The Pygmy Dipole Resonance in the neutron rich nucleus $^{68}$Ni

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Darmstadt, October 2009
OUTLINE

- Motivation
- Experiment description
- Results
- Comparison with theory
- Conclusions and perspectives
**Giant Dipole Resonance**
Collective oscillation of neutrons against protons

**Pygmy Dipole Resonance**
Collective (coherently) oscillation of neutron skin against the core

E1 strength shifted towards low energy (centroid energy depends on the thickness of n-skin)

Why the Pygmy Resonance is important?

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

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

Nupecc long range plan 2004


and how collective properties change with n number.
One can derive:

- **Nuclear symmetry energy**
- **Neutron skin**

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

- **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

Exotic nuclei

Virtual photon breakup

LAND experiment

Stable nuclei

\( \gamma, \gamma' \), \( \gamma, n \)...

Adrich et al. PRL 95(2005)132501
Search for pygmy strength in $^{68}$Ni

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

Theoretical predictions:

\[ \text{RMF} \]

\[ \text{RPA} \]

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

G. Colo private communications

$^n$ excess vs inert core: oscillation of the neutron skin

$^n$ excess

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Search for pygmy strength in $^{68}$Ni

$^n$ excess vs inert core: oscillation of the neutron skin

+$^n$ 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

Virtual photon scattering technique

\[ \frac{d \sigma}{d E^*} = \sum_{\pi \lambda} \frac{1}{E^*} N_{\gamma}^{\pi \lambda} (E^*) \cdot \sigma_{\gamma}^{\pi \lambda} (E^*) \]

\[ E_{\text{max}} = \frac{\beta \gamma}{b_{\text{min}}} \hbar c \]

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

Relativistic Coulomb excitation (v/c \~ 0.8%)
Virtual photon scattering technique
High selectivity for dipole excitation !!

- 600 MeV/u $^{68}$Ni + $^{197}$Au (high statistics)
- 400 MeV/u $^{68}$Ni + $^{197}$Au (small statistics)

Virtual photon excitation and decay of GDR - PYGMY

$GQR \approx 20$

$\frac{\sigma(GDR)}{\sigma(GQR)} \approx 2 \frac{\sigma}{\sigma}$

At relativistic energies $\sigma$ for GR Coul-ex > nuclear geometrical $\sigma$!

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

$\rightarrow$ Virtual photon excitation and decay of GDR - PYGMY

[Beene et al PRC 41(1990)920]

$\rightarrow$ Virtual photon scattering technique
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[Beene et al PRC 41(1990)920]
High resolution $\gamma$-spectroscopy at the FRS of GSI

- $^{68}$Ni beam by fragmentation of $^{86}$Kr @ 900 MeV/u on Be target (4g/cm$^2$):

- $10^{10}$ pp spill $^{86}$Kr, Spill length 6s, period 10 s

FRS provides secondary radioactive ion beams

MW41, 42 x y --> Position --> Track of the beam

MUSIC --> dE

SCI 21, 41 --> TOF --> $\beta$

D. Magnet --> B $\rho$

$\{ --> Z$

$\{ --> A/Q$

$A = B \rho e \beta \gamma c u$

$Q$
Euroball 15 Clusters
  at 16.5°, 33°, 36°, E th. ~ 100 keV

Hector 8 BaF₂
  at 142° and 88° E th ~ 2 MeV

Miniball 7 HPGe segmented detectors
  at 46°, 60°, 80°, 90° E th ~ 100 keV

Beam identification and tracking detectors
  Before and after the target

Calorimeter
Telescope for beam identification
CATE
Position sensitive
Coulomb excitation of $^{68}\text{Ni}$ @ 600 AMeV

From fragmentation $^{86}\text{Kr}$ at 900 MeV/u

$^{68}\text{Ni}$

After the FRS

$^{68}\text{Ni}$

$^{68}\text{Ni}$ -1p

$^{68}\text{Ni}$ -1n

$E - \Delta E$

Telescopes

~ 6 Days of effective beam time

~ 400 GB of data recorded

~ $1 \times 10^8$ ‘good $^{68}\text{Ni}$ events’

Incoming + Outgoing $^{68}\text{Ni}$
The good timing properties allows to distinguish events originating from interactions occurring outside the target.
Coulomb excitation: $^{197}\text{Au}(^{68}\text{Ni} @ 600\text{AMeV}, ^{68}\text{Ni}^*)^{197}\text{Au}$

“Euroball Clusters”
Add-Back and DC

Gamma-ray spectra
Doppler corrected data
Plus response function simulated by GEANT

Forward angles

Forward: EUROBALL

Structure @ 11 MeV in all detectors
following lorentz boost and E1 angular distribution

Gamma-ray spectra Doppler corrected data

Backward angles

Backward HECTOR
Coulomb excitation of the $2^+$ state in $^{68}$Ni at 600 MeV/u

$E2$ in $^{68}$Ni

Consistency check for
- Doppler correction
- mass identification
- cross section

Comparison RISING with GANIL exp.
excitation of the $2^+$ in $^{68}$Ni

Statistical emission of γ-rays from:
- target nuclei (\(^{197}\text{Au}\))
- beam nuclei (\(^{68}\text{Ni}\))

folded with Response Function including Doppler correction!

