Symmetry Energy from Pigmy Dipole and Giant Resonances

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OUTLINE

- Motivation
- Experiment description
- Results
- Comparison with theory
- Conclusions and perspectives
Electric Dipole response in Nuclei

two Phonon couplings $2^+ \otimes 3^-$

Dipole response

PDR

GDR

Average Transition charge densities

Richter NPA 731(2004)59
Electric Dipole response in Nuclei

Dipole response
PDR  GDR

GDR

Stable Nuclei ⇒ Photoabsorption

two Phonon couplings $2^+ \otimes 3^-$

Dipole strength shifts at low energy

T. Hartmann PRL5(2000)274
**Electric Dipole response in Nuclei**

- **two Phonon couplings** $2^+ \otimes 3^-$
- **Dipole response**
  - PDR
  - GDR

**Stable nuclei** $\Rightarrow$ **Photoabsorption**

**Neutron rich nuclei**
- $\Rightarrow$ **Virtual photon scattering**
- $\Rightarrow$ **Neutron breakup**
Why the Pygmy Resonance is important?

- Is it collective?
- How collective properties change with neutron number?
- How deformation acts?
Why the Pygmy Resonance is important?

- Is it collective?
- How collective properties change with neutron number?
- How deformation acts?
- How PDR affects the r-process nucleosynthesis?

“Giant Resonances are of paramount importance for nuclear astrophysics. Often, relevant reaction rates under astrophysical conditions are dominated by giant resonances contributions frequently in unstable nuclei. For instance neutron rich nuclei with loosely bound valence neutrons may exhibit very strong ($\gamma$,n) strength components near particle threshold and thus, in turn, enhanced neutron capture rates.”

NUPECC long range Plan 2004
Why the Pygmy Resonance is important?

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How PDR affects the r-process nucleosynthesis

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NUPECC long range Plan 2004

As in a hydrodynamic approach the excitation energy of IVGDR depends on a combination of volume and surface symmetry energy, can PDR provide information on L and neutron skin?

“we suggest that the electromagnetic excitation of both the pygmy and giant dipole resonances will continue to provide powerful constraints on the density dependence of the symmetry energy”
Piekarewicz PRC83(2011)034319

“We can conclude that our more general analysis of the extraction of the slope parameter L from the PDR is able to provide a firm result”
A.Carbone et al. PRC81(2010)041301
PDR in neutron rich nuclei

Light nuclei

Virtual photon breakup
Riken, GSI experiments
Virtual photon scattering
MSU, RISING experiments

Medium Mass nuclei

J. Gibelin et al PRL 101, 212503 (2008)

Lots of work but few data available


+ this work on $^{68}$Ni
Search for pygmy strength in $^{68}$Ni in theory

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

Theoretical predictions before the experiments

D. Vretnar et al. NPA 692(2001)496

G. Colo private communications

J. Liang et al., PRC75(2007)

fRPA: 7-8%
Virtual photon scattering technique

- Peripheral heavy-ion collision on a high $Z$ target at relativistic energies
- Virtual photon excitation and decay
- Relativistic Coulomb excitation has very high selectivity for dipole excitation

$\sigma(GDR) / \sigma(GQR) \approx 20$

Maximum excitation energy (adiabatic cut off) ca. $E = 18.5$ MeV
Virtual photon scattering technique

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Virtual photon excitation and decay of GDR + PYGMY

Maximum excitation energy (adiabatic cut off) ca. $E = 18.5$ MeV

\[ ^{197}\text{Au}( ^{68}\text{Ni}, ^{68}\text{Ni}^* + \gamma) ^{197}\text{Au} \]

\[ 600 \text{ MeV/u} \, ^{68}\text{Ni} + ^{197}\text{Au} \]

\[ 400 \text{ MeV/u} \, ^{68}\text{Ni} + ^{197}\text{Au} \]
High resolution γ-spectroscopy at the FRS of GSI

- $^{86}$Kr @ 900 MeV/u on Be target (4g/cm$^2$) $\Rightarrow$ $^{68}$Ni
- $10^{10}$ ppspill $^{86}$Kr, Spill length 6s, period 10 s
- $^{68}$Ni @ 600 MeV/u on Au target (1g/cm$^2$)
- cocktail of $10^4$ pps ions Spill length 6s, period 10 s

FRS provides secondary radioactive ion beams

CATE
Position sensitive E-ΔE Telescope for beam identification after target
Coulomb excitation of $^{68}$Ni @ 600 AMeV

