Electric Dipole Response of Nuclei
Studied by Proton Scattering

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on behalf of the RCNP-E299, E282, E316, E498 and the CAGRA+GR collaborations

Nuclear Photonics 2018 (NP2018)
June 24 – 29, 2018, Brasov, Romania
Electric Dipole Response of Nuclei

Photo-absorption by $^{208}$Pb

Photodipole Response (PDR) and Giant Dipole Resonance (GDR)

Photon energy $\omega$ (MeV)

$\frac{dB(E1)}{d\omega}$

Nuclei in an oscillating electric field $E(\omega)$

$E(\omega)$
I. Static Dipole Polarizability of Nuclei

Photo-absorption by $^{208}$Pb

from the inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{1}{E_x} \frac{dB(E1)}{E_x}$$

A.B. Migdal: 1944
Electric Dipole Response of Nuclei

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A.B. Migdal: 1944

Symmetry energy of the nuclear EOS

X. Roca-Maza et al., PRC92, 064304 (2015)
Symmetry Energy of the Nuclear EOS
is important for nuclear physics and nuclear-astrophysics

Core-collapse supernova

Neutron star mass vs radius


Langanke and Martinez-Pinedo

Nucleosynthesis


Neutron Star Merger
Gravitational Wave

Neutron star cooling


http://www.astro.umd.edu/~miller/nstar.html

https://www.youtube.com/watch?v=iZhNWh_lFuI

Neutron star structure
Probing the E1 response of nuclei

- **Missing mass spectroscopy:**
  Total strength is measured independently of the decay channels.

- **Multipole decomposition** of the strength in the continuum:
  Includes the contribution of unresolved small states

- **Coulomb excitation:**
  Absolute determination of the transition strength.

**Virtual Photon Scattering**

Select $q \sim 0$ (~0 deg.)

Comparison between the virtual and real photon methods.
Talk by P. von Neumann-Cosel tomorrow
Research Center for Nuclear Physics (RCNP), Osaka University

High-resolution Spectrometer
Grand Raiden

Polarized $p$ beam at 295 MeV

High-resolution WS beam-line (dispersion matching)
High-Resolution Spectrometer “Grand Raiden”

Proton scattering at very forward angles at RCNP, Osaka Univ.

High resolution of 20-30 keV: dispersion matching.

208Pb target: 5.2 mg/cm²
Intensity: 1-8 nA

0 deg. Beam Dump (GR = 0 deg.)

Polarized Proton Beam at 295 MeV

AT et al., NIMA605, 326 (2009)
Neglect of data for $\Theta > 4$: $(p,p')$ response too complex

Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg
Electric Dipole Polarizability: $^{208}$Pb, $^{120}$Sn

$^{208}$Pb$(p,p')$ at $E_p=295$ MeV

$(p,p')$ at 0.0–2.5 deg

$\sigma_{\gamma,\text{abs}}$ at Mainz

$B(E1)\uparrow \frac{dB(E1)\uparrow}{dE_x}$

$\frac{dB(E1)\uparrow}{dE_x}$ (e²fm²/0.2 MeV)

$E_x$ 0 10 16.2 20 130 MeV

$\alpha_D$

1.2 fm³

total 20.1±0.6 fm³

AT et al., PRL107, 062502(2011)
Electric Dipole Polarizability: $^{120}\text{Sn}$

$\alpha_D = 8.93 \pm 0.36 \text{ fm}^3$

Polarization Transfer Analysis

T. Hashimoto et al., PRC 92, 031305(R) (2015).
Constraints on $J-L$ from the EDP data

X. Roca-Maza et al., PRC92, 064304(2015)

T. Hashimoto et al., PRC92, 031305(R)(2015).


**RCNP** $^{208}\text{Pb}$: AT et al., PRL107, 062502 (2011).

**RCNP** $^{120}\text{Sn}$: T. Hashimoto et al., PRC92, 031305(R)(2015).

**GSI** $^{68}\text{Ni}$: D.M. Rossi et al., PRL111, 242503 (2013).
Electric Dipole Polarizability of $^{48}$Ca

where the EDF and ab-initio calculations meet

A new measurement on $^{48}$Ca is planned at RCNP for reducing the exp. uncertainty.

J. Birkhan et al., PRL119, 252501(2017)
II Pygmy Dipole Resonances

Photo-absorption by $^{208}$Pb

Nuclei in an oscillating electric field

Pygmy Dipole Resonances (PDRs)

Dipole oscillation of excess neutrons?
Campaign experiments in Oct. – Dec. 2016 at RCNP

CAGRA
12 Clover HPGe from ANL, ARL, (Tohoku,) and IMP
+ 4 LaBr$_3$
With large volume from Milano
CAGRA+GR Campaign Exps. in Oct-Dec 2016

E441: The \((^6\text{Li},^6\text{Li}'[3:56\text{MeV}])\) reaction as a novel probe for studying the inelastic neutrino-nucleus response in astrophysical scenarios  
\((^6\text{Li}, ^6\text{Li}^*)\text{ on }^{12}\text{C etc} \)

