Physics on the two-nucleon system: past achievements and future challenges

Seminar

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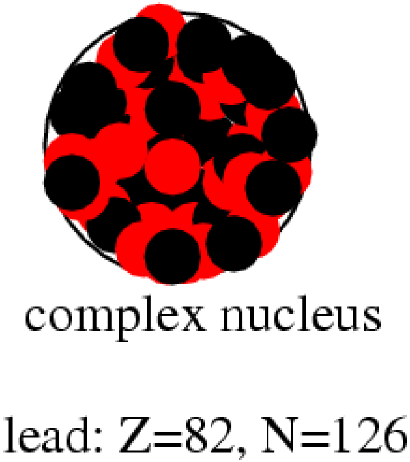
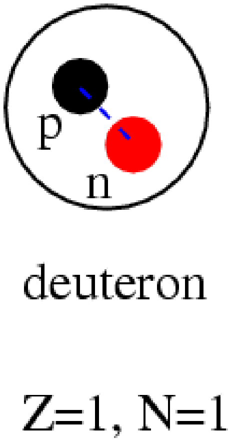
1. Introduction and motivation

- One of the most exciting challenges of physics: understanding of **nuclear structure**





- simplest nucleus: **deuteron**

Chadwick and Goldhaber (1934):

Heavy hydrogen ... is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen is in atomic theory

In the following, empirical proof of this statement:

(i) historic overview

(ii) future challenges

2. Historic overview

early 20th century:
known "elementary" particles: proton and α-particle

1920:
$Z < \frac{A}{2}$ for most atomic nuclei $\longrightarrow$ postulation of an elementary particle, the neutron, with atomic weight ≈ 1 and charge 0 (**Rutherford**)

1932:
Experimental discovery of neutron by **Chadwick**

$$^{9}_{4}Be + \alpha \longrightarrow n + ^{12}_{6}C$$

At first, mass of neutron was only known on the level of ± 10 percent

1932:
Experimental discovery of deuterium (heavy hydrogen) by **Urey, Brickwedde and Murphy (UBM)**:

– Small discrepancy between chemical atomic weight of hydrogen and mass of hydrogen determined by mass spectroscopy

– Hypothesis of Birge and Menzel: existence of heavy hydrogen ($A = 2$) (deuterium)

– Recall: energy eigenvalues of nonrelativistic hydrogen atom:

$$E_n = \frac{m_e e^4}{8\epsilon_0^2 h^2 1 + \frac{m_e}{m_K}} \frac{1}{n^2}$$

with m_K denoting nuclear mass

– larger mass of deuterium leads to satellite lines at somewhat higher energies as for normal hydrogen, experimentally observed by UBM

1933:
mass spectroscopic investigation of deuterium by **Bainbridge**

1934:
Investigation of deuteron photodisintegration by **Chadwick and Goldhaber**:

$$D + \gamma \rightarrow H + n$$

starting point of photonuclear physics

Determination of deuteron binding energy with help of known γ-energy and measured energy of decay protons: $BE_d \approx 2.1$ MeV
$\longrightarrow$ precise determination of **neutron mass**:

$$m_d = m_p + m_n - BE_d$$

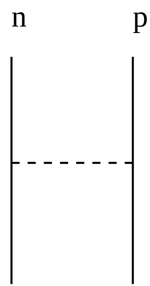
leads to

$$m_n = 1.0080u \pm 0.0050u$$

Conclusion I: Shortly after its discovery, deuterium served as a tool to study fundamental neutron properties!

Some selected further highlights:

1935:
Postulation of mesons by **Yukawa**; internal quantum numbers completely hypothetic at first (Kemmer, Proca and others)



1939:
Experimental determination of deuteron quadrupole moment by **Rabi**:

$$Q_d = \int d^3r \rho(\vec{r}) \left(3z^2 - r^2\right) = 0.2860\mathrm{fm}^2$$

$Q_d \neq 0 \longrightarrow$ nuclear force has **noncentral** piece!

