Complete electric dipole response in ^{120}Sn from high resolution polarized proton scattering

Anna Maria Heilmann

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- Motivation
- Proton scattering experiment at RCNP
- Results
- Outlook

***Supported by the DFG within SFB 634 and 446 JAP 113/267/0-2**

Motivation

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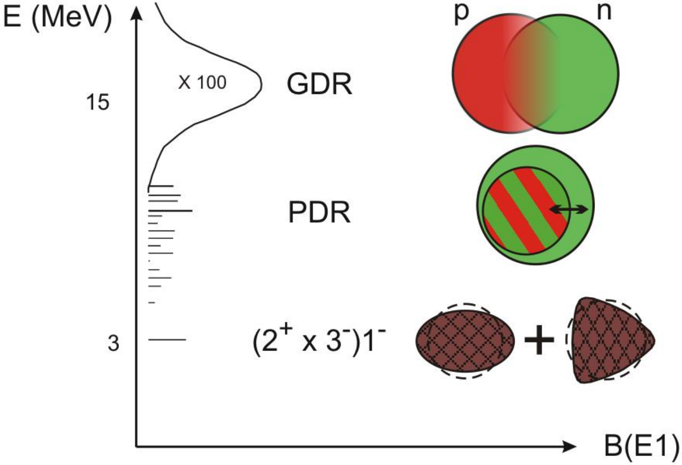

Electric pygmy dipole resonance (PDR)

- PDR: resonance-like structure, typically close to neutron threshold
- Strength related to neutron excess
  - measure of the polarizability
  - measure of neutron skin
  - measure of the density dependence of the asymmetry energy
- Strength distribution around neutron threshold relevant for nucleosynthesis (r-process, p-process)

Experimental problems

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- **Missing strength**
  - (γ, γ') reaction measures strength (roughly) up to threshold only
  - Experimental quantity $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
  - assumption in most analyses: $\frac{\Gamma_0}{\Gamma} = 1 \rightarrow$ **lower limit**
  - alternatively correction with statistical model calculation $\rightarrow$ **upper limit**

- Motivation for new experiment

New experimental access by $(\vec{p}, \vec{p}')$ at 0°

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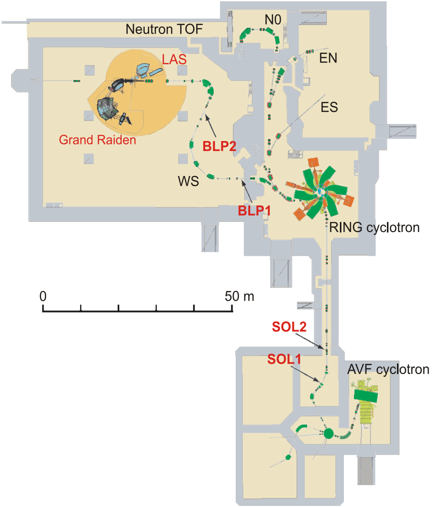
- Complete B(E1) strength
- high resolution (30 keV)
- Spin-isospin excitations
  $\rightarrow$ at 0° selectivity on ΔL=0 transitions (spinflip M1)
- Effective separation of E1 and M1 cross sections
  $\rightarrow$ two independent methods
  - analysis of the angular distribution
  - polarization transfer

RCNP facility



- 295 MeV
- beam intensity 2-3 nA
- high resolution
- degree of polarization: 70%

Spectrometer at RCNP facility

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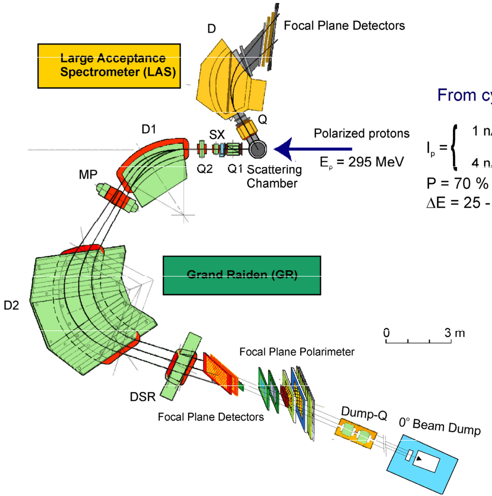

From cyclotrons:

$$I_p = \begin{cases} 1\text{ nA } (\Theta = 0^\circ) \\ 4\text{ nA } (2.5^\circ < \Theta < 10^\circ) \end{cases}$$

