Halifax, 18/July/2003
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Developments on the Theory of the Deuteron

1. Introduction
2. Results for specific reactions
3. Summary and Outlook

Collaborators: H. Arenhövel, Th. Wilbois, P. Wilhelm, E. Darwish

References:

Phys. Lett. B 407, (1997) 1; Phys. Lett. B 420, (1998) 255
Nucl. Phys. A 690 (2001) 647; Nucl. Phys. A 690 (2001) 682; Nucl. Phys. A 696 (2001) 556
Eur. Phys. J. A 16 (2003) 111; nucl-th/0302031 (in press)

1. Introduction

Basic aim of few-body physics:

- study of the properties and structure of few-body nuclei,
- few-body nuclei as laboratories for testing effective descriptions of the strong interaction,
- light nuclei may serve as effective neutron targets.

Present theoretical approaches are based on the following steps:

- Introduction of **effective** degrees of freedom (d.o.f.) on the level of mesons and baryons,
- Hadron properties and couplings are taken from phenomenology,
- The hadronic NN-interaction is determined by fitting onshell NN-scattering and deuteron data either using
  (i) a **semiphenomenological** approach with a general operator structure, e.g. recent **Argonne** potentials, or

(ii) a **meson theoretical** approach, usually with scalar, pseudoscalar and vector meson exchanges, e.g. **Bonn** potentials, or

(c) in the low energy regime **Effective Field Theory**,

- electromagnetic current operators are constructed by minimal substitution (if possible).

In this work:

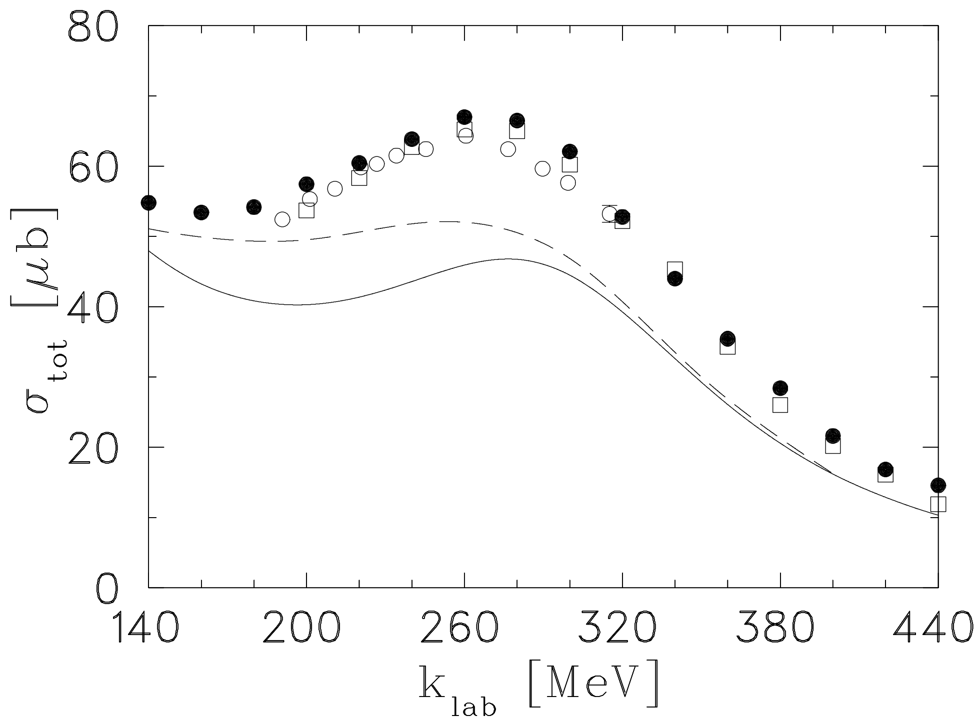
Special emphasis to energies above the pion threshold, studying especially

- the structure of the NN- and NΔ-interaction at higher energies,
- the role of relativity, e.g. retardation effects,
- the role of offshell effects, i.e. the change of single particle properties of bound nucleons,
- the question whether the deuteron can serve as an effective neutron target, e.g. for the GDH-sum rule.

2. Results for specific reactions

$\gamma d \to NN$ IN THE Δ-REGION

Situation in standard (static) approaches:



red: Tanabe and Ohta (1989)

black: Wilhelm and Arenhövel (1993)

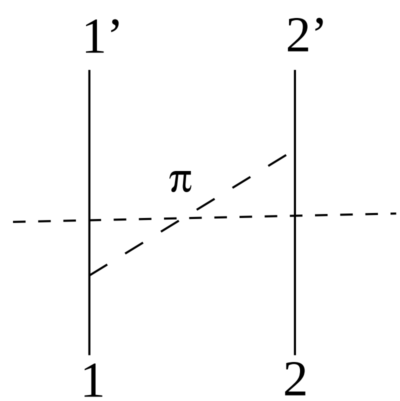
experiment:

□ Bonn (1984), ○ LEGS (1995), • Daphne (1996) general features of models:

- realistic **static** NN-interaction (Paris, Bonn)
- consistent π- and ρ-MEC
- dynamical treatment of the Δ
- **no** free parameters concerning $\gamma d \to NN$

Wilhelm and Arenhövel (1993):

Retardation Important?



retarded propagator:

$$G_0(z) = (z - E_N(1') - E_N(2) - E_\pi)^{-1}, \quad z = E + i\epsilon$$

characteristic features:

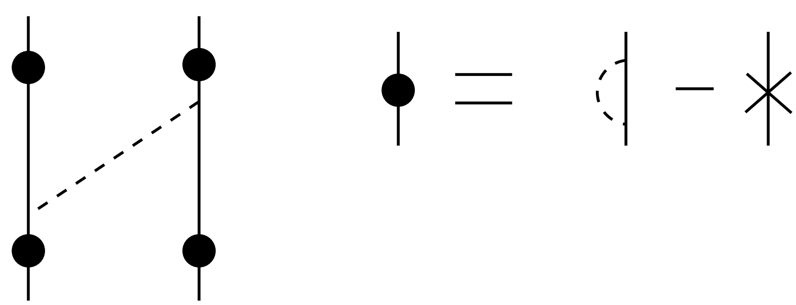
- nonlocal
- nonhermitean
- existence of singularities above pion-threshold
  $\to$ coupling of NN- to πNN-system

→ low energy approximation: **static limit**, i. e. nucleons are infinitely heavy during meson exchange:

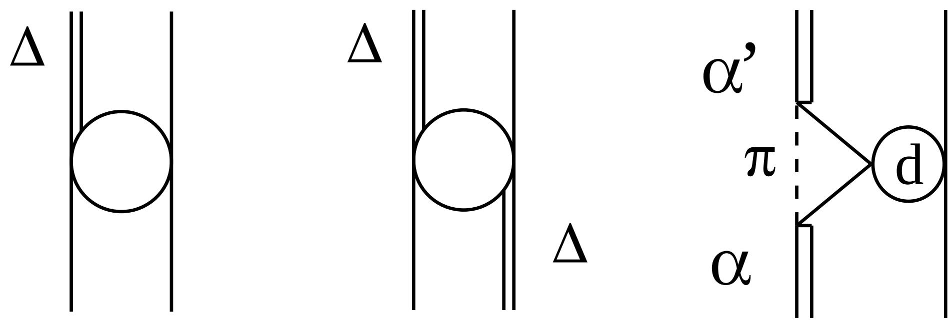
$$G_0(z) \to G_0^{stat} := -E_\pi^{-1}$$

- advantage: feasability
- disadvantages: violation of unitarity and failure in describing $\gamma d \to NN$ in Δ-region