1944:
Pauli: Pseudoscalar coupling necessary for correct sign of Q_d

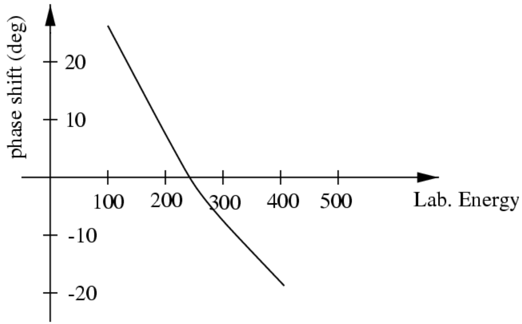
Apart from deuteron, also **nucleon-nucleon** scattering essential for understanding of strong force

Summary of essential properties of NN-force:

- NN-force is of short range (a few fm).
- NN-force is attractive in its intermediate range.
- The nuclear force has a repulsive core.

  rough estimate:

  Experiment: ${}^1S_0$-phase shift in NN-scattering becomes negative for $E_{Lab} \approx 250$ MeV



Classical orbital angular momentum L involved in a range R is given by

$$L \approx R\, p$$

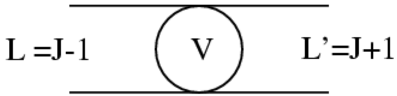
where p denotes the momentum of the incoming nucleon in the CM-frame:

$$E_{Lab} = \frac{2p^2}{M_N} \; .$$

With $L \leq 1$, $E_{Lab} = 250\,\mathrm{MeV}$ one obtains

$$R \leq 0.6\,\mathrm{fm} \; .$$

- There exists a tensor force, generating a transition from a NN-state with orbital angular momentum $L = J - 1$ to one with $L = J + 1$ (with J the total angular momentum: $\vec{J}=\vec{L} + \vec{S}$):



  experimental evidence: nonvanishing deuteron quadrupole moment ($\rightarrow$ D-state contribution necessary).

- There is a Spin-Orbit force $\sim\vec{L} \cdot \vec{S}$
  experimental evidence: triplet P-wave-phase-shifts $({}^3P_0, {}^3P_1, {}^3P_2)$ can only be explained by assuming a strong spin-orbit force.

- Moreover, there exists a pure spin-spin force
  $\sim \vec{\sigma}\ (1)\cdot\ \vec{\sigma}\ (2)$, where $\frac{1}{2}\ \vec{\sigma}\ (i)$ is the spin operator for nucleon i, which is however less important and therefore neglected in the forthcoming discussion.

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Summarizing:

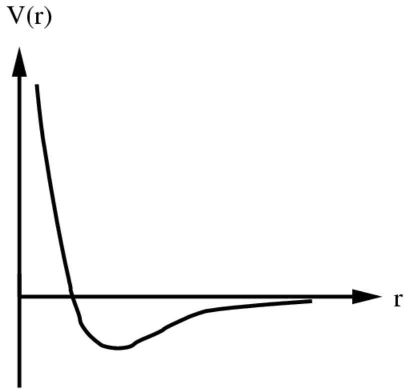
Nuclear force can be described in first approximation (local, nonrelativistic limit) by

$$V(\overrightarrow{r}) = V_c(r) + V_T(r)S_{12} + V_{LS}(r)\ \overrightarrow{L} \cdot \overrightarrow{S}$$

with tensor operator

$$S_{12} = \frac{3\,(\vec{\sigma}(1) \cdot \vec{r})\,(\vec{\sigma}(2) \cdot \vec{r})}{r^2} - \vec{\sigma}(1) \cdot \vec{\sigma}(2)$$

Important question: How to fix V_C, V_T and V_{LS}?

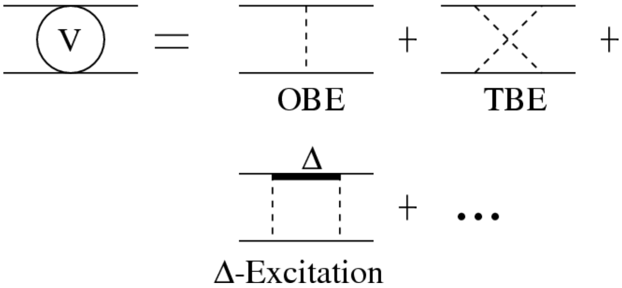


Models for the NN-interaction (no complete list!!!):

- **phenomenological** treatments: Hamada/Johnson (1962), Yale (1962), Reid (1968)

  Drawback: typically 30-50 free parameters!

