WORKSHOP **RIKEN Nishina Center** **February 5, 2011**

Scintillator-based High-resOlution Gamma-ray spectrometer for Unstable Nuclei (SHOGUN) based on the novel scintillator LaBr3:Ce

RIKEN Nishina Center for Accelerator-Based Science

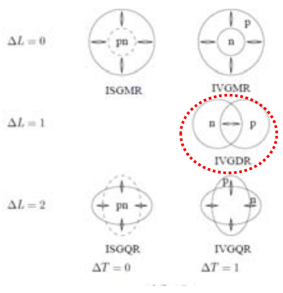
Dipole Response of Exotic Nuclei and Neutron Skin – Possible Experiments for a next generation $LaBr_3(Ce)$ scintillator based setup at RIBF

O. Wieland, A. Bracco, F. Camera, B. Million, S. Leoni, G. Colo
INFN sez. di Milano and Universita di Milano, Italy

GIANT RESONANCES IN NUCLEI

- Collective response of nuclei to external excitation
- Macroscopically: oscillation of neutrons and protons
- Microscopically: superposition of particle-hole excitations
- GDR described with a Lorentzian

$$\sigma(E) = \frac{\sigma_m \Gamma_m^2 E^2}{(E - E_m)^2 + \Gamma_m^2 E^2}$$



SUM rules

IVGDR $\int \sigma(1^-)\, dE = 60 \frac{NZ}{A}$ MeV mb

and for the IVGQR:

$$\int \frac{\sigma(2^+)}{E^2}\, dE = 0.255 \langle r^2 \rangle \frac{NZ}{A} \text{ MeV}^{-1}\,\mu\text{b}$$

which yields for the IVGQR:

$$\int \sigma(2^+)\, dE \approx 0.255 \langle r^2 \rangle E(2^+)^2 \frac{NZ}{A} \text{ MeV}\,\mu\text{b}$$

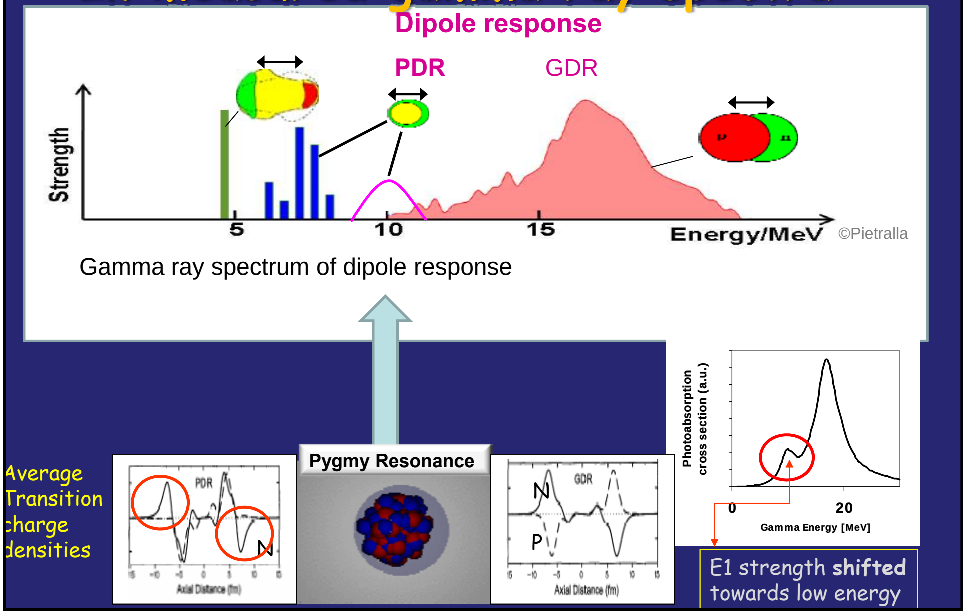
Observables
(E*, J, ... dependend):

Centroid,
Width,
Strength,
Lineshape

→Information on nuclear structure

Symmetry energy,
damping,
collectivity,
deformation

Electric Dipole response in Nuclei
In measured gamma ray spectra



Pygmy Resonance

Collective oscillation of neutron skin against the core

Open Questions

-Level of collectivity ?
-How (collective) properties change with n ?
-How isospin changes mean field ?
-In exotic nuclei: does PDR strength exist also below neutron threshold ?
-No High resolution measurements available
-Various nuclei and mass regions
-Effect of deformation ?
-Proton Pygmy?

Different Models give (sometimes very) Different predictions of PDR parameters

Relativistic RPA calc.
Vretenar, Paar, Ring *et al*

RQTBA-2
Litvinova, Ring and Tselyaev

RRPA and (RMF + RRPA)
Cao L.-G. and Ma Z.-Y.

QRRPA calculations
Cao L.-G. and Ma Z.-Y.

HFB+QRPA
S. Peru et al.

Extended RMF+BCS

Skyrme-RPA+phonon coupl.
Bortignon, Colo, *et al.*

Relativistic QRPA
Vretenar, Paar, Ring *et al*

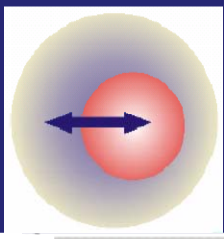
A lot of Ingredients, A lot of Assumptions

In exotic Nuclei: Open Problem, extremely few experimental Data available

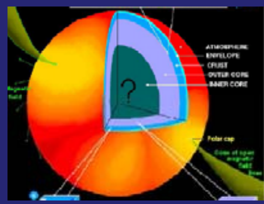
- Theory: Different approaches give different predictions in terms of collectivity, strength and line-shape of the pygmy resonance

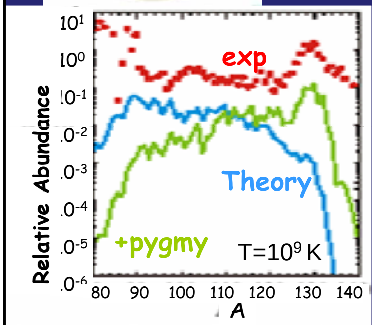
Why the Pygmy Resonance is (so) important ?

There is an **extrapolation** of 18 orders of magnitude from the **neutron radius** of a nucleus (from 5-6 fm to 10 km radius) of a **neutron star**.



Yet both radii depend on the **knowledge of equation of state** of neutron rich matter.