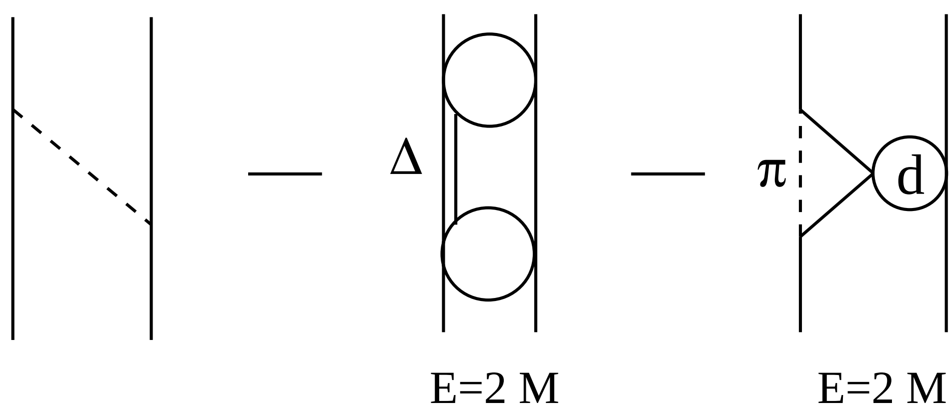
- Note: Due to Gauge invariance, retardation has to be taken into account **consistently** both in NN-interaction and MEC
- General procedure for construction of retarded interaction (necessary for deuteron bound state and FSI):
  - Use of retarded NN-potential known from literature (Elster et al., Phys. Rev. C 37 (1988), 1647) based on retarded meson exchange plus nucleonic self-energy contributions necessary for satisfying unitarity:



– For application in the Δ-region, additional mechanisms are added ($\alpha, \alpha' \in \{N, \Delta\}$):

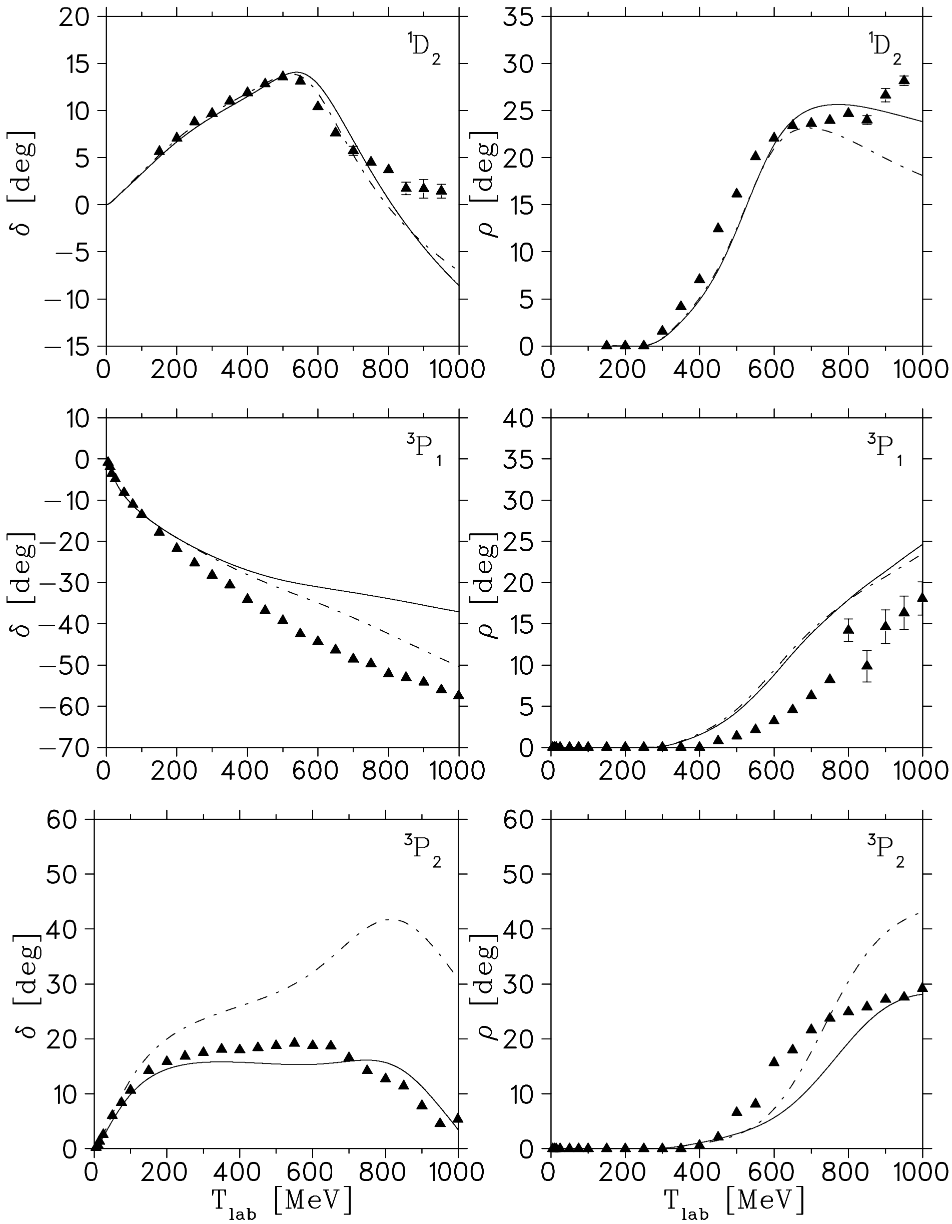


– In order to avoid double counting, box renormalization procedure is applied:



– Δ-Parameters of additional $NN \to N\Delta$, $N\Delta \to N\Delta$-interaction and of πd-channel are fixed by studying $^1D_2$-channel in NN-scattering.

Result for NN-scattering



red: static calculation, based on Bonn-OBEPR

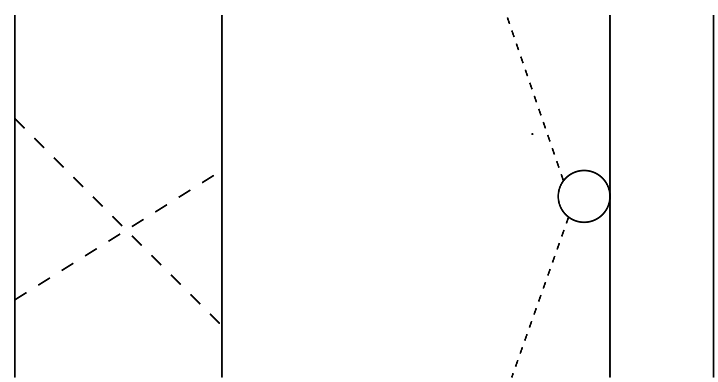
black: full retarded calculation

Additional Comments:

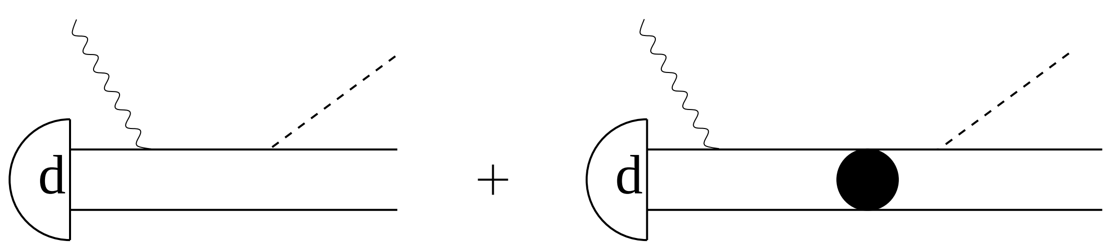
- overall description of phase shifts and inelasticities is only fairly well above π-threshold
- static and retarded approach of same quality
- considerable improvement would be a complete refit of the parameters

  open problems/questions:

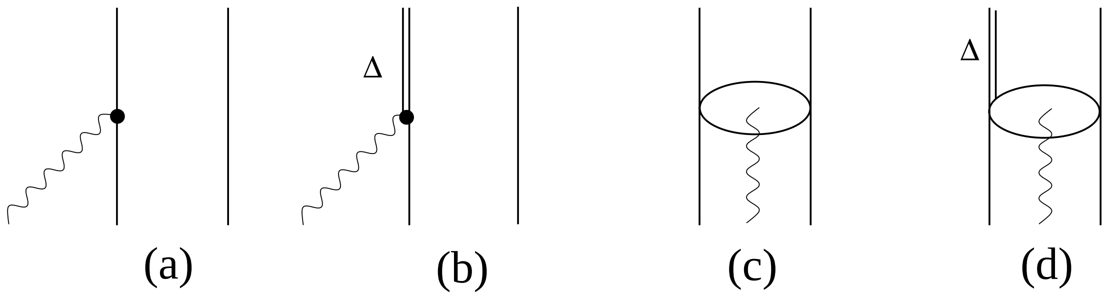
- high dimensional fit procedure
- relevance of neglected mechanisms



- forthcoming studies necessary!