- **field-theoretical** models, based on the assumption that meson-exchange is able to describe the NN-force:



→ Bonn-potential in various parametrizations (OBEPR, OBEPQ, full Bonn, etc.). Alternative approach by the Nijmegen-group.
Advantage: typically only 10-12 free parameters

- in the low energy regime **Effective Field Theory** (see next chapter)

Example:

field-theoretical derivation of 1-pion-exchange-potential (OPEP)

- starting point: Interaction Lagrangian for describing $\pi N \leftrightarrow N$-interaction, simplest choice: pseudoscalar coupling (isospin neglected for sake of simplicity)

$$\mathcal{L}_\pi = -\frac{g_\pi}{2M_N}\bar{\psi}\gamma^5\psi\phi_\pi$$

with the field operators for nucleons and pions:

$$\begin{aligned} \psi(x) &= \frac{1}{(2\pi)^{\frac{3}{2}}}\sum_\lambda \int d^3p \; u(\vec{p},\lambda)e^{-ip_\mu x^\mu} \; b_\lambda(p) \; , \\ \phi_\pi(x) &= \int \frac{d^3k}{(2\pi)^3 \, 2\omega_\pi(k)} \; \left(a_\pi^\dagger(k) \; e^{ik_\mu x^\mu} + a_\pi(k)\, e^{-ik_\mu x^\mu}\right) \; , \end{aligned}$$

where $b_\lambda^\dagger(p), a_\pi^\dagger(k), b_\lambda(p), a_\pi(k)$ denote the corresponding creation and annihilation operators. $u(\vec{p},\lambda)$ denotes the usual Dirac-spinor

$$u(\vec{p},\lambda) = \sqrt{\frac{E+m}{2E}}\begin{pmatrix} 1 \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\end{pmatrix}\chi_\lambda \; .$$

- In the Schrödinger-picture, the time-independent $\pi N \leftrightarrow N$ interaction is given by

$$V_\pi := \int d^3x \left[\mathcal{L}_\pi(\vec{x}, t)\right]_{t=0}$$

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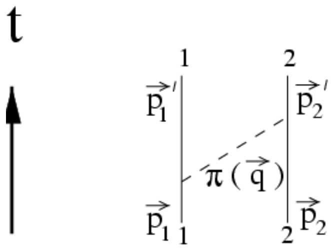
- One-pion-exchange potential:



$$\begin{aligned} V^{OPEP} \;=\; & \langle N(\vec{p}_1{}', \lambda_1'); N(\vec{p}_2{}', \lambda_2')|V_\pi(2) \\ & G_0(W + i\epsilon)V_\pi(1)|N(\vec{p}_1, \lambda_1); N(\vec{p}_2, \lambda_2)\rangle \end{aligned}$$

with the πNN-propagator

$$G_0(z) = \left(W + i\epsilon - H_0^N(1) - H_0^N(2) - H_0^\pi\right)^{-1}$$

- static limit as further approximation (nucleon mass is assumed to be infinitely heavy during the meson exchange):

$$G_0(z) \longrightarrow -\left(H_0^\pi\right)^{-1}$$

- final result in the strictly nonrelativistic limit (isospin omitted):

$$V^{OPEP} = -\frac{g_\pi^2}{4M_N^2}\frac{\left(\vec{\sigma}\,(1)\cdot\,\vec{q}\right)\,\left(\vec{\sigma}\,(2)\cdot\,\vec{q}\right)}{q^2+m_\pi^2}$$

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- Note: nucleons are not pointlike $\longrightarrow$ introduction of a hadronic form factor

$$F_\pi(q) := \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2+q^2}\right)^{n_\pi}$$

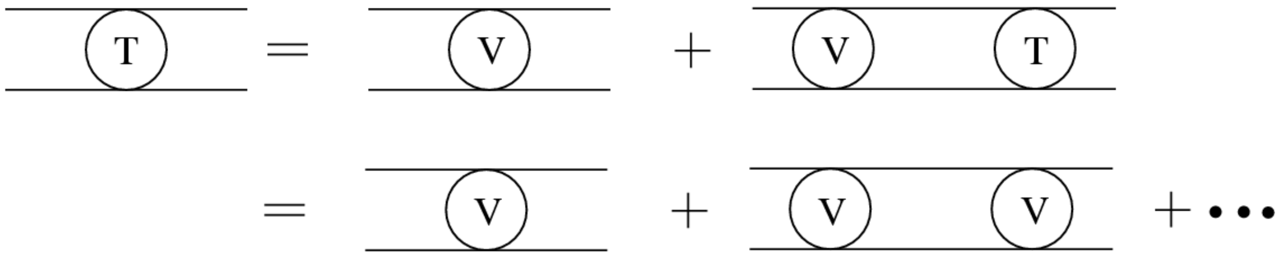
at each vertex in order to suppress contributions from very high pion momenta q ($\leftrightarrow$ small distance r between the two nucleons):

$$V^{OPEP} \;\to\; V^{OPEP}\,F_\pi^2$$

Cutoff Λ_π is a free parameter (around 1-2 GeV).