S.Goriely, Phys. Lett. B436 10 (1998)
S.Goriely and E. Khan, Nucl. Phys. A706 (2002) 217

Pygmy Resonance has an important impact on the r-process nucleosynthesis

Nupecc long range plan 2004-2010

"Giant resonances are of paramount importantce for nuclear astrophysics. … …., neutron-rich nuclei … *strength* near particle threshold…"

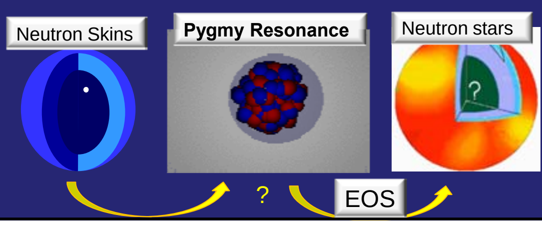
Litvinova at al. NPA 823(2009)26
RQTBA **n-capture** rates (relevant for r-process) in Ni isotpoes
Are **sensitive** to the **fine structure** of low lying **dipole strength**

In addition from the measurment of the pygmy dipole resonance one may also derive

- ❑ Nuclear symmetry energy
- ❑ Neutron skin

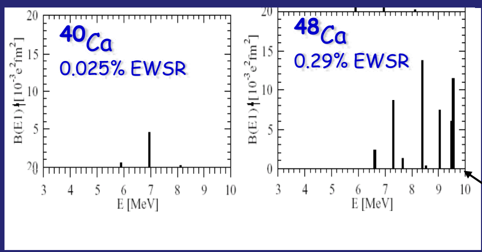
(Data on neutron rms radius constrain the isospin-asymmetric part of the Equation of state of nuclear matter)

Note that:
Relation between neutron skin and neutron stars :
both are built on neutron rich nuclear matter
so that one-to-one correlations can be drawn



Features of this mode

There is a trend of the strength to increase with the **proton-to-neutron asymmetry**



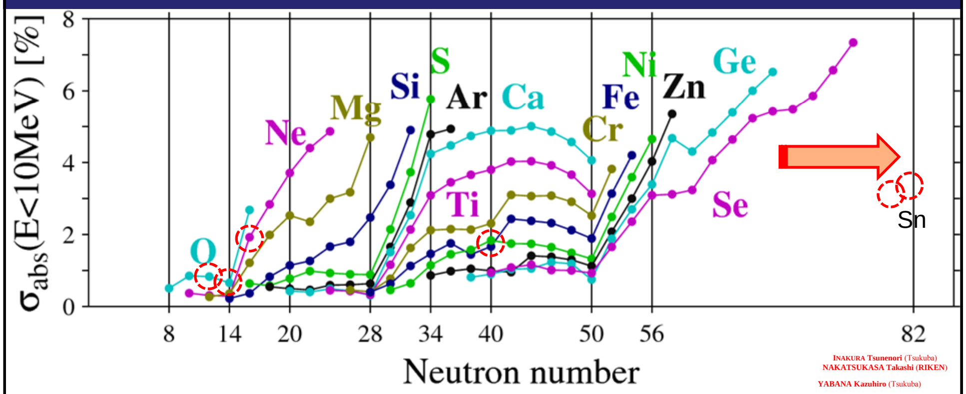
Stable nuclei ⇒
photon scattering,Photoabsorption
(γ,γ '),(γ,n)...

T. Hartmann PRL85(2000)274

Exotic nuclei
?

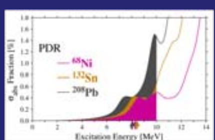
Low-lying E1 (PDR)

Systematic Calculation of Electric Dipole Strengths with Fully Self-consistent Skyrme RPA



Calculated by Inakura (RIKEN)
Method: PRC 80, 044301 (2009); PRC 76, 024318 (2007)

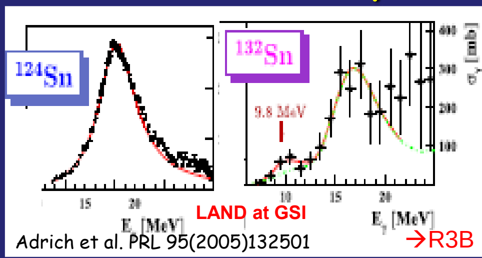
$$PDR : \int_0^{10MeV} dE\, \sigma_{abs}(E)$$



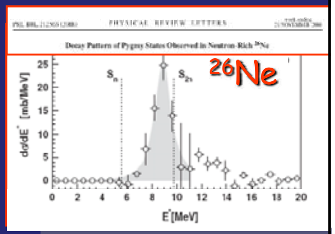
Measurments in neutron rich unstable nuclei

How to excite this mode in exotic nuclei ??

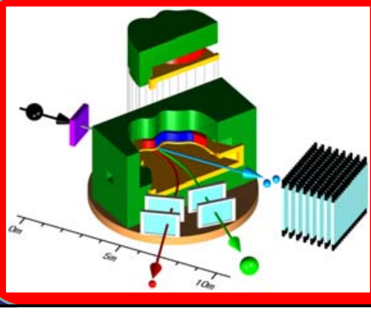
Coulomb break-up (above S_n)



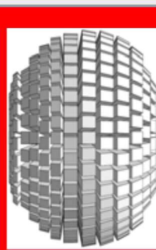
Adrich et al. PRL 95(2005)132501



RIKEN experiment at 58 MeV/u
Measured and extracted
pygmy with 4.9 (+/- 1.6) % EWSR (45mbarn)



Future:
SAMURAI,
Shogun



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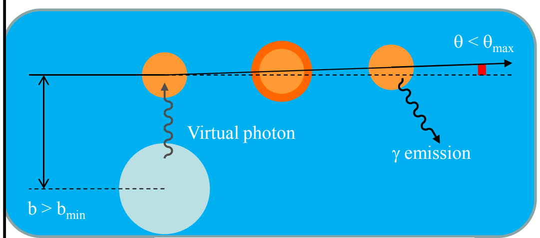
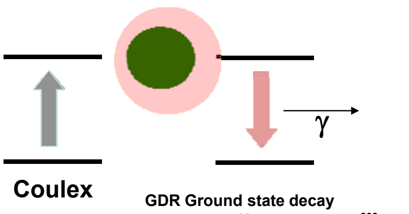
Photon scattering technique

High *selectivity* for dipole excitation !!



$$\frac{d\sigma_C}{dE^*} = \sum_{\pi\lambda} \frac{1}{E^*} N_\gamma^{\pi\lambda}(E^*) \cdot \sigma_\gamma^{\pi\lambda}(E^*)$$

Photon excitation
and decay of **GDR - PYGMY**



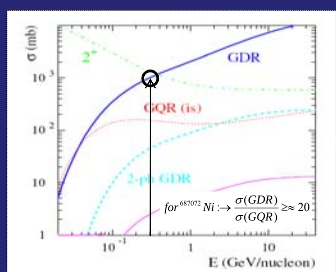
GDR Ground state decay branching ratio ~ 2% measured on ^{208}Pb

To excite Dipole states one needs:

- High beam energy
  - Large cross sections
  - Large $\sigma_{GDR}/\sigma_{GQR}$ ratio

To Select projectile PDR one needs:

- High beam energy
  - Large Doppler effects
    →Background REDUCTION
  - Good Z_{proj}/Z_{target} ratio