Effective Current Operators



(a) nucleonic one-body current

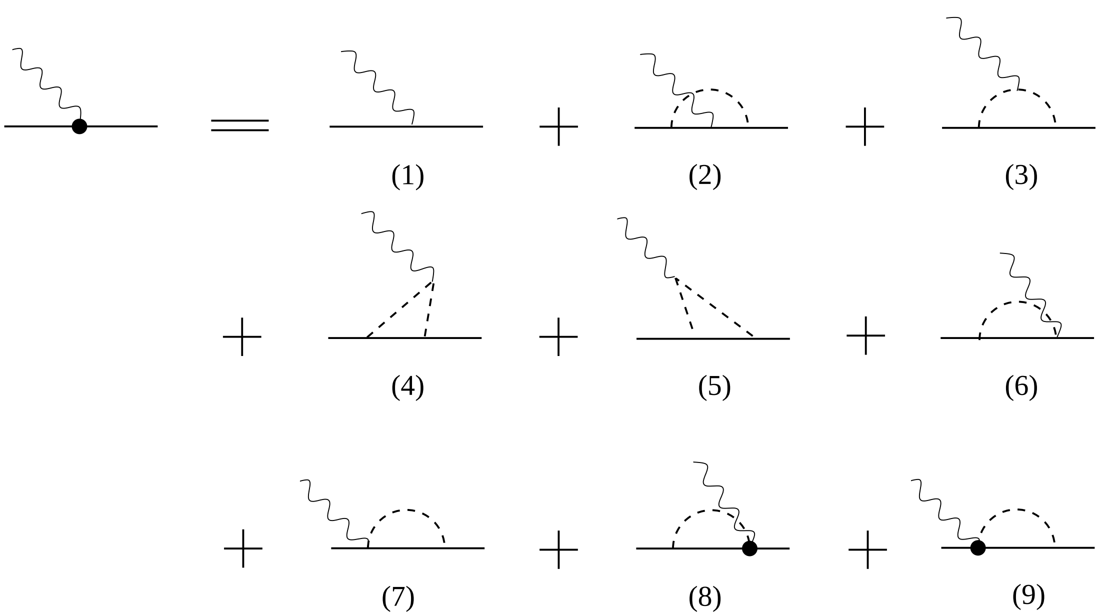
$$\mathbf{J}_N^{[1]} = \mathbf{J}_{con} + \mathbf{J}_{spin} + \mathbf{J}_{so} + \mathbf{J}_{loop} + \mathbf{J}_{counter}$$

– convection current $\mathbf{J}_{con}$

– spin current $\mathbf{J}_{spin}$, containing the correct anomalous magnetic moment of the nucleon

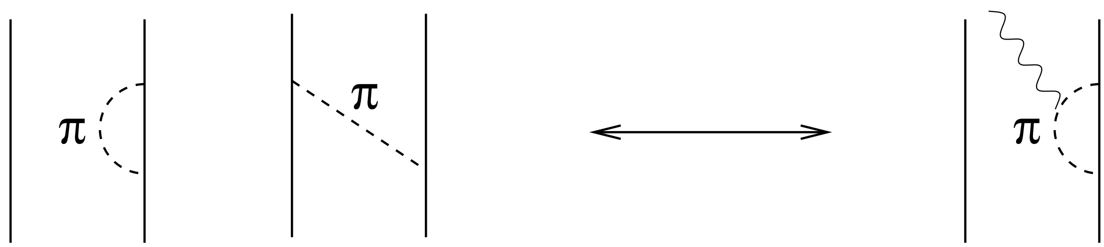
– spin-orbit-current $\mathbf{J}_{so}$

– loop corrections $\mathbf{J}_{loop}$



Note:

- loop corrections necessary for satisfying unitarity
- The NN-interaction, the internal nucleon structure described by a pion cloud and the electromagnetic loop diagrams are based on the **same** pion nucleon vertex



- Loop corrections yield unrealistic contributions to the anomalous magnetic moment of the nucleon

  → introduction of a countercurrent which cancels the loop corrections onshell and guarantees the correct anomalous magnetic moment of the nucleon on its mass shell

  → loop corrections yield only offshell contributions

- The matrixelement of the loop corrections depends on the external momenta **and** on the invariant energy E_{sub} of the active nucleon ($z = E_{sub} + i\epsilon$):

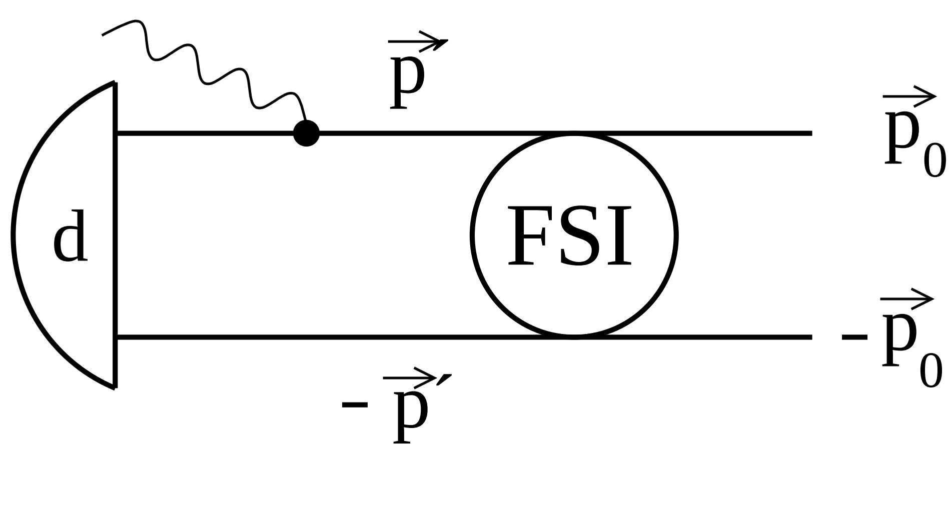
$$\langle \vec{p}^{\,\prime} | \vec{j}_{loop}(z, \vec{k}) + \vec{j}_{counter}(\vec{k}) | \vec{p} \rangle = e\delta(\vec{p}^{\,\prime} - \vec{p} - \vec{k}) \times$$
$$\Big(B(z,p')2\vec{p}^{\,\prime} + C(z,p')\vec{k} + D(z,p')\vec{\sigma} \times \vec{p}^{\,\prime} + E(z,p')\vec{\sigma} \times \vec{k} \Big)$$

- Note: E_{sub} is fixed by k and p and therefore not independent.

