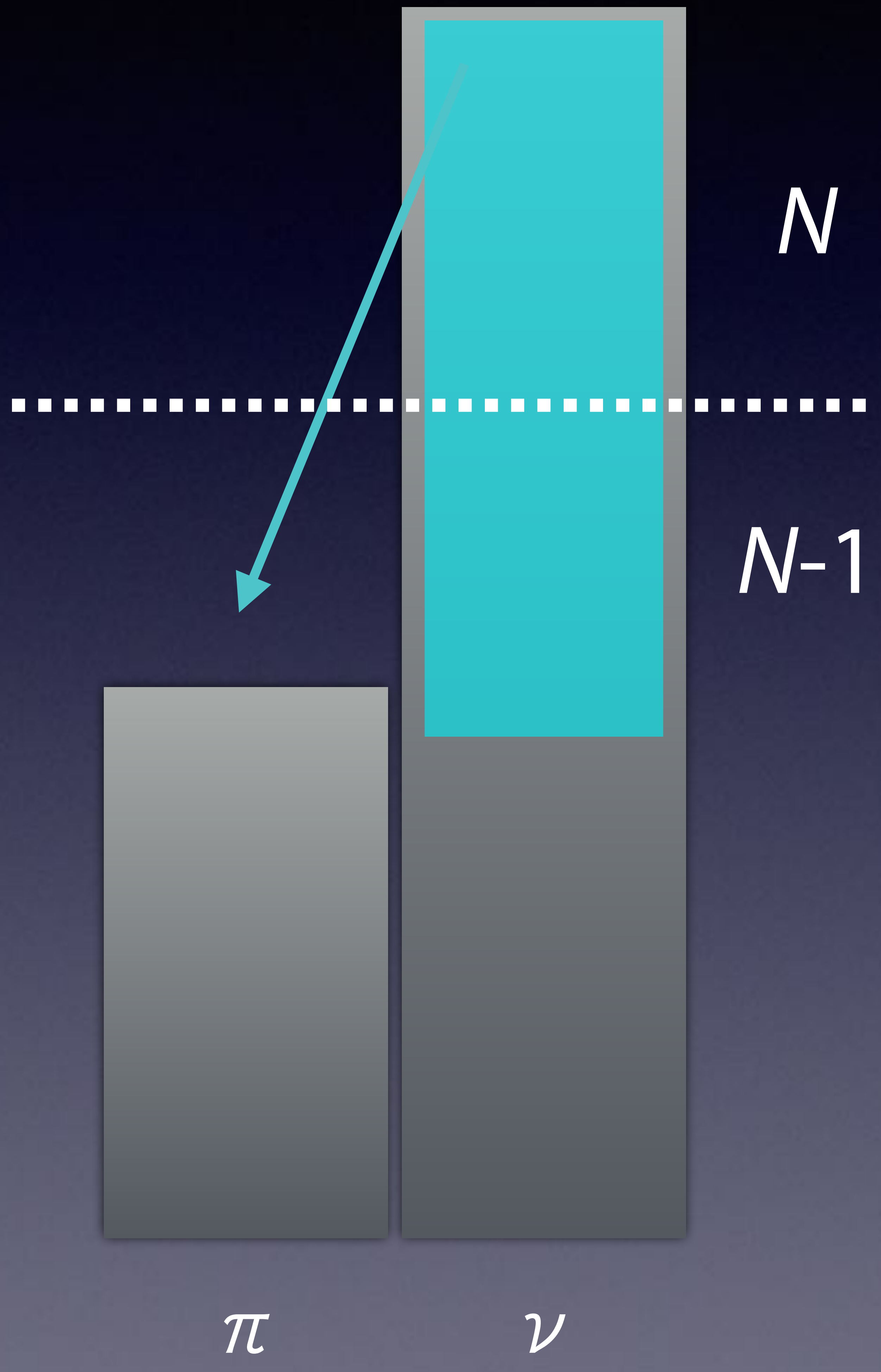
cross-shell ($N \rightarrow N$-1) excitation in low-energy

$-1\hbar\omega$ excitation

neutrons are weakly bound
(quasi)neutrons are in the continuum when $|\lambda| \simeq 0$