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

\(\gamma\)-rays spectrum of \(\text{BaF}_2\) detectors

**an excess yield due to beam emission!!**
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 ratio

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

Coulomb excitation probability is directly proportional to the Photonuclear cross section

\[
N(E_\gamma E1) = 2\pi \int b(n(E_\gamma E1))db
\]
the Thomas-Reiche-Kuhn sum rule for $E1$ excitations,

\[ \int \sigma_{\gamma}^{E1}(\varepsilon) \, d\varepsilon \simeq 60 \frac{NZ}{A} \text{ MeV mb} \]

\[
\frac{d^2\sigma_{C\gamma}}{d\Omega dE_\gamma} (E_\gamma) = \frac{1}{E_\gamma} \frac{dn_{\gamma}}{d\Omega} (E_\gamma) \sigma_{\gamma} (E_\gamma) R_{\gamma} (E_\gamma).
\]
**Gamma decay - Branching ratio and level density**

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

**Branching Ratio for \( \gamma \)**

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

\[ R_\gamma(E_\gamma, \rho_{LD}) = \frac{\Gamma_0^{GR}}{\Gamma^{GR}} + \frac{\Gamma_0^{GR \dagger}}{\Gamma^{GR}} C\frac{\langle \Gamma_0^c \rangle}{\langle \Gamma^c \rangle}. \]

[Beene, et al PLB (1985)]

C.N. Gilbreth and Y. Alhassid, private communication
Shell model Monte Carlo (SMMC)
The measured gamma yield for Coul-ex has a cross section directly proportional to the:

Photonuclear cross section

virtual photons

Gamma branching

\[
\frac{d\sigma_{C\gamma}}{dE_\gamma} = RF \left\{ \frac{1}{E_\gamma} N_\gamma(E_\gamma) \cdot \sigma_\gamma(E_\gamma) \cdot R_\gamma(E_\gamma) \right\}
\]

Response Function

without pygmy
Pygmy dipole resonance in $^{68}$Ni

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

Width $\approx 2$ MeV mainly due to Doppler Broadening

$5 \text{ (p/m 1.5) } \%$ of the EWSR

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

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

O. Wieland et al., PRL102(2009)092502
Compare the strength in $^{68}$Ni with Sn data

- Lower value of the B(E1) in $^{68}$Ni as compared 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
Correlation between EWSR and Symmetry energy

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

\[ S(\rho) = S_0 + \frac{L}{3} \left( \rho - \rho_0 \right) / \rho_0 + K_{sym} \left( \left( \rho - \rho_0 \right) / \rho_0 \right)^2 + \ldots \]

Expansion around density

\[ \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) \]

\[ \rho_0 = \text{saturation density} \]

Skyrme's interactions
Relativistic models

From experiment

68Ni

L slope parameter of the \( E_{sym} \)

L slope parameter

K_{sym} curvature parameter at saturation density

%EWSR

\( r_{fit}^2 = 0.88 \)
$^{68}\text{Ni}$ compared with $^{132}\text{Sn}$

The correlation among the EWSR and $L$

For $^{68}\text{Ni}$ and $^{132}\text{Sn}$

$L$ (MeV) is the slope parameter of the density expansion of the Symmetry energy

$S_0$ and $L$ for $^{68}\text{Ni}$ and $^{132}\text{Sn}$

From the $L$ value deduced one gets the $S_0$ value

$30 < S_0 < 34$ from Sn analysis of ref PRC76(2007)051601
Extract the neutron radius for $^{68}\text{Ni}$ and $^{132}\text{Sn}$

The analysis of Klimkiewicz for $^{132}\text{Sn}$ data gave

\[ R_n - R_p = 0.24 \pm 0.04 \]

ref PRC76(2007)051601

$^{68}\text{Ni}$ data gave

\[ R_n - R_p = 0.20 \pm 0.02 \]

$^{132}\text{Sn}$

\[ R_n - R_p = 0.25 \pm 0.045 \]
Extract the neutron radius for $^{208}\text{Pb}$

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

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

Use the $L$ value from the analysis of the experiment of $^{68}\text{Ni}$

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

$$R_n - R_p = 0.185 \pm 0.035 \text{ for } ^{208}\text{Pb}$$
Neutron skin: $R_n - R_p$ summary for $^{132}\text{Sn}$, $^{68}\text{Ni}$ and $^{208}\text{Pb}$

Lines from fit of results based on different forces including relativistic calculations

<table>
<thead>
<tr>
<th></th>
<th>$R_n - R_p$ (fm)</th>
<th>Present analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{132}\text{Sn}$</td>
<td>0.24 +/- 0.04</td>
<td>0.250 +/- 0.045</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>0.18 +/- 0.035</td>
<td>0.185 +/- 0.035</td>
</tr>
<tr>
<td>$^{68}\text{Ni}$</td>
<td>------------</td>
<td>0.200 +/- 0.020</td>
</tr>
</tbody>
</table>
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 $^{112}\text{Sn}$ and $^{124}\text{Sn}$ with improved quantum molecular dynamics transport model

M.B. Tsang et al. PRL102(2009)122701
Analysis using theory......

A. Carbone, P.F. Bortignon, A. Bracco, F. Camera, G. Colò, O. Wieland (University of Milano and INFN)
Conclusions

- Measurement of high energy γ-rays from Coulex of $^{68}$Ni at 600 MeV/u.

- **Strength at 11 MeV** has been observed (5% EWSR)

- The theory (RMF and RRPA calculations) predicts 4-8% at 9-10MeV

- An analysis based on an correlation of the EWSR with the symmetry energy $L$ parameter deduced for the available different forces gives

  - The radius of the neutron skin (verified for $^{208}$Pb and $^{132}$Sn)

  - Contraints on the symmetry energy in agreement with heavy ion fragmentation

- The results open new perspectives for other experiments and are very promising for future measurements especially with higher resolution

Thanks for the attention !!