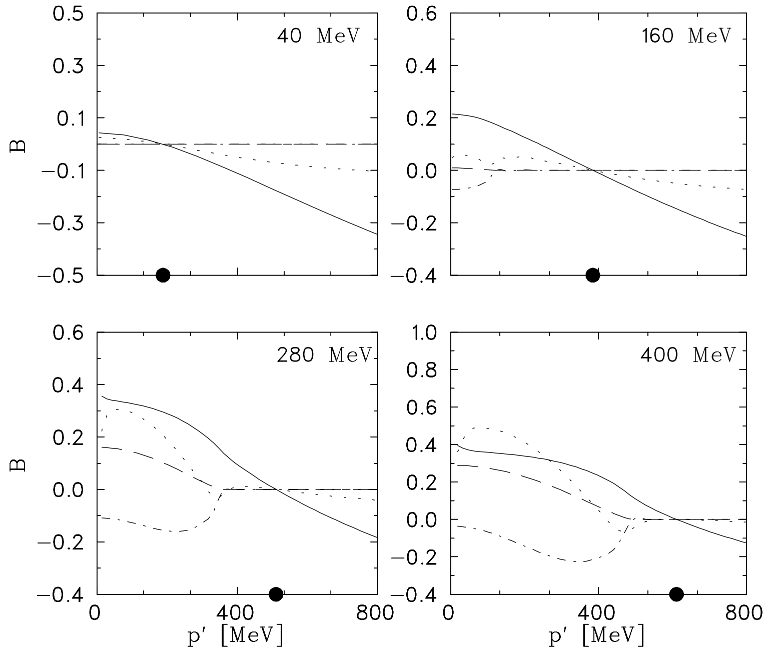
  Example: deuteron photodisintegration in the CM frame using the spectator onshell approach:

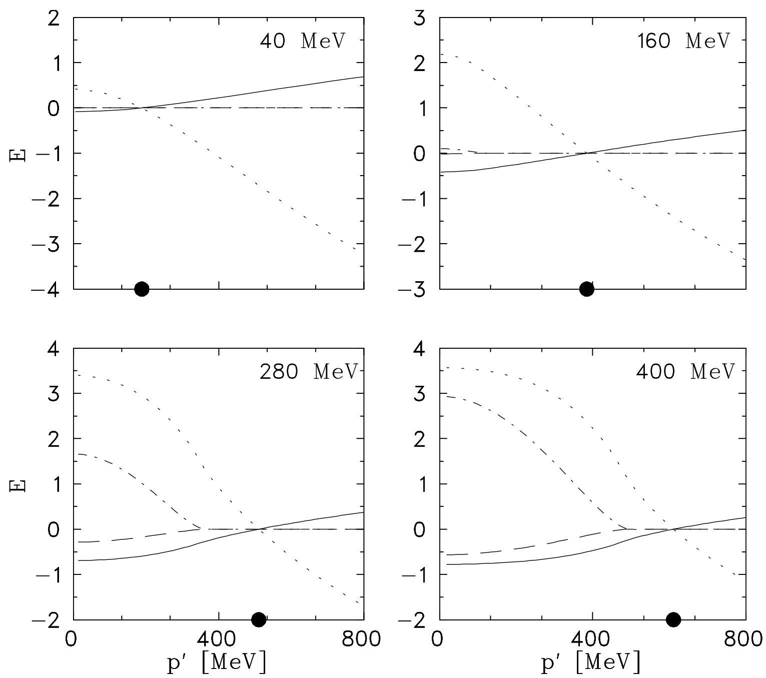
$$E_{sub} \equiv E_{sub}(k,p') = W - \sqrt{M_N^2 + p'^2} \quad \text{with}$$

$$W = \sqrt{M_d^2 + 2M_d k_{lab}}$$



Result:





Notation:

solid: real isoscalar part

dashed: imaginary isoscalar part

dotted: real isovector part

dash-dotted: imaginary isovector part

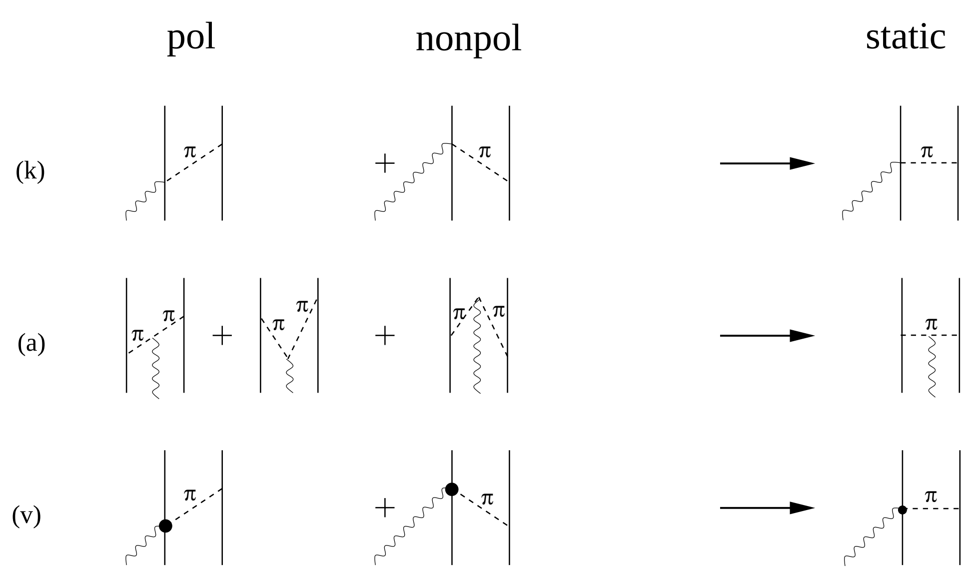
(b) Δ-excitation one-body-current

$$\mathbf{J}_{\Delta}^{[1]}(W,\mathbf{k}) = \frac{G_{M1}^{\Delta\widetilde{N}}(z=W+i\epsilon,k)}{2M_{\widetilde{N}}}\ \tau_{\Delta N,0}\ i\,\boldsymbol{\sigma}_{\boldsymbol{\Delta N}} \times \mathbf{k}$$

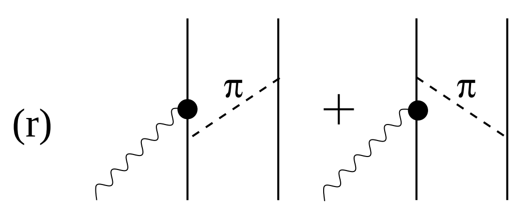
determination of $G_{\Delta\widetilde{N}}^{M1}$ by fitting photopionproduction on the nucleon in the $M_{1+}(3/2)$-channel.