↓

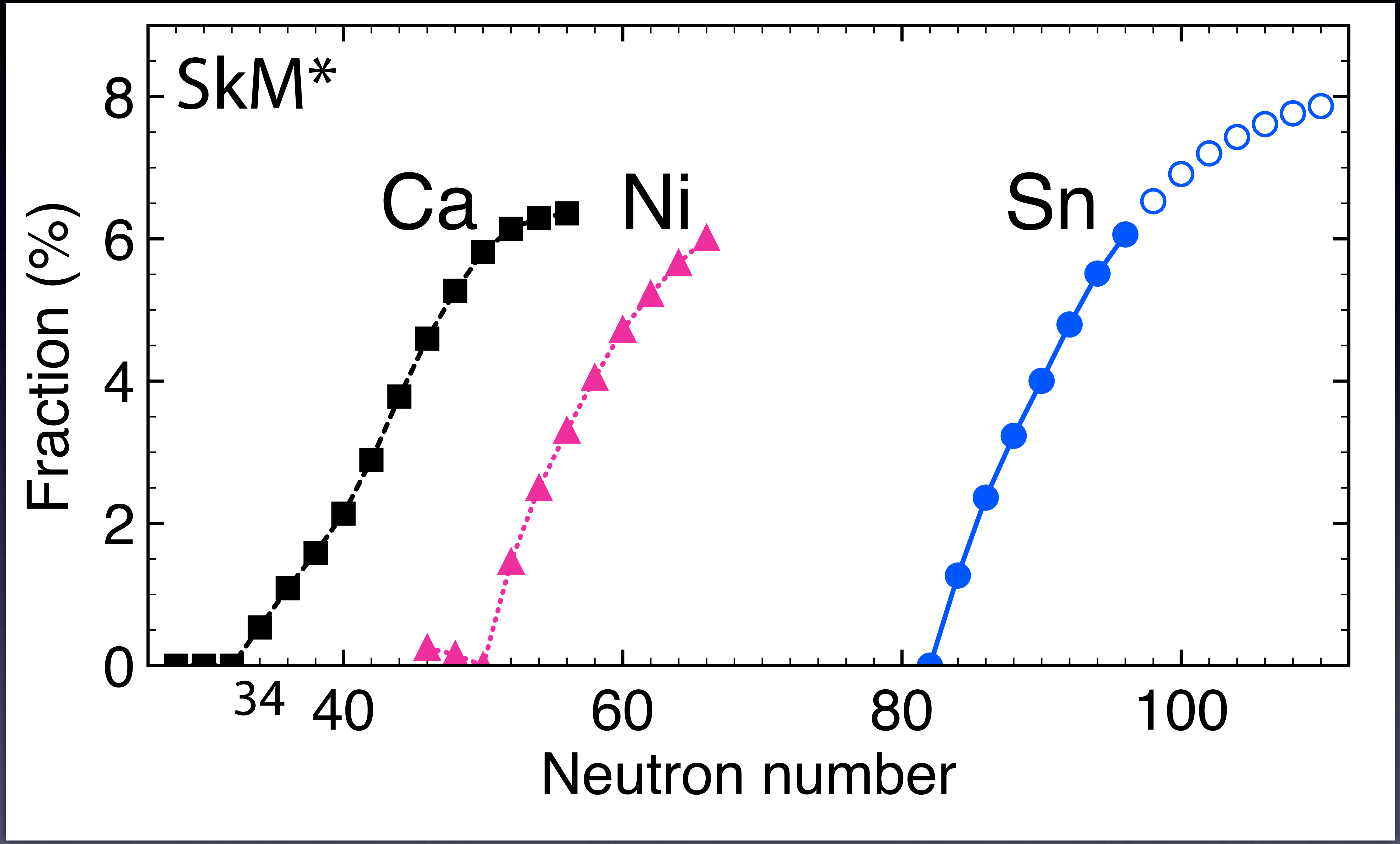
protons are deeply bound



Onset of low-lying FFV mode: sensitive to the shell structure

summed strength in low-energy (ω < 15 MeV)