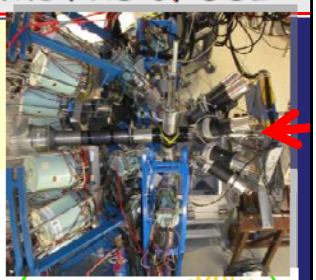
n-knockout some mbarn

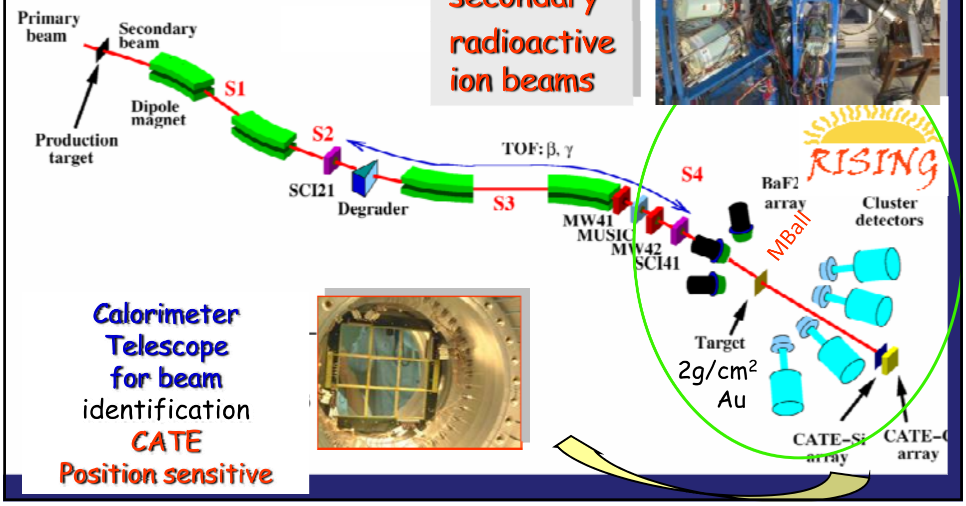
T.Aumann et al EPJ 26(2005)441

High resolution γ-spectroscopy at the FRS of GSI

- ^{68}Ni beam by fragmentation of ^{86}Kr @ 900 MeV/u on Be target (4g/cm^2):
- 10^{10} ppspill ^{86}Kr, Spill length 6s,period 10 s

FRS provides secondary radioactive ion beams





Ground state gamma-ray decay from a GR state following a Coulomb excitation

The measured γ-ray yield is due to the product of 3 terms:
Virtual photon N, photoabsorption cross sect, Branching

$$\frac{d^2\sigma_{C\gamma}}{d\Omega dE_\gamma}(E_\gamma) = \frac{1}{E_\gamma}\frac{dn_\gamma}{d\Omega}(E_\gamma)\,\sigma_\gamma(E_\gamma)\,R_\gamma(E_\gamma).$$

[… Beene, Bortignon, Bertulani …]

! Coulomb excitation probability is directly proportional to the Photonuclear cross section

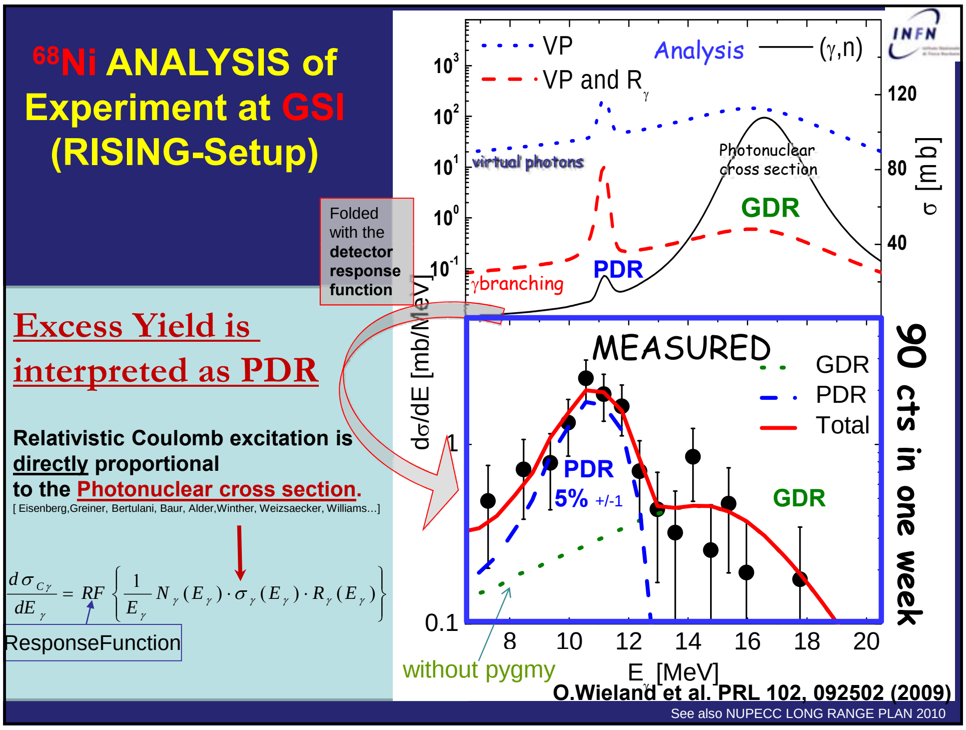
[Eisenberg,Greiner, Bertulani,Alder,Winther,...]

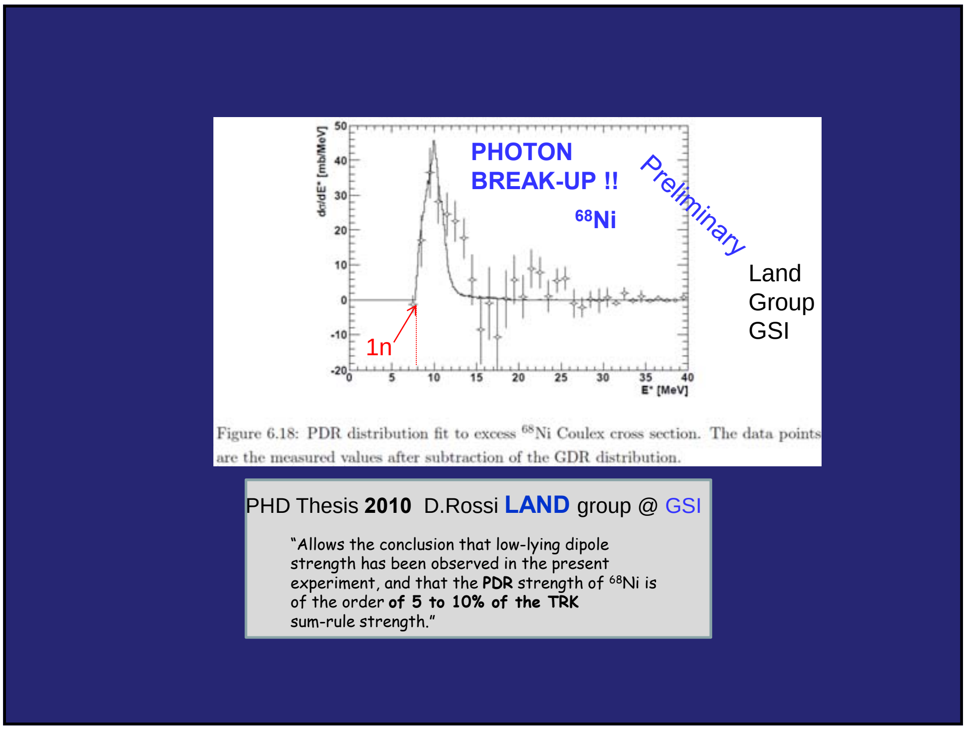
Branching Ratio for γ

Two-steps model, direct GR decay + the compound states :