(c) nucleonic two-body current besides static ρ-MEC

– **retarded** π-contact/flight/vertex-MEC

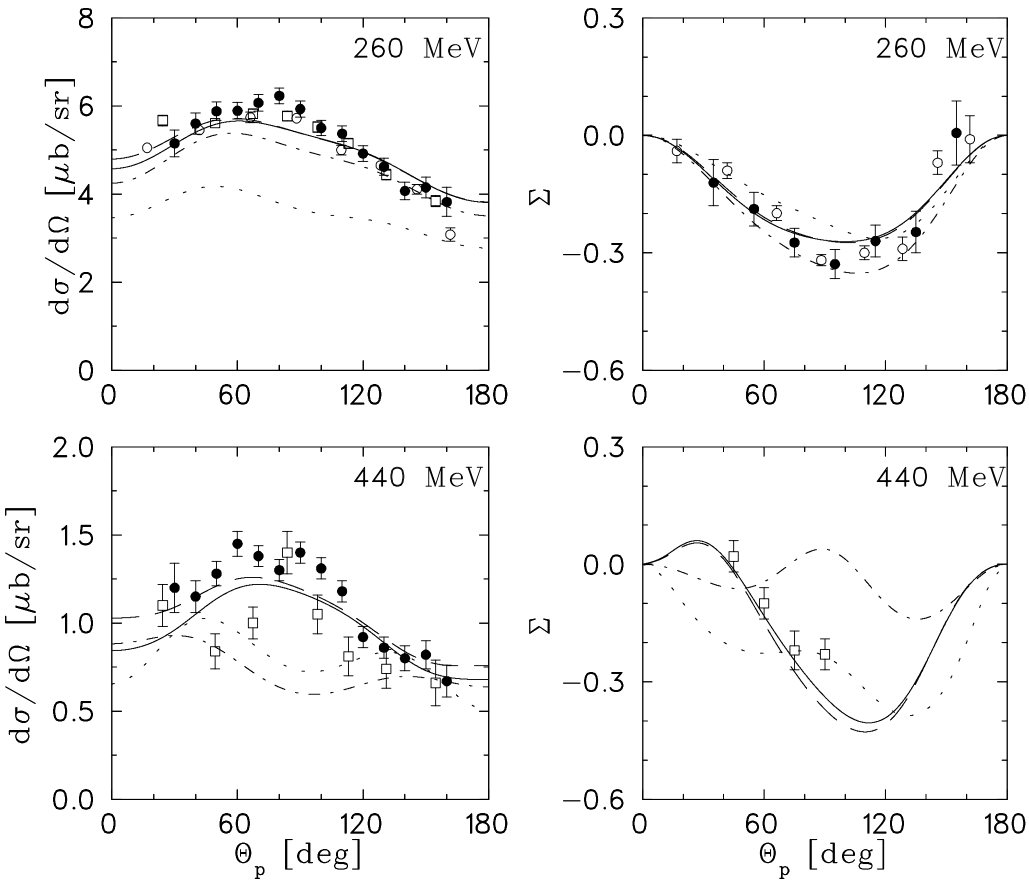


- **retarded** recoil-MEC (not present in static calculations)



- additional (less important) current contributions like $\gamma\pi\rho/\gamma\pi\omega$-current (dissociation current) and two-body $NN \to N\Delta$-currents

Result for $\gamma d \to NN$



green: static calculation of Wilhelm et al. (1993)

red: improved static calculation (including πd, ρ-exchange in $N\Delta$-interaction, improved $\gamma N\Delta$-coupling, dissociation currents)

blue: retardation in hadronic interaction and MEC switched on, offshell effects neglected

black: full retarded calculation

experimental data for cross section:

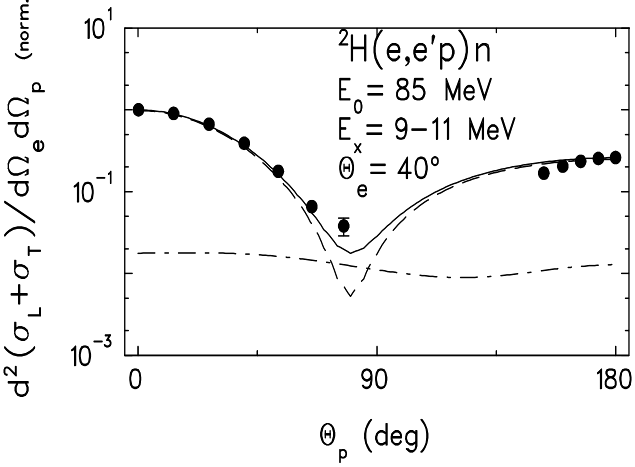
□ Bonn (1984), ∘ LEGS (1995), • Daphne (1996)

experimental data for photon asymmetry:

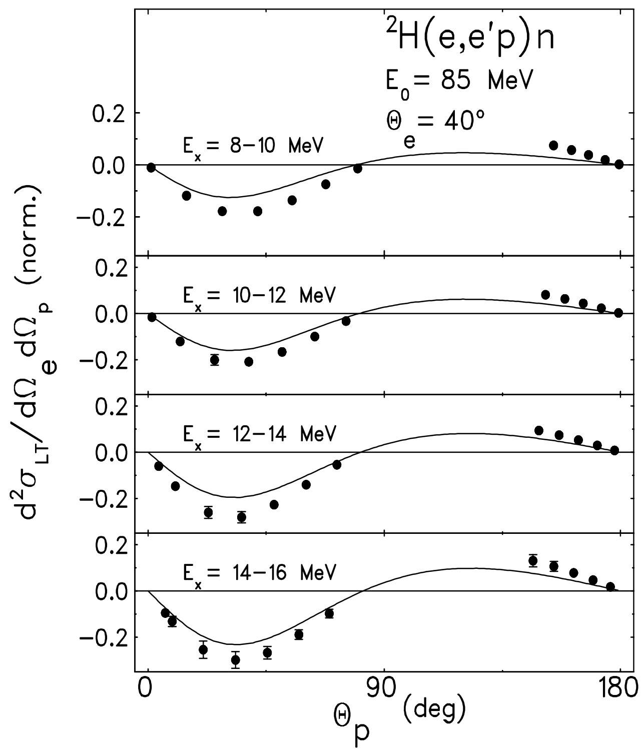
□ Adaminan et al. (1991), ∘ LEGS (1995), • Daphne (1999)

ELECTRODISINTEGRATION

Resent result for $d(e,e'p)n$ at low energy and low momentum transfer (P. von Neumann-Cosel et al., P.R.L. 88, 202304 (2002)):



Sum of the double-differential longitudinal and transverse cross sections ($\sigma_L + \sigma_T$) at $E_0 = 85$ MeV for excitation energy bin $E_x = 9 - 11$ MeV. Dashed and dashed-dotted: static theory for σ_L and σ_T, solid: sum of both.



σ_{LT} at $E_0 = 85$ MeV for various excitation energy bins. Solid lines: static theory.

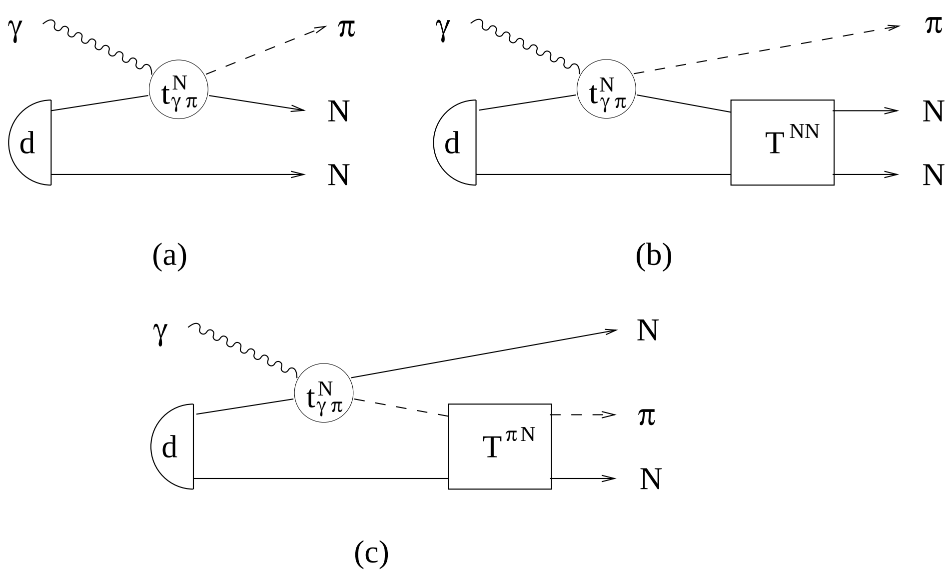
→ large discrepancy up to 45 % in the LT contribution between theory and experiment!

Physical motivation:

- hope: well-known deuteron structure allows to obtain information on production process on the neutron
- disturbing effect to be studied: final-state-interaction

Model:

Impulse approximation plus complete rescattering in all two-body subsystems:



(a) impulse approximation (IA),

(b) NN rescattering,

(c) πN rescattering.