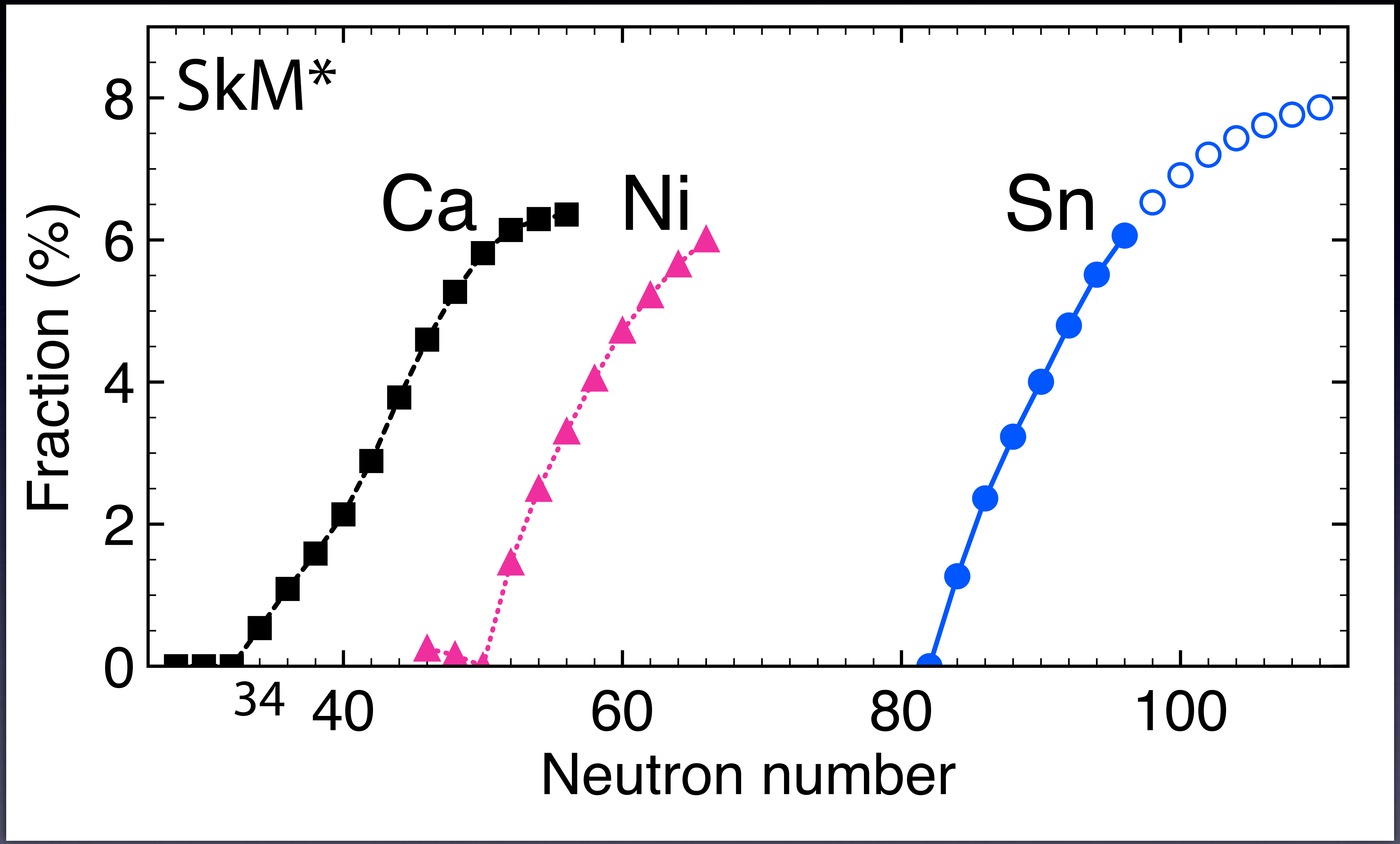
SkM*



strong shell effect

Onset of low-lying FFV mode: sensitive to the shell structure

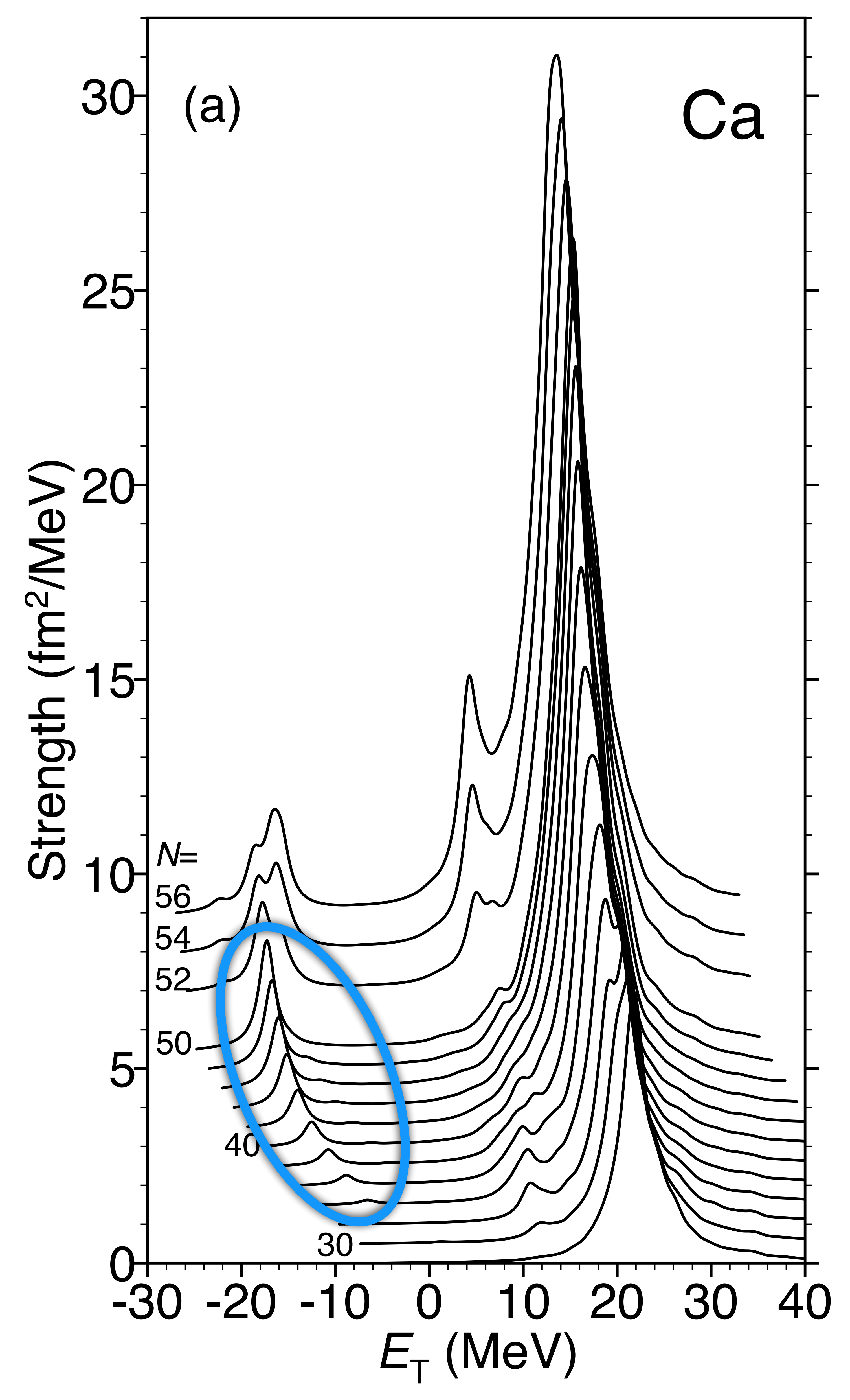
summed strength in low-energy



Is this because the occupation of $f_{5/2}$ begins?

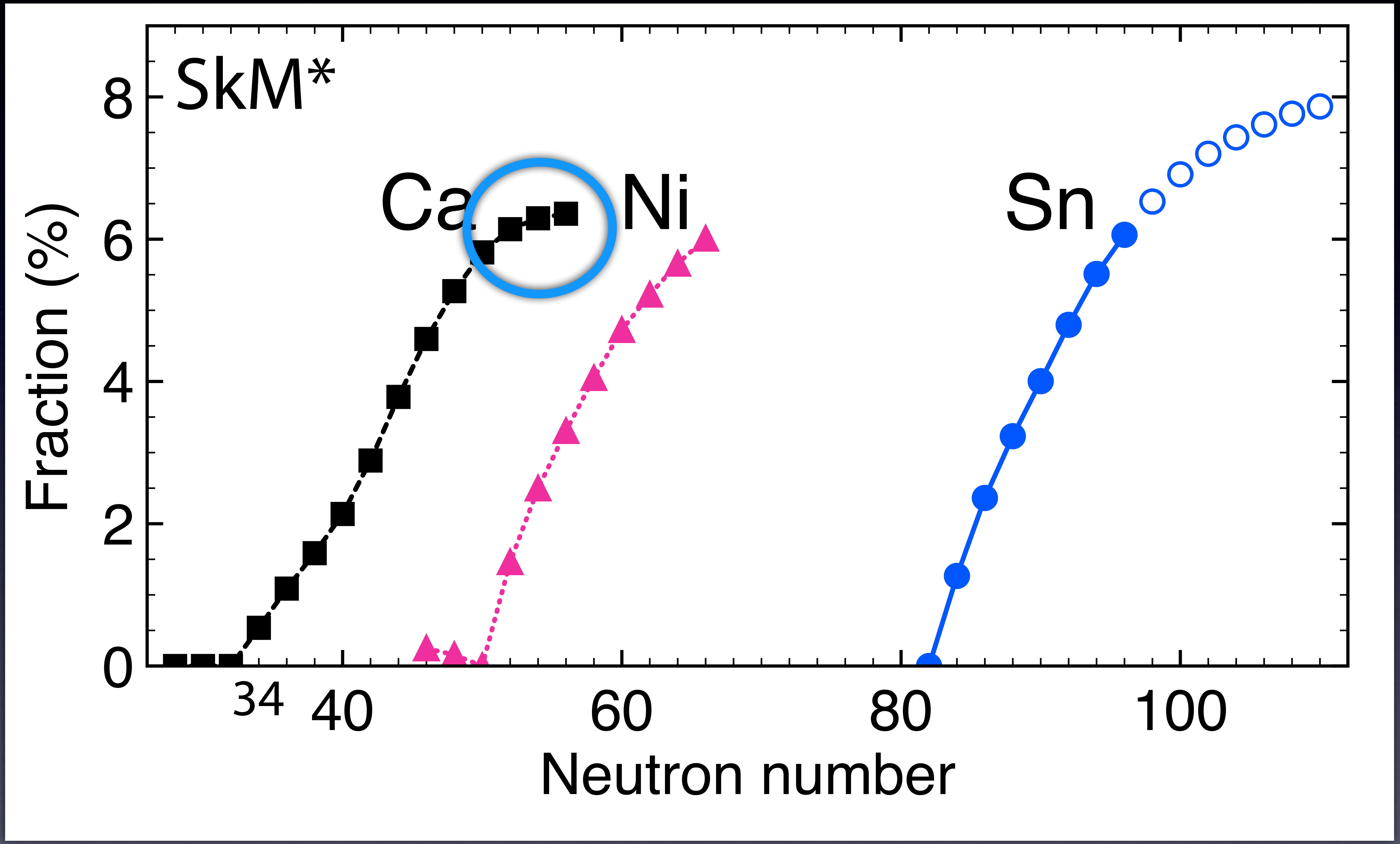
No, occupation of $g_{9/2}$ begins due to pairing