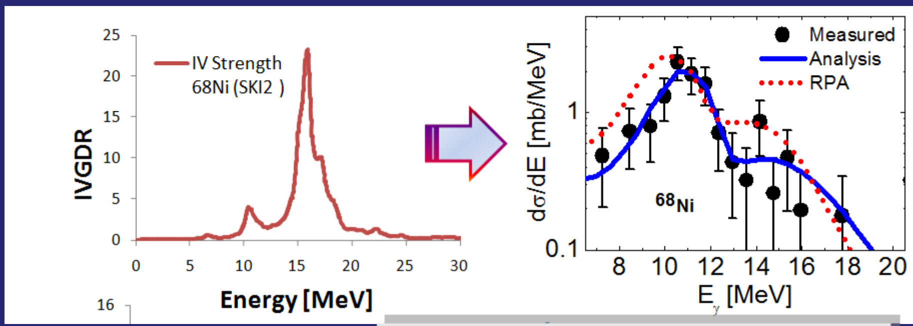
$$R_\gamma(E_\gamma, \rho_{LD}) = \frac{\Gamma_0^{GR}}{\Gamma^{GR}} + \frac{\Gamma^{GR\downarrow}}{\Gamma^{GR}} C \frac{<\Gamma_0^c>}{<\Gamma^c>}.$$

[Beene, et al PLB (1985)]


68Ni ANALYSIS of Experiment at GSI (RISING-Setup)
Folded with the detector response function
Excess Yield is interpreted as PDR
Relativistic Coulomb excitation is directly proportional to the Photonuclear cross section.
[Eisenberg,Greiner, Bertulani, Baur, Alder,Winther, Weizsaecker, Williams...]
$\frac{d\sigma_{C\gamma}}{dE_\gamma} = RF\left\{\frac{1}{E_\gamma}N_\gamma(E_\gamma)\cdot\sigma_\gamma(E_\gamma)\cdot R_\gamma(E_\gamma)\right\}$
ResponseFunction
VP
VP and Rγ
Analysis
(γ,n)
virtual photons
Photonuclear cross section
GDR
PDR
γbranching
σ [mb]
dσ/dE [mb/MeV]
MEASURED
GDR
PDR
Total
PDR
5% +/-1
GDR
90 cts in one week
without pygmy
Eγ [MeV]
O.Wieland et al. PRL 102, 092502 (2009)
See also NUPECC LONG RANGE PLAN 2010


PHOTON BREAK-UP !!
68Ni
Preliminary
Land Group GSI
1n
dσ/dE* [mb/MeV]
E* [MeV]
Figure 6.18: PDR distribution fit to excess 68Ni Coulex cross section. The data points are the measured values after subtraction of the GDR distribution.
PHD Thesis 2010 D.Rossi LAND group @ GSI
"Allows the conclusion that low-lying dipole strength has been observed in the present experiment, and that the PDR strength of 68Ni is of the order of 5 to 10% of the TRK sum-rule strength."

Compare strength of pygmy in ^{68}Ni with theory

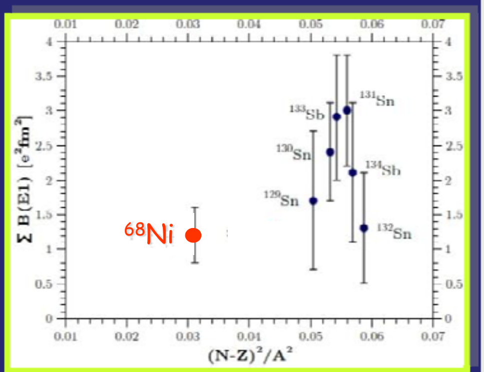


Note that the shape and strengh depends on the effective force

Calculations of different types are available:

- Microscopic Hartree-Fock + random phase approximation [A.Carbone et al. PRC **81, 041301(R) (2010)**]
- Relativistic Quasi particle Random Phase approximation [Vretenar, Paar, Ring *et al.*, NPA692, 496 .]
- ...

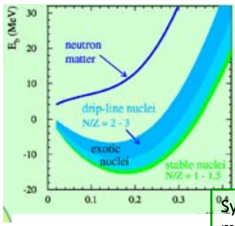
Compare the strength in ^{68}Ni with Sn data



- Lower value of the B(E1) in ^{68}Ni as compare to the Sn region
- This is consistent with the fact that $(N-Z)^2/A^2$ is smaller
- $(N-Z)^2/A^2$ governs the symmetry energy in finite nuclei

This is the first hint that from the strength of the pygmy one could get information on the symmetry energy

The **density dependence** of the **symmetry energy** is poorly constrained and one would like to know the key parameters !!!



Symmetric matter EOS

Symmetry energy S

Nuclear matter **EOS**

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\,\delta^2 \quad \text{where } \delta = (\rho_n - \rho_p)/\rho\,,\ \rho = (\rho_n + \rho_p)$$

The symmetry energy is associated with the exchange of protons into neutrons, and E/A in neutron matter is E/A in symmetric matter plus S !

$E(\rho,\delta) = E_0(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4)$

where
$$S(\rho_0) = J,\quad S'(\rho_0) = L/3\rho_0,\quad S''(\rho_0) = K_{sym}/9\rho_0^2$$

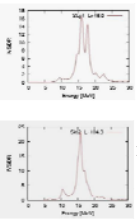
$$S(\rho) = J + L/3\ ((\rho-\rho_0)/\rho_0) + K_{sym}\ ((\rho-\rho_0)/\rho_0)^2 + \dots$$

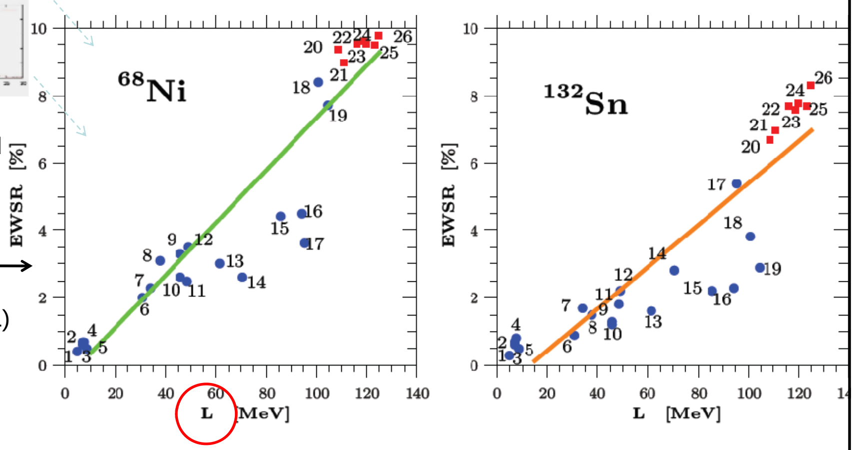
Expansion around density with ρ_0 = saturation density