After constructing the potential V, one has to determine the **scattering amplitude** T given by ($z = W + i\epsilon$)

$$T(z) = V + VG_0(z)T(z) \ .$$



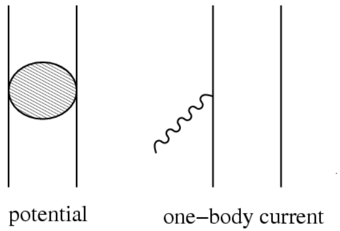
The matrixelements of T(z) determine the observables in NN-scattering (phase shifts, mixing angles etc.)

Summary of the results:

- One-boson-exchange of π, ρ, ω- and fictitious σ-meson is sufficient to obtain a reasonable description of the deuteron properties and the NN-phase shifts till π-threshold.
- major contributions:
  (a) π (spin 0, isospin 1): tensor force, long range part
  (b) ρ (spin 1, isospin 1): tensor force (opposite to π),
  (c) ω (spin 1, isospin 0) tensor force (opposite to π), repulsive part of central force, spin-orbit force
  (d) σ (spin 0, isospin 0) attractive part of central force, spin-orbit force
- additional mesons (δ, η) for fine tuning
- number of free parameters: 10-12 (OBEPR, OBEPQ)
- an improved, almost perfect description of the experimental data can be achieved by choosing different parameter sets for each partial wave ($\longrightarrow$ CD-Bonn)

Back to photonuclear physics:

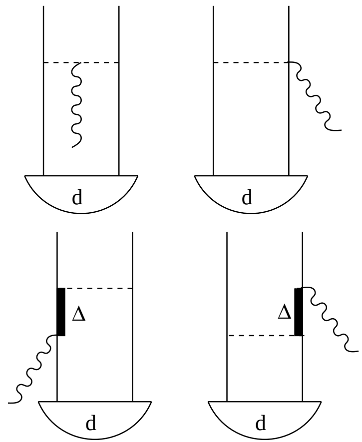
Problem in 1960s:
"classical" theory, incorporating solely nucleonic degrees of freedom in current operators, underestimates significantly thermal *np*-capture cross section ($n + p \longrightarrow d + \gamma$)



New concept: introduction of **subnuclear** degrees of freedom in electromagnetic current operators:

meson exchange currents (MEC):
Riska and Brown (**1972**)

virtual Δ-excitation and deexcitation:
Stranahan (**1964**); Arenhövel, Danos and Williams (**1971**)



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1982:
Further important insight (**Cambi, Mosconi and Ricci**): relativistic contributions (RC) to electromagnetic current operators turn out to be important at even low energies:

Dirac-equation of nucleon in electromagnetic field:

$$\left(p_\mu\gamma^\mu - eA_\mu\gamma^\mu - \frac{\kappa}{4M_N}\sigma_{\mu\nu}F^{\mu\nu} - M_N\right)\Psi = 0$$

p/M_N-expansion of resulting current yields

(a) nonrelativistic currents/charges:

$$\begin{aligned}\langle\vec{p}\,'|\rho^{nr}|\vec{p}\rangle &= \delta(p' - \vec{k} - \vec{p})e \\ \langle\vec{p}\,'|\vec{\jmath}^{nr}|\vec{p}\rangle &= \delta(p' - \vec{k} - \vec{p})\left\{\frac{e}{2M_N}(\vec{p}\,' + \vec{p}) + \frac{e+\kappa}{2M_N}i\vec{\sigma}\times\vec{k}\right\}\end{aligned}$$