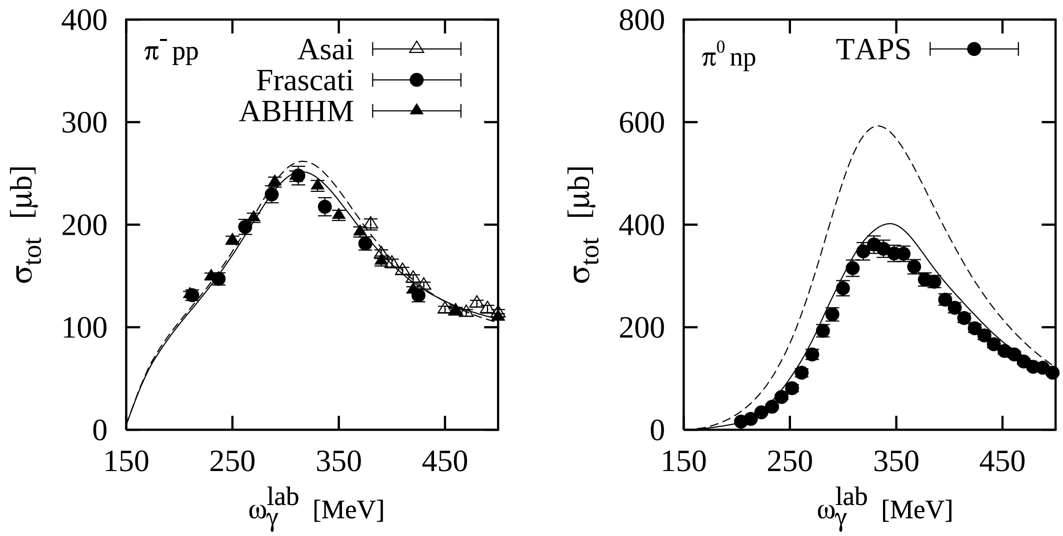
Deuteron wave function and NN interaction: Paris potential.

NN and πN interactions in separable form.

Complete T-matrices from solution of LS-equation.

For NN rescattering all partial waves with $J \leq 3$, for πN rescattering S through D waves included.

Result for total cross section



dashed:	impulse approximation (IA)
full:	IA + NN + πN rescattering

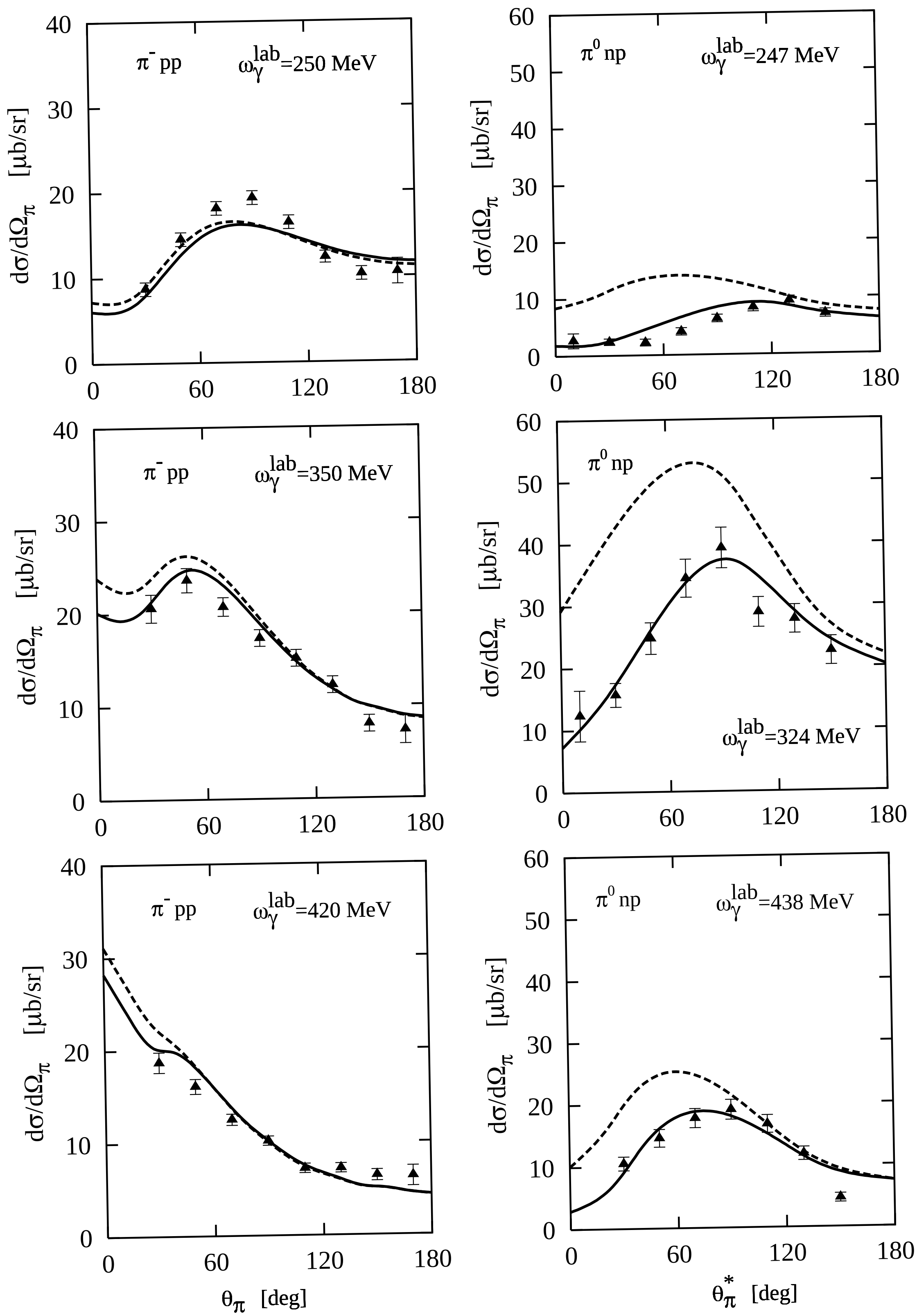
experimental data:

ABHHM: P. Benz et al., Nucl. Phys. B 65, 158 (1973)

Frascati: G. Chiefari et al., Nouvo Cimento 13, 129 (1975)

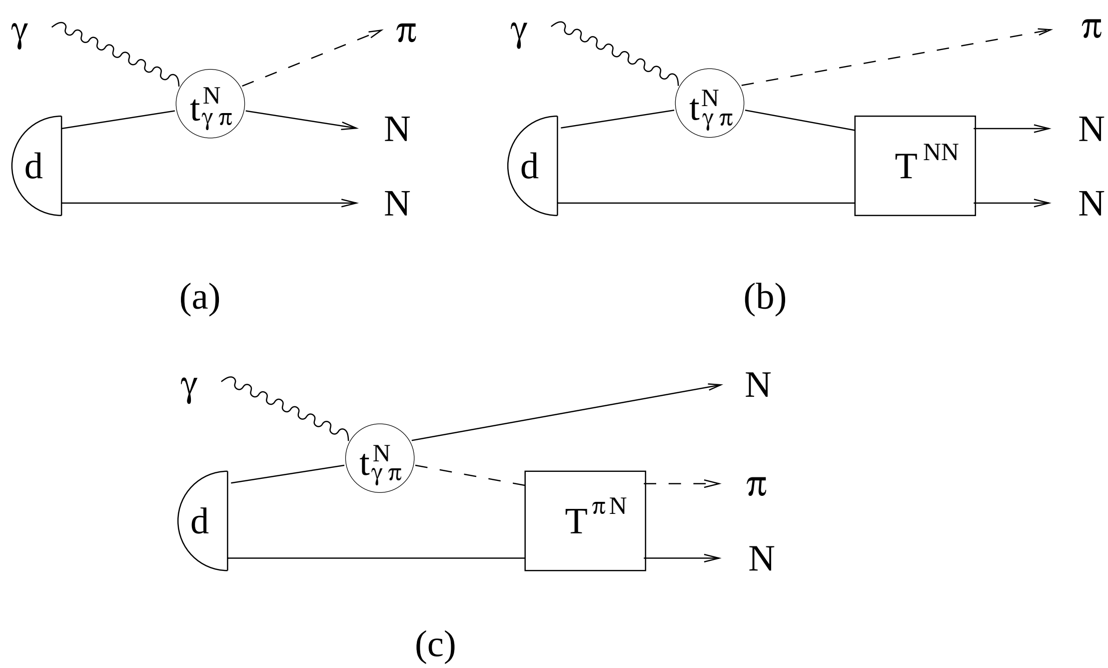
Asai: M. Asai et al., Phys. Rev. C 42, 837 (1990)

