Experiments with relativistic radioactive beams
The dipole response of neutron-rich nuclei investigated at R3B

Thomas Aumann

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Nuclei in the Laboratory and in the Cosmos
Erice-Sicily

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Reactions with neutron-proton asymmetric nuclei

R3B
Reactions with Relativistic Radioactive Beams

rp-process
r-process

stable nuclei
N/Z = 1 - 1.5

drip-line nuclei
N/Z = 2 - 3

technetium nuclei
Reactions with neutron-proton asymmetric nuclei

A laboratory for studying nuclear properties as a function of isospin and density:

- Nuclear Structure of exotic nuclei
- Neutron-Proton asymmetric matter
- Nuclear Astrophysics

rp-process

r-process

Neutron-Proton asymmetric matter

Dip-line nuclei

N/Z = 2 - 3

Exotic nuclei

Stable nuclei

N/Z = 1 - 1.5

\[ E_{nucleus} \]
Reactions with neutron-proton asymmetric nuclei

A laboratory for studying nuclear properties as a function of isospin and density:

- Nuclear Structure of exotic nuclei
- Neutron-Proton asymmetric matter
- Nuclear Astrophysics
- Neutron-Proton asymmetric nuclei
  - Dipole response of N-Z asymmetric nuclei
    - Redistribution of collective strength (Pygmy and Giant Resonances)
    - Nucleosynthesis processes
    - Symmetry energy (neutron pressure)

Symmetry energy (neutron pressure)

Neutron-Proton asymmetric nuclei
RQTBA dipole transition densities in $^{68}\text{Ni}$ at 10.3 MeV

Theory: RQTBA-2

Elena Litvinova (GSI, WMU&MSU)
Review

Experimental studies of the Pygmy Dipole Resonance

D. Savran a,b,*, T. Aumann c,d, A. Zilges e

Progress in Particle and Nuclear Physics 70 (2013) 210–245
Systematics of Pygmy dipole strength?

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Systematics of Pygmy dipole strength?

\[ \Delta_{CCF} = \frac{(S_{2p} - S_{2n})}{2 + E_C} \text{[MeV]} \]

Review

Experimental studies of the Pygmy Dipole Resonance

D. Savran\textsuperscript{a,b,*}, T. Aumann\textsuperscript{c,d}, A. Zilges\textsuperscript{e}

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Next-generation experiments – Goals:
- extraction of full dipole strength function (below and above threshold, extracting E2 contribution, $\gamma$ (-cascade) and neutron channels)
- development of strength with neutron excess
- relation to symmetry energy
- characteristic of low-lying strength (isospin structure, decay properties)

See talk today by Andrea Horvat
Symmetry energy $S_2(\rho)$ and neutron skin in $^{208}\text{Pb}$

$$E(\rho, \alpha) = E(\rho, 0) + S_2(\rho) \alpha^2 + O(\alpha^4), \quad \alpha = \frac{N-Z}{A}$$

$$S_2(\rho) = \frac{1}{2} \left. \frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2} \right|_{\alpha=0} =$$

$$= a_4 + \frac{p_0}{\rho_0^2} (\rho - \rho_0) + \frac{\Delta K_0}{18 \rho_0^2} (\rho - \rho_0)^2 + ...$$

Alex Brown,
PRL 85 (2000) 5296

R.J.Furnstahl
NPA 706 (2002) 85-110

- strong linear correlation between neutron skin thickness and parameters $a_4, p_0$
Symmetry energy and dipole response

neutron-skin thickness  
dipole response  
density dependence of  
symmetry energy  
properties of  
neutron-rich matter

\[ \text{n-skin from Pygmy strength} \]
\[ \text{n-skin from polarizability} \]

\[ S. \, \text{Typel and B.A. Brown, Phys. Rev. C 64 (2001) 027302} \]

\[ J. \, \text{Piekarewicz, PRC 83, 034319 (2011)} \]

A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)
Electromagnetic excitation at high energies

High velocities \( v/c \approx 0.6-0.9 \)

\( \Rightarrow \) High-frequency Fourier components

\[ E_{\gamma,\text{max}} \approx 25 \text{ MeV (at 1 GeV/u)} \]

Absorption of ‘virtual Photons’

\[ \sigma_{\text{elm}} \sim Z^2 \]

Determination of ‘photon energy’ (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)
Production of fast exotic nuclei

- Stable beams from SIS, fragmentation on Be target or in-flight fission
- Selection of radioactive beams in Fragment Separator (FRS)

\[
\begin{align*}
A &= \frac{e \cdot B\rho}{Z} \\
Z &= \frac{m_u c \beta\gamma}
\end{align*}
\]
The LAND reaction setup @GSI

**Mixed beam**

**Charged fragments**

ToF, $\Delta E$

tracking $\rightarrow B\rho \sim A/Q\beta\gamma$

**Neutrons**

LAN D

ToF, $x, y, z$

$\sim 12$ m

**Photons**

ALADIN

large-acceptance dipole

**Beam**

projectile tracking

**Crystal Ball**

and **Target**

**Excitation energy** $E^*$ from kinematically complete measurement of all outgoing particles:

$$E^* = \left( \sqrt{\sum_i m_i^2} + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos \theta_{ij}) - m_{proj} \right) c^2 + E_\gamma$$
Analysis of $^{68}$Ni: decay after Coulomb excitation

**Neutron kinetic energy**

- $^{68}$Ni($\gamma^*$,1n) channel
- $^{68}$Ni($\gamma^*$,2n) channel

- Consistent fit taking into account:
  1. Invariant mass, but also information of subsets like $E_{\text{kin}}(n)$, $E_{\gamma\text{sum}}$ etc.
  2. Detailed knowledge about detector response function