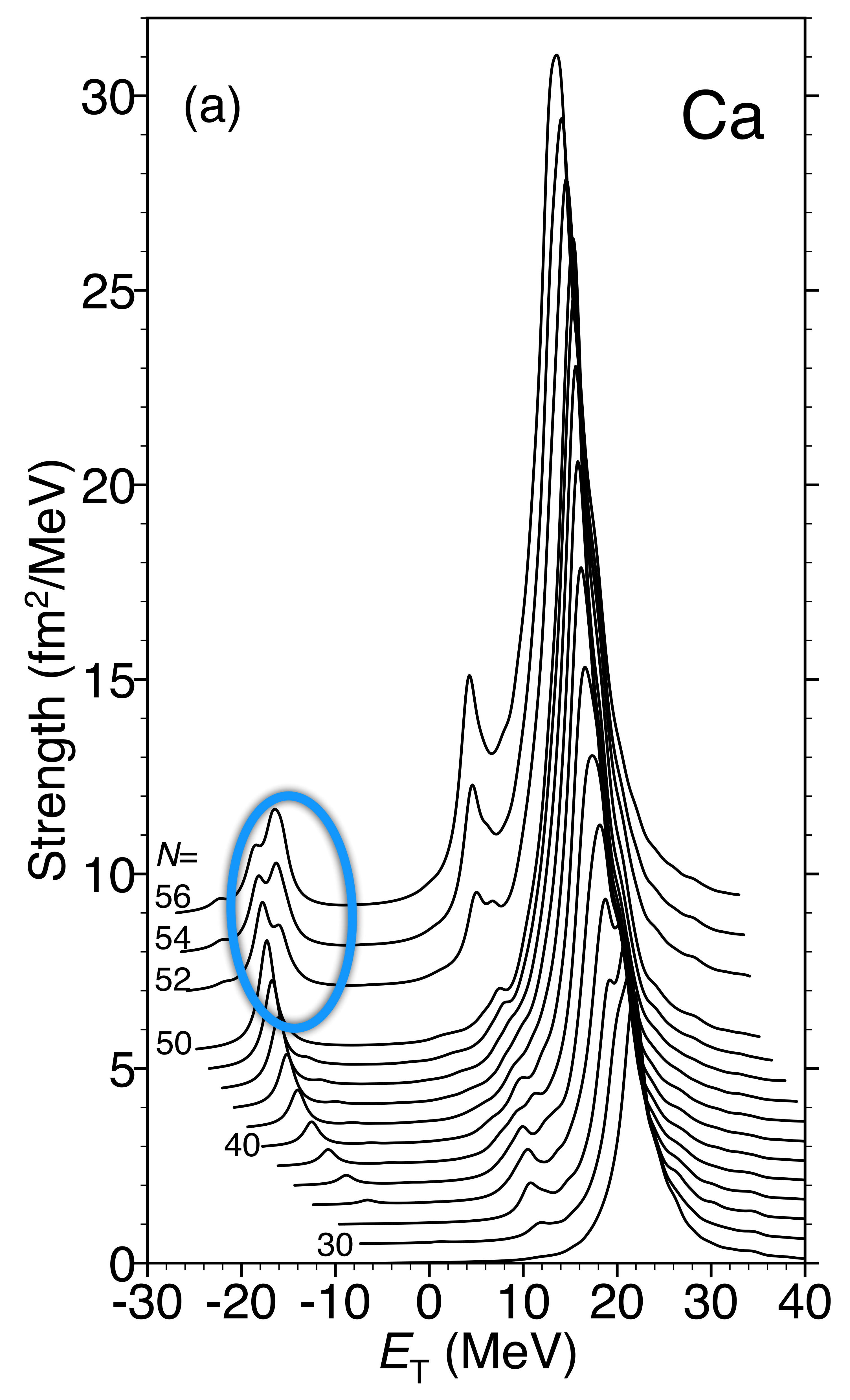
$\nu g_{9/2} \rightarrow \pi f_{7/2}$



Onset of low-lying FFV mode: sensitive to the shell structure

summed strength in low-energy



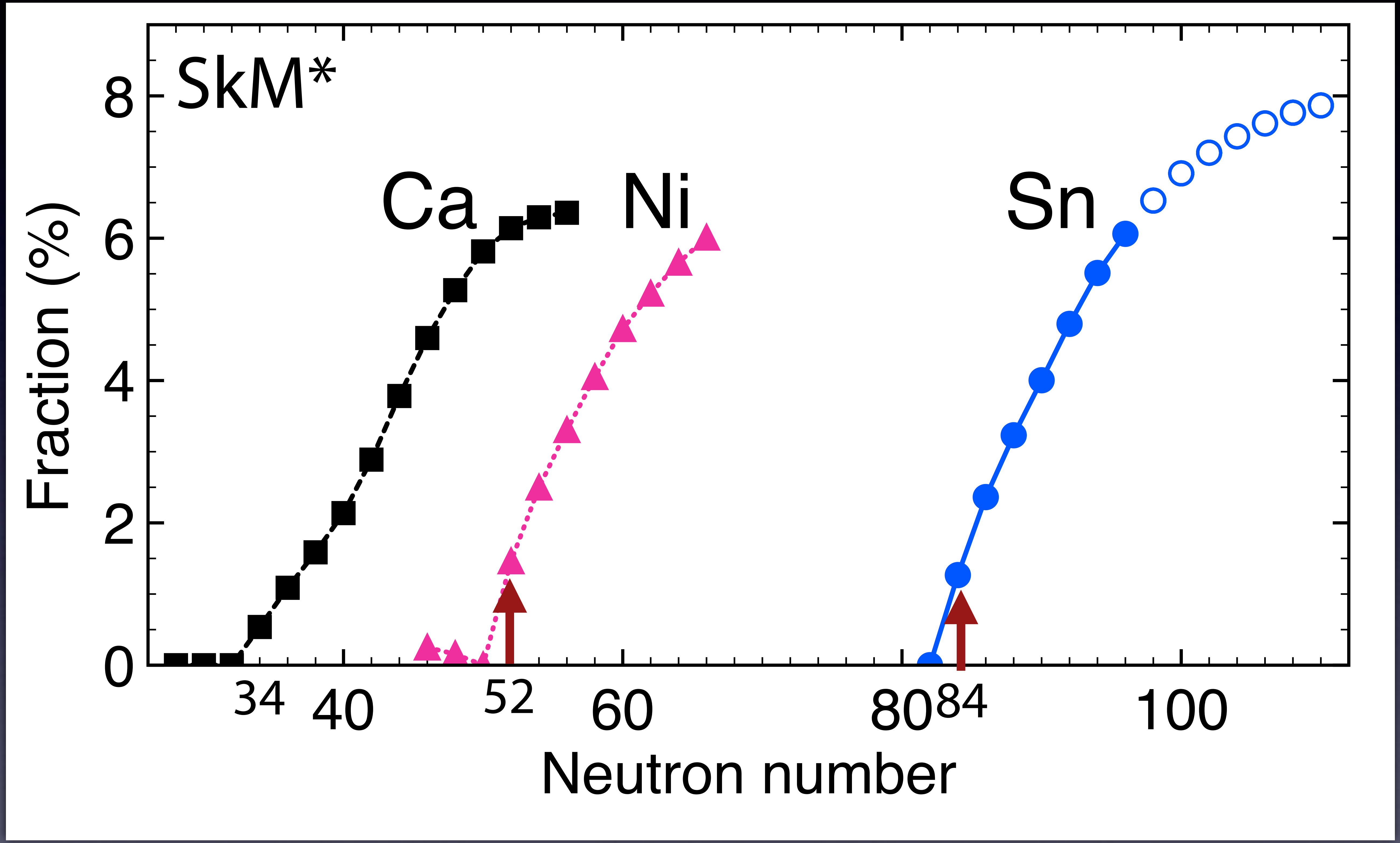


Neutrons start occupying the loosely-bound $d_{5/2}$

λ=-0.4~-0.6 MeV

Onset of low-lying FFV mode: sensitive to the shell structure

summed strength in low-energy