L slope parameter K_{sym} curvature parameter at saturation density

Possible Correlation that connects L and the PDR strenght

Carbone et al. Phys. Rev. C 81, 041301(R) (2010)



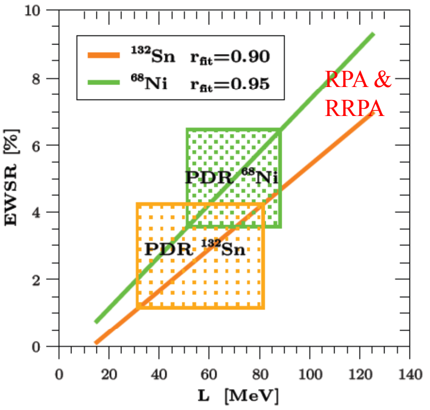


Predicted Strength Of PDR For different Forces (L)

1,2,3,…..19 Skyrme forces   20,…26 RMF (meson exchange) Lagrangians

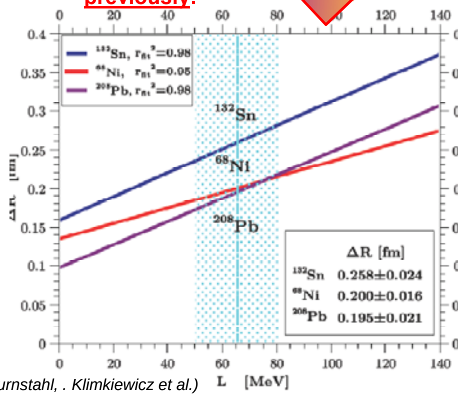
B.A. Brown, PRL 85, 5296 (2000);
S. Typel and B.A. Brown, PRC 64, 027302(R) (2001).
R.J. Furnstahl, NPA 706, 85 (2002);
S. Yoshida and H. Sagawa, PRC 69, 024318 (2004).

Exp. values from O. Wieland *et al.*, PRL 102, 092502 (2009);
A. Klimkiewicz *et al.*, PRC 76, 051603(R) (2007).



(L=slope parameter of
symmetry energy at saturation)

Correlations between L and ΔR (the neutron skin thickness) have been noticed previously.

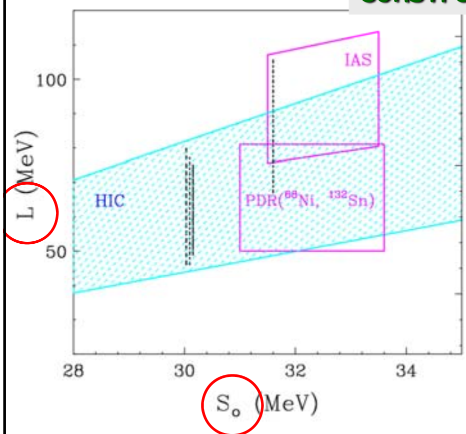


The idea has been previously presented, and exploited in part (Furnstahl, . Klimkiewicz et al.)

However, here for the first time the approach has been pursued with different nuclei **and many different classes of EDFs**. Carbone et al. Phys. Rev. C 81, 041301(R) (2010)

Comparison with heavy ions fragmentation reactions

Two different analysis and measured quantities give consistent constraints to the symmetry energy !

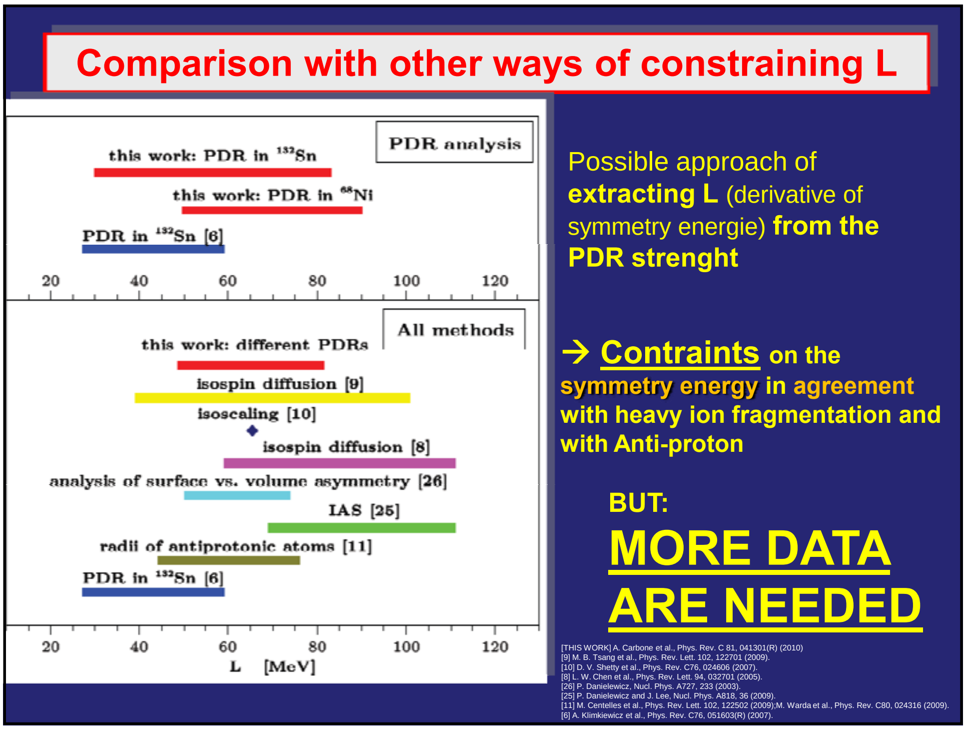


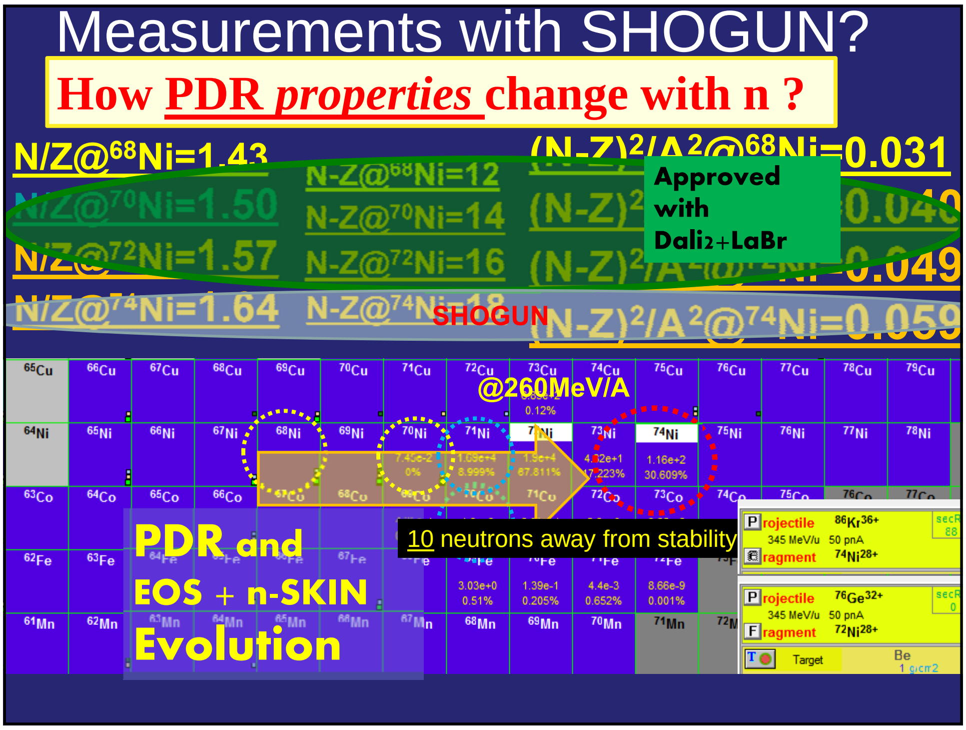
Constraints on the Density dependence of the Symmetry Energy

