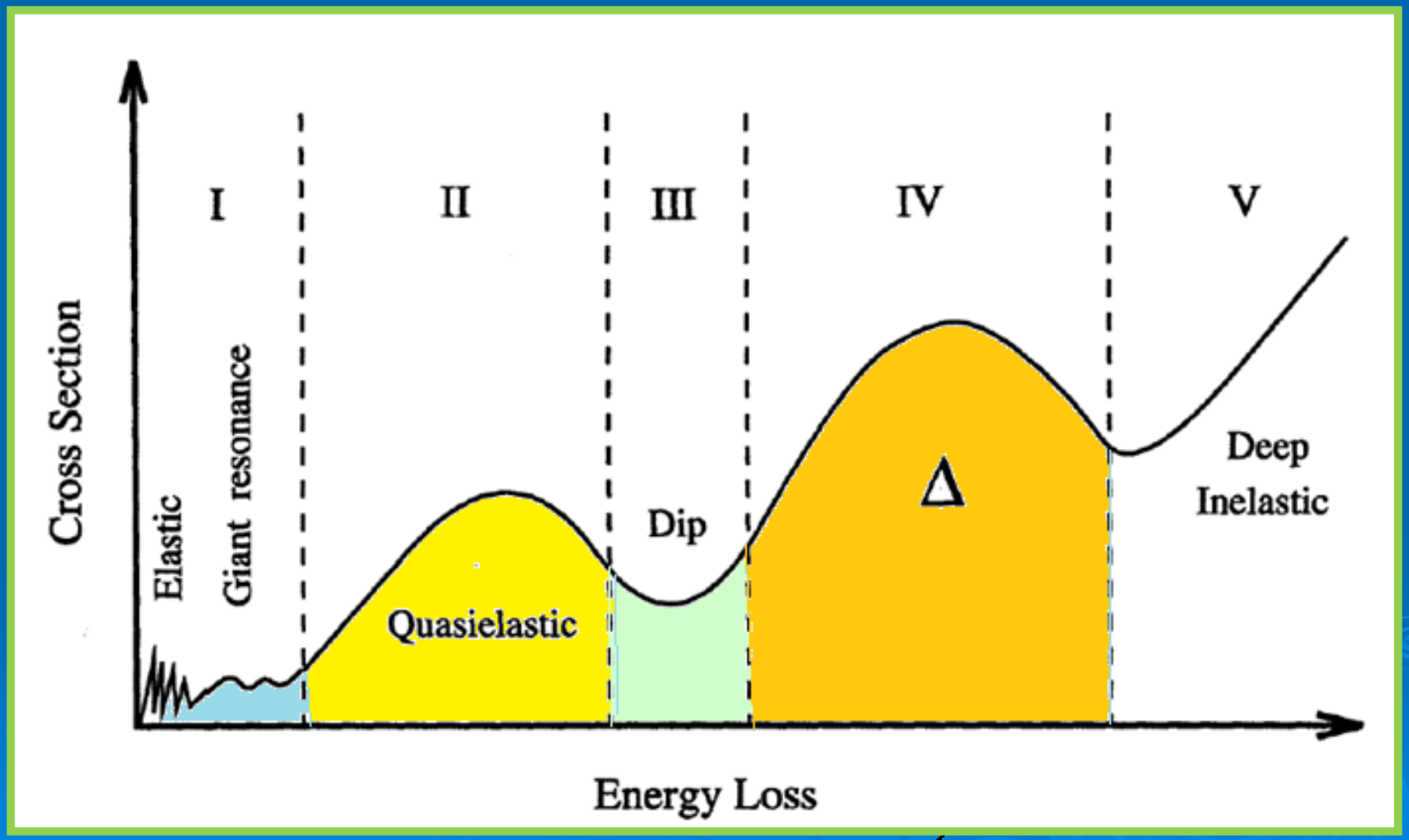
Investigating Exotic Nuclei by Nuclear Reactions

H. Lenske

Classification of Nuclear Reactions > 1AGeV:

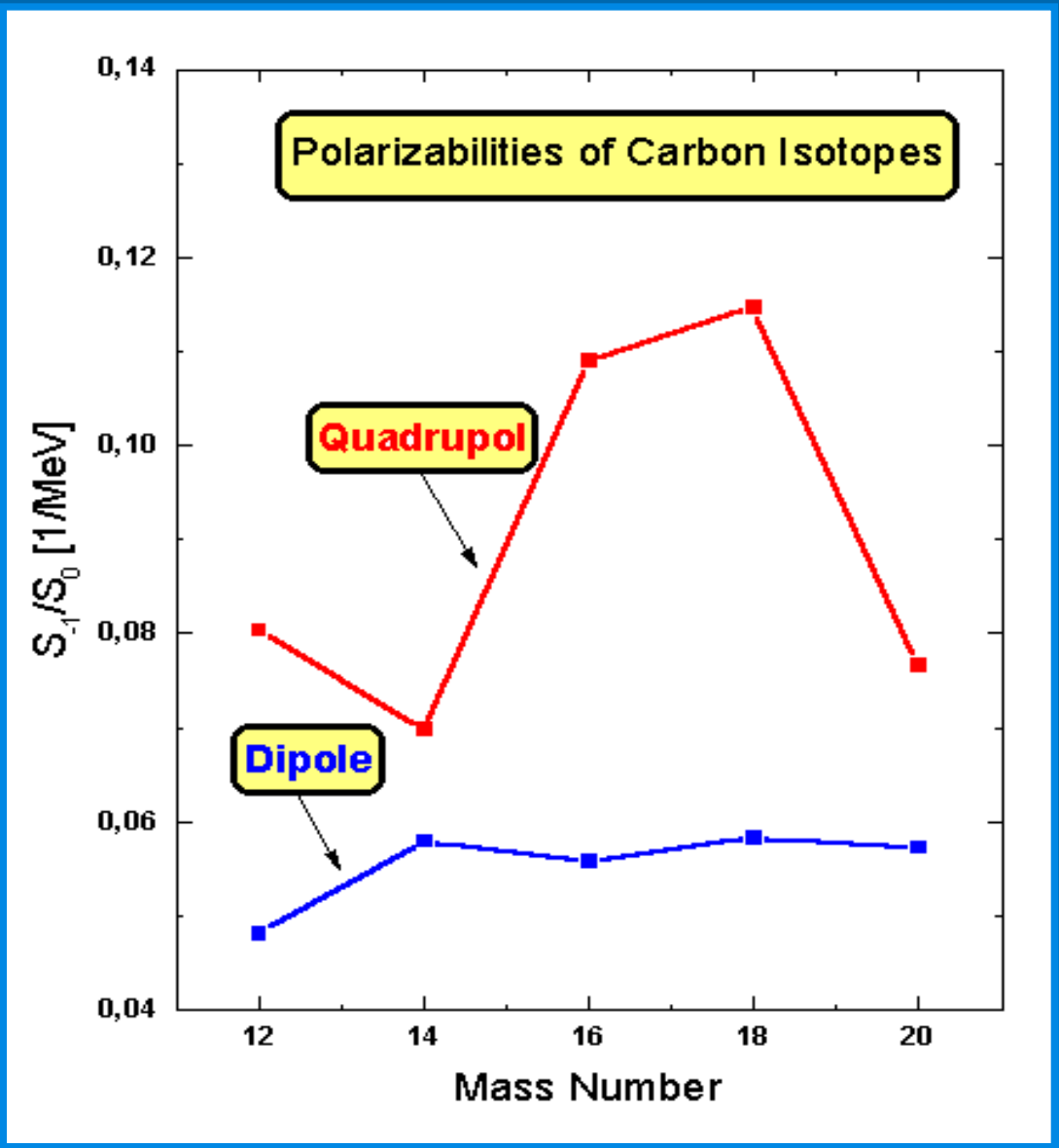


Agenda:

- Nuclear Structure far off Stability: Continuum Dynamics
- New Modes of Excitations
- Antiprotons for Nuclear Structure Research
- New Territory: Nucleon Resonances in Exotic Nuclei

I. Continuum Spectroscopy

The Softness of Exotic Nuclei



…reduced Separation Energies:

S_n~8 MeV → ~100 keV

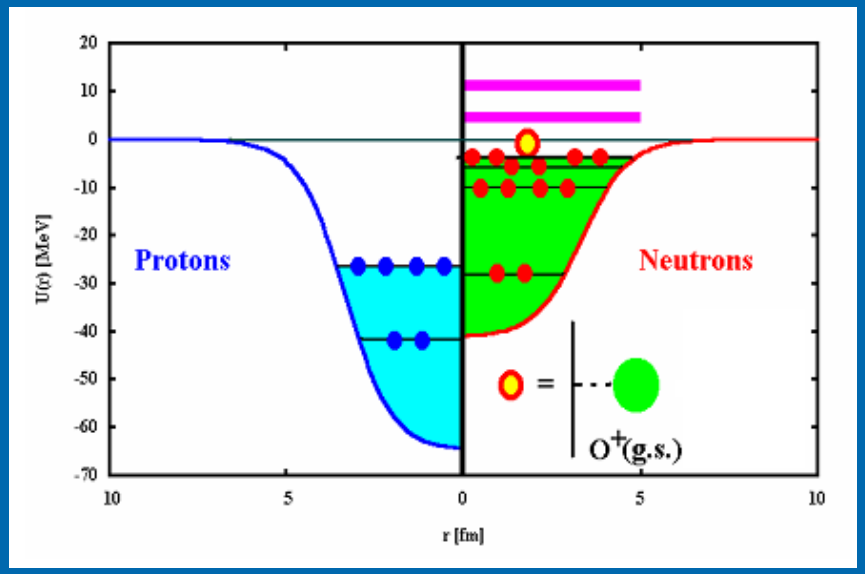
HFB & QRPA Calculations

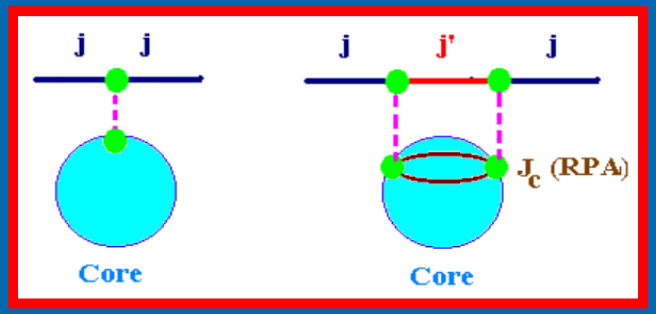
Polarizability Coefficients from Sum Rules:

$$P_\lambda = S_{-1}(\lambda)/S_0(\lambda)$$

$$S_n(\lambda) = \Sigma_c \, |M_c(\lambda)|^2 \, E^n{}_c$$

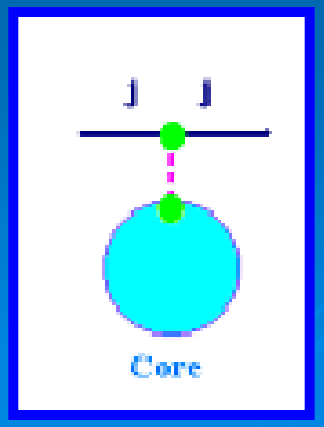
Mean-Field and Correlation Dynamics: ^{19}C

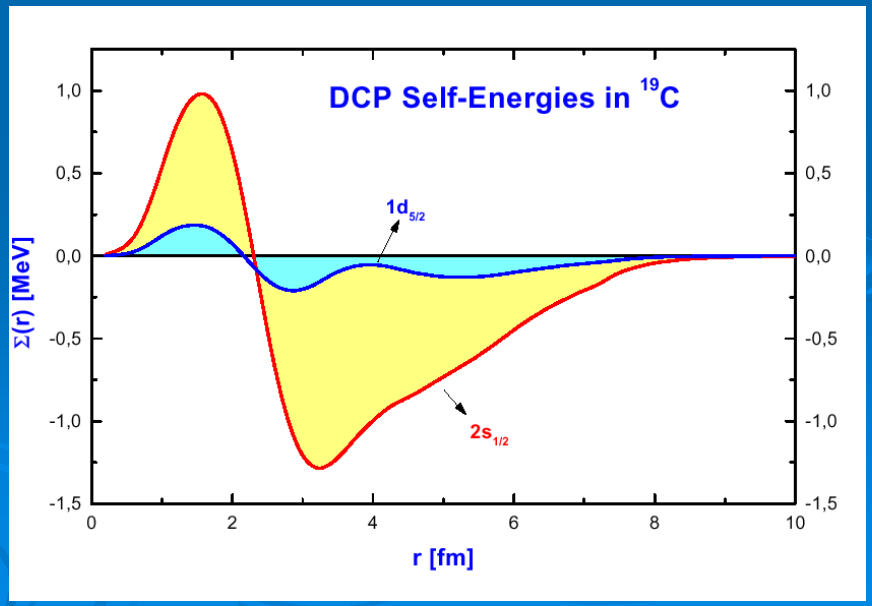




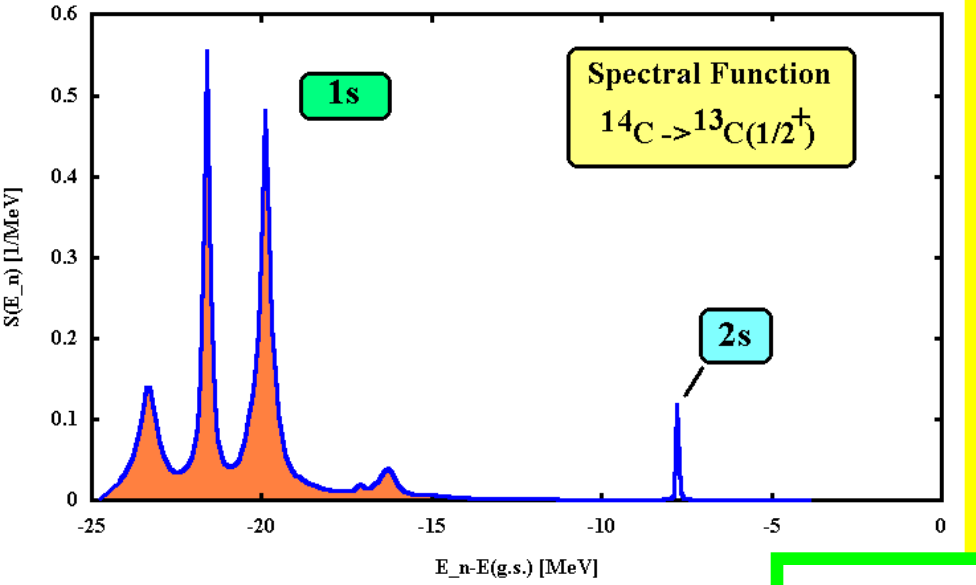
The DCP picture: Binding by Core Polarization Potential