occupation of $d_{5/2}$

occupation of $f_{7/2}$

Microscopic structure of the low-lying FFV mode in Ni isotopes

N=52~56

$\nu 2d_{5/2} \rightarrow \pi 2p_{3/2}$

N=58~

$\nu 2d_{5/2} \rightarrow \pi 2p_{3/2}$

$\nu 3s_{1/2} \rightarrow \pi 2p_{1/2}$

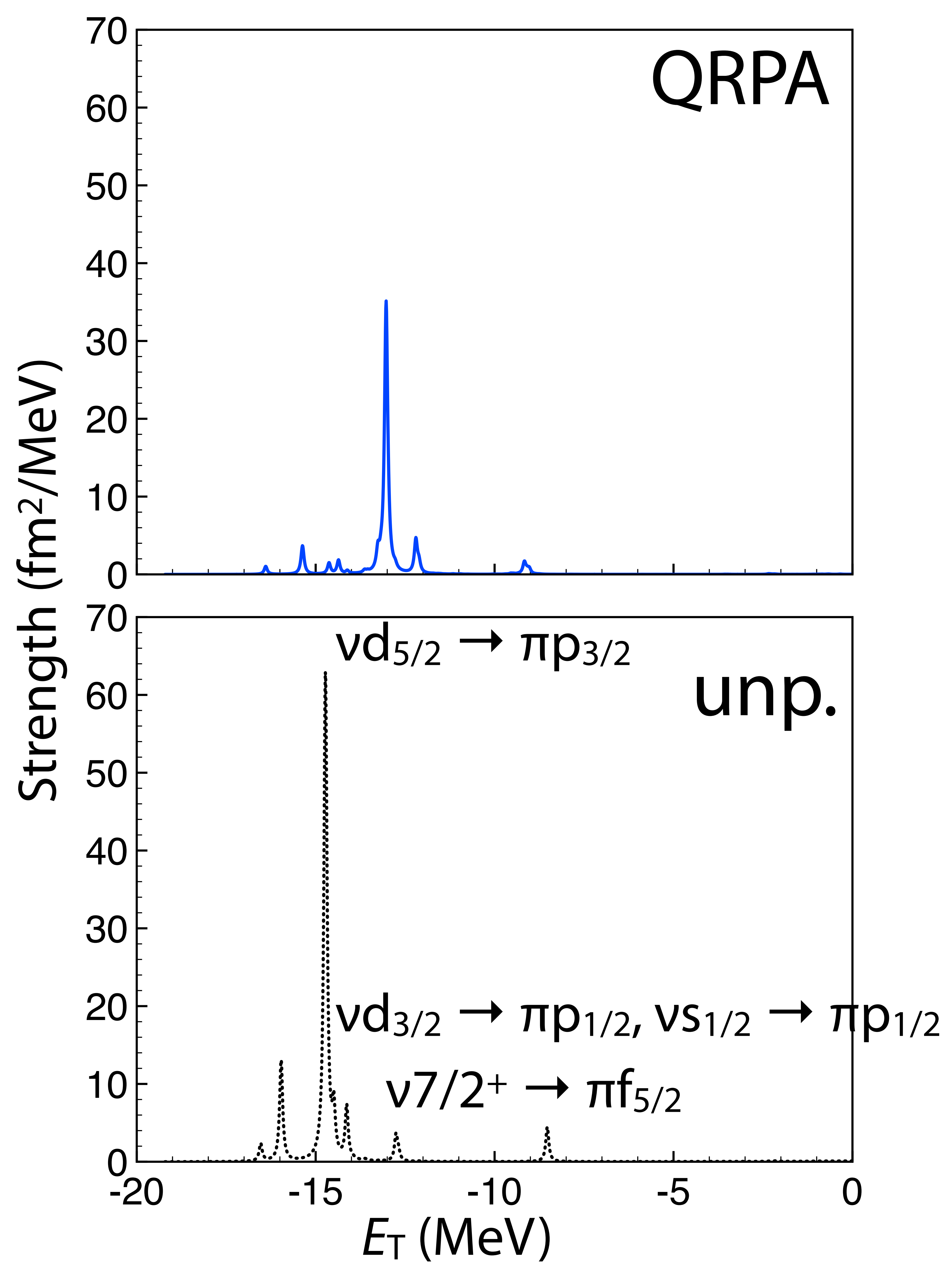
s-wave q.p.resonance

$\nu 7/2^{+} \rightarrow \pi 2p_{1/2}$