Measurements from collisions Involving ^{112}Sn and ^{124}Sn with improved quantum molecular dynamics transport model

M.B. Tsang et al. PRL102(2009)122701 + this analysis

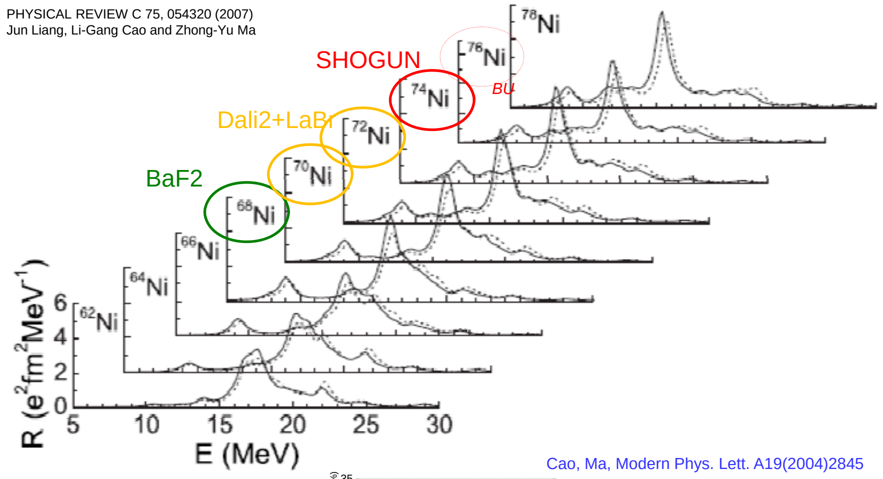
Isospin effects in **Heavy Ion Collisions** (HIC)-Method and **Energy of Isobaric Analogue State** (*IAS*)-Method


Comparison with other ways of constraining L
PDR analysis
this work: PDR in 132Sn
this work: PDR in 68Ni
PDR in 132Sn [6]
20 40 60 80 100 120
All methods
this work: different PDRs
isospin diffusion [9]
isoscaling [10]
isospin diffusion [8]
analysis of surface vs. volume asymmetry [26]
IAS [25]
radii of antiprotonic atoms [11]
PDR in 132Sn [6]
20 40 60 80 100 120
L [MeV]
Possible approach of extracting L (derivative of symmetry energie) from the PDR strenght
→ Contraints on the symmetry energy in agreement with heavy ion fragmentation and with Anti-proton
BUT:
MORE DATA ARE NEEDED
[THIS WORK] A. Carbone et al., Phys. Rev. C 81, 041301(R) (2010)
[9] M. B. Tsang et al., Phys. Rev. Lett. 102, 122701 (2009).
[10] D. V. Shetty et al., Phys. Rev. C76, 024606 (2007).
[8] L. W. Chen et al., Phys. Rev. Lett. 94, 032701 (2005).
[26] P. Danielewicz, Nucl. Phys. A727, 233 (2003).
[25] P. Danielewicz and J. Lee, Nucl. Phys. A818, 36 (2009).
[11] M. Centelles et al., Phys. Rev. Lett. 102, 122502 (2009);M. Warda et al., Phys. Rev. C80, 024316 (2009).
[6] A. Klimkiewicz et al., Phys. Rev. C76, 051603(R) (2007).

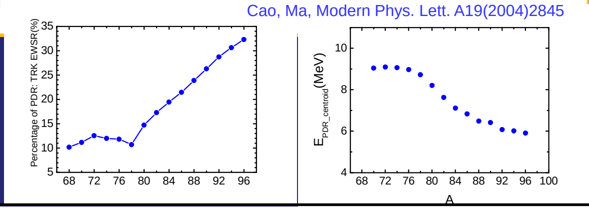

Measurements with SHOGUN?
How PDR properties change with n ?
N/Z@68Ni=1.43
N-Z@68Ni=12
(N-Z)2/A2@68Ni=0.031
N/Z@70Ni=1.50
N-Z@70Ni=14
0.040
N/Z@72Ni=1.57
N-Z@72Ni=16
0.049
Approved with Dali2+LaBr
N/Z@74Ni=1.64
SHOGUN
(N-Z)2/A2@74Ni=0.059
@260MeV/A
PDR and EOS + n-SKIN Evolution
10 neutrons away from stability
Projectile 86Kr36+ 345 MeV/u 50 pnA
Fragment 74Ni28+
Projectile 76Ge32+ 345 MeV/u 50 pnA
Fragment 72Ni28+
Target Be

Evolution of the Pygmy strength in Ni isotopes

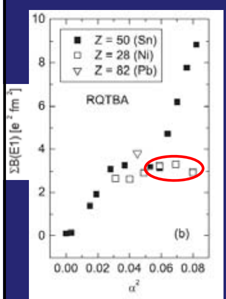
PHYSICAL REVIEW C 75, 054320 (2007)
Jun Liang, Li-Gang Cao and Zhong-Yu Ma



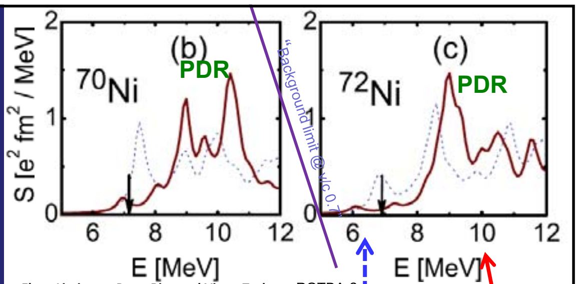
Cao, Ma, Modern Phys. Lett. A19(2004)2845



Theoretical Predictions



E.Litvinova et al, PRC **79, 054312 (2009)**



Elena Litvinova, Peter Ring and Victor Tselyaev RQTBA-2
Phys. Rev. Lett. 105, 022502 (2010)
"the $^{70;72}$Ni isotopes can be suggested for future measurements."

