Test of the Brink-Axel Hypothesis with Gamma Strength Functions from Forward Angle Inelastic Proton Scattering

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- Gamma strength functions and Brink-Axel hypothesis
- The case of $^{208}$Pb
- The case of $^{96}$Mo
- Level densities from fine structure

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Gamma Strength Function (GSF)

\[
\langle \Gamma (E_i) \rangle = \frac{1}{\rho(E_i)} \int_0^{E_i} E_\gamma^3 \ f^{E/M\lambda}(E_\gamma) \ \rho(E_f) \ dE_\gamma
\]

- GSF describes average \( \gamma \) decay probability
- Depends on level densities at initial and final energies
- Sum over all multipolarities but E1 dominates
- Applications in astrophysics (large-scale reaction network calculations), reactor modeling and waste transmutation
Brink-Axel Hypothesis

- **Strength**
  - depends only on $E_\gamma$
  - is independent of the initial and final state structure: $E_x, J^\pi, \ldots$

- Central assumption for modeling finite temperature effects in astrophysical reaction network calculations

- Same GSF for $\gamma$ absorption and emission $\rightarrow$ needs to be tested
Electric Dipole Response in Nuclei

- BA hypothesis approximately holds in GDR region for temperatures < 1.5 MeV
- What about the PDR region?

Oscillations of neutron skin against N ≈ Z core
Pygmy Dipole Resonance (PDR)

Oscillations of neutrons against protons
Giant Dipole Resonance (GDR)
Influence of the PDR on r-Process Rates

New Experimental Tool for Complete Dipole Strength Distributions

- Polarized proton scattering at 300 MeV and 0° at RCNP
  - relativistic Coulomb excitation dominates: E1 strength
  - Spinflip-M1 cross sections separated: M1 strength
  - high resolution ΔE ≈ 25 keV (FWHM): level density of 1^- states

- $^{208}\text{Pb}$ and $^{120}\text{Sn}$ as reference cases
$^{208}$Pb Spectrum

$\Delta E = 25$ keV (FWHM)

PDR + Spin-M1

GDR

$^{208}$Pb($p,p'$)

$E_p = 295$ MeV

$\Theta = 0^\circ - 2.5^\circ$
GSF in $^{208}$Pb: Comparison with Oslo Data

* (p,p')*: S. Bassauer, PvNC, A. Tamii, Phys. Rev. C (submitted)

* ($^3$He,$^3$He'γ)*: N.U.H. Syed et al., Phys. Rev. C 79, 024316 (2009); reanalyzed by M. Guttormsen (priv. comm.)

- Violation of BA hypothesis in the PDR region?
- Problem of decomposition of GSF and level densities in Oslo method?
Level density of $J^{\pi} = 1^-$ states in $^{208}$Pb

Total Level Density in $^{208}\text{Pb}$

- Good agreement with Oslo results
GSF in $^{96}$Mo

(p,p'): D. Martin et al., to be published


- Consistent with decay results in the PDR region
Total Level Density in $^{96}$Mo

- Consistent with results from decay experiments
J = 1 Level Densities in Heavy Deformed $^{154}$Sm

Level densities

$^{154}$Sm(p,p')

Preliminary

Level density [MeV$^{-1}$]

4 5 6 7 8 9 10 11 12
Excitation Energy [MeV]

BSFG (Rauscher)
vonEgidy
HFB
Data
Summary

- Polarized proton scattering at 300 MeV and 0°: a new experimental tool
- Extraction of GSF (E1 and M1) and level densities from the same data
- Level densities in $^{96}$Mo and $^{208}$Pb agree with those from Oslo data
- Disagreement of GSF with Oslo data in the PDR region for $^{208}$Pb: large intensity fluctuations because of too small level density?
- Brink-Axel hypothesis seems to hold in the PDR region for $^{96}$Mo
Collaboration

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Fluctuation Analysis

- Background from MDA
- Stationary spectrum $\frac{g(E_x)}{g_{\geq}(E_x)}$
- Autocorrelation function $C(\varepsilon) - 1$
Autocorrelation Function and Mean Level Spacing

- $C(\varepsilon) = \frac{\langle d(E_x) \cdot d(E_x + \varepsilon) \rangle}{\langle d(E_x) \rangle \cdot \langle d(E_x + \varepsilon) \rangle}$
  - autocorrelation function

- $C(\varepsilon = 0) - 1 = \frac{\langle d^2(E_x) \rangle - \langle d(E_x) \rangle^2}{\langle d(E_x) \rangle^2}$
  - variance

- $C(\varepsilon = 0) - 1 = \frac{\alpha \langle D \rangle}{2\sigma \sqrt{\pi}}$
  - level spacing $\langle D \rangle$

- $\alpha = \alpha_{PT} + \alpha_W$
  - statistical properties

- $\sigma$
  - resolution
M1 Strength in $^{208}$Pb

R. Köhler et al., PRC 35, 1646 (1987)

$$\sum B(M1) = 14.8^{+1.5}_{-1.9} \mu_N^2$$
for $E_x \leq 8$ MeV


$$\sum B(M1) = 16.0(1.2) \mu_N^2$$
for $E_x \leq 8$ MeV

$$\sum B(M1) = 20.5(1.3) \mu_N^2$$
for full resonance
Level Density Spin Distribution in $^{208}$Pb

- Average over different models

$E_x = 8$ MeV

- BSFGM (RIPL-3)
- BSFGM (Rauscher et al.)
- BSFGM (von Egidy et al.)