(b) relativistic corrections, e.g. spin-orbit:

$$
\begin{aligned}
\langle \vec{p}\,'|\rho^{so}|\vec{p}\rangle &= -\delta(p' - \vec{k} - \vec{p})\frac{e+2\kappa}{8M_N^2} i\vec{\sigma}\times(\vec{p}\,' + \vec{p}) \\
\langle \vec{p}\,'|\vec{\jmath}^{\,so}|\vec{p}\rangle &= \delta(p' - \vec{k} - \vec{p})\left[H, \frac{e+2\kappa}{8M_N^2} i\vec{\sigma}\times(\vec{p}\,' + \vec{p})\right]
\end{aligned}
$$

Large sensitivity of forward cross section of deuteron photodisintegration (Friar et al.):

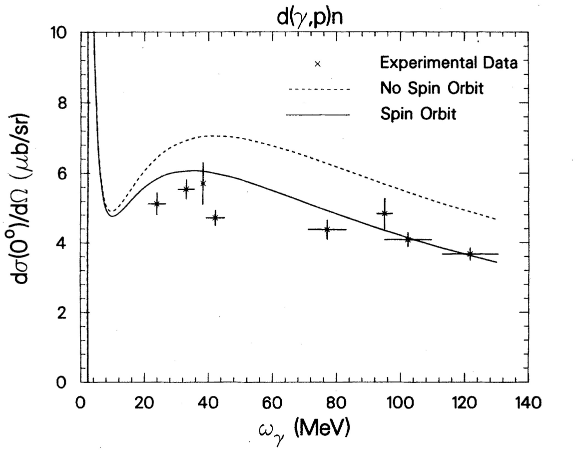
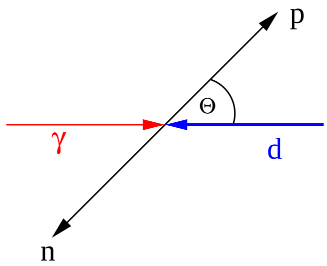
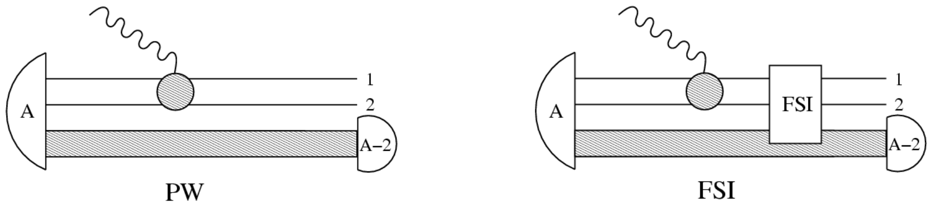
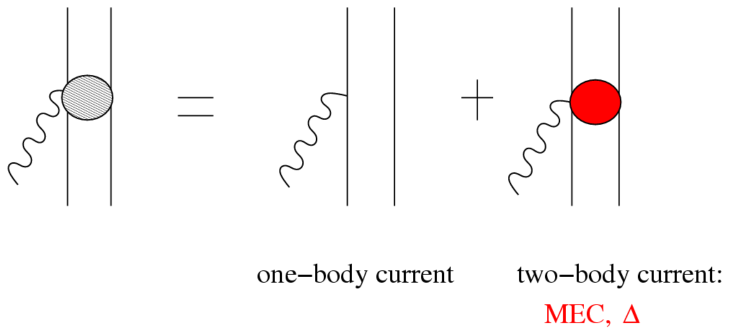


FIG. 2. Deuteron forward photodisintegration for the Paris potential with and without the spin-orbit dipole operator.



Note: Incorporation of MEC, Δ-excitation and RC nowadays standard in photonuclear physics, even in much more complicated reactions like $(e, e'NN)$ off ^{16}O:





Conclusion II: Deuteron serves as an ideal laboratory to study fundamental reaction mechanisms in nuclear physics

Further highlight: Determination of electric neutron formfactor G_{En}

Dirac-current of non-pointlike nucleon:

$$\langle \vec{p}\,'|j^\mu|\vec{p}\rangle \;=\; \bar{u}(\vec{p}\,')\left[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma^{\mu\nu}q_\nu\right]u(\vec{p})$$

with **Dirac** formfactors F_1, F_2.
Suitable linear combination (**Sachs** formfactors)

$$\begin{aligned} G_E(q^2) &= F_1(q^2) + \frac{\kappa q^2}{4M_N^2}F_2(q^2) \\ G_M(q^2) &= F_1(q^2) + \kappa F_2(q^2) \end{aligned}$$

can be interpreted as charge/magnetization density in the nucleon

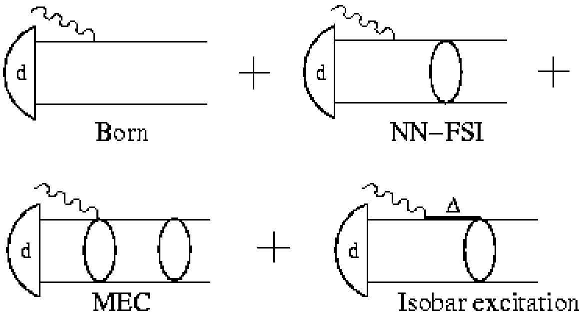
G_E, G_M are fundamental quantities!