P = 70 %

ΔE = 25 - 30 keV

Spectra of ^{120}Sn(p,p')

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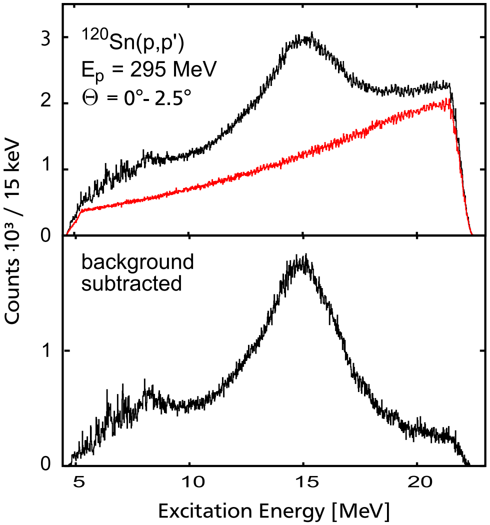

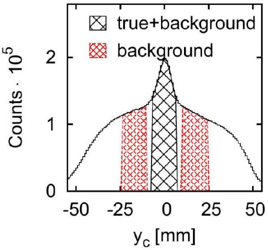

Comparison with γ,γ' experiment

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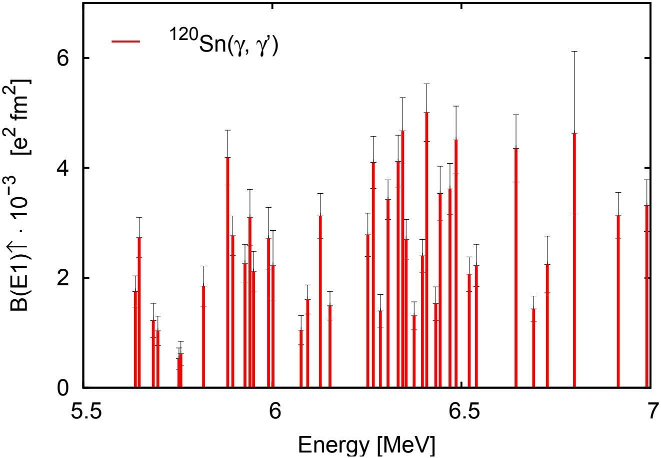
- $^{120}Sn(\gamma,\gamma')$ data from B. Özel



Comparison with γ,γ' experiment

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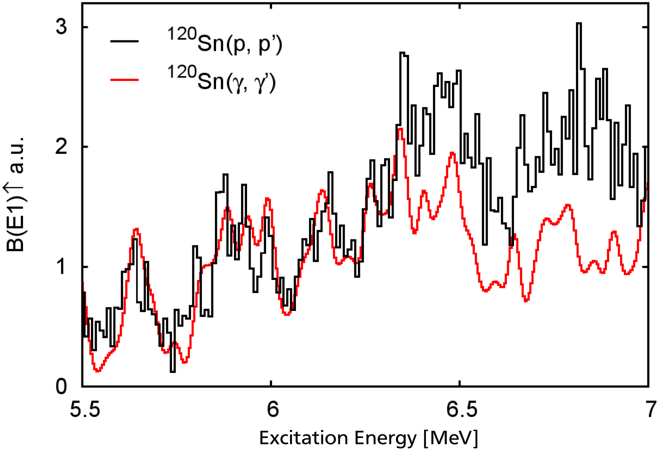
- ^{120}Sn(γ,γ') data from B. Özel
- folded with ΔE= 30 keV

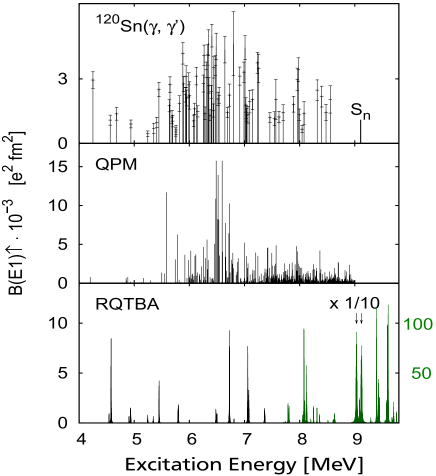


Comparison with theoretical calculations

^{120}Sn(γ,γ') data from B. Özel

Quasiparticle **P**honon **M**odel
(3 phonon)
V. Yu. Ponomarev

Relativistic **Q**uasiparticle **T**ime
Blocking **A**pproximation *(2 phonon)*
E.Litvinova
PRL 102, 022502 (2010)