Differential cross section



Remarks:

- πN-FSI in general negligible
- Note: in charged pion production, $^3S_1$-contribution to NN-final state is forbidden (isospin) $\rightarrow$ small effect of FSI
- In π^0 production, $^3S_1$ channel is suppressed in full calculation, but not in IA:



relevant quantity: $T(\gamma d \rightarrow \pi NN) \sim \langle \pi NN|\mathcal{O}|d\rangle$

Note:

$$\langle NN(^3S_1)|d(^3S_1)\rangle = 0$$

in full calculation, but not in IA
$\rightarrow$ large effect of NN-FSI in π^0 production

GDH-SUM RULE

The spin-asymmetry $\sigma^P(k) - \sigma^A(k)$ of the total photoabsorption cross section determines the **GDH** sum rule:

$$\int dk \frac{\sigma^P(k) - \sigma^A(k)}{k} = 4\pi\kappa^2 \frac{e^2}{M_d^2} S$$

Note:

GDH sum rule links a ground state property – the anomalous magnetic moment – to the whole internal excitation spectrum, i.e., the total integrated and energy weighted spin asymmetry of the absorption cross section!

$\kappa \neq 0 \longrightarrow$ particle possesses internal structure

Definition of finite **GDH** integral:

$$I^{GDH}(k) = \int_0^k \frac{dk'}{k'} \left(\sigma^P(k') - \sigma^A(k') \right) .$$

- GDH sum rule values for proton and neutron

$$I_p^{GDH}(\infty) = 204.8\,\mu\text{b}\,,$$

$$I_n^{GDH}(\infty) = 233.2\,\mu\text{b}\,.$$

- Recent experimental results for **proton** from J. Ahrens et al., P.R.L. 87, 022003 (2001) (A2- and GDH-Collaborations in Mainz)

An important question is:

What is the spin asymmetry of the neutron?

In the absence of neutron targets it has been suggested that

one can one measure the spin asymmetry of the total photo absorption cross section of the neutron using polarized deuteron or ^{3}He targets.

This would rest on two assumptions:

- Polarized deuteron or ^{3}He constitutes an **effective polarized neutron target**.
- The spin asymmetry on the deuteron is dominated by the **quasifree process**, so that binding and final state effects arising from the presence of the spectator nucleons can be neglected essentially, resulting in an incoherent sum of proton and neutron contributions.

With respect to the first assumption:

- Neutron is **not** completely polarized in a completely vector polarized deuteron target. Same applies to a polarized ^{3}He target.
- Neutron polarization is **slightly model dependent** due to the model dependence of the deuteron wavefunction.

With respect to the second assumption:

- Deuteron is isoscalar and its anomalous magnetic moment is very small

$$\kappa_d = -0.143$$

$$\boxed{\rightarrow\ I_d^{GDH}(\infty)\ =\ 0.65\,\mu\mathrm{b}}$$

- Intuitively: incoherent π-production is dominated by quasifree production.

  → **Positive GDH contribution of order**

$$\boxed{I_p^{GDH}(\infty) + I_n^{GDH}(\infty)\ =\ 438\,\mu\mathrm{b}}$$

  → **Large negative GDH contribution needed!**

- For GDH on the deuteron, besides π-production also the breakup-channel has to be taken into account, i.e.

$$\gamma + d \rightarrow \pi d \quad \text{coherent } \pi\text{-production}$$

$$\gamma + d \rightarrow \pi NN \quad \text{incoherent } \pi\text{-production}$$

$$\gamma + d \rightarrow NN \quad \text{Photodisintegration}$$

For obtaining detailed information, each channel has to be investigated explicitly.

Deuteron photodisintegration

- At low energies **dominant E1 and M1**
  - **Strong destructive interference** of various E1 contributions to spin asymmetry.
  - **Dominance of isovector M1 transition**

    $$d(^3S_1) \rightarrow {}^1S_0 \text{ resonant near threshold}$$

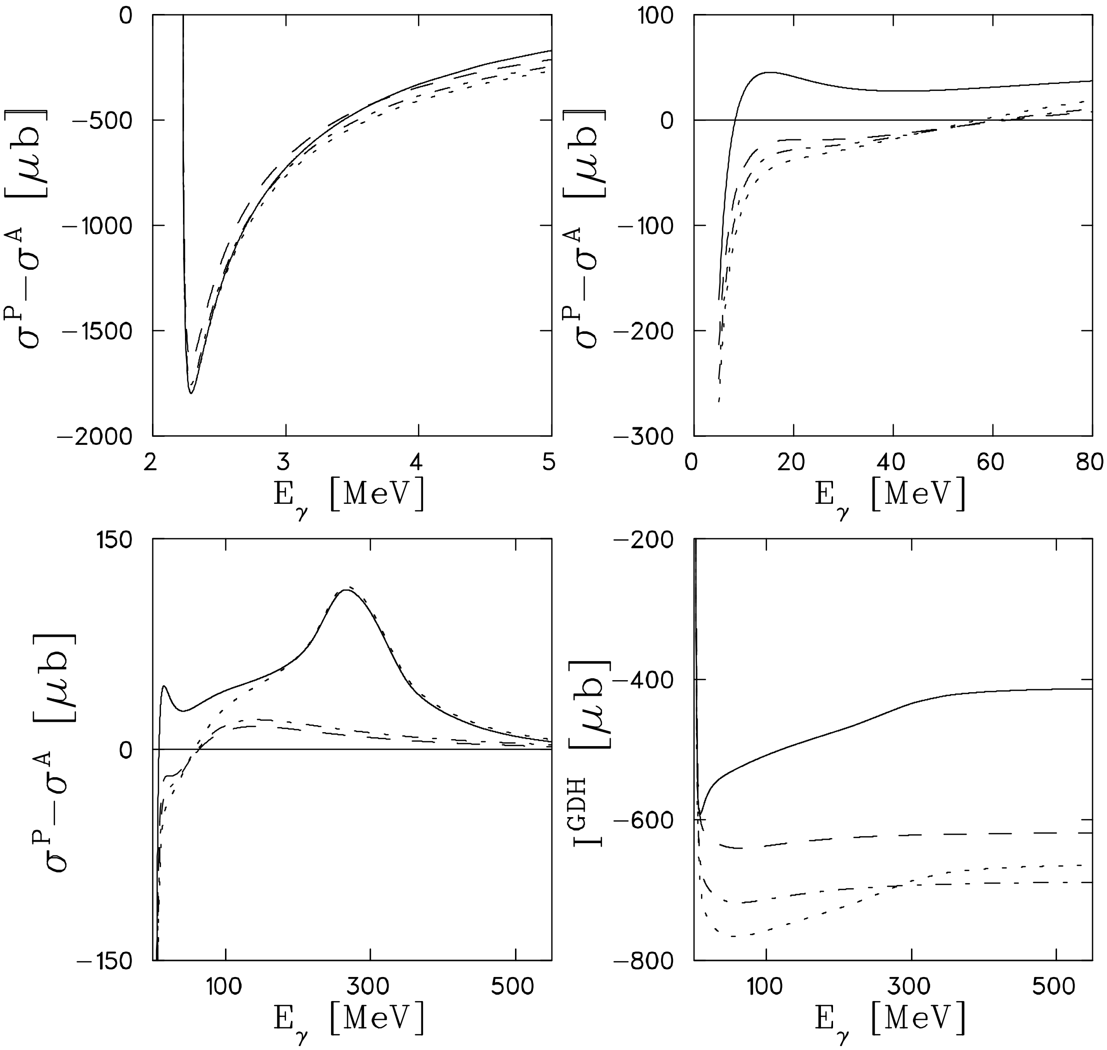
    because of large isovector anomalous nucleon magnetic moment.
- $^1S_0$ can only be reached for **antiparallel** photon and deuteron spins.