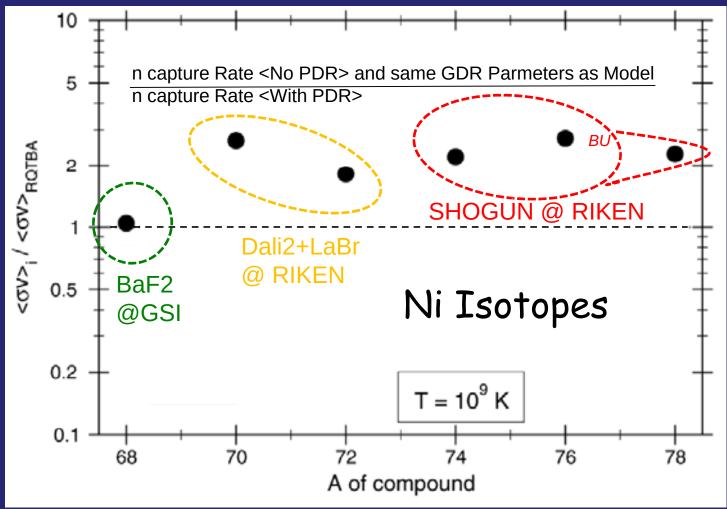
PHOTON SCATTERING
POSSIBLE **ONLY** AT RIKEN

+possibly (Lower states 1-,2+,.
(large scale) Shell model
Calculations to be done
(in ^{68}Ni K. Langanke,)

	B.E.(MeV)	r_c (fm)	r_n-r_p(fm)
^{16}O	-128.112(-127.619)	2.735(2.730)	-0.15
^{40}Ca	-341.578(-342.052)	3.470(3.485)	-0.14
^{48}Ca	-413.615(-415.990)	3.470(3.484)	0.14
^{72}Ni	-612.168(-613.152)	3.892	0.26

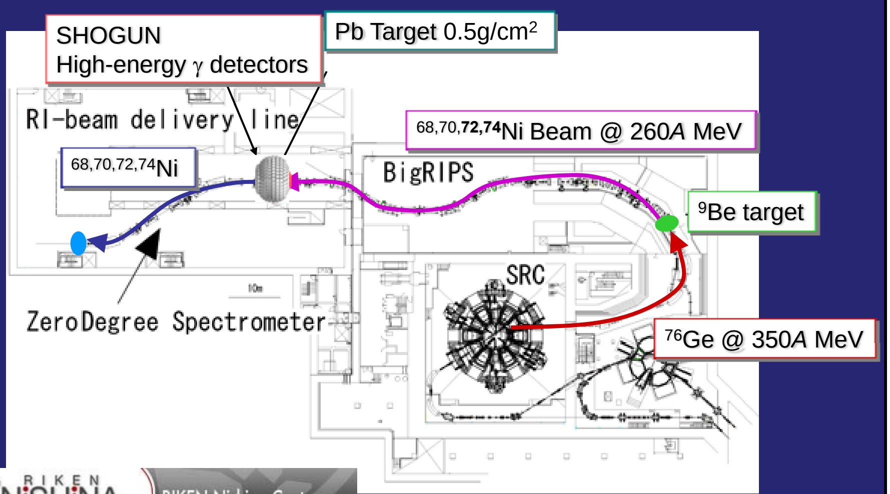
G. A. Lalazissis, et al. Phys.Lett. B 647,111(2007)

Ni chain and astrophysics impact of PDR



Data From
Litvinova at al. NPA 823(2009)26
RQTBA n-capture rates (calc for Ni-chain) relevant for r-process
show modest sensitive to low lying dipole strength

Setup Shogun + (BigRIPS + Zero Degree Spectrometer)



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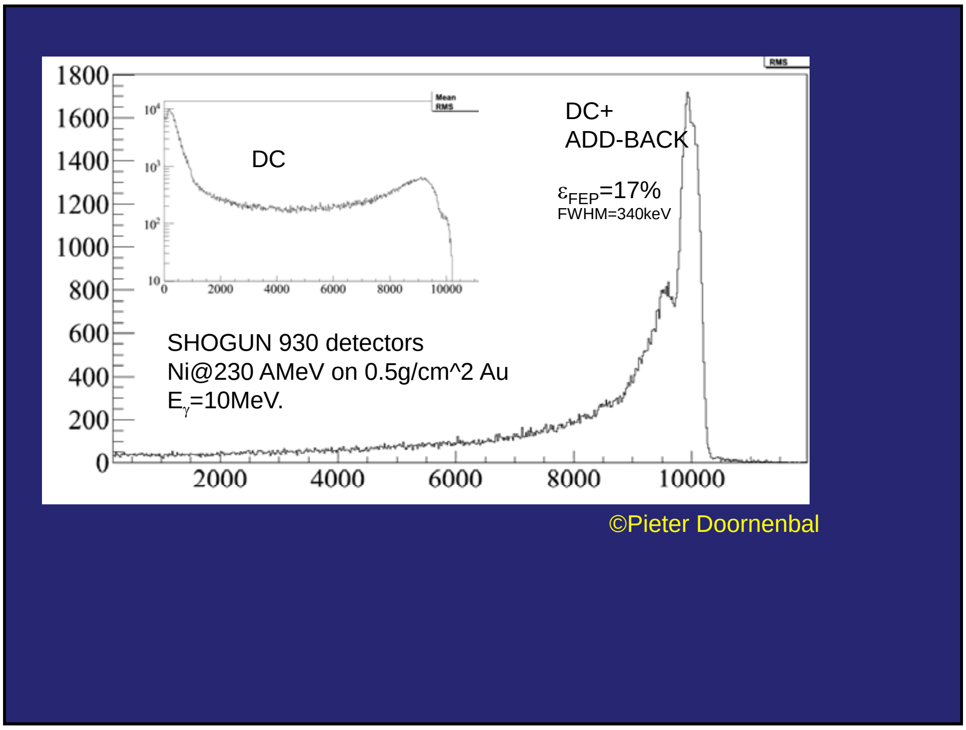
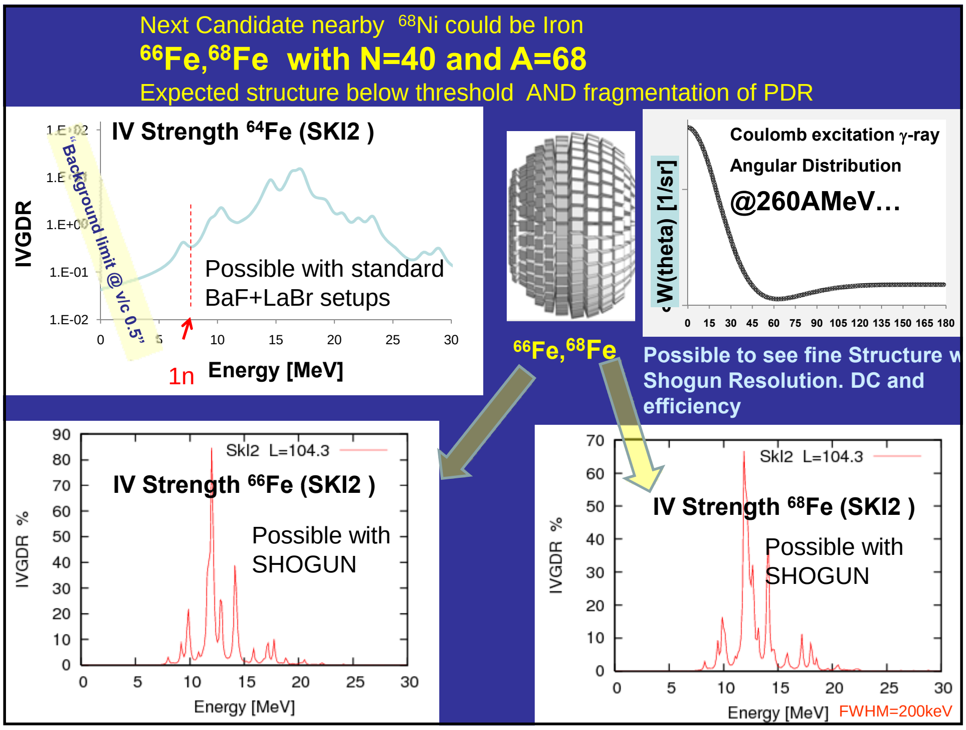
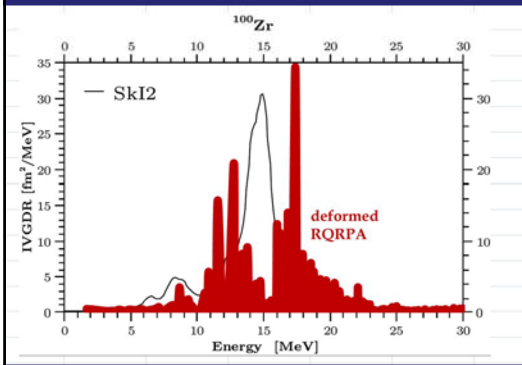
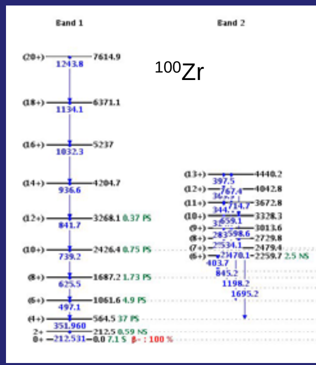