The s.p. shell model picture: Prevalence of a static potential



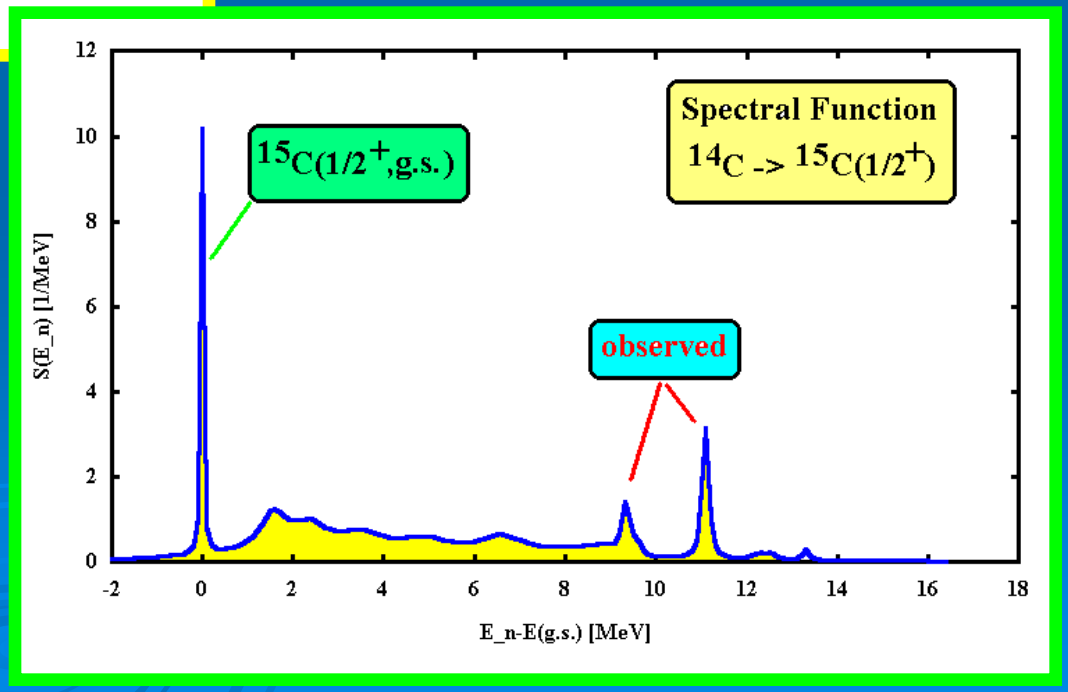


Core Polarization: $1/2^+$ QRPA Strength Functions in ^{14}C

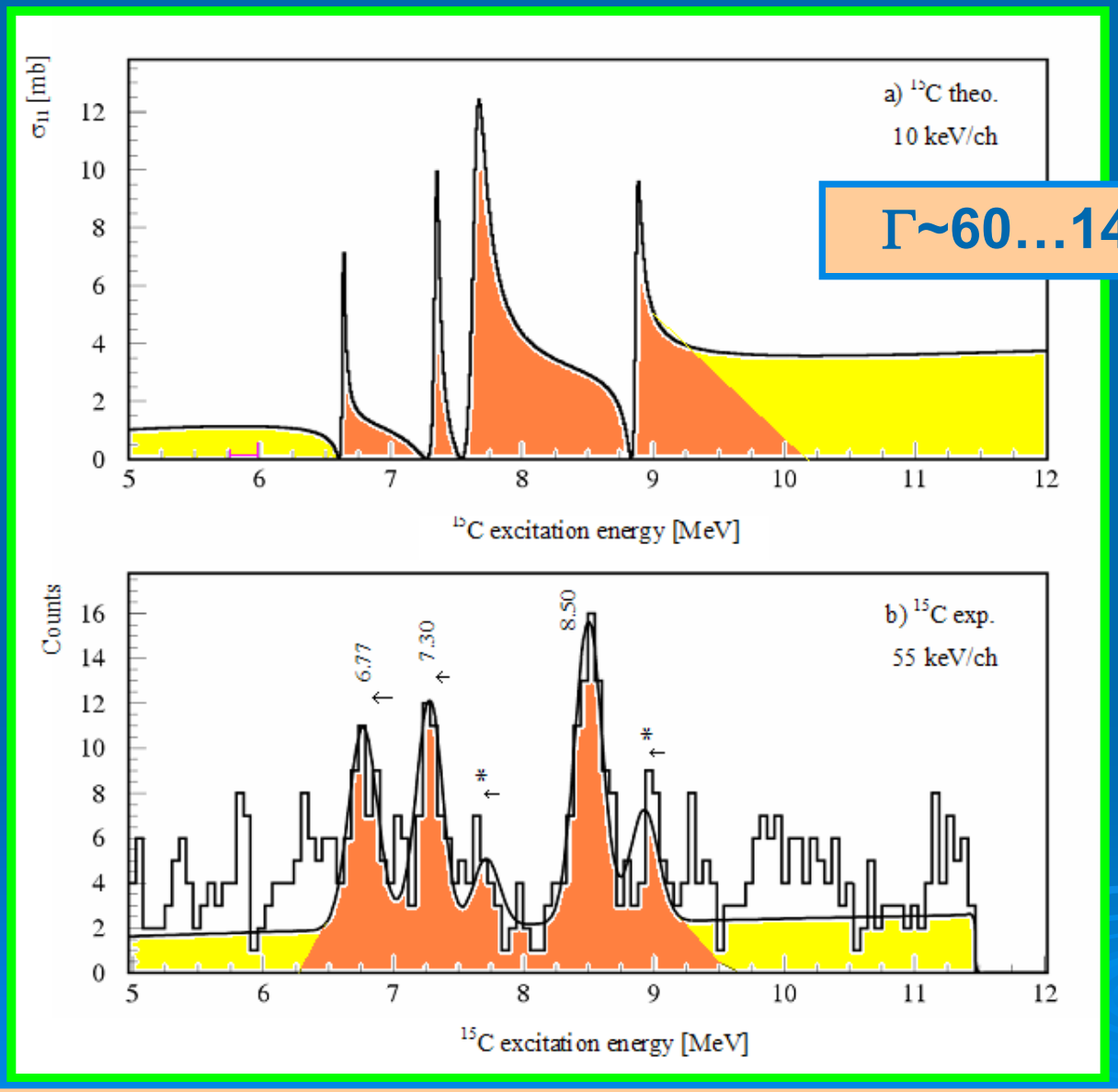


Hole strength function

Particle strength function



Correlation Dynamics in an Open Quantum System: Fano-Resonances in ^{15}C



Γ~60…140keV

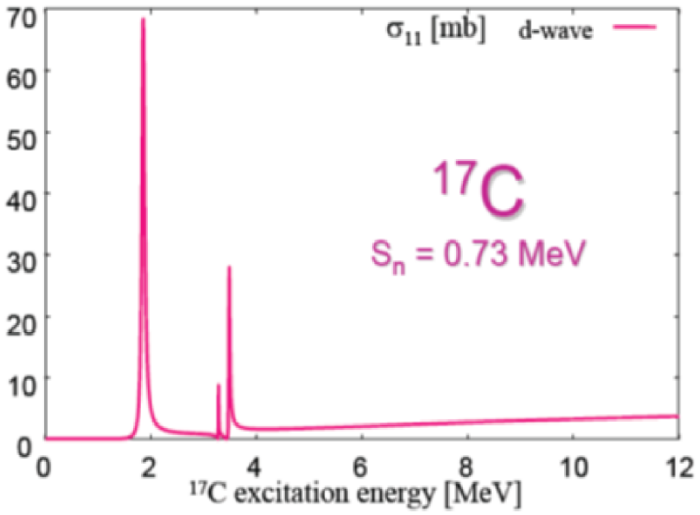
Sonja Orrigo, H.L., Phys.Lett. B633 (2006) ; exp. proposal at TRIUMF

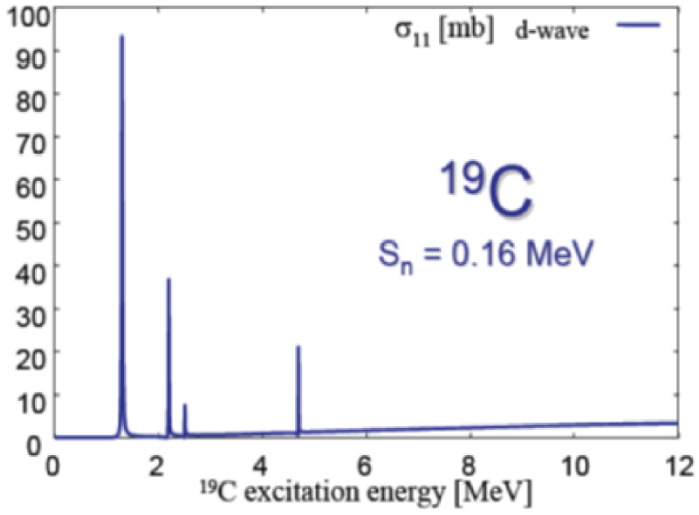
Fano-Dynamics at the Dripline:

Bound States embedded into the Continuum (BSEC) in $^{17,19}C$

^{16}C states: $E_C(J^\pi)$ = 1.766(2^+), 3.986(2^+), 4.142(4^+) MeV

^{18}C states: $E_C(J^\pi)$ = 1.620(2^+), 2.967(4^+), 3.313(2^+), 5.502(1^-) MeV



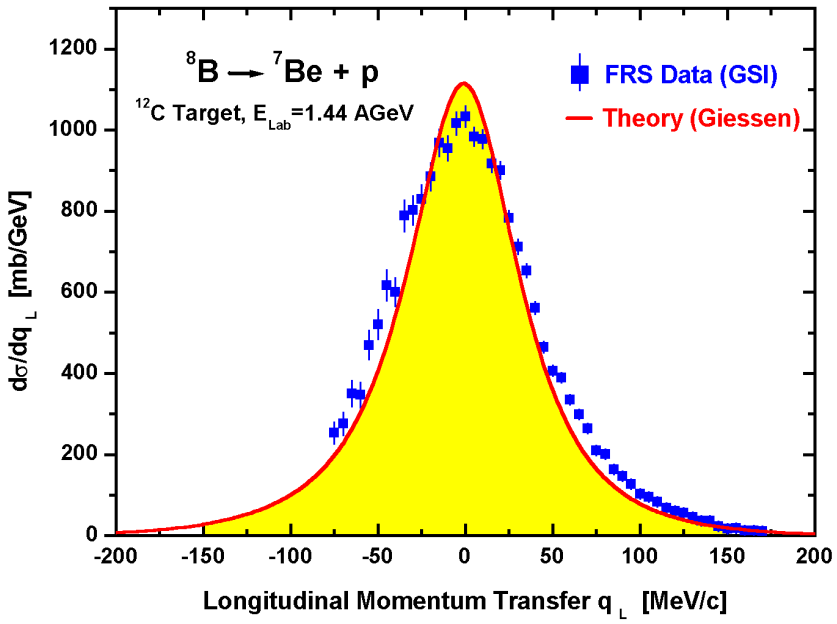


Increased effect of the correlations

BSEC structures move towards lower energies with increasing the neutron excess

S.E.A. Orrigo, H.Lenske

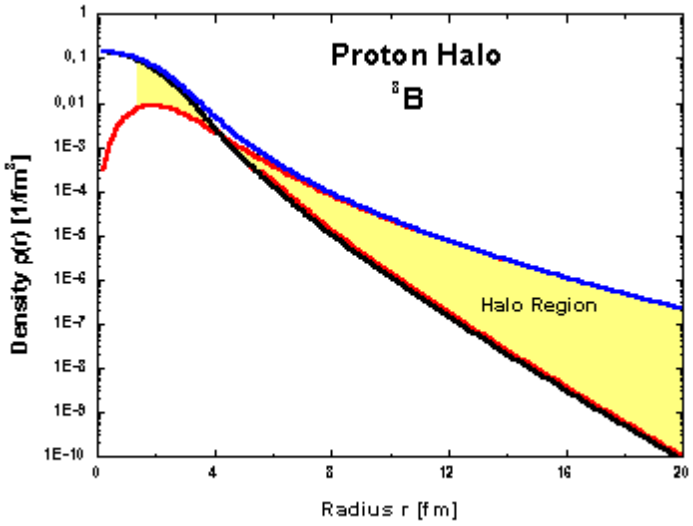
A text book example:
$^{8}B(2^{+}) \rightarrow {}^{7}Be+p$ removal reaction
Eikonal Reaction Theory and microscopic folding U_{opt}



- Relativistic eikonal theory
- NN T-Matrix
- 3-body kinematics
- dynamical correlations

Γ(the.): 75 MeV/c
Γ(exp.): 91 ± 5 MeV/c

σ(-1p,the.): 104 mb
σ(-1p,exp.): 98 ± 6 mb



$^{7}Be(3/2^{-},0.0)$) p3/2: 62%
$^{7}Be(3/2^{-},0.0)$) p1/2: 11%
$^{7}Be(3/2^{-},0.0)$) f 7/2: 10%
$^{7}Be(3/2^{-},0.0)$) f 5/2: 4%
$^{7}Be(1/2^{-},0.420)$: 13%

PHYSICAL REVIEW C **85**, 044312 (2012)

One-neutron removal reactions on Al isotopes around the $N = 20$ shell closure

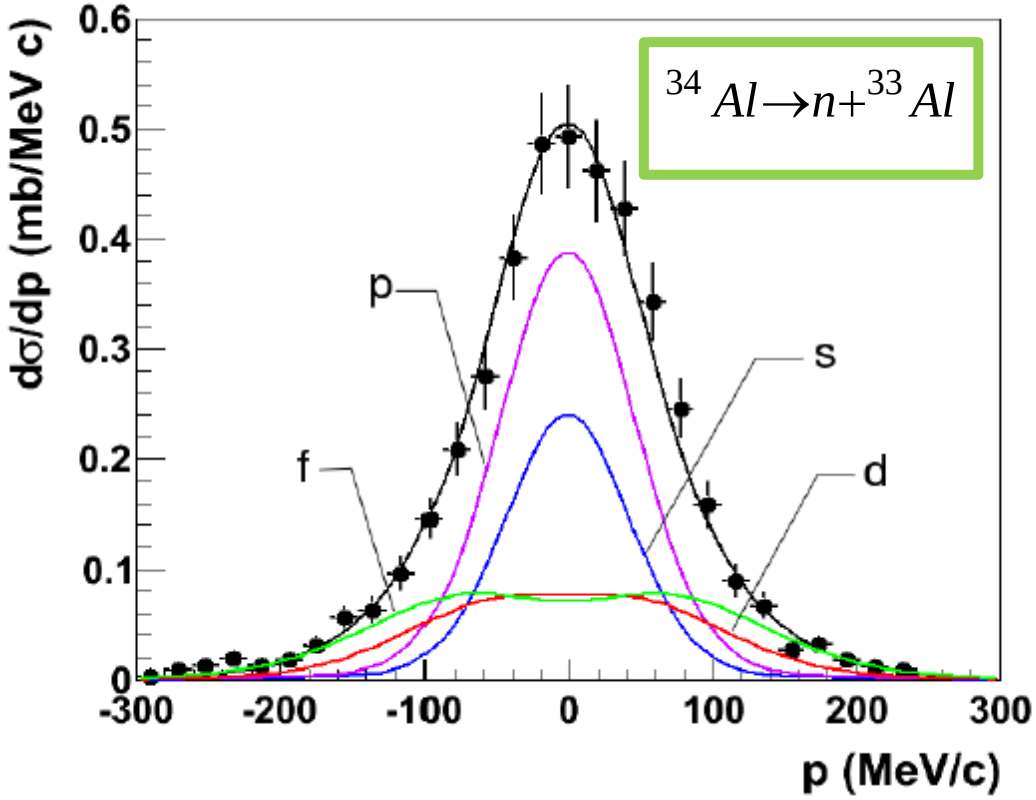
C. Nociforo,[1] A. Prochazka,[1,2] R. Kanungo,[3] T. Aumann,[1] D. Boutin,[2] D. Cortina-Gil,[4] B. Davids,[5] M. Diakaki,[6] F. Farinon,[1,2] H. Geissel,[1,2] R. Gernhäuser,[7] R. Janik,[8] B. Jonson,[9] B. Kindler,[1] R. Knöbel,[1,2] R. Krücken,[7] N. Kurz,[1] M. Lantz,[9] H. Lenske,[2] Yu. A. Litvinov,[1] B. Lommel,[1] K. Mahata,[1] P. Maierbeck,[7] A. Musumarra,[10,11] T. Nilsson,[9] C. Perro,[3] C. Scheidenberger,[1,2] B. Sitar,[8] P. Strmen,[8] B. Sun,[2] I. Szarka,[8] I. Tanihata,[12] H. Weick,[1] and M. Winkler[1]