Pygmy Dipole Resonances (PDR)

E450: Study of the Structure of the Pygmy Dipole Resonance States via the \((p, p' \gamma)\) and \((\alpha,\alpha' \gamma)\) Reactions  
25.0 days

E454: Study of the Structure of the Pygmy Dipole Resonance States in \(^{64}\text{Ni}\) via \((p, p' \gamma)\) and \((\alpha,\alpha' \gamma)\) Reactions  
6.0 days

\((\alpha,\alpha' \gamma)\text{ and } (p, p' \gamma)\text{ on }^{64}\text{Ni}, ^{90,94}\text{Zr}, ^{120,124}\text{Sn}, ^{206,208}\text{Pb}\)

E470: Search for superdeformed states in \(^{28}\text{Si}\) via \(\gamma\)-particle coincidence measurements  
6.0 days

\((\alpha,\alpha' \gamma)\text{ on }^{28}\text{Si}\)

E471: Study of high-spin state population by light-ion reactions  
3.0 days

\((^6\text{Li},^6\text{Li})\text{ on }^{40}\text{Ca}\)

In total 45 days of beam time
Study of the Structure of the Pygmy Dipole Resonance States via the \((p, p' \gamma)\) and \((\alpha, \alpha' \gamma)\) Reactions in \([^{90,94}\text{Zr}]\) \(E_{\text{proton}} = 80\ \text{MeV}\) (6.6 deg), \(E_{\alpha} = 130\ \text{MeV}\) (4.5 deg)

- E450 Spokespersons A. Bracco, F. Crespi and N. Pietralla

\((\alpha,\alpha'\gamma)\) Reaction in \(^{90}\text{Zr}\), \(E_{\alpha} = 130\ \text{MeV}\)

Decay to the Ground State

Decay to the first \(2^+\) excited state

\(E_{\gamma}\), Energy in Gamma (Ge) [keV]

\(E_{\text{beam}}\), Excitation Energy (Grand Raiden) [keV]

\(^{90}\text{Zr}(\alpha,\alpha'\gamma)\)

\(^{90}\text{Zr}(\gamma, \gamma')\)

\(^{90}\text{Zr}\) \(E_{\text{beam}} = 130\ \text{MeV}\)

\(^{90}\text{Zr}\) \(E_{\text{beam}} = 80\ \text{MeV}\)

\(^{94}\text{Zr}\) \(E_{\text{beam}} = 130\ \text{MeV}\)

\(^{94}\text{Zr}\) \(E_{\text{beam}} = 80\ \text{MeV}\)

alpha: IS, surface sensitive

(proton: dominantly IS

gamma: IV and IS

Courtesy of F. Crespi
\[ ^{64}\text{Ni} (\alpha, \alpha'\gamma) : E_\gamma \text{-projection} \]

- \[ E_\gamma = E_x \text{ (MeV)} \]
- \[ ^{64}\text{Ni} (\alpha, \alpha'\gamma) \text{ @ 4.5°} \]
  \[ E_\alpha = 140 \text{ MeV} \]

- \[ ^{64}\text{Ni} (p, p') \text{ @ 0.4°} \]
  \[ E_p = 295 \text{ MeV} \]

\[ \text{dominantly Coul-ex. IV+IS} \]

- \[ \text{dominant isoscalar ?} \]

\[ \text{dominant isovector ?} \]

- \[ \text{E454 Spokespersons D. Savran, A. Zilges,} \]
Collaboration (in alphabetic order, spokespersons + participants during the beam time)

M. P. Carpenter, Shaofei Zhu
James J. Carroll
D. L. Balabanski

C. Iwamoto
S. Noji
D. Savran
T. Hashimoto
M. Krzysiek, M. Ciemała, Maria Kmiecik, A. Maj, B. Wasilewska

S. Courstin, G. Fruet, D. Montanari,
V. Derya, S. G. Pickstone, M. Spieker, J. Wilhelmy, A. Zilges

M. N. Harakeh
N. Blasi, A. Bracco, F. Camera, F. C. L. Crespi, O. Wieland

C. J. Guess, E. R. Hudson, C. I. Kacir
T. Koike
Y. N. Watanabe
S. Bassauer, T. Klaus, P. von Neumann-Cosel, N. Pietralla, G. Steinhilber, V. Werner
L. Donaldson
A. S. Brown, D. G. Jenkins, P. J. Davies, L. Morris
III. Fine Structure and Damping Mechanism of the GDR

3. Fine structure of the GDRs

Dumping mechanism of the giant resonances

Gamma decay from GDR:

RCNP-E498
scheduled in July 2018

E498 set up with Large volume LaBr$_3$ detectors from Milano
Summary

Electric Dipole Response of Nuclei Studied by Proton Scattering

I Static Electric Dipole Polarizability and the Symmetry Energy

II Pygmy Dipole Resonance

III Gamma Decay of the GDR

Thank you for your attention!