Outlook

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- extraction of the differential cross sections and multipole decomposition *(→ I. Poltoratska HK 3.1)*
- analysis of polarization transfer *(→ J. Simonis HK 33.4)*
- identification of M1 excitations
- comparision with theoretical models
- → better understanding of the pygmy dipole resonance

Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

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- → better understanding of the pygmy dipole resonance

- deformed nucleus ^{154}Sm will be measured in May 2011

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Reconstruction of scattering angles

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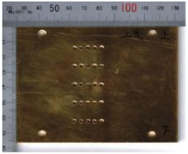
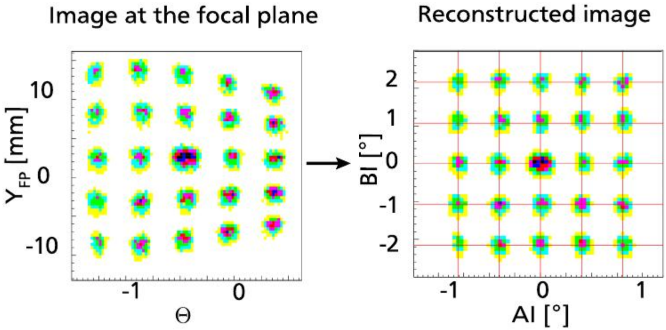
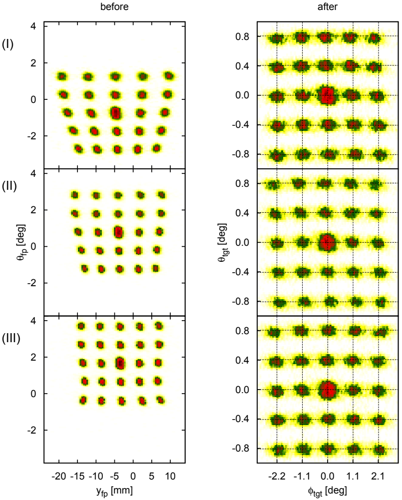
- Sieve–slit placed in front of GR
- $Al = f(\Theta, Y)$ dominated by Θ
- $Bl = f(\Theta, Y)$ dominated by Y

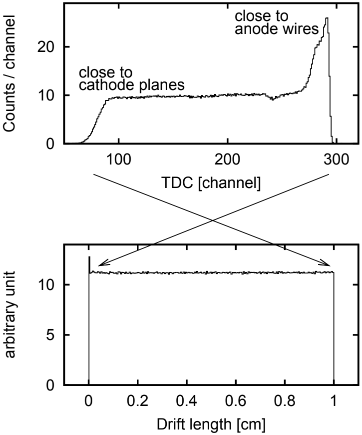




Reconstruction of scattering angles



Track Reconstruction



High resolution correction - vertical direction

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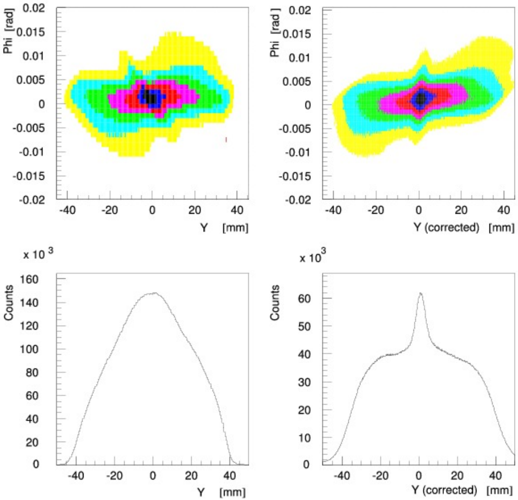

High resolution correction - horizontal direction

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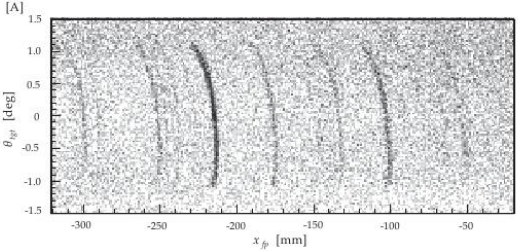