Problem in experimental determination of neutron formfactor:

- no free neutron target
- G_{En} small quantity

Solution (**Dombey** (1969), **Arenhövel et al.** (1988)):
Determination of G_{En} in quasifree kinematics with help of selected polarization observables in $d(e,e'n)p$ like $d(\vec{e},e'\vec{n})p$

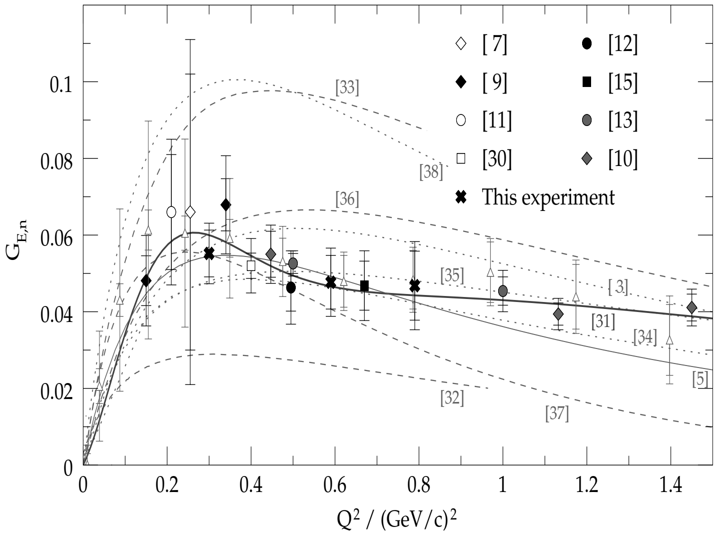
relevant mechanisms:



Promising observable: neutron polarization P'_x in quasifree kinematics

$$P'_x \sim G_{E_n} \cdot G_{M_n} \qquad \text{in Born approximation}$$

Present status:



A1 collaboration: Glazier et al. (2005)

Conclusion: deuteron serves as an ideal effective neutron target for determination of fundamental neutron properties like G_{En}!

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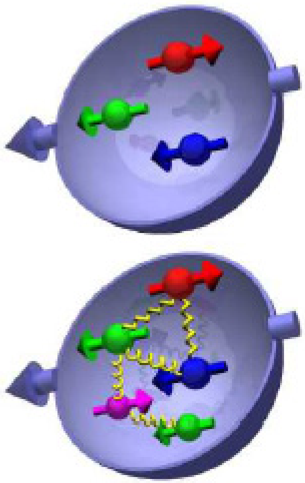
3. Future challenges

Repetition:

- fundamental theory of strong interaction:

  Quantum chromodynamics (QCD)

- QCD – as a nonabelian gauge theory – cannot be applied in low energy region
  $\longrightarrow$ construction of effective theories, based on "effective" degrees of freedom like nucleons, mesons, resonances



Central challenge:

Construction of standard model for effective description of nuclear physics

Some selected questions:

- Description of properties of hadrons and nuclei in the low-energy sector $\longrightarrow$ deuteron serves as an ideal starting point for understanding of nuclei
- Determination of limits of effective picture

3.1. The low energy domain below pion threshold

Basic idea of effective field theories:

- Construction of most general Lagrangian consistent with symmetries of QCD
- Introduction of "power counting" for classification of occurring diagrams with respect to their relative importance at low energies $\rightarrow$ possibility of estimating errors!