$$^{33...36}Al \rightarrow n + ^{32...35}Al$$

Low-energy Structure Physics by high-energy RIB: 1n-Removal @900 AMeV

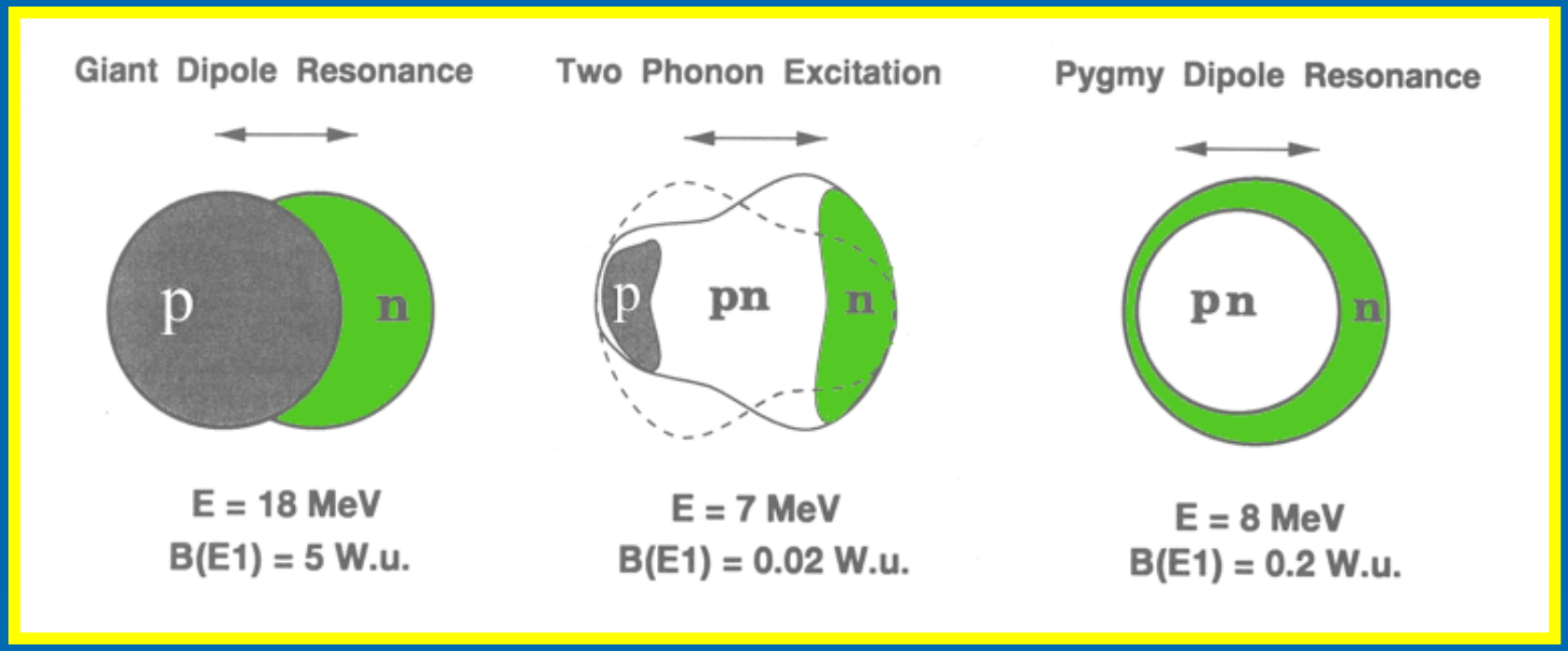
C. Nociforo et al. PRC 85 (2012)

Theory: HFB/QRPA/SM and Eikonal-Description



II. (γ,γ')-Scattering and New Modes of Excitation at the Particle Threshold

Electric Dipole Response of Exotic Nuclei



$$\vec{D} = \frac{1}{2}\sum_i \vec{\xi}_i(1-\tau_{3i}) = -\frac{1}{2}\sum_i \vec{\xi}_i \tau_{3i}\,.$$

The Giessen Approach:

Density Functional Theory and Multi-Phonon QRPA Theory

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n}\left(\left(T_q + U_q(\rho_0)\right)\delta\rho_q + \Delta_q\delta\kappa_q\right) + \sum_{q,q'=p,n} f_{qq'}(\rho_0)\delta\rho_q\delta\rho_{q'} + \ldots$$

$$U_q = \frac{\delta}{\delta\rho_q}\frac{1}{2}\langle V\rangle = \sum_{q'} V_{qq'}(\rho)\rho_{q'} + \frac{1}{2}\sum_{q'q''}\rho_{q'}\rho_{q''}\frac{\delta}{\delta\rho_q}V_{q'q''}(\rho)$$

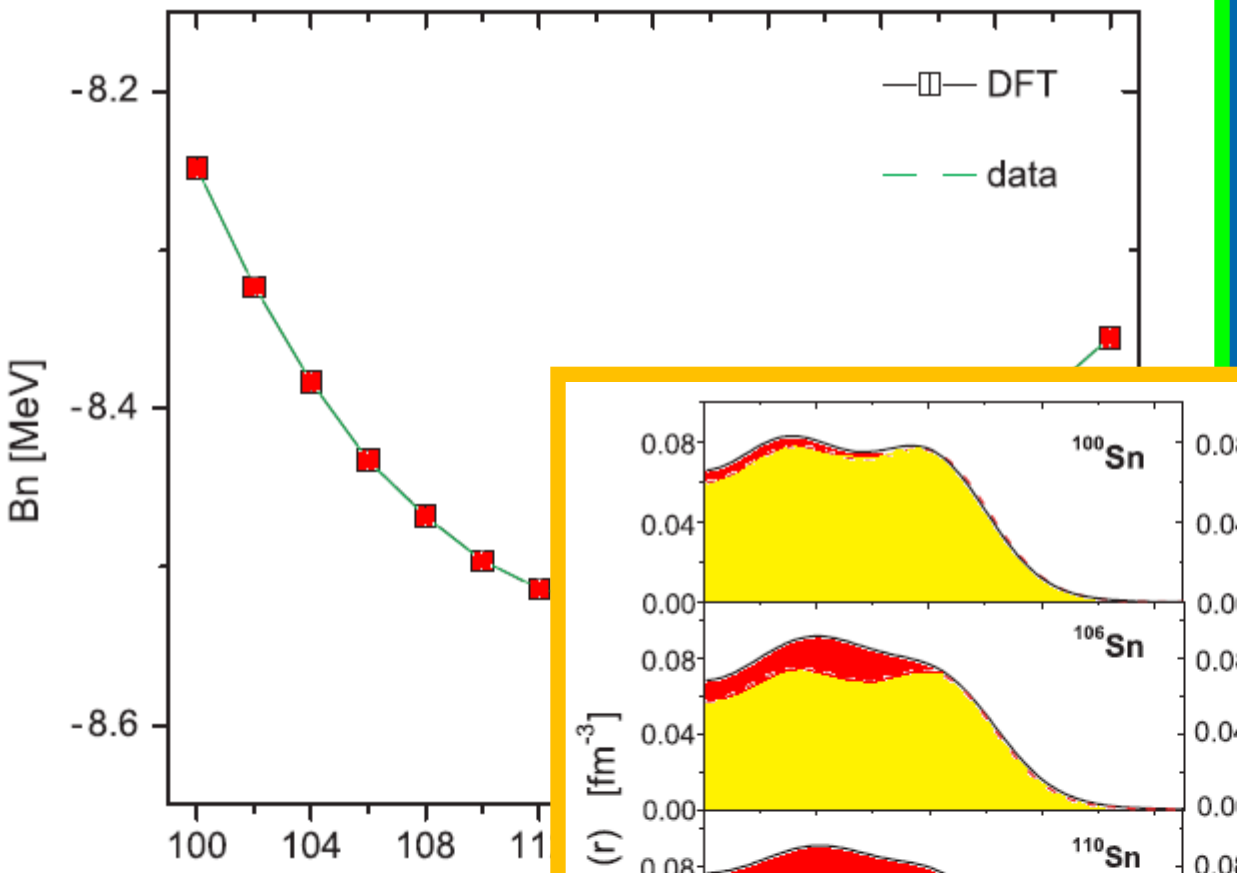
$$f_{qq'} = V_{qq'}(\rho) + 2\sum_{q''}\rho_{q''}\frac{\delta}{\delta\rho_q}V_{q'q''}(\rho) + \frac{1}{2}\sum_{k'k''}\rho_{k'}\rho_{k''}\frac{\delta^2}{\delta\rho_q\delta\rho_{q'}}V_{k'k''}(\rho)$$

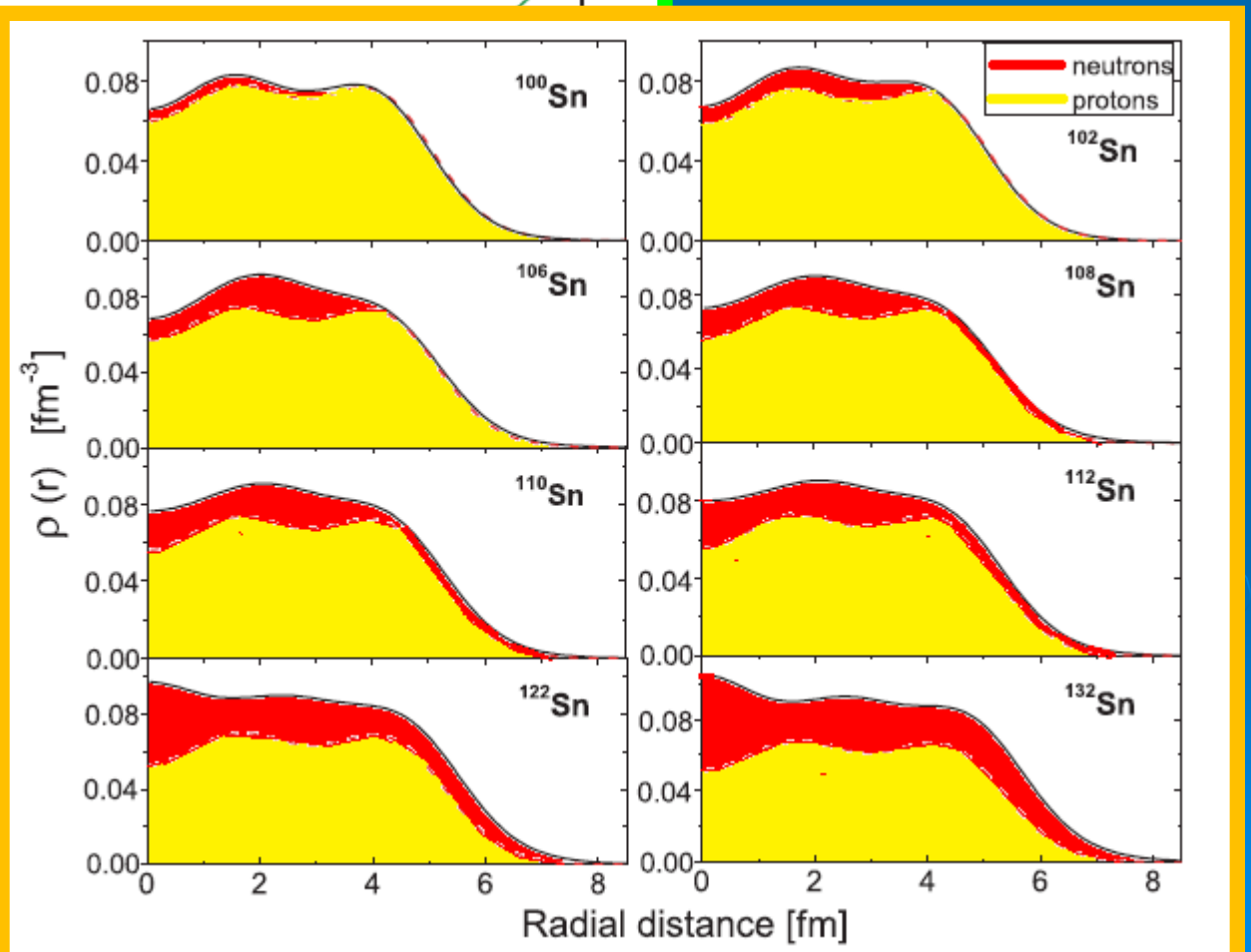
Excited States:

$$\left|E_\alpha J_\alpha\right\rangle = \left(\sum_n z_n\Omega^\dagger_{nJ_\alpha} + \sum_{n_1n_2} z_{n_1n_2}\left[\Omega^\dagger_{n_1J_1}\Omega^\dagger_{n_2J_2}\right]_{J_\alpha} + \sum_{n_1n_2n_3} z_{n_1n_2n_3}\left[\Omega^\dagger_{n_1J_1}\Omega^\dagger_{n_2J_2}\Omega^\dagger_{n_3J_3}\right]_{J_\alpha}\right)\left|0\right\rangle$$

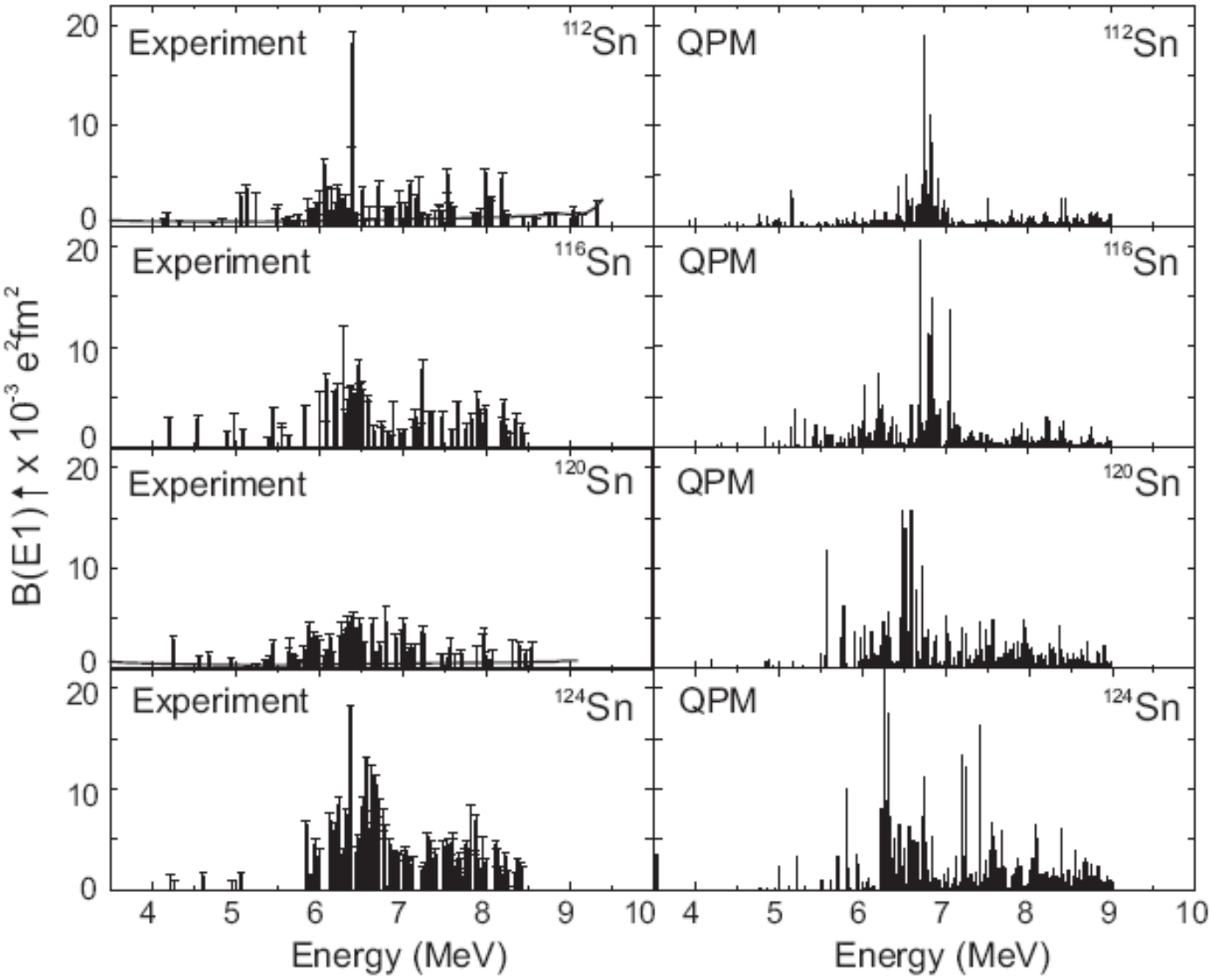
Sn Isotopes: DFT-HFB Results

(N. Tsoneva, HL, PRC77 (2008))





3-Phonon PDR Results (QPM)