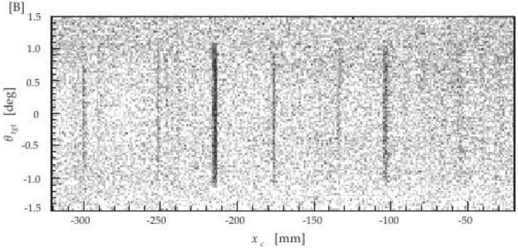

Determination of the background

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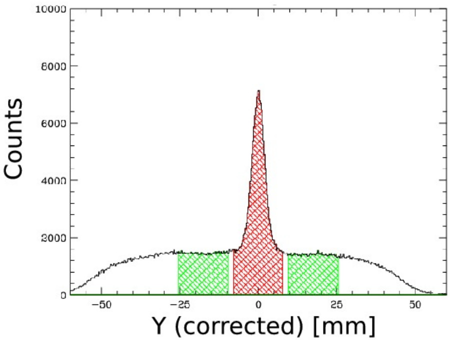
vertical position of protons projected on vertical focal plane

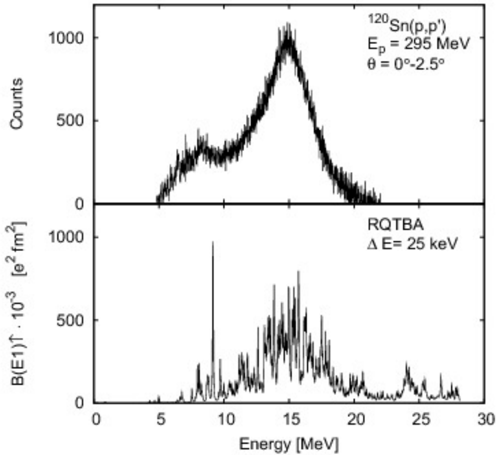
Gates on Y

- central region:
  true + background
- side region: background



Comparison with theory RQTBA

- RQTBA – E.Litvinova

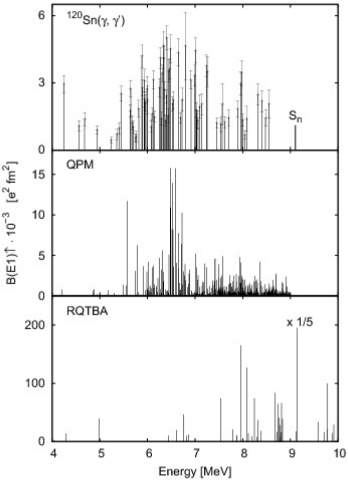


Comparison with theory
QPM and RQTBA

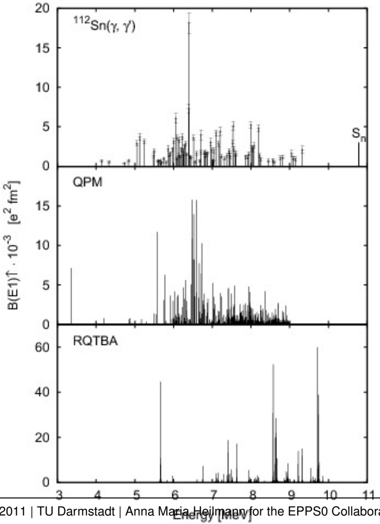
Theoretical models predictions differ

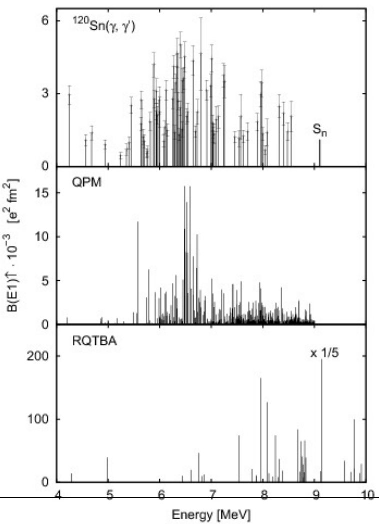
- ^{120}Sn(γ,γ') data from B. Özel
- QPM – V. Yu. Ponomarev
- RQTBA – E.Litvinova