discretised continuum besides the $g_{7/2}$ hole-like resonance

^{88}Ni

Γ=0.1 MeV



Appearance of the FFV modes

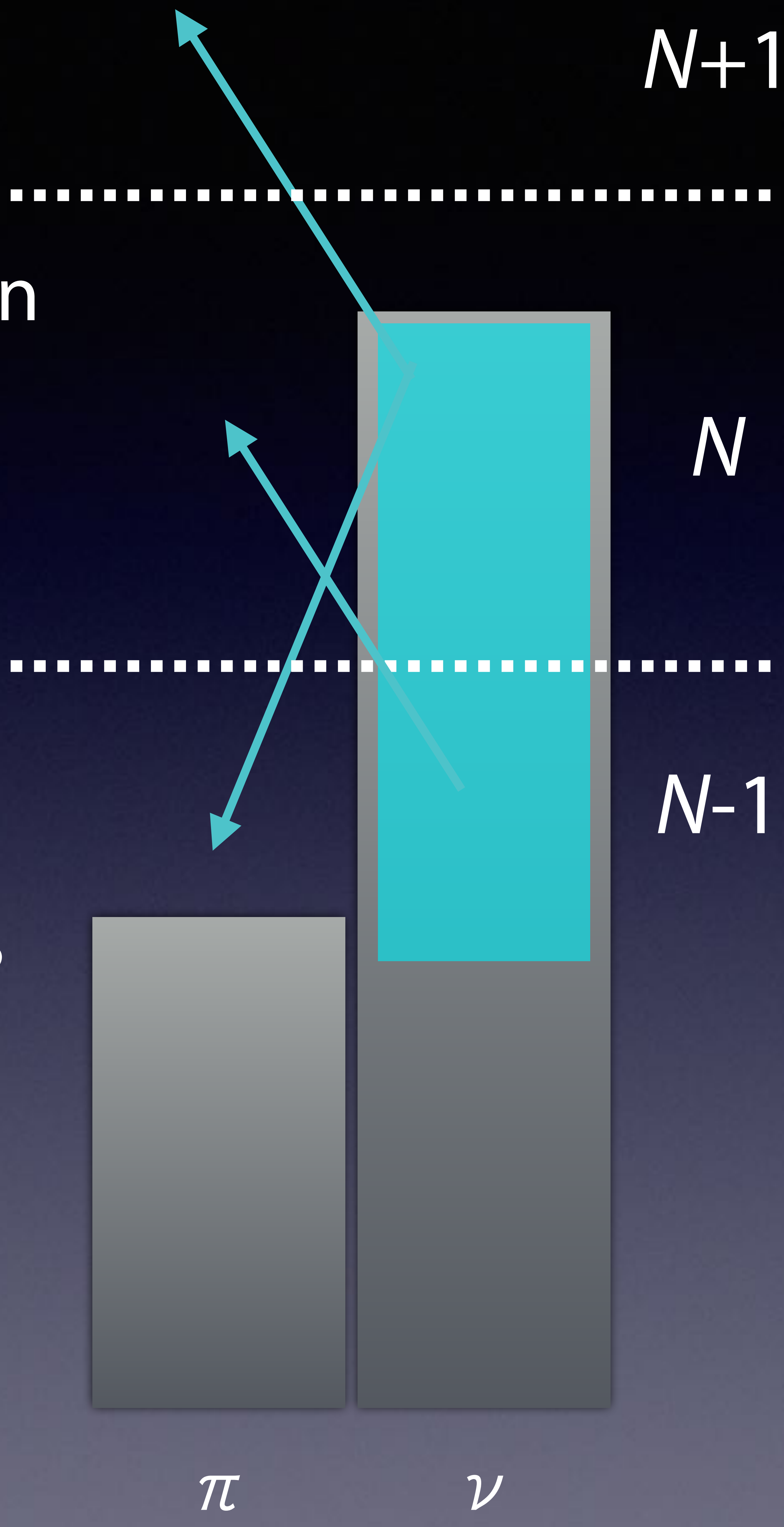
cross-shell ($N \to N\pm1$) excitation for negative-parity excitation

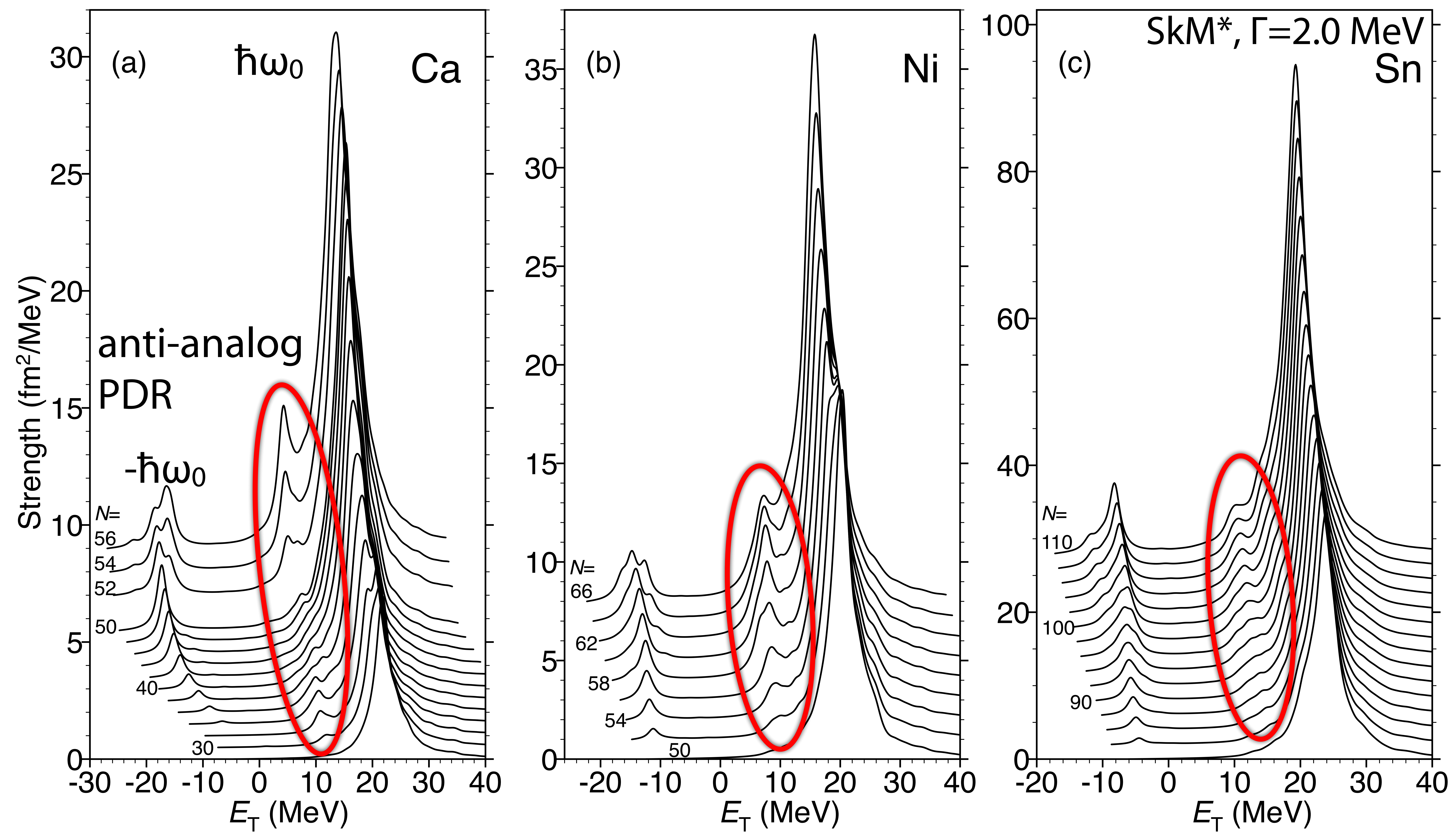
neutrons are weakly bound

↓

protons are deeply bound: low-lying mode

protons are in the continuum: giant resonance and pygmy?