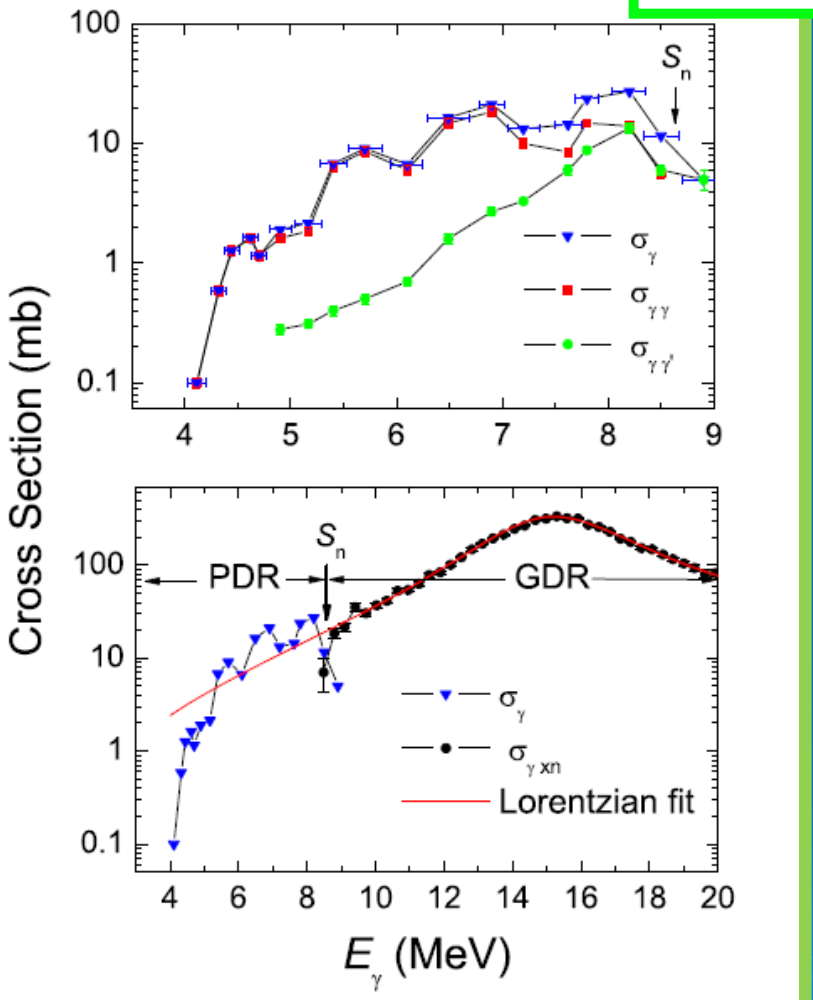


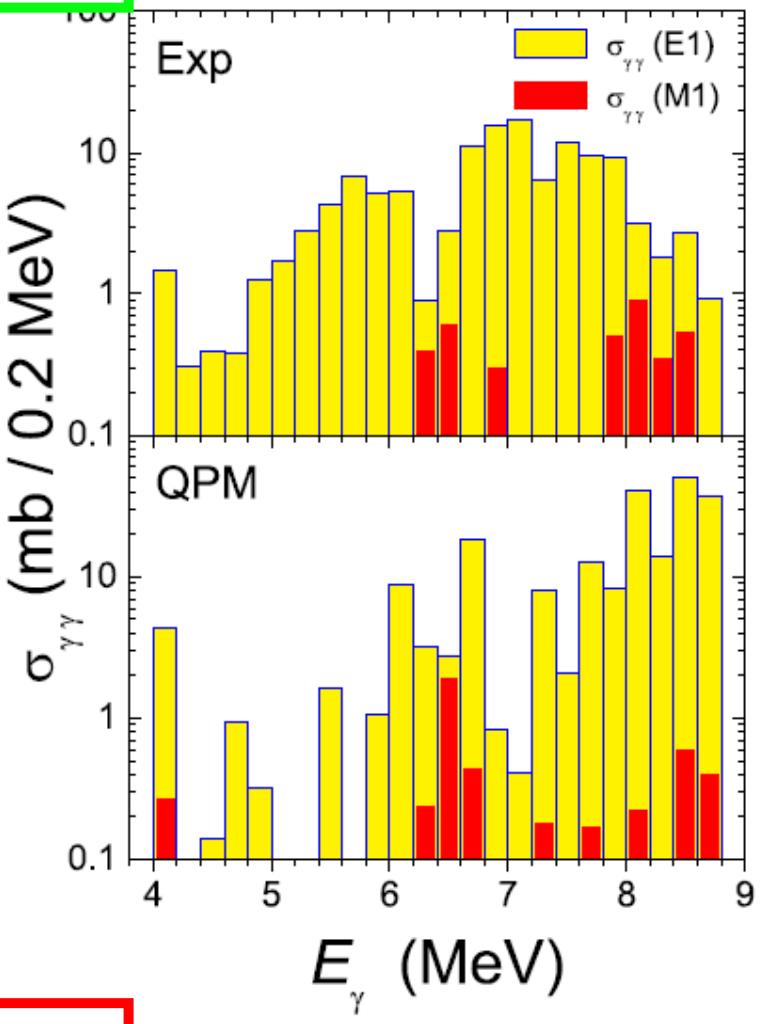
Data: P. von Neumann-Cosel et al.

N. Tsoneva, H. Lenske, PRC 77:024321 (2008)

Low Energy Dipole Response: Parity Assignment

$^{138}\mathrm{Ba}(\vec{\gamma}, \gamma')$





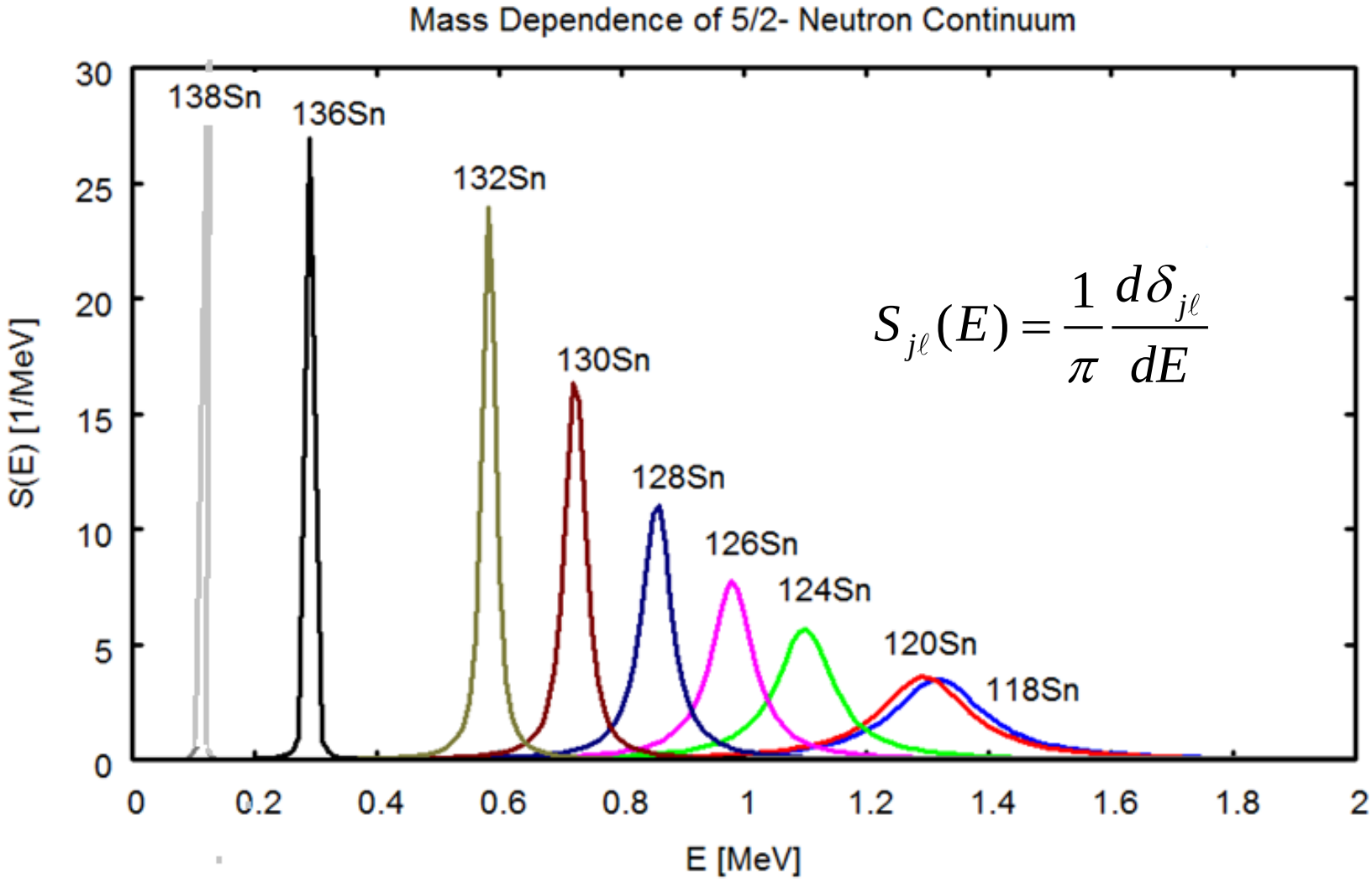
HI$\vec{\gamma}$S facility

PRL 104, 072501 (2010)

III. Other Manifestations of the Nuclear Skin

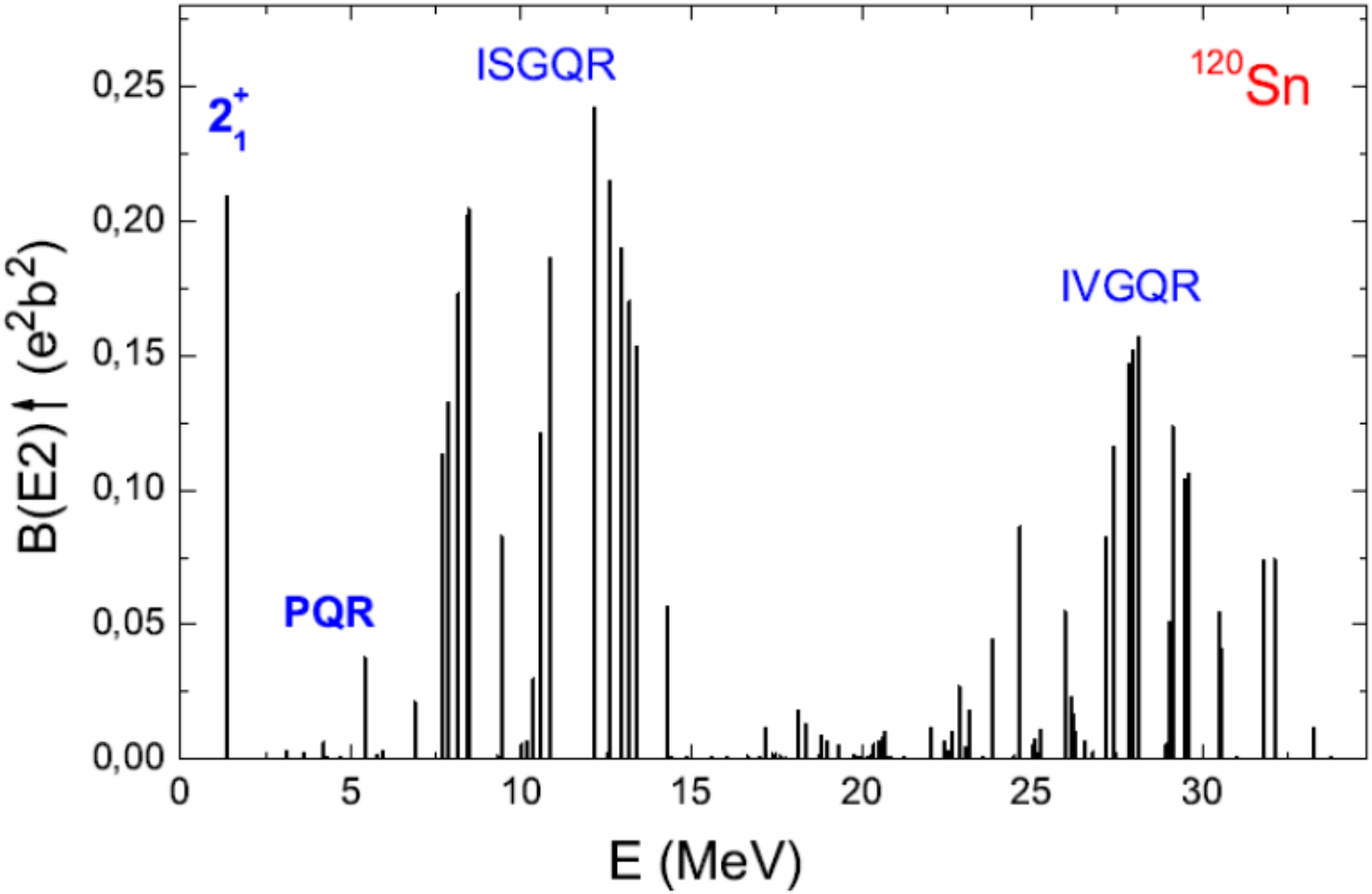
Evolution of Single Neutron Continuum Strength

Level Density in the Continuum → Speed plot



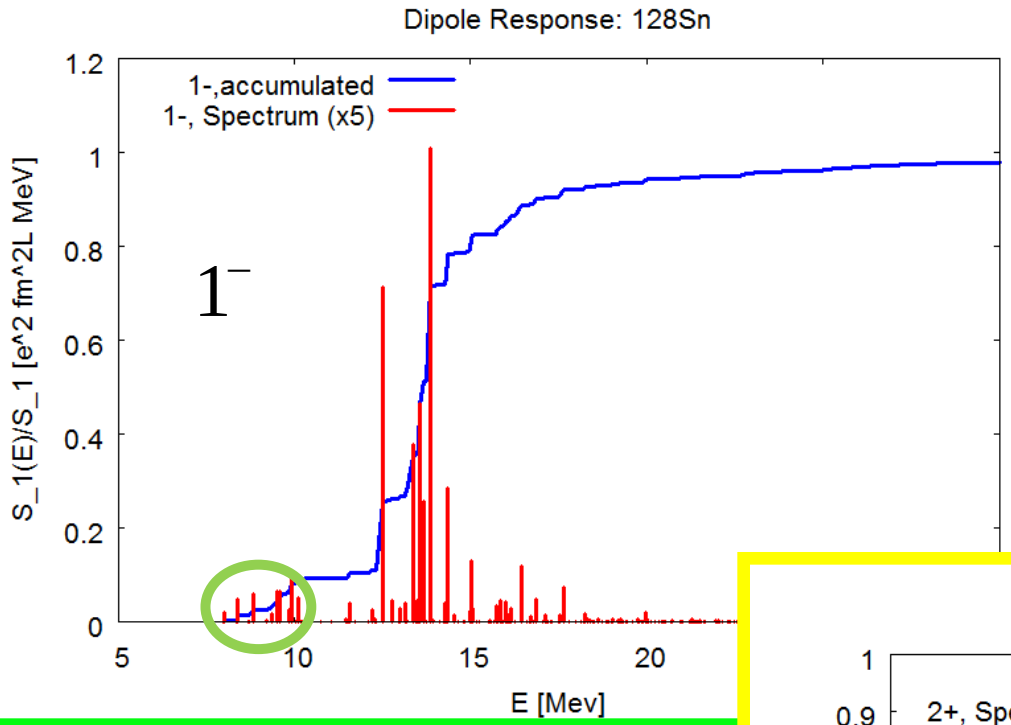
$$S_{j\ell}(E) = \frac{1}{\pi}\frac{d\delta_{j\ell}}{dE}$$