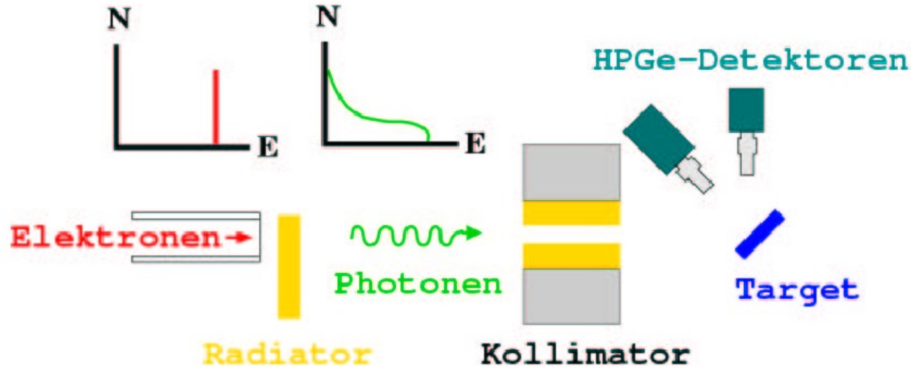
- ^{120}Sn(γ,γ') data from B. Özel



Comparison with theory
^{112}Sn and ^{120}Sn






N
E
N
E
HPGe-Detektoren
Elektronen
Photonen
Target
Radiator
Kollimator

VOLUME 82, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1999

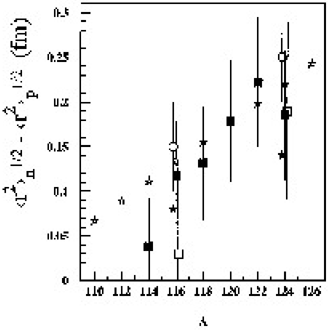
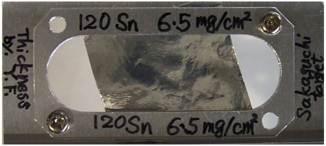
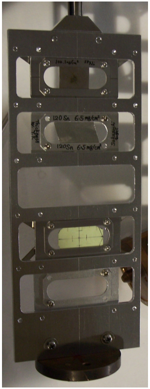


FIG. 3. The difference of the neutron and proton root-mean-square radii as a function of the mass number of the Sn isotopes. The full squares with error bars show the present results. The previous experimental results measured in p, p^0 reaction [5] and by using the GDR excitations [6] are shown as open circles and squares with error bars, respectively. The open and full stars show the theoretical results of Angeli *et al.* [19] and Dechargé *et al.* [21], respectively.

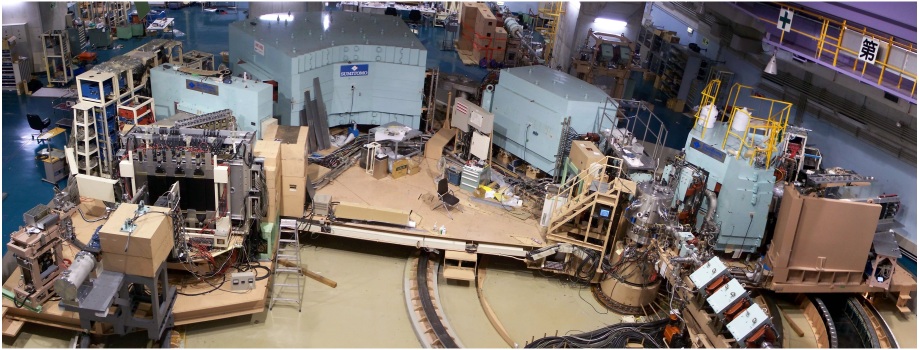
Targets

- tin foil isotropically enriched to 98.39 % ^{120}Sn
- thickness 6.5 mg$\cdot$ cm^{-2}
- further targets: ^{12}C, ^{208}Pb





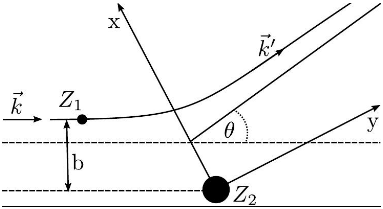
Spectrometer hall



Inelastic proton scattering

- coulomb excitation
- nucleon-nucleus scattering
- polarized proton scattering

Coulomb Scattering
Classical



$$\left(\frac{d\sigma}{d\Omega}\right)_{Ruth} = a^2 \sin^{-4}\left(\frac{\theta}{2}\right)$$

$$\text{with } a = \frac{1}{4\pi\epsilon_0}\frac{Z_1 Z_2 e^2}{4E}$$

Coulomb Scattering
Relativistic (1)