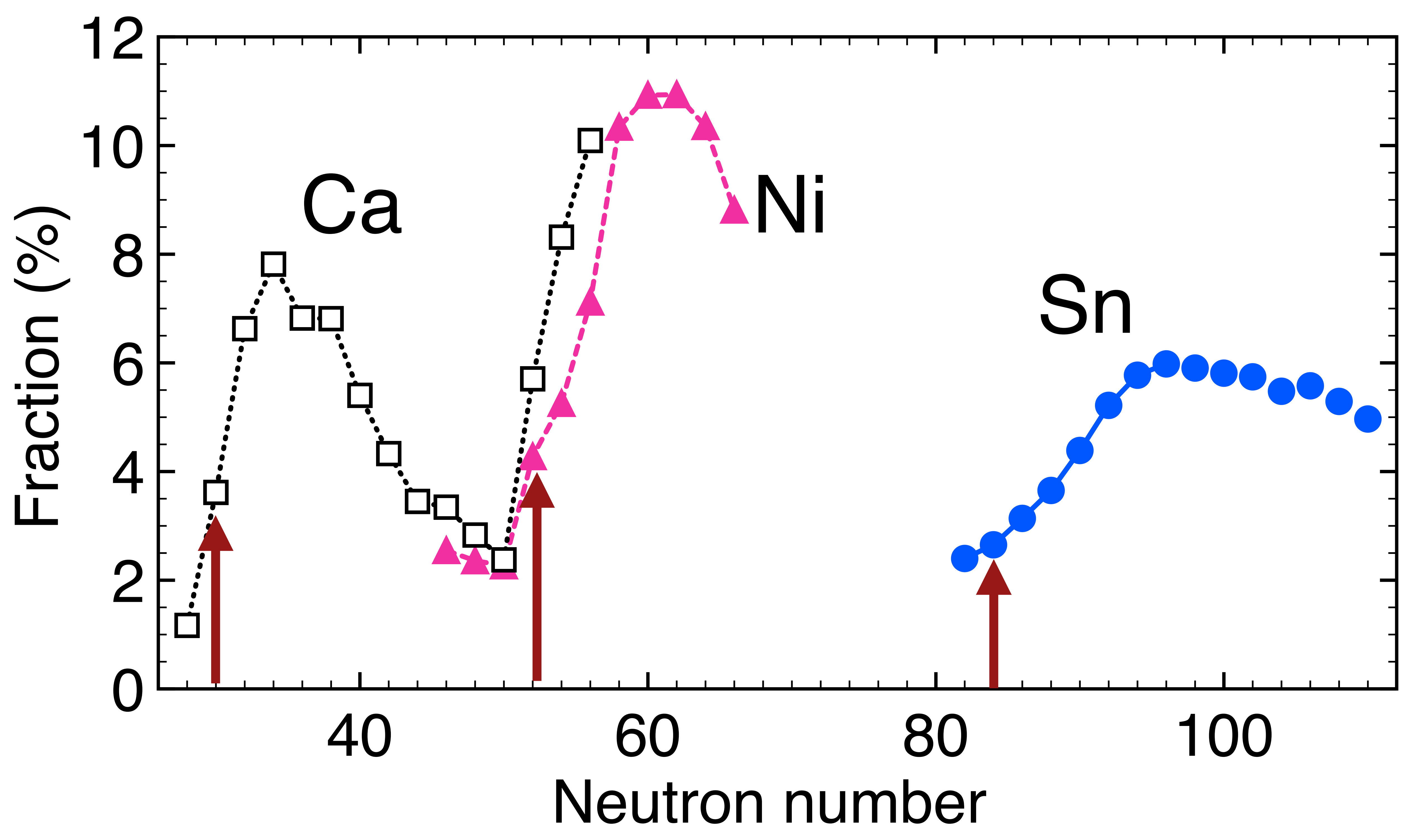



(a)
ħω₀
Ca
anti-analog
PDR
-ħω₀
N=
56
54
52
50
40
30
Strength (fm²/MeV)
0
5
10
15
20
25
30
-30
-20
-10
0
10
20
30
40
E_T (MeV)
(b)
Ni
N=
66
62
58
54
50
35
(c)
SkM*, Γ=2.0 MeV
Sn
N=
110
100
90
60
80
100