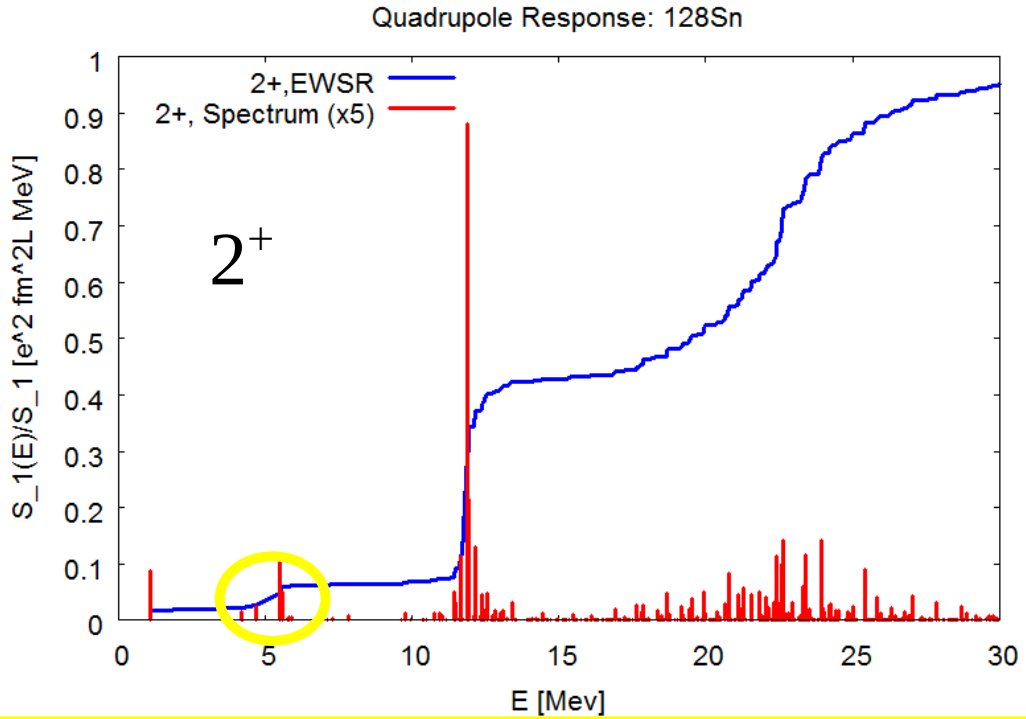
The „PQR": Low-Energy Quadrupole Response- B(E2) Transition Strength



N. Tsoneva, H. Lenske, Phys. Lett. B695, 174180 (2011).

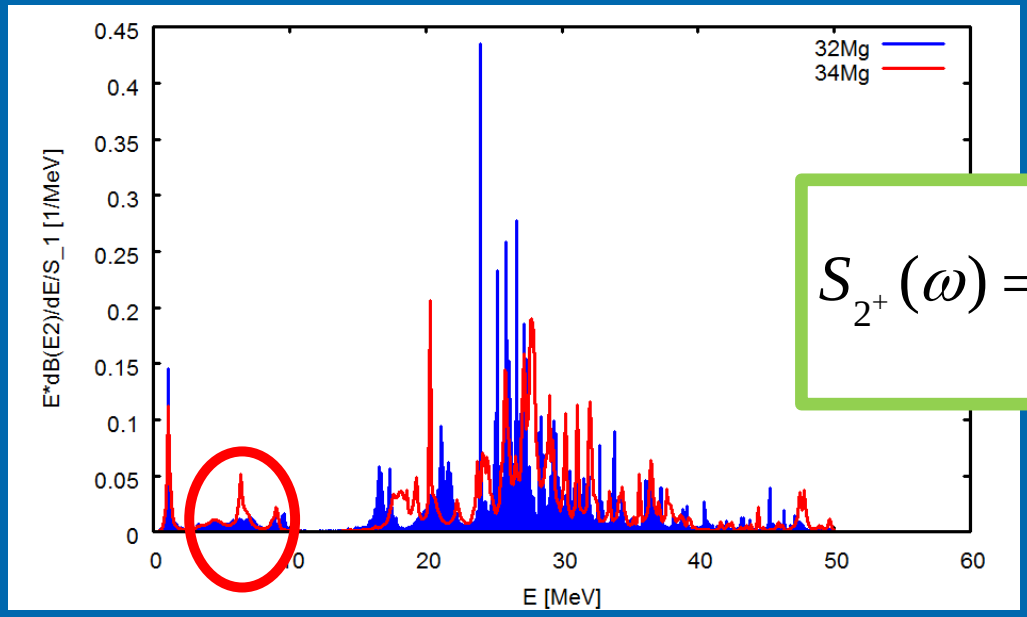
QRPA 1^- and 2^+ Multipole-Response ^{128}Sn Microscopic DD-QRPA





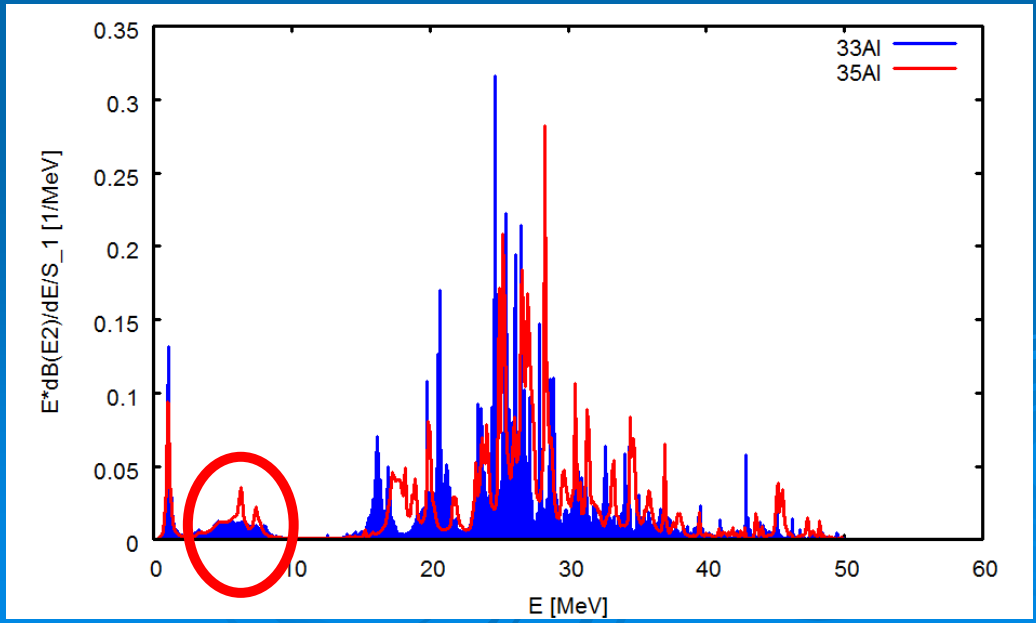
QRPA Spectral Distribution normalized to EWSR

B(E2) ^{32}Mg/^{34}Mg:



$$S_{2^+}(\omega) = \frac{\omega R_{2^+}(\omega)}{\left\langle \omega R_{2^+}(\omega) \right\rangle}$$

B(E2) ^{33}Al/^{35}Al:

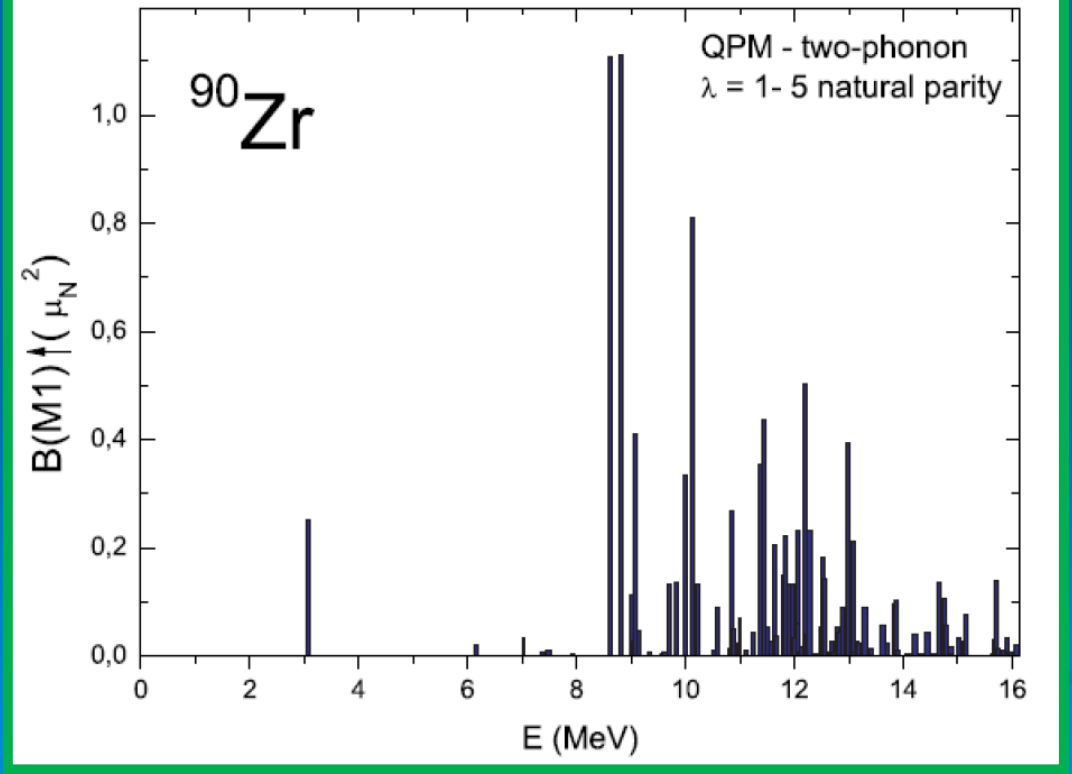


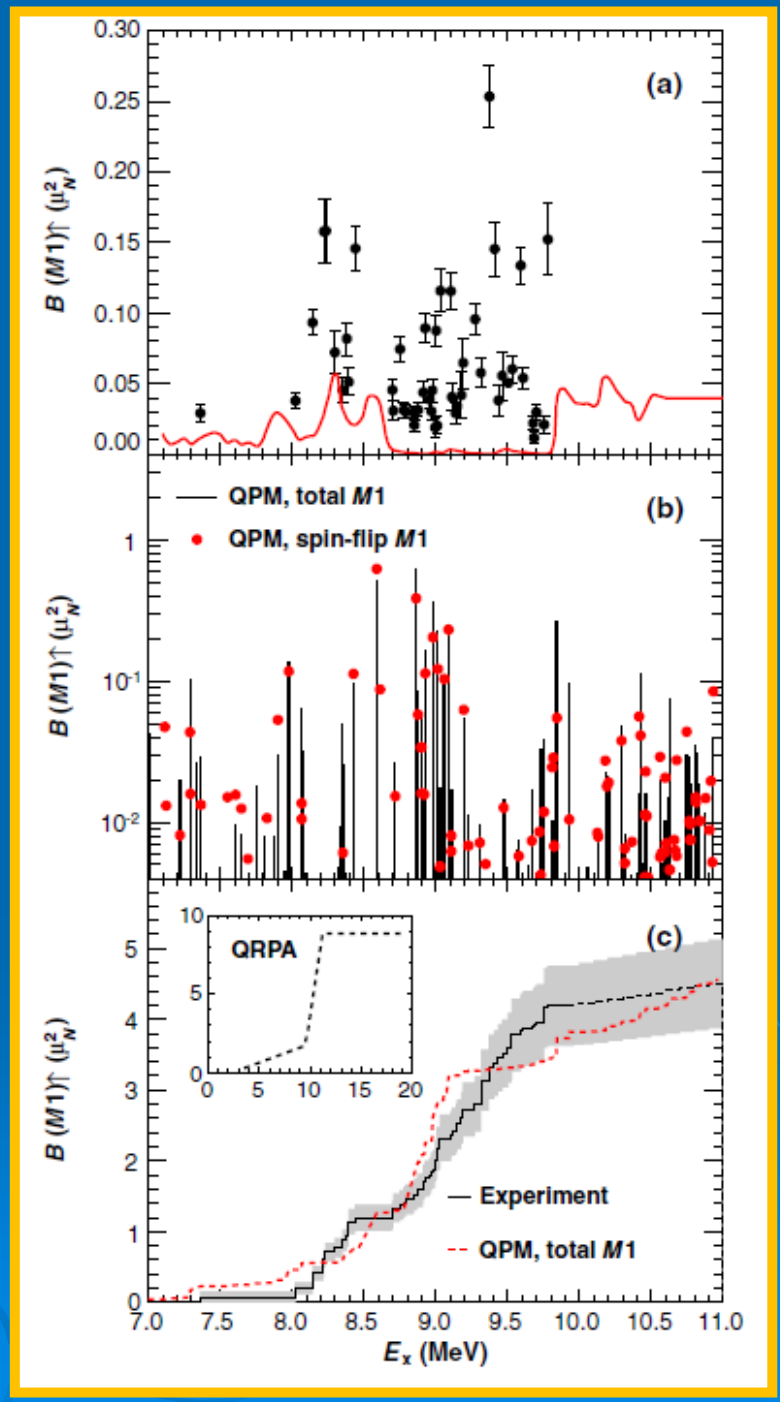
PRL 110, 022503 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Fine Structure of the Giant *M*1 Resonance in ^{90}Zr

G. Rusev,[1,2,*] N. Tsoneva,[3,4] F. Dönau,[5] S. Frauendorf,[5,6] R. Schwengner,[5] A. P. Tonchev,[1,2,†] A. S. Adekola,[2,7,‡] S. L. Hammond,[2,7] J. H. Kelley,[2,8] E. Kwan,[1,2,†] H. Lenske,[3] W. Tornow,[1,2] and A. Wagner[5]

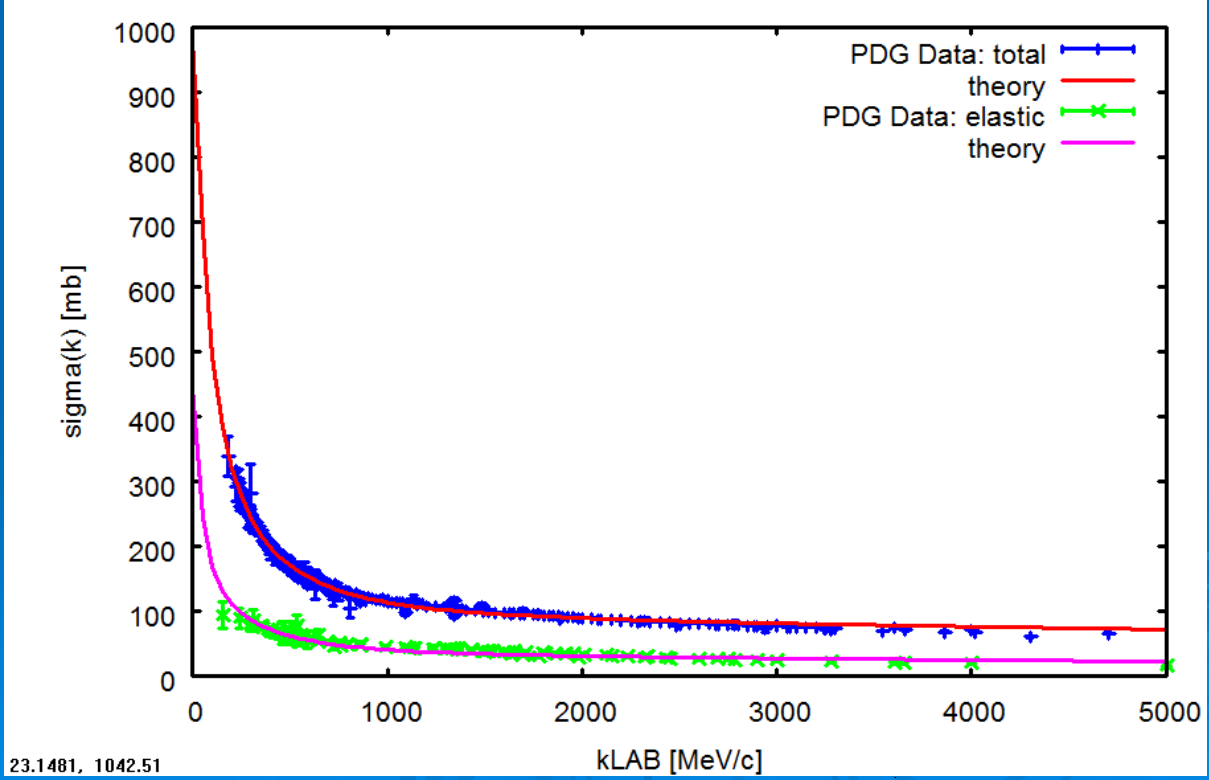
- 1^+ Data: HIγS facility@Duke
- Theory: DFT-QRPA plus multi-phonon configurations
- 1-phonon states with $J \leq 6$





…true "Alleinstellungsmerkmal" (uniqueness) of NUSTAR@FAIR:

…access to antiprotons/antimatter!