- $R_{\text{direct}} = 24(4)\%$

**Gamma sum energy**

![Image](image_url)

**Analysis:**
- Dominic Rossi
- PhD Thesis
- Univ. Mainz
- PostDoc GSI
- Now MSU
Dipole strength distribution of $^{68}$Ni

Simultaneous fit of spectra with 8 individual energy bins as free fit parameters: „deconvolution“

<table>
<thead>
<tr>
<th></th>
<th>This work</th>
<th>Lit.</th>
<th>Ref.</th>
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<tbody>
<tr>
<td>GDR</td>
<td>$E_m$ [MeV]</td>
<td>17.1(2)</td>
<td>17.84</td>
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<tr>
<td></td>
<td>$\Gamma$ [MeV]</td>
<td>6.1(5)</td>
<td>5.69</td>
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<td>$S_{EWSR}$ [%]</td>
<td>98(7)</td>
<td>100</td>
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<tr>
<td></td>
<td>$\sigma$ [MeV]</td>
<td>0.51(13)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td>$S_{EWSR}$ [%]</td>
<td>2.8(5)</td>
<td>5.0(1.5)</td>
</tr>
</tbody>
</table>

Direct gamma-decay branching ratio
$\Gamma_0/\Gamma = 7(2)\%$

O. Wieland et al., PRL 102, 092502 (2009)
D. Rossi et al., PRL 111 (2013) 242503
Polarizability and neutron skin

\[ \alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma(E)}{E^2} dE \]

Neutron-skin thickness
\[ \Delta R_{n,p} = 0.175(21) \text{ fm} \]

Theoretical calculations from
J. Piekarewicz, PRC 83, 034319 (2011)

D. Rossi et al., PRL 111 (2013) 242503
Neutron skin in $^{208}$Pb from different methods

But:
X. Roca-Maza et al., PRC
88 (2013) 024316
Neutron skin in $^{208}\text{Pb}$ from different methods

The parity-violating asymmetry in the elastic scattering of ultrarelativistic elastically scattered electrons with positive and negative parity-violating asymmetry is defined as the relative difference $\Delta A_{\text{pol}} = A_{\text{pol}}(+) - A_{\text{pol}}(-)$.

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Clustering at surface changes neutron-skin thickness

-> relation slope symmetry energy – n-skin

-> experiment to test a preformation in heavy nuclei (p,pα) at RCNP (Aumann, Uesaka, Typel et al.) with RIB: SAMURAI, R3B

Measurement of the dipole polarizability of the unstable neutron-rich nucleus $^{68}$Ni

D. M. Rossi,$^{1,2,*}$ P. Adrich,$^{1}$ F. Aksouh,$^{1,†}$ H. Alvarez-Pol,$^{3}$ T. Aumann,$^{4,1,‡}$ J. Benlliure,$^{3}$ M. Böhmer,$^{5}$ K. Boretzky,$^{1}$ E. Casarejos,$^{6}$ M. Chartier,$^{7}$ A. Chatillon,$^{1}$ D. Cortina-Gil,$^{3}$ U. Datta Pramanik,$^{8}$ H. Emling,$^{1}$ O. Ershova,$^{9}$ B. Fernandez-Domínguez,$^{3,7}$ H. Geissel,$^{1}$ M. Gorska,$^{1}$ M. Heil,$^{1}$ H. T. Johansson,$^{10,1}$ A. Junghans,$^{11}$ A. Kelic-Heil,$^{1}$ O. Kiselev,$^{1,2}$ A. Klimkiewicz,$^{1,12}$ J. V. Kratz,$^{2}$ R. Krücken,$^{5}$ N. Kurz,$^{1}$ M. Labiche,$^{13,14}$ T. Le Bleis,$^{1,9,15}$ R. Lemmon,$^{14}$ Yu. A. Litvinov,$^{1}$ K. Mahata,$^{1,16}$ P. Maiерbeck,$^{5}$ A. Movsesyan,$^{4}$ T. Nilsson,$^{10}$ C. Nociforo,$^{1}$ R. Palit,$^{17}$ S. Paschalis,$^{4,7}$ R. Plag,$^{9,1}$ R. Reifarth,$^{9,1}$ D. Savran,$^{18,19}$ H. Scheit,$^{4}$ H. Simon,$^{1}$ K. Sümmerer,$^{1}$ A. Wagner,$^{11}$ W. Waluś,$^{12}$ H. Weick,$^{1}$ and M. Winkler$^{1}$

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$^{18}$ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany
$^{19}$Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany
Summary

• Dipole response of n-rich nuclei – Pygmy Resonance
  - Low-lying dipole strength observed in n-rich nuclei, ‘proton-Pygmy’ in $^{32}\text{Ar}$
  - many open questions – next-generation experimental program planned at GSI, RIKEN, SDALINAC, HIγS, Osaka, …
  - systematics, strength and position as a function of N-Z (and mass)
  - isospin character (isoscalar dipole)
  - decay properties
  - relation to nuclear-matter properties
  - relation to observed low-lying strength for stable nuclei
  - extraction of quadrupole strength

• Dipole response of $^{68}\text{Ni}$
  - 25(2)% non-statistical decay
  - PDR: 2.8(5)% EWSR, 7(2)% direct gamma decay
  - Dipole polarizability extracted for the first time for a radioactive nucleus

This opens the possibility for systematic studies as a function of N-Z which will enable to provide tight constraints on neutron skins and the density dependence of the symmetry energy