→ Large negative GDH contribution near threshold

- For **vanishing** anomalous nucleon magnetic moment one finds

$$I_d^{GDH}(550\,\mathrm{MeV})_{\kappa_N=0} = \mathbf{7.3}\,\mu\mathrm{b}$$

GDH contribution from photodisintegration:

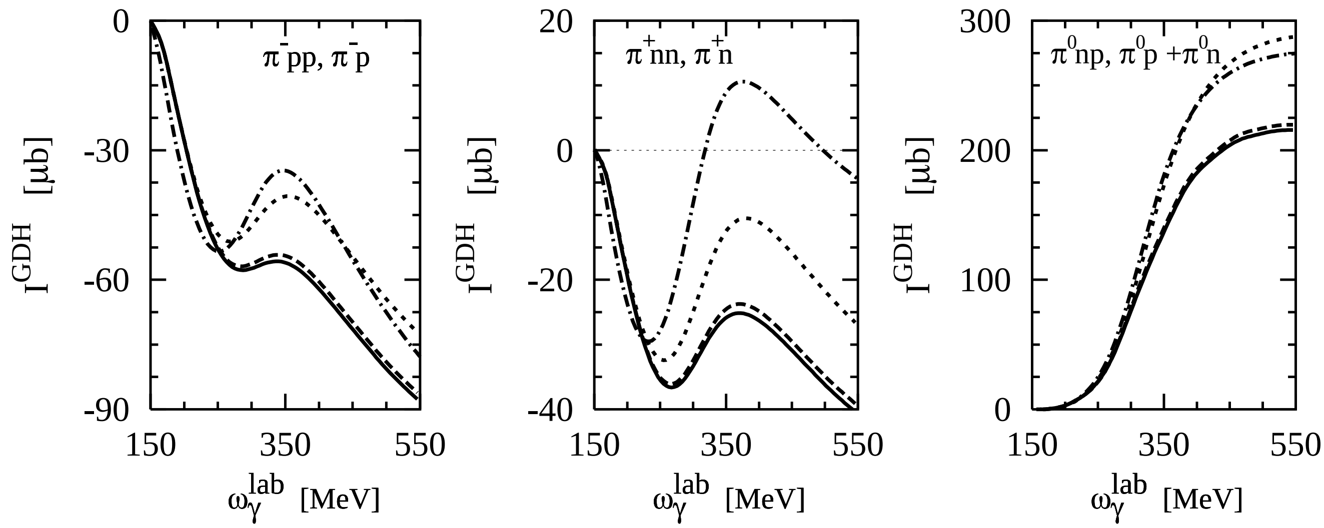


Notation:

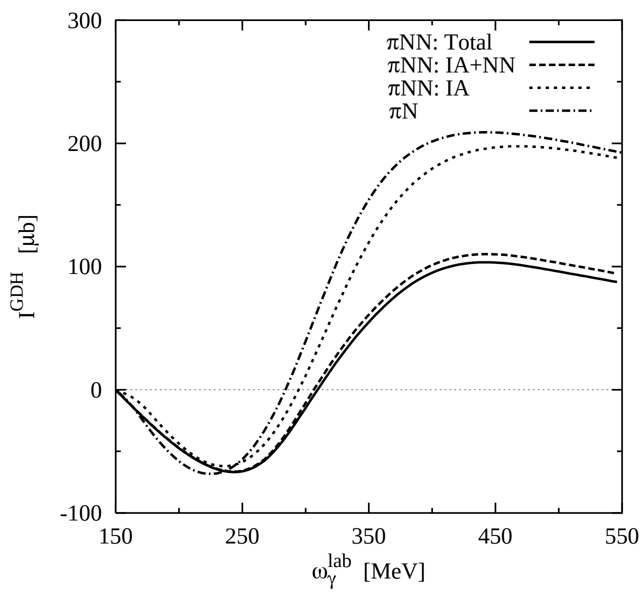
— — — —	N (normal, including Siegert MEC)
— · — · —	N + MEC
· · · · · ·	N + MEC + IC
————	total (N + MEC + IC + RC)

Model needs to be improved: only perturbative treatment of Δ, no retardation included

incoherent pion production contribution:

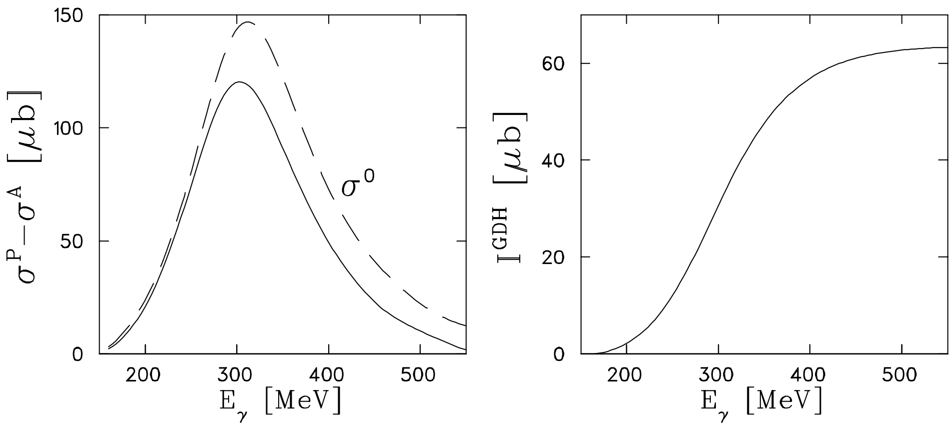


Total GDH integral for pion production on deuteron and nucleon:



Short-dashed:	IA;
Dashed:	IA + NN rescattering;
Solid:	IA + NN + πN rescattering;
Dash-dot:	for nucleon.

contribution from coherent pion production:



CC-Model from Wilhelm and Arenhövel (Nucl. Phys. A609 (1996) 469)

Summary of the results and conclusions

- The spin asymmetry by itself is a very interesting observable because of the strong **anticorrelation** of photodisintegration and pion production.
- Photodisintegration: relativistic effects and FSI very important
- incoherent pion production: FSI reduces significantly the GDH integral up to 550 MeV from its IA-value (almost by half).
- Future improvement: unique treatment of all three reactions, escpecially incorporation of MEC and full 3-body-approach in incoherent pion-production.

3. Summary and Outlook

- Study of electromagnetic and hadronic reactions on the two-nucleon system is an ideal tool to test effective theory.
- Two-nucleon system of specific importance to study neutron properties.
- studied reactions:
  - NN-scattering: theoretical description needs to be improved above pion-threshold
  - Photodisintegration: Retardation very important
  - Incoherent pion production: NN-FSI very important in π^0-channel
  - GDH on the deuteron: FSI in incoherent pion production not negligible, strong anticorrelation between photodisintegration and pion production
- in future: test of the retarded approach in pion-production and electrodisintegration, conceptual improvements (hadronic interaction, relativistic contributions)

  ...