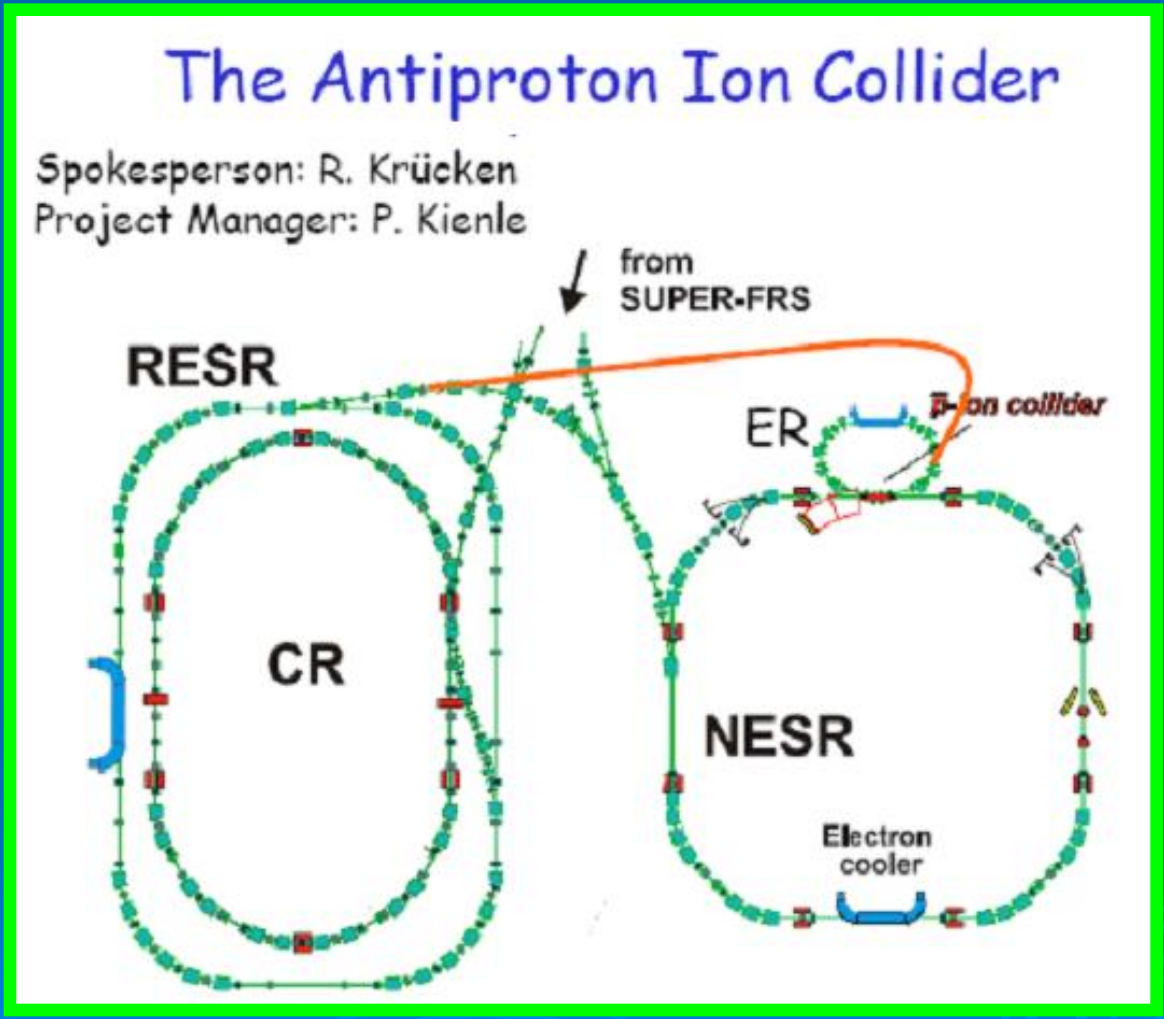
S. Lourenco, S. Wycech H.L.

IV. Antiproton Physics on Exotic Nuclei: The AIC-Proposal

…dedicated to Paul Kienle

* 11. August 1931; † 29. Januar 2013

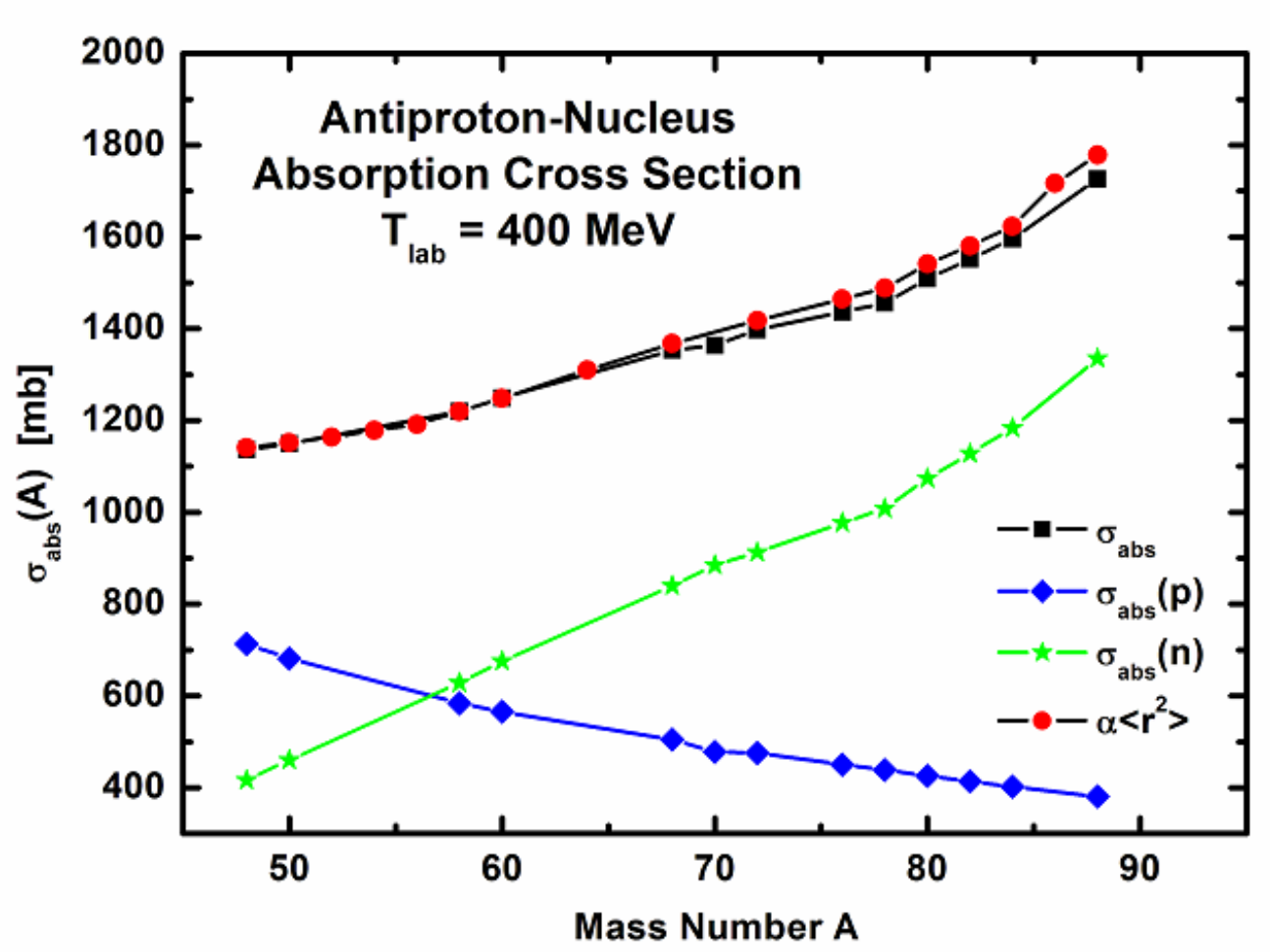
Measuring Neutron Skins on Isotopic Chains (Ni,Sn…): $\bar{p}$ + A Absorption@FAIR: the AIC Proposal



P. Kienle, NMB 214 (2004) and AIC@FAIR Proposal (2005)

H.L., P. Kienle, Phys.Lett. B647 (2007) 82-87

Measuring Neutron Skins on Isotopic Chains (Ni,Sn…): $\bar{p}$ + A Absorption on protons and neutrons

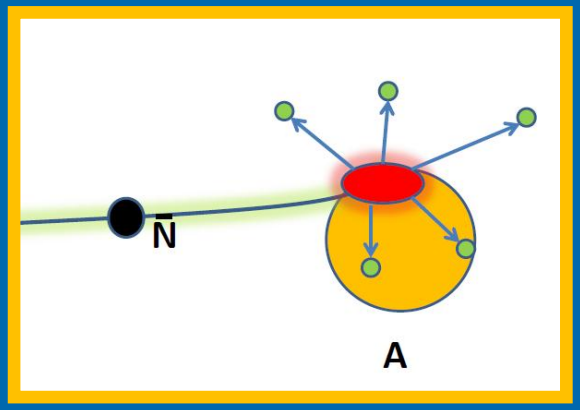


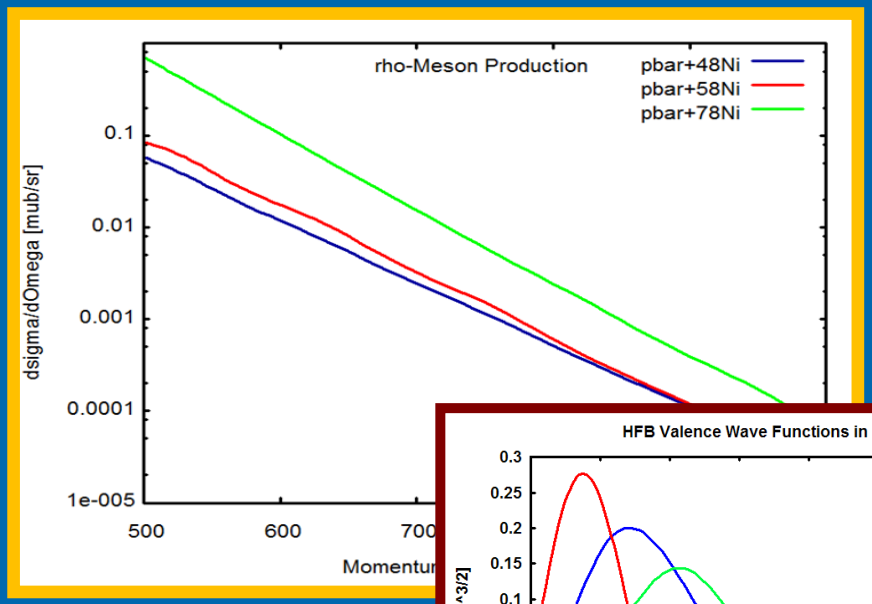
$$\sigma_{abs} = \left(g^2_{\bar{p}p} h(E_{\bar{p}}, Z) \left\langle r^2 \right\rangle_p + g^2_{\bar{p}n} h(E_{\bar{p}}, N) \left\langle r^2 \right\rangle_n \right) = \alpha\left(E_{\bar{p}}, N, Z\right) \left\langle r^2 \right\rangle$$

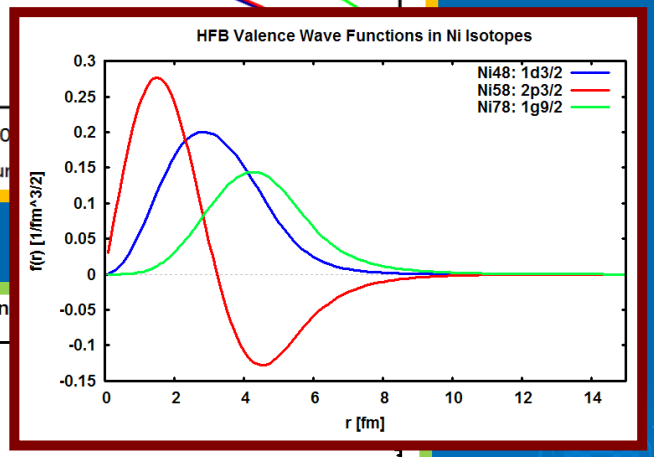
H.L., P. Kienle, Phys.Lett. B647 (2007) 82-87

Meson Production by Antinucleon Annihilation on Nuclei

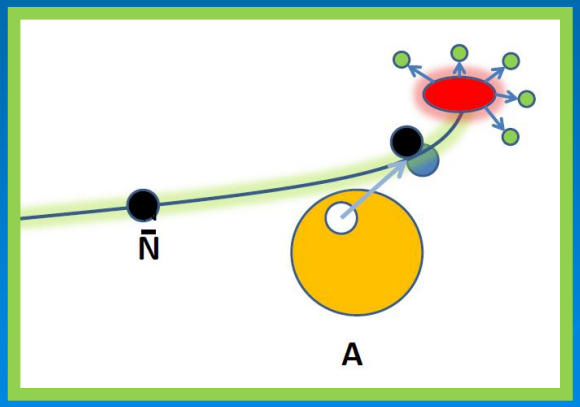
In-situ Annihilation:

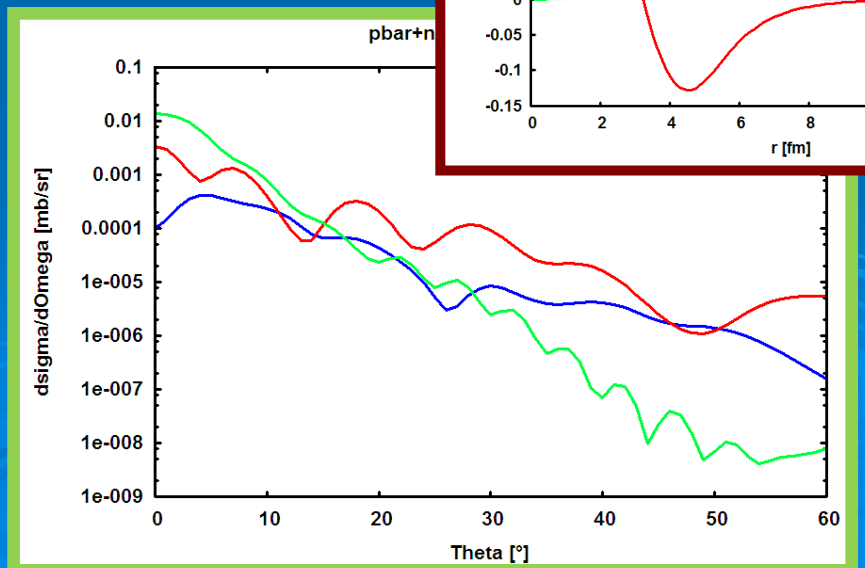






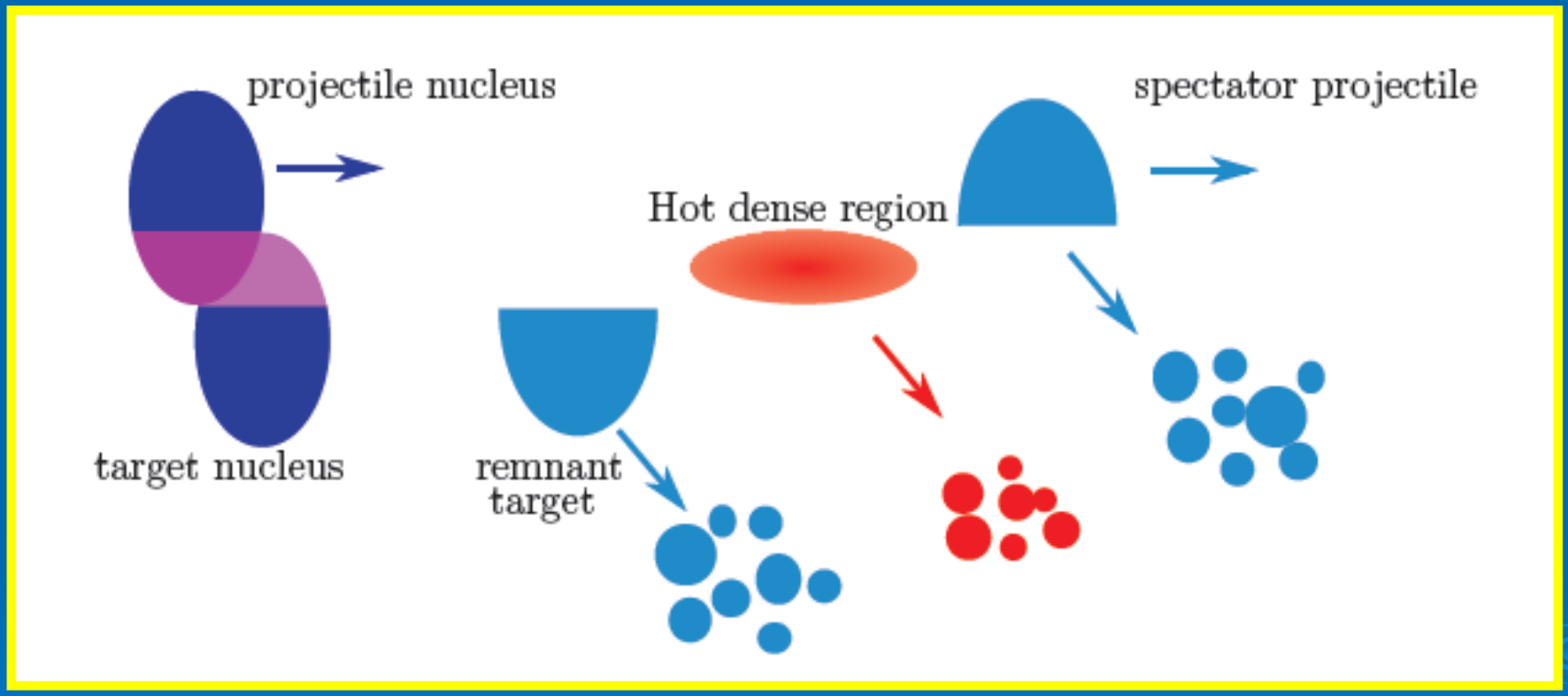
In-flight Annihilation:





V. Heavy Ion Fragmentation Reactions

Scenario of a fragmentation reaction Transport theory (GiBUU) and Statistical Multi-Fragmentation Model (SMM)



(T_{lab}>2AGeV)

Phys. Lett. B **675**, 297 (2009) **NPA 881:240 (2012)** Phys. Lett. B **663**, 197 (2008)

NPA (2013) in print

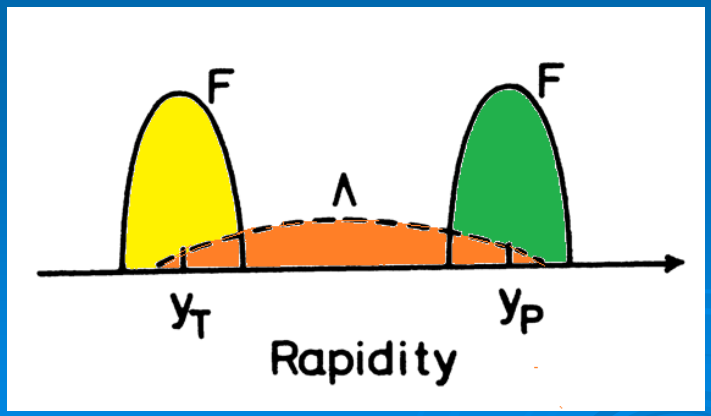
Formation of a Hypernucleus by capturing a Λ to a pre-formed Fragment F:

$$\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(\Lambda F)}}{dk_c^2} = \left[\frac{m_\Lambda + m_F}{m_\Lambda m_F}\right]^3 S_{\Lambda F} \left[\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(\Lambda)}}{dk_c^3}\right] \left[\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(F)}}{dk_c^3}\right]$$

Coalescence

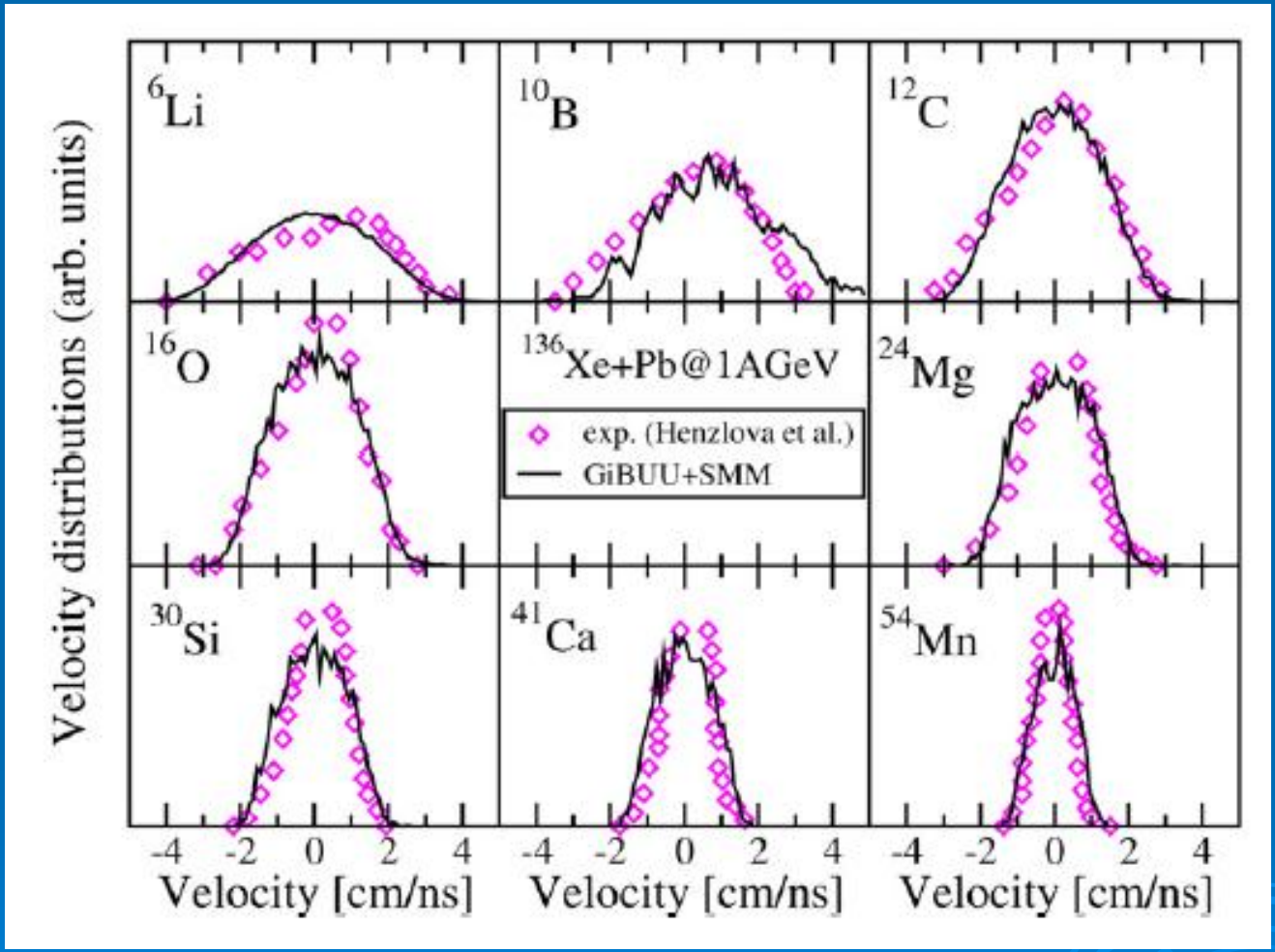
Λ Production X-section (GiBUU)

Fragment Production X-section (SMM)



M. Wakai, H. Bando, M. Sano, Phys. Rev. C 38 (1988) 748.

Production of Light Nuclei by GiBUU+SMM (FOPI data)

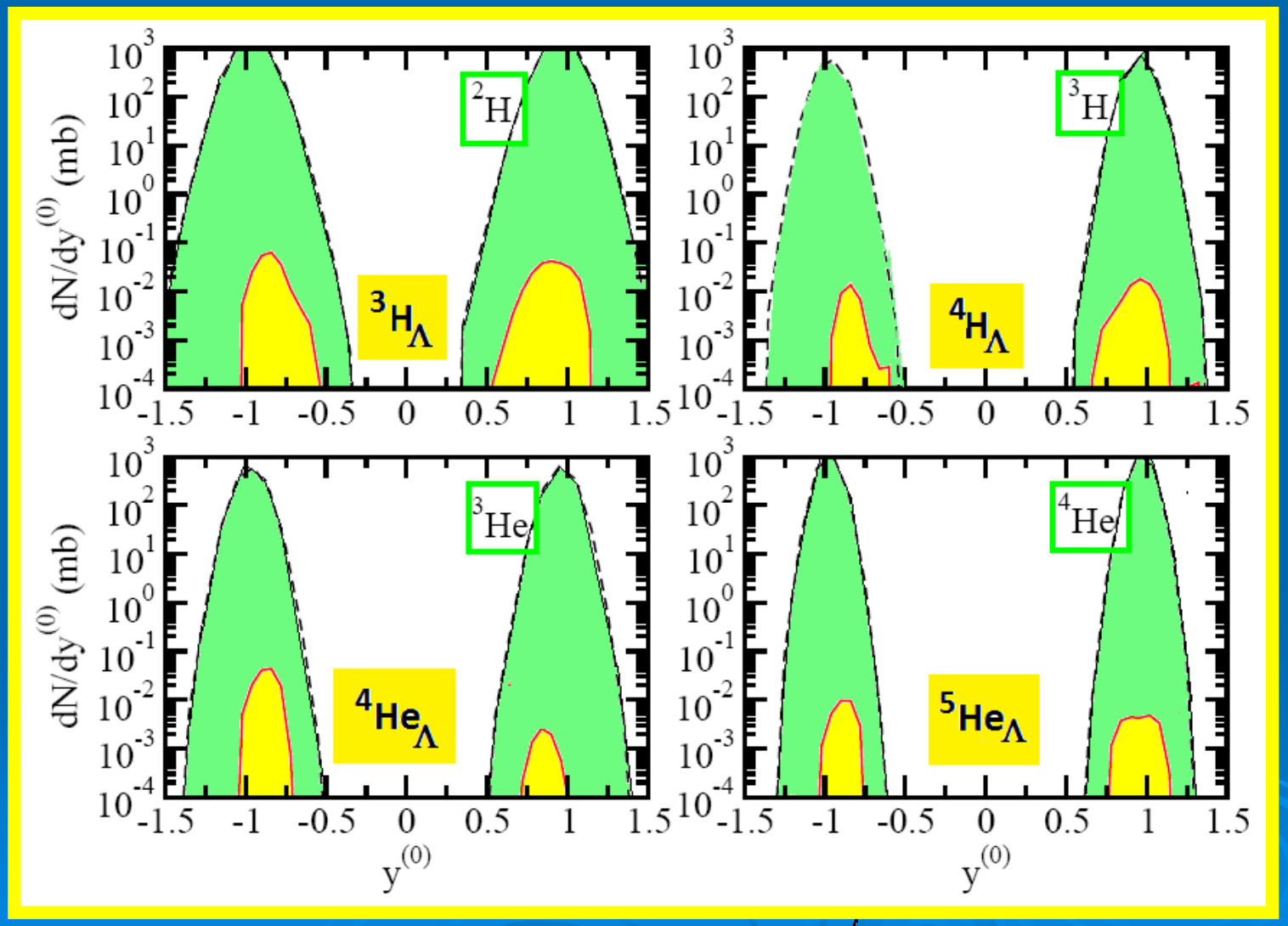


Longitudinal velocity distributions in the projectile frame

Th. Gaitanos, HL et al., Phys. Lett. B 675:297 (2009), NPA 881:240 (2012)

Production of Hypernuclei in $^{12}C+^{12}C$@2AGeV

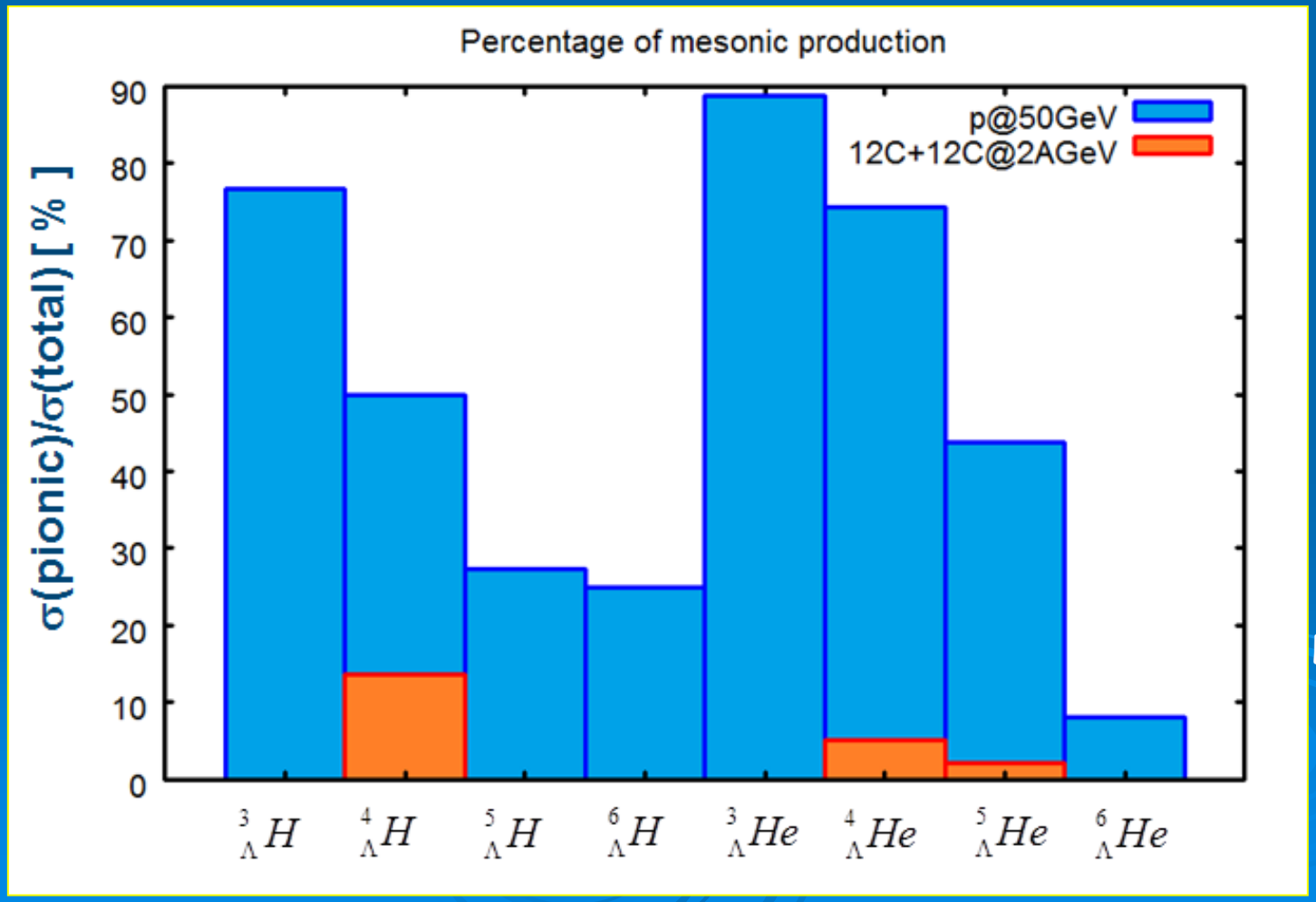
(→ HypHI-Experiment)



Th. Gaitanos, HL et al., NPA 881:240 (2012), NPA 2013 (in print)

Production of Hypernuclei in HI-Collisions: where do the hyperons come from?