Spin Distribution Function $f(J)$ vs Spin $J$
GSF in $^{208}\text{Pb}$: Contributions

![Graph showing the Total GSF (MeV$^{-3}$) vs Energy (MeV) with different contributions labeled as E1-GSF (exp.), M1-GSF (exp.), and E2-GSF (exp.) $\times E_x^2$.](image-url)
Gamma Strength Function (GSF)

\[
\langle \Gamma(E_i) \rangle = \frac{1}{\rho(E_i)} \cdot \int_0^{E_i} E_\gamma^3 f^{E_1}(E_\gamma) \rho(E_i - E_\gamma) \, dE_\gamma
\]

\[
\langle \Gamma_{i \rightarrow g.s.} \rangle = \frac{f^{E_1}(E_\gamma) \cdot E_\gamma^3}{\rho(E_i)}
\]

\[
f^{E_1}(E_\gamma) = \frac{\sigma_{abs}(E_i)}{3(\pi \hbar c)^2 \cdot E_\gamma}
\]
Multipole Decomposition of Angular Distributions

$^{208}\text{Pb}(p,p')$
$E_p = 295 \text{ MeV}$
$\Theta = 0^\circ - 2.5^\circ$

$d^2\sigma / d\Omega dE$ (mb/ sr MeV)

Excitation Energy (MeV)

$\Delta E_x = 7.26 - 7.37 \text{ MeV}$
$\Delta E_x = 7.37 - 7.41 \text{ MeV}$
$\Delta E_x = 13.2 - 13.4 \text{ MeV}$

$\Theta_{lab}$ (deg)
E1/M1 Decomposition by Spin Observables

Polarization observables at 0° spinflip / non-spinflip separation (model-independent)

\[ \Delta S = D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 & \text{for } \Delta S = 1 \to 1^+ \\ 3 & \text{for } \Delta S = 0 \to 1^- \end{cases} \]

At 0° \( D_{SS} = D_{NN} \) Total Spin Transfer \( \Sigma \equiv \frac{3 - (2D_{SS} + D_{LL})}{4} = \begin{cases} 1 & \text{for } \Delta S = 1 \\ 0 & \text{for } \Delta S = 0 \end{cases} \)

Decomposition into Spinflip / Non-Spinflip Cross Sections

\[ \frac{d^2\sigma}{d\Omega dE} \text{ (mb/ sr MeV)} \]

\[ ^{208}\text{Pb}(\vec{p},\vec{p}') \]

\[ E_p = 295 \text{ MeV} \]

\[ \Theta = 0^\circ - 2.5^\circ \]

Excitation Energy (MeV)
Comparison of Methods

\[ ^{208}\text{Pb}(\bar{p},\bar{p}') \]
\[ E_p = 295 \text{ MeV} \]
\[ \Theta = 0^\circ \text{ - } 2.5^\circ \]

Total

\[ \Delta S = 1 \]

\[ \Delta S = 0 \]
B(E1) Strength in $^{208}$Pb

$^{208}$Pb($\gamma,\gamma'$) + $^{207}$Pb(n,$\gamma$)

$E_p = 295$MeV
$\Theta = 0^\circ$ - $0.94^\circ$

$B(E1)$ (10$^{-3}$ $e^2$fm$^2$)

Excitation Energy (MeV)

$\sigma_{\text{tot}}$ (mb)

Excitation Energy (MeV)
Differential Cross Sections

$^{96}\text{Mo}(p,p')$

$E_p = 295 \text{ MeV}$

full acceptance

$\frac{d^2\sigma}{d\Omega\, dE} \text{ (mb/sr MeV)}$

Excitation Energy (MeV)

$0^\circ$

$3^\circ$

$4.5^\circ$
E1/M1 Decomposition

\[ ^{120}\text{Sn}(p,p') \]
\[ E_p = 295 \text{ MeV} \]
\[ \theta = 0^\circ - 2.5^\circ \]

\[ \Delta S = 1 \]

\[ \Delta S = 0 \]

Excitation Energy (MeV)
Polarization Transfer Observables in $^{96}$Mo

$^{96}$Mo(p,p')
$E_p = 295$ MeV
$\theta_{GR} = 0^\circ$
full acceptance

$\Sigma$

$\frac{d^2\sigma}{d\Omega \, dE}$ (mb/sr MeV)

Excitation Energy (MeV)
Comparison: PTA vs. MDA

\[ ^{96}\text{Mo}(p,p') \]
\[ E_p = 295 \text{ MeV} \]
\[ \theta = 0^\circ - 2.6^\circ \]

![Graph a](image1)

![Graph b](image2)

\[ \Delta S = 1 \]

\[ \Delta S = 0 \]

Excitation Energy (MeV)

$d^2\sigma/d\Omega dE$ (mb/sr MeV)
0° Setup at RCNP

Measured observables:
- \( \frac{d\sigma}{d\Omega} \) - angular distributions (0° ≤ Θ ≤ 10°)
- \( A_y \) - asymmetry
- \( D_{SS} \) at 0° - sideways polarization
- \( D_{LL} \) at 0° - longitudinal polarization

A. Tamii et al., NIMA 605 (2009) 326