Beam cocktail of 5 isotopes

~ 6 Days of effective beam time

~ 400 GB of data recorded

~ $1 \times 10^8$ 'good $^{68}$Ni events'
Highly selective gates

- Large reduction in statistics

- **Conditions:**
  - $^{68}\text{Ni}$-incoming-selection
  - $^{68}\text{Ni}$-outgoing-selection
  - TOF-in prompt
  - Outgoing angle check
  - Doppler correction
  - $m_\gamma=1$
  - Detector specific (PSA, AddBack)
High energy $\gamma$-ray spectra measured in BaF$_2$ detectors evidence a clear excess of $\gamma$-rays between 10-12 MeV

Same evidence in HPGe cluster detectors
Ground state $\gamma$ decay from a GDR state after a Coulomb excitation

The measured $\gamma$-ray yield is due to the product of 3 terms:

Virtual photon number, $\sigma$ photoabsorption, Branching Ratio

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

Known from theory

Integration over $\Omega$ or $b$
Ground state $\gamma$ decay from a GDR state after a Coulomb excitation

The measured $\gamma$-ray yield is due to the product of 3 terms:

- Virtual photon number, $\sigma$ photoabsorption, Branching Ratio

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

Beene, Bortignon, Bertulani

Our final objective


Thanks to J. Alhassid
Ground state $\gamma$ decay from a GDR state after a Coulomb excitation

The measured $\gamma$-ray yield is due to the product of 3 terms:

Virtual photon number, $\sigma$ photoabsorption, Branching Ratio

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

$$\sigma_\gamma(E_\gamma) = \frac{1}{E_\gamma} \frac{dn_\gamma}{d\Omega}(E_\gamma) \bullet \sigma_\gamma(E_\gamma)$$

$$\frac{1}{E_\gamma} \frac{dn_\gamma}{d\Omega}(E_\gamma) \bullet \sigma_\gamma(E_\gamma) \bullet R_\gamma(E_\gamma)$$
RESULT: Pygmy dipole resonance in $^{68}$Ni

Centroid $\approx 11$ MeV
Width $\approx 2$ MeV
Instrumental (Doppler Broadening)

Strength = 5 ($\pm 1.5$) % of the EWSR

$B(E1) = 1.2 \text{ e}^2\text{fm}^2$

Next steps:
- Deduce L
- Deduce the Neutron radius

O. Wieland et al., PRL102(2009)092502
Correlation between L and the PDR

Several theoretical works have shown that PDR properties can be correlated and provide constraint to the symmetry energy slope

However this approach:

- is not fully accepted
- gives predictions which strongly depends on the used nuclear force

we belive that PDR measurements are a valuable tool in the study of symmetry energy and that a correlation between PDR and L exist.

- see talk of X. Roca-Maza
Correlation between \( L \) and the PDR

This technique has been previously used but here the approach has been pursued using different nuclei and different classes of forces (Blue=Skyrme; red=RMF)

A.Carbone et al. PRC81(2010)041301
See talk of X. Roca-Maza
Once extracted a value for L it is possible to infer, using the same technique, a value for the neutron skin thickness.

B.A. Brown, PRL 85, 5296 (2000);
R.J. Furnstahl, NPA 706, 85 (2002);

Exp. values from
O. Wieland et al., PRL 102, 092502 (2009);
P. Adrich et al., PRL 95, 132501 (2005)
A. Klimkiewicz et al., PRC 76, 051603(R) (2007).

Theory
A. Carbone et al. PRC81(2010)041301
The analysis of Klimkiewicz et al. based on $^{132}$Sn data gave for $^{208}$Pb

$$R_n - R_p = 0.18 \pm 0.035 \text{ for } ^{208}\text{Pb}$$

For other isotopes:

- $R_n - R_p = 0.195 \pm 0.021 \text{ fm for } ^{208}\text{Pb}$
- $R_n - R_p = 0.20 \pm 0.02 \text{ fm for } ^{68}\text{Ni}$
- $R_n - R_p = 0.25 \pm 0.045 \text{ fm for } ^{132}\text{Sn}$
Comparison with other ways of constraining L

The used approach to extract L from the measured PDR EWSR produce a results which is compatible/comparable to the experimental results from data analysis of heavy-ion collisions experiment.
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

This work

$S_0 = 32.3 \pm 1.3 \text{ MeV}$

$L = 64.8 \pm 15.7 \text{ MeV}$

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

• We have measured the Pygmy Dipole Resonance in $^{68}\text{Ni}$ using the virtual photon scattering technique

• Combined analysis of our $^{68}\text{Ni}$ PDR data and that of $^{132}\text{Sn}$ have provided a value for $L$ and for $\Delta R$

• Data from LAND on $^{68}\text{Ni}$

• We have planned experiments on $^{70,72}\text{Ni}$ and on $^{64}\text{Fe}$ using an array LaBr$_3$:Ce
• Experiment planned for $^{20-24}\text{O}$ in Riken (Baba) using an array LaBr$_3$:Ce
• Hopefully others

• Theoretical work and data are needed to fix the correlation between PDR and $L$
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Analysis using theory.......
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