The Pygmy resonance in $^{68}$Ni and the neutron skin

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OUTLINE

- Motivation
- Experiment description
- Results
- Comparison with theory
- Conclusions and perspectives
The Pygmy Dipole Resonance (PDR) in neutron rich nuclei (\(^{68}\)Ni)

Simple picture: More or less Collective (coherently) oscillation of (loosely bound) neutrons (skin) against the core

![Diagram showing PDR and GDR](image)

Richter NPA 731(2004)59

- EI strength shifted towards low energy
- (PDR centroid energy depends on the thickness of n-skin)

Why the Pygmy Resonance is important?

1. One needs an extrapolation of 18 orders of magnitude
   To go from the neutron radius of a nucleus to that of a neutron star (10 fm → 10 km)
   BUT both radii depend on the knowledge of the equation of state of neutron rich matter.

2. Pygmy Resonance may have an important impact on the r-process nucleosynthesis

3. How collective properties change with neutron number

![Graph showing relative abundance](image)

Features of this mode

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

Stable nuclei ⇒

photon scattering, Photoabsorption \((\gamma,\gamma'),(\gamma,n)\)...

T. Hartmann PRL 85(2000)274

Exotic nuclei

Virtual photon breakup

LAND experiment

Search for pygmy strength in \(^{68}\text{Ni}\) in theory

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

Theoretical Predictions Before the experimental results

\[ + \ J. \ Liang \ et \ al., \ PRC \ 75(2007)\]
\[ \text{RMF: 68Ni} \]
\[ \text{RPA: 7-8\%} \]
Virtual photon scattering technique (1)

- Peripheral heavy-ion collision on a high Z target at relativistic energies
- Virtual photon excitation and decay

\[ \frac{d\sigma_e}{dE_e} = \sum_{i} \frac{1}{E_{i}} N_{i}^{\text{in}}(E^*) \cdot \sigma_{i}^{\text{in}}(E^*) \]

\[ E_{\text{max}} = \frac{\beta \gamma}{h} \]

Relativistic Coulomb excitation (\(\nu/c \sim 0.8\%\))

Virtual photon spectra \(E_1\)

Virtual photon excitation and decay of GDR + PYGMY

\[ \sigma(GDR) \approx 20 \]

\[ \sigma(GQR) \]

At large energies the cross section for the Coulomb excitation of the GR overcomes the nuclear geometrical cross section!

ADVANTAGE: High selectivity for dipole excitation !!

Virtual photon scattering technique (2)

GDR + PYGMY Excitation

- \(^{197}\text{Au}(^{68}\text{Ni},^{68}\text{Ni}^{*} + \gamma)^{197}\text{Au}\)
- \(600\text{ MeV/u}^{68}\text{Ni} + ^{197}\text{Au}\) (April 2005)
- \(400\text{ MeV/u}^{68}\text{Ni} + ^{197}\text{Au}\) (May 2004)

Virtual photon excitation and decay of GDR + PYGMY

\[ \sigma(GDR) \approx 20 \]

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

Coulex

\[ g.s. \]

maximum excitation energy (adiabatic cut off) ca. \(E_{\text{max}}=18.5\text{ MeV}\)

[Beene et al PRC 41(1990)920]

[T. Aumann et al EPJ 26(2005)441]

[Source: EPJ C41(1990)220]
High resolution \(\gamma\)-spectroscopy at the FRS of GSI

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

FRS provides secondary radioactive ion beams

Calorimeter Telescope for beam identification
CATE Position sensitive

Coulomb excitation of \(^{68}\text{Ni} \oplus 600\text{ AMeV}\)

\(~ 6\text{ Days of effective beam time}\)
\(~ 400\text{ GB of data recorded}\)
\(~ 10^{10} \text{ ‘good }^{68}\text{Ni events’}\)

Incoming + Outgoing \(^{68}\text{Ni}\)
\( \gamma \)-rays spectrum of \( \text{BaF}_2 \) detectors

\[
\frac{d^2\sigma_{\gamma\gamma}}{d\Omega dE_{\gamma}} (E_{\gamma}) = \frac{1}{E_{\gamma}} \frac{dN_{\gamma}}{d\Omega} (E_{\gamma}) \sigma_{\gamma} (E_{\gamma}) R_{\gamma} (E_{\gamma}).
\]

Conditions:
- \(^{68}\text{Ni}\)-incoming-selection
- \(^{68}\text{Ni}\)-outgoing-selection
- TOF-in prompt
- Outgoing angle check
- Doppler correction
- \( m_g = 1 \)
- Detector specific (PSA, AddBack)

Statistical emission of \( \gamma \)-rays from:
- target nuclei (\(^{197}\text{Au}\))
- beam nuclei (\(^{68}\text{Ni}\))
folded with Response Function including Doppler correction!