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$$\sigma(E_\gamma) = \sum_{\pi\lambda} \int \sigma_{\gamma,\pi\lambda}(E_\gamma)\, n_{\pi\lambda} \frac{1}{E_\gamma} \mathrm{d}E_\gamma.$$

Photon numbers are:

$$n_{E1} \approx \frac{Z^2\alpha}{\pi^2} \frac{1}{\gamma^2 - 1} \left(g_0(\xi) + \gamma^2 g_1(\xi) \right),$$

$$n_{E2} \approx \frac{Z^2\alpha}{\pi^2} \frac{1}{\gamma^2 - 1} \left(3\gamma^2 g_0(\xi) + (\gamma^2 + 1) g_1(\xi) + \gamma^2 g_2(\xi) \right),$$

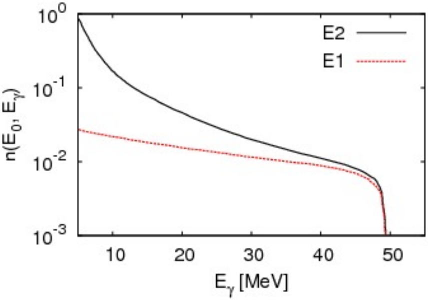
$$n_{M1} \approx \frac{Z^2\alpha}{\pi^2} g_1(\xi).$$

The argument of g_m: adiabaticity parameter

$$\xi = \frac{\omega b}{\gamma v_0} \qquad \text{with } \omega = E_\gamma/\hbar$$

Coulomb Scattering
Relativistic (2)

$$\sigma(E_\gamma) = \sum_{\pi\lambda} \int \sigma_{\gamma,\pi\lambda}(E_\gamma)\, n_{\pi\lambda} \frac{1}{E_\gamma} \mathrm{d}E_\gamma .$$



E.Wolynec *et.al*, Phys. Rev. Lett. 42 (1979) 27.

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Nucleon-Nucleus Scattering (1)

Protons may excite resonances:

- isoscalar non-spin-flip ($\Delta T = 0, \Delta S = 0$),
- isoscalar spin-flip ($\Delta T = 0, \Delta S = 1$),
- isovector non-spin-flip ($\Delta T = 1, \Delta S = 0$),
- isovector spin-flip ($\Delta T = 1, \Delta S = 1$).

Nucleon-Nucleus Scattering (2)

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$$V_{ip}(r_{ip}) = V^C(r_{ip}) + V^{LS}(r_{ip})\,\vec{L}\cdot\vec{S} + V^T(r_{ip})\,S_{ip}\,.$$

central term V^C, spin-orbit term V^{LS} and a tensor component V^T

$\vec{L}$	relative angular momentum	
$\vec{S}$	relative spin	$\vec{S} = \vec{\sigma}_i + \vec{\sigma}_p$
$\vec{L}\cdot\vec{S}$	spin-orbit operator	
S_{ip}	tensor operator	$\vec{S_{ip}} = 3\vec{\sigma}_i \cdot \hat{r}\ \vec{\sigma}_p \cdot \hat{r} - \vec{\sigma}_i \cdot \vec{\sigma}_p\,, \quad \hat{r} = \vec{r}/\lvert\vec{r}\rvert$
$\vec{\sigma}$	Pauli spin matrices	

For small angles $\rightarrow$ small momentum transfer $q < 1\ \mathrm{fm}^{-1}$, spin-orbit and tensor part of the interactio are small compared to the central interaction

Nucleon-Nucleus Scattering (3)

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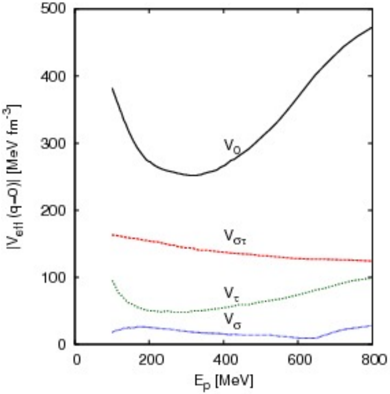
$$V_{ip}(r_{ip}) = V_0^C(r_{ip}) + V_\sigma^C(r_{ip})\,\vec{\sigma}_i\cdot\vec{\sigma}_p + V_\tau^C(r_{ip})\,\vec{\tau}_i\cdot\vec{\tau}_p + V_{\sigma\tau}^C(r_{ip})\,\vec{\sigma}_i\cdot\vec{\sigma}_p\vec{\tau}_i\cdot\vec{\tau}_p$$



W.G. Love and M.A. Franey *Phys. Rev.* C24 (1981) 1073

- small momentum transfer $q < 1\ \mathrm{fm}^{-1}$

Interactions with

- $\vec{\tau}_i\cdot\vec{\tau}_p \rightarrow$ isospin-flip transitions
- $\vec{\sigma}_i\cdot\vec{\sigma}_2 \rightarrow$ spin-flip transitions.