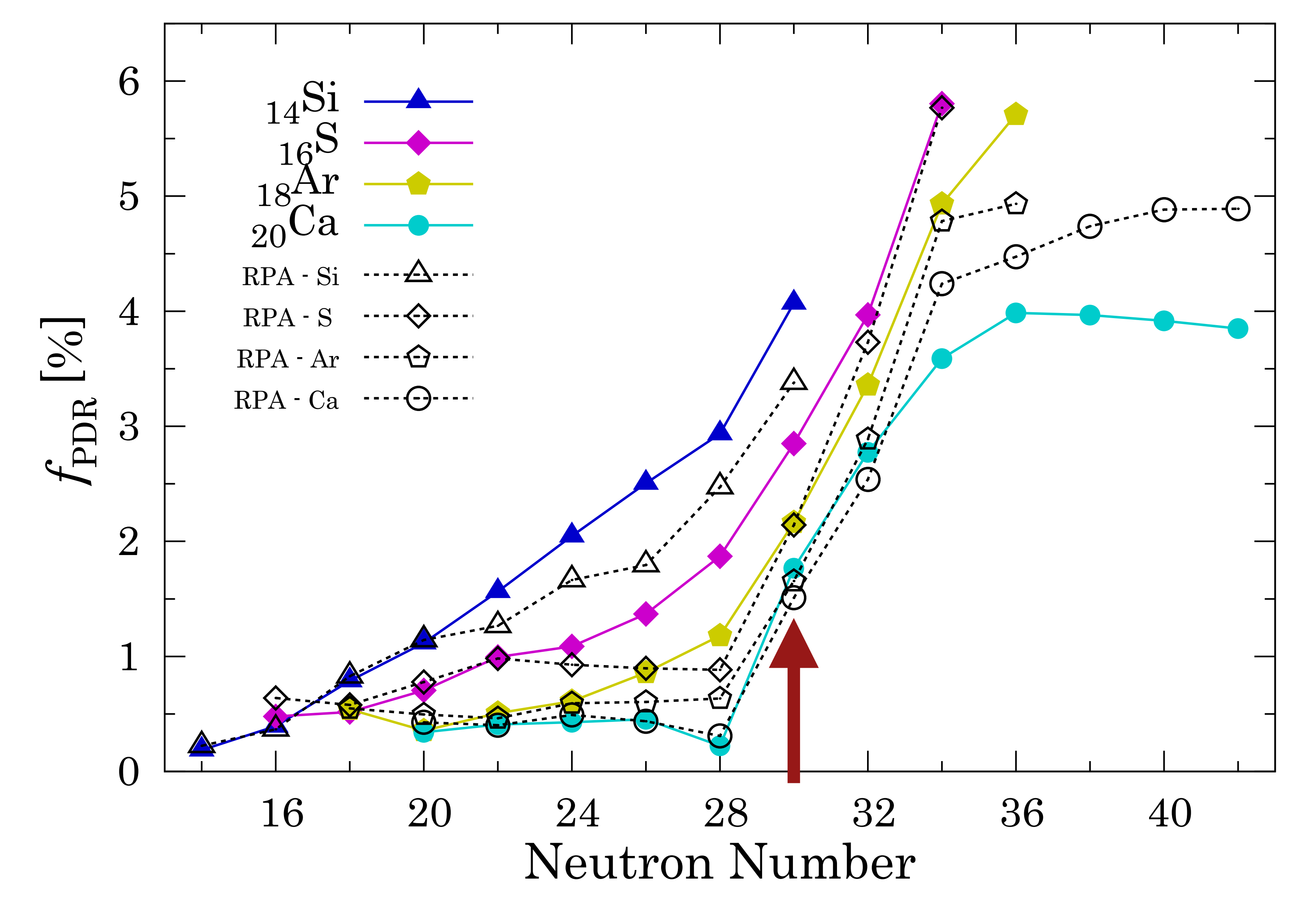
Appearance of anti-analog-PDR

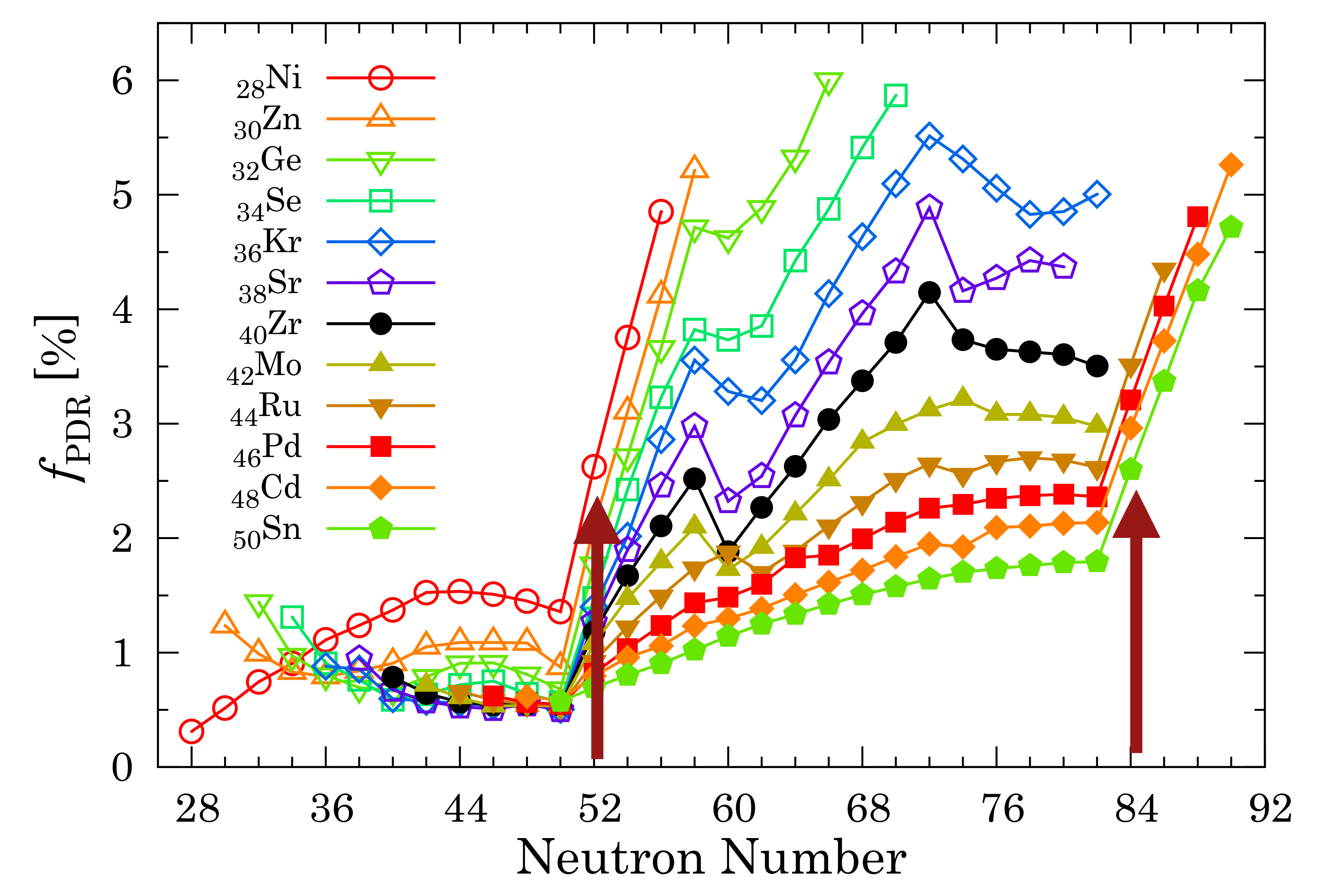
S. Ebata et al., PRC90(2014)024303

summed strength below GDR (except the low-lying states)



occupation of weakly-bound $p_{3/2}$ (N>28), $d_{5/2}$(N>50), and $f_{7/2}$ and $f_{5/2}$ (N>82)





Summary (II)

- ✓ LLFFV state appears uniquely in very neutron-rich nuclei
  - $-1\hbar\omega$ excitation
- ✓ strong shell effect
  - steady selection rule due to deeply-bound proton orbitals
  - weak collectivity
    - # of neutron hole states satisfying the selection rule is limited
- ✓ effect on the beta-decay rate and beta-delayed neutron emission in future
  - axial-vector (spin-dipole) modes also should be considered
- ✓ emergence of (anti)analog PDR below giant resonance