DC
DC+
ADD-BACK
ε_{FEP}=17%
FWHM=340keV
SHOGUN 930 detectors
Ni@230 AMeV on 0.5g/cm^2 Au
E_γ=10MeV.
©Pieter Doornenbal


Next Candidate nearby ^{68}Ni could be Iron
^{66}Fe,^{68}Fe with N=40 and A=68
Expected structure below threshold AND fragmentation of PDR
IV Strength ^{64}Fe (SKI2)
"Background limit @ v/c 0.5"
IVGDR
Possible with standard
BaF+LaBr setups
1n
Energy [MeV]
Coulomb excitation γ-ray
Angular Distribution
@260AMeV…
W(theta) [1/sr]
^{66}Fe,^{68}Fe
Possible to see fine Structure w
Shogun Resolution. DC and
efficiency
SkI2 L=104.3
IV Strength ^{66}Fe (SKI2)
Possible with
SHOGUN
IVGDR %
Energy [MeV]
SkI2 L=104.3
IV Strength ^{68}Fe (SKI2)
Possible with
SHOGUN
IVGDR %
Energy [MeV]
FWHM=200keV

Search for pygmy in deformed ^{10X}Zr

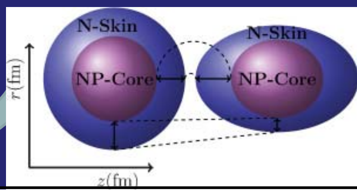
OPEN QUESTION: Deformation hinders the dipole strength
BUT low-lying *E1 strength increases with the neutron* number
D. Pena Arteaga, E. Khan, and P. Ring PRC ***79, 034311 (2009)***





To disentangle the PDR finestructure good DOPPLER correction is needed

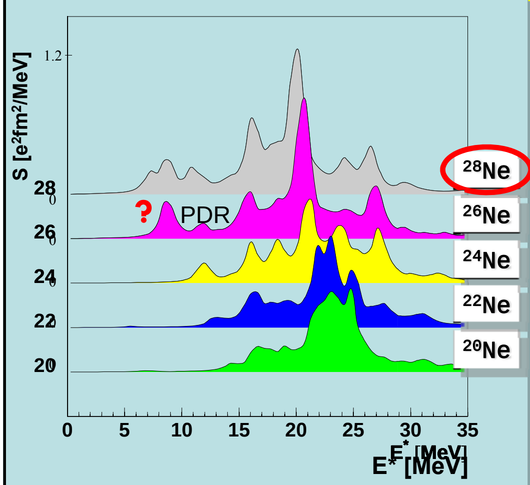
RQRPA highly **deformed** with beta=0.4
calculations done by
Daniel Pena Arteaga ipno.in2p3.fr Orsay



Fragmentation of the strength in ^{26}Ne

Virtual Photon Breakup Method
@ 85AMeV ***RIKEN***
→Needs confirmation, continue
→And additional information
With Photon scattering

"Systematic" E1 Strength predicted by QRRPA calculations (for deformed Ne nuclei)
Neon Mass Number



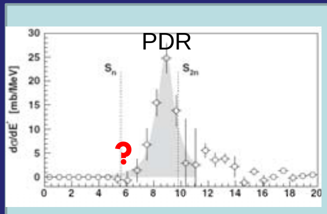


Figure 1: Reconstructed excitation energy spectra from the Coulomb break up measurement [10] of the dipole strength distributions for ^{26}Ne in function of the gamma ray energy after substraction of background and E2 contributions.

J. Gibelin *et al.*, Phys. Rev. Lett. 101, 212503 (2008).

B(E1) = 0.60±0.06 e^2fm^2
or 5.9 ±1.0% of TRK sum rule @ 9 MeV

Cao L.-G. and Ma Z.-Y. Phys. Rev. C 71, 034305 (2005)

RESUME

Great perspectives with SHOGUN

1. Ni chain, (→^{74}Ni) PDR properties, neutron radius
2. Zr chain, (→^{10X}Zr) PDR in deformed nuclei
3. Fe chain, PDR nearby Ni (^{66,8}Fe←→^{68}Ni n=40,A=68)
4. Ne chain deformed light nucleus (complem. to PhotonBreakup)
5. Sn chain, and higher or lower O chain (→$^{24,..}$O) mass region
6. Combination with PhotonBreakup !
7. Different probes and E_{beams}
   to study nuclear contributions and IV, IS part

OPEN QUESTIONS

- -Level of collectivity ?
- -How (collective) properties change with n ?
- -How isospin changes mean field ?
- -In exotic nuclei: PDR strength also below neutron threshold, or varies with threshold?
- -No High resolution measurements available
- -Various nuclei and mass regions
- -Effect of deformation ?
- -Proton Pygmy?
- -astrophysical impact…

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Analysis using theory…….
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Preparation for RIKEN, … DALI2, SHOGUN, ZDS, BIGRIPS,…..TEAMs

ありがとう
Thank You