- measurements with E=300 MeV

Polarized Proton Scattering (1)

Nucleon-nucleon scattering amplitude in PWIA:

$$M(q) = A + B\sigma_{i\hat{n}}\sigma_{p\hat{n}} + C\left(\sigma_{i\hat{n}} + \sigma_{p\hat{n}}\right) + E\sigma_{i\hat{q}}\sigma_{p\hat{q}} + F\sigma_{i\hat{p}}\sigma_{p\hat{p}}.$$

amplitude coefficients consists of isoscalar and isovector terms: $A = A_0 + A_\tau \vec{\tau_1} \cdot \vec{\tau_2}$

$$M(q) = A + \frac{1}{3}(B + E + F)\vec{\sigma_i} \cdot \vec{\sigma_p} + C(\sigma_i + \sigma_p) \cdot \hat{n} + \frac{1}{3}(E - B)S_{ip}(\hat{q}) + \frac{1}{3}(F - B)S_{ip}(\hat{p})$$

In the PWIA the T-matrix for the NN scattering is given by

$$T = \left\langle f|M(q)e^{-i\vec{q}\cdot\vec{r}}|i\right\rangle.$$

Polarized Proton Scattering (2)

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$$T = \left\langle f \middle| M(q) e^{-i\vec{q}\cdot\vec{r}} \middle| i \right\rangle .$$

From the T-matrix to cross section and polarisation transfer:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\mathrm{Tr}(TT^\dagger), \qquad D_{ij} = \frac{\mathrm{Tr}(T\sigma_j T^\dagger \sigma_i)}{\mathrm{Tr}(TT^\dagger)}$$

For spin-flip transitions under 0°:

$$\begin{aligned} D_{SL} &= D_{LS} = 0\,, \\ D_{SS} &= D_{NN} = \frac{\left(|B_i|^2 - |F_i|^2\right) X_T^2 - |B_i|^2 X_L^2}{\left(|B_i|^2 + |F_i|^2\right) X_T^2 + |B_i|^2 X_L^2}\,, \\ D_{LL} &= \frac{\left(-3|B_i|^2 + |F_i|^2\right) X_T^2 + |B_i|^2 X_L^2}{\left(|B_i|^2 + |F_i|^2\right) X_T^2 + |B_i|^2 X_L^2}\,. \end{aligned} \tag{1}$$

X_T, X_L: spin-transverse and spin-longitudinal form factors

Polarized Proton Scattering (3)

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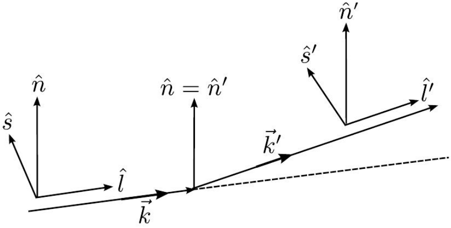

For spin-flip transitions under 0°:

$$D_{SS} = D_{NN} = \cdots$$
$$D_{LL} = \cdots$$

$$\Sigma = \frac{3 - (D_{SS} + D_{NN} + D_{LL})}{4}$$

At forward angles total spin transfer

$$\Sigma = \left\{ \begin{array}{ll} 1 & \text{spinflip} \\ 0 & \text{non-spinflip} \end{array} \right\}$$

From PT measurements the spinflip and non-spinflip cross sections can be extracted

$$\frac{d\sigma}{d\Omega}(\Delta S = 1) \equiv \Sigma \left(\frac{d\sigma}{d\Omega} \right) ,$$
$$\frac{d\sigma}{d\Omega}(\Delta S = 0) \equiv (1 - \Sigma) \left(\frac{d\sigma}{d\Omega} \right) .$$

Summing-Up: Inelastic Proton Scattering

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- Nucleon-Nucleus Scattering
- Coulomb Excitation
- Polarized Proton Scattering

nonspin-flip cross sections $\rightarrow$ E1 excitations
spinflip cross sections $\rightarrow$ M1 exciations