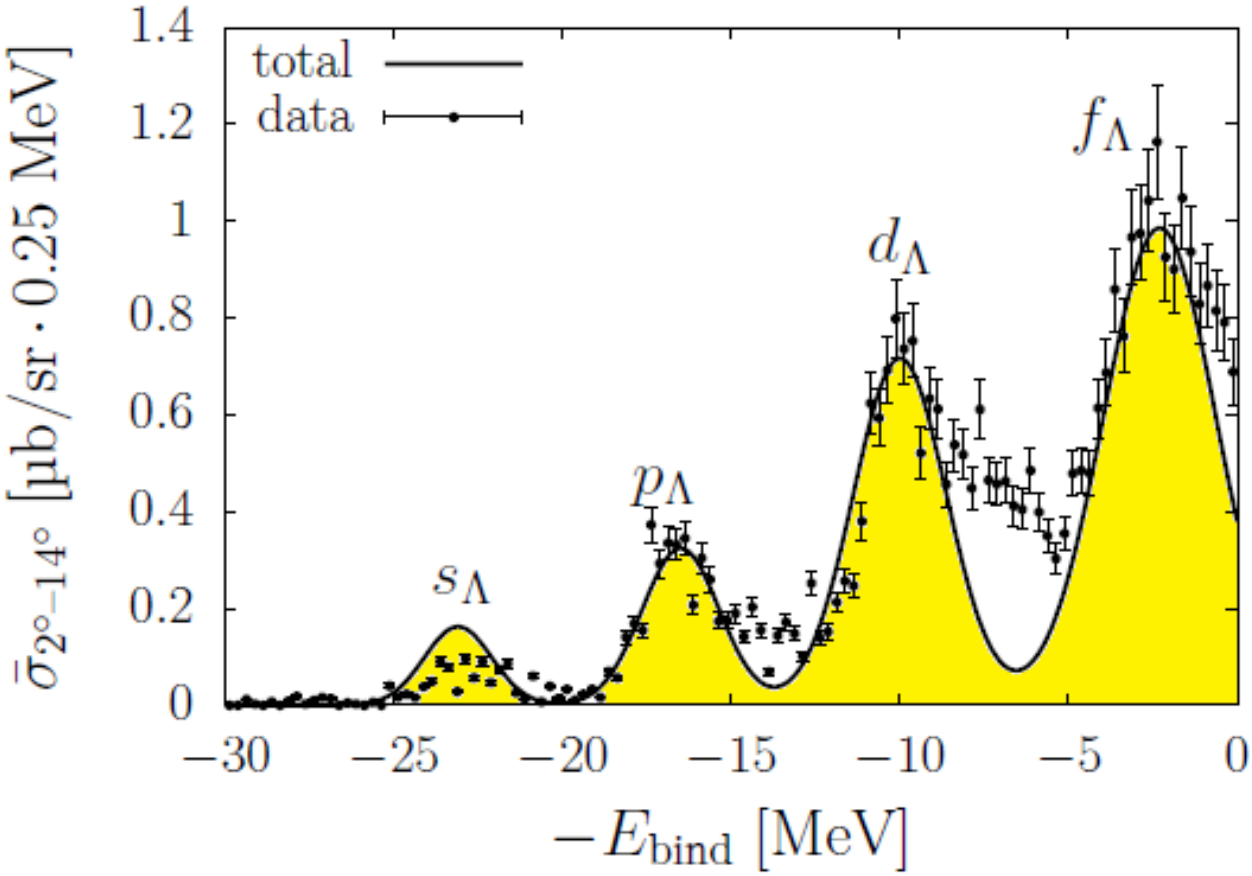
- primary (resonance) production: N+N→N+N*→N+Y+K
- secondary (mesonic) production: π+N→N*→Y+K



Th. Gaitanos, HL, et al., Phys. Lett. B 675, 297 (2009))

Results for $^{89}Y(\pi^+,K^+)^{89}Y_\Lambda$: Gießen resonance model and microscopic nuclear structure

(KEK data: Hotchi et al.)

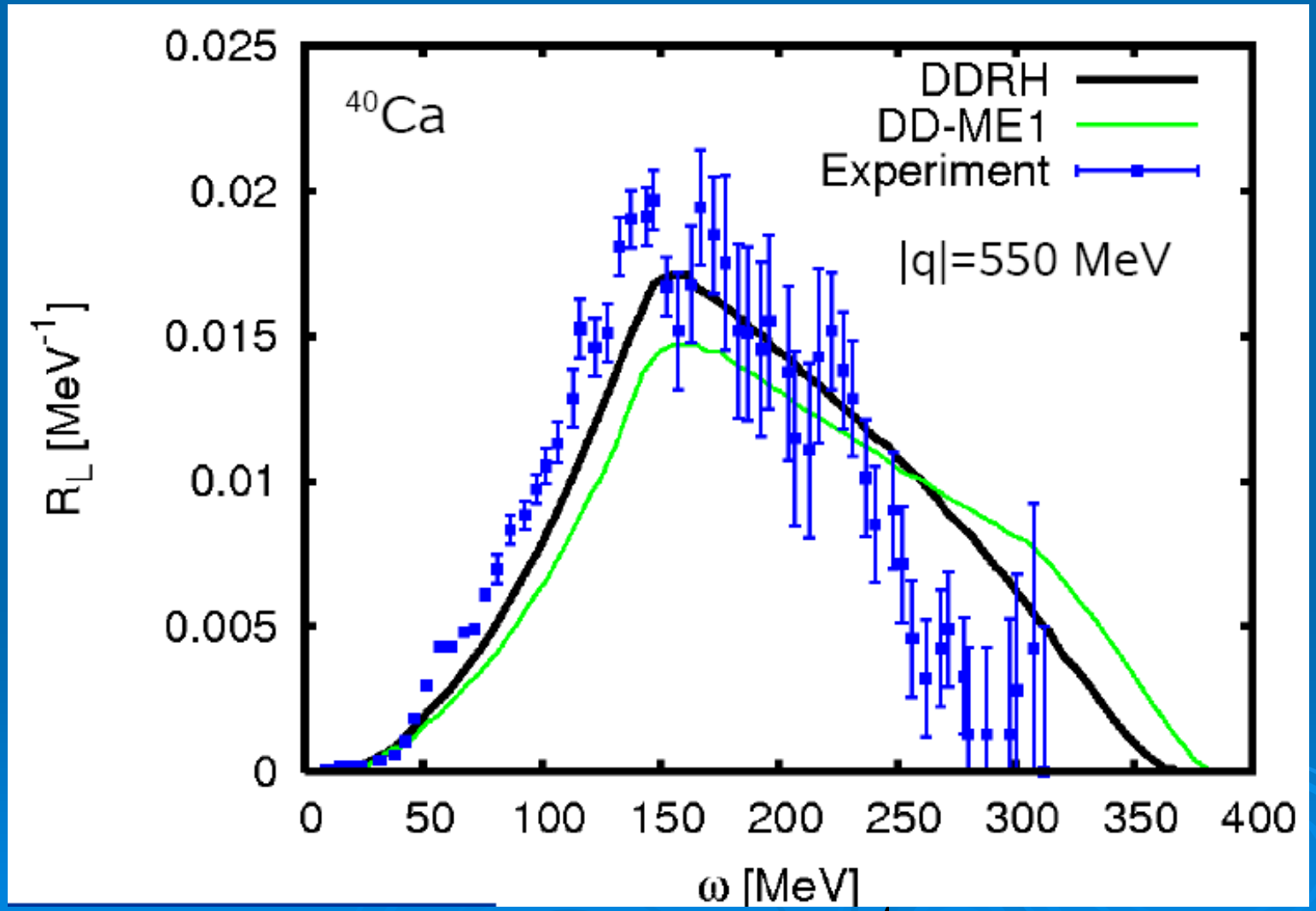


The total averaged cross section for the $^{89}_{\Lambda}$Y hypernucleus.

S. Bender, R. Shyam, HL, Nucl.Phys.A839:51,2010

V. Nucleon Resonances in Exotic Nuclei

Reaction at large 4-momentum transfer: Quasi-free (e,e'p)/(p,pp') Scattering Longitudinal (RPA) Response Functions



Data from: Meziani et al., PRL 52, 2130 (1984)

A. Fedoseew, H.L., in progress

Resonance Excitation at the FRS:

S364 collaboration

Access to proton and neutron radial distributions using Δ resonance excitation in isobar charge-exchange reactions

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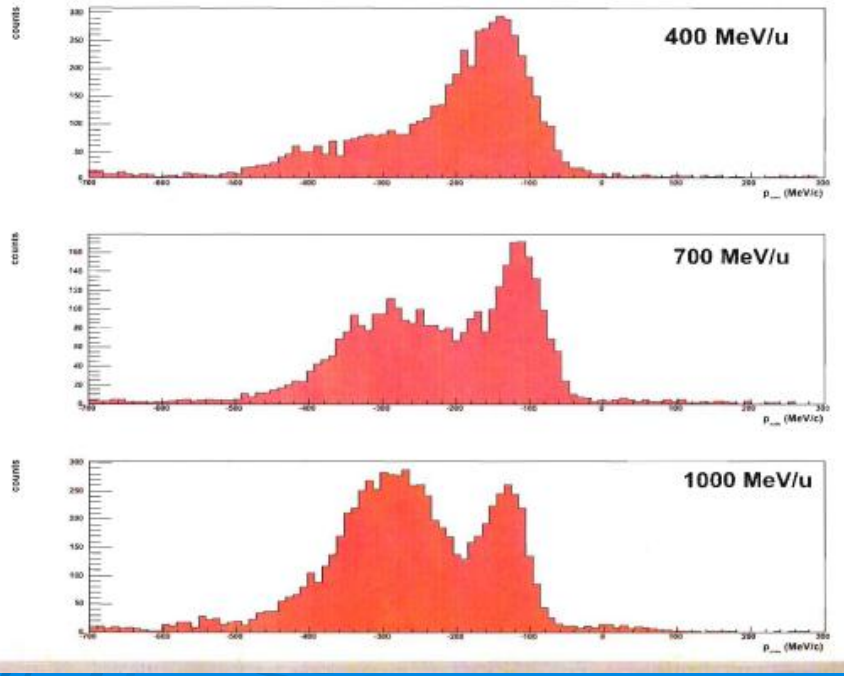
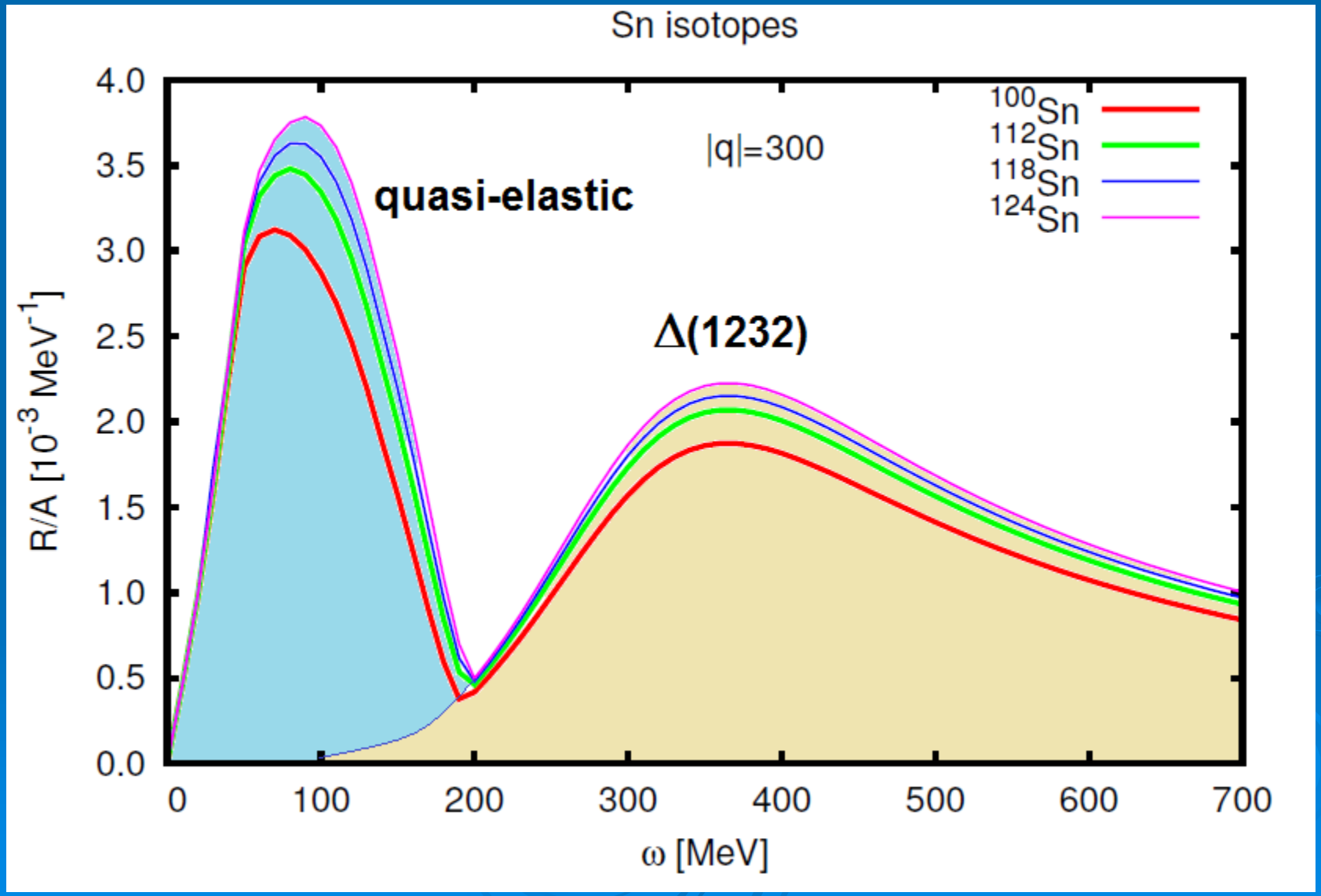
- **Calibration Group:** J. Benlliure, H. Weick, S. Pietri, A. Estrade, D. Pérez, E. Casarejos, H. Álvarez

Energy dependance ^{112}Sn



(H. Geissel)

Resonance excitation in Sn-isotopes: RPA results for $T_a=\tau_-$ charge exchange: (N,Z)→(N-1,Z+1) transitions - ^{A}Sn→ ^{A}Sb



Neutrino-Nucleus Cross Sections and Response Functions

$$\nu_l(\bar{\nu}_l) + A \longrightarrow l^-(l^+) + X$$

$$\nu_l(\bar{\nu}_l) + A \longrightarrow \nu_l(\bar{\nu}_l) + X$$

$$\begin{aligned}
\frac{\partial^2\sigma}{\partial\Omega\partial k'} = \frac{G_F^2\cos^2\theta_c(k')^2}{2\pi^2}\cos^2\frac{\theta}{2}\Bigg\{ & G_E^2\left(\frac{q_\mu^2}{q^2}\right)^2 R_\tau^{NN} \\
& + G_A^2\frac{(M_\Delta - M_N)^2}{2q^2}R_{\sigma\tau(L)}^{N\Delta} + G_A^2\frac{(M_\Delta - M_N)^2}{q^2} \\
& \times R_{\sigma\tau(L)}^{\Delta\Delta} + \left(G_M^2\frac{\omega^2}{q^2} + G_A^2\right)\left(-\frac{q_\mu^2}{q^2} + 2\tan^2\frac{\theta}{2}\right) \\
& \times \left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right] \pm 2G_A G_M\frac{k+k'}{M_N} \\
& \times \tan^2\frac{\theta}{2}\left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right]\Bigg\}
\end{aligned}$$

V. Summary

- Nuclear Dynamics around the Particle Threshold
- Dynamics of the Nuclear Skin
- Antiprotons for Exotic Nuclei
- Hypernuclei from HI-fragmentation
- Resonances in Exotic Nuclear Matter

…with contributions by
Urnaa Badarch, Andreas Fedoseew, Theo Gaitanos, Stefanie Lourenco, Anika Obermann, Sonja Orrigo, Vladimir Ponomarev (TUD), Nadia Tsoneva, Slawomir Wycech (Warschau)

"The best way to predict the future is to create it."

Peter Drucker (*1909-†2005)
Austrian-American economist and
„management-guru“