ANALYSIS: ground state gamma-ray decay from a GR state following a Coulomb excitation

The measured \( \gamma \)-ray yield is due to the product of 3 terms:
- Virtual photon \( N \), photoabsorption cross sect, Branching
- Coulomb excitation probability is directly proportional to the Photonuclear cross section

\[ N(E_\gamma, E_1) = 2\pi \int b(n(E_\gamma, E_1)) db \]

Integration over \( \Omega \) or \( b \)
ANALYSIS:

The measured gamma yield for Coul-ex
has a cross section directly proportional
to the :

Photonuclear
cross section

virtual photons

Gamma branching

\[ \frac{d\sigma}{dE} = \frac{1}{E} \sigma(E) \rho(E) \]

Response Function

RESULT: Pygmy dipole resonance in $^{68}\text{Ni}$

Pygmy in $^{68}\text{Ni}$ at 11 MeV

Width \approx 2 MeV mainly due
to Doppler Broadening

5 (\pm 1.5) % of the EWSR

\[ B(E1) = 1.2 e^2 fm^2 \]

Next steps:

- Compare strength with Sn data
- Compare with theory
- Deduce the Neutron radius
- Deduce Symmetry energy and
- Compare with fragmentation results
**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

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

- Note that the shape and strength depends on the effective force
- Calculations of different types are available:
  - Microscopic Hartree-Fock + random phase approximation
  - Relativistic Quasi particle Random Phase approximation
Associated EOS quantities

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!

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

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

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

\[
S(\rho) = J + \frac{L}{3} \left(\frac{(\rho - \rho_o)}{\rho_o}\right) + K_{sym} \left(\frac{(\rho - \rho_o)}{\rho_o}\right)^2 + \ldots
\]

Expansion around density \(\rho_0\) = saturation density

where \(S(\rho_o) = J\)

\(S'(\rho_o) = \frac{L}{3\rho_o}\)

\(S''(\rho_o) = K_{sym}/9\rho_o^2\)

Correlation between L and the PDR

The idea has been previously presented, and exploited in part.

However, here for the first time the approach has been pursued with different nuclei and different classes of EDFs. Blue=Skyrme; red=RMF.
**Constraint on J and L**

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

We deduce the weighted average for $L$ then, $J$ under that constraint.

From the $L$ value deduced one gets the $J$ value $30 < S_0 < 34$ from Sn analysis of ref PRC76(2007)051601.

**Extract the neutron radius for $^{208}$Pb**

Strong correlations between $L$ and $\Delta R$ (the neutron skin thickness) have been noticed previously.


The analysis of Klimkiewicz based on $^{132}$Sn data gave for $^{208}$Pb

$$R_n-R_p=0.18+/-.035 \text{ for } ^{208}\text{Pb}$$

Use the $L$ value from the analysis of the exp of $^{68}$Ni and $^{132}$Sn

and using the value of $L$ deduced from $^{68}$Ni and $^{132}$Sn for $^{208}$Pb one obtains

$$R_n-R_p=0.195+/-.021 \text{ for } ^{208}\text{Pb}$$
Our general approach of extracting L from the PDR makes its value compatible with those from analysis of heavy-ion collisions.

**Comparison with other ways of constraining L**

![Graph showing comparison with other ways of constraining L]

**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 \(^{114}\)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
Conclusions + Perspectives

- Pygmy resonance for the first time with virtual photon scattering technique in $^{68}\text{Ni}$
- Combined analysis with $^{132}\text{Sn}$ → neutron skin radius deduced

- More neutron rich nuclei (strength at lower energy below neutron binding and larger neutron skin radius?)
- Finite temperature – interesting perspectives but higher intensity are needed for this method
- Proton rich nuclei?
- Even odd nuclei

Thanks for the attention!!
FIG. 3: Low-lying dipole spectrum of $^{68,70,72}\text{Ni}$ calculated within the BQTBA-2 with a smearing of 20 keV (thin curves, pink) and 200 keV (filled area). Panel (a) contains also the data from Ref. [1] (open circles, units on the right). The arrows show the neutron thresholds.
All s th n lusi n th t l
All ow s th e c o n c lu si o n at l ow-l y-ing dipole strength has been observed in the present experiment, and that the PDR strength of $^{68}\text{Ni}$ is of the order of 5 to 10% of the TRK sum-rule strength.)