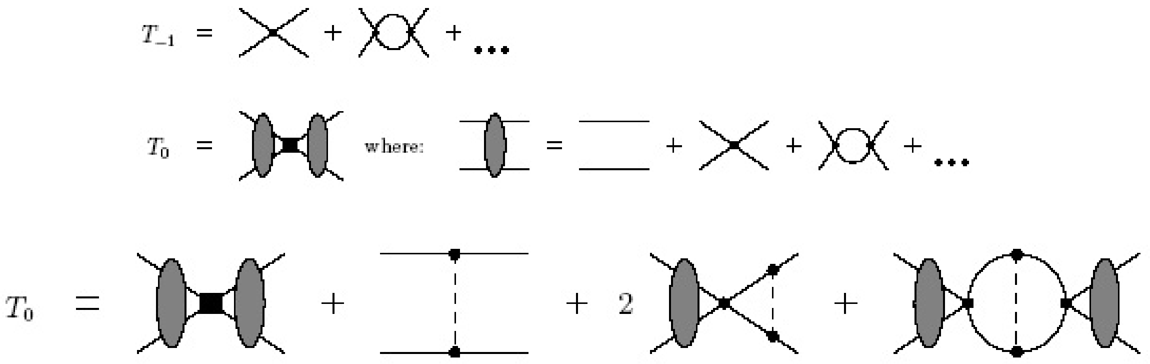
Problem in two-nucleon sector:
(quasi)-bound state in ${}^1S_0$- and ${}^3S_1/{}^3D_1$-channel

$\longrightarrow$ large problems due to nonperturbative effects!

Various treatments:

- Kaplan, Savage and Wise (KSW):
  - contact interaction of lowest order can be treated nonperturbatively
  - perturbative treatment of pion loops and higher order contact interactions
  - Structure of ${}^1S_0$ amplitude ($T_q \sim p^q$):

$$T = T_{-1} + T_0 + T_1 + \ldots$$



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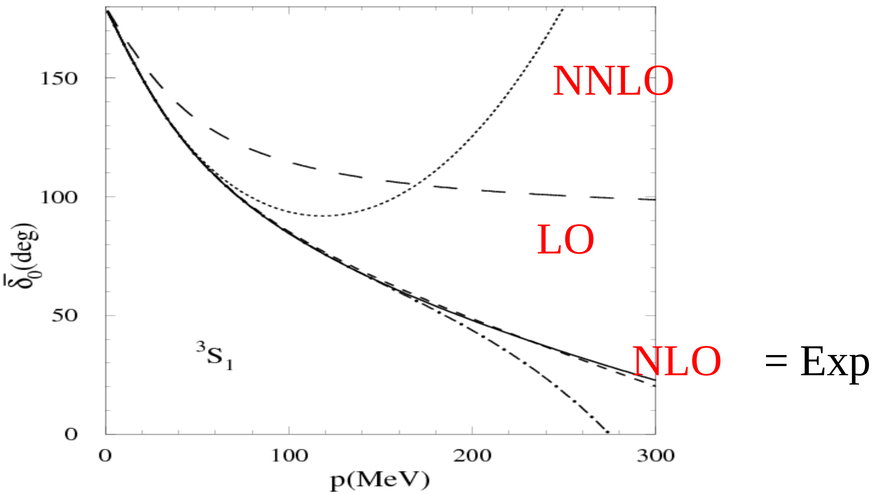
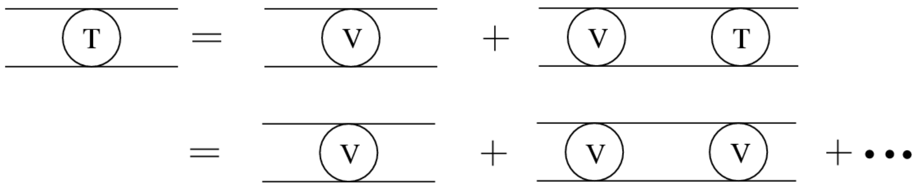
– Serious problem: no convergence!



Fleming et al.

- Weinberg-approach (→ Meissner, Epelbaum,...):
  - nonperturbative treatment of NN-problem with help of Lippmann-Schwinger equation:

$$T(z) = V + VG_0(z)T(z) = V + VG_0(z)V + VG_0(z)VG_0(z)V + \ldots$$



  - Power-Counting on level of potential (contact interactions, pion exchange)
  - Introduction of hadronic formfactors to avoid ultraviolet divergences in loop integrals

$$V(p,q) \rightarrow e^{-\frac{p^6}{\Lambda^6}} V(p,q) e^{-\frac{q^6}{\Lambda^6}}$$

with (in certain limits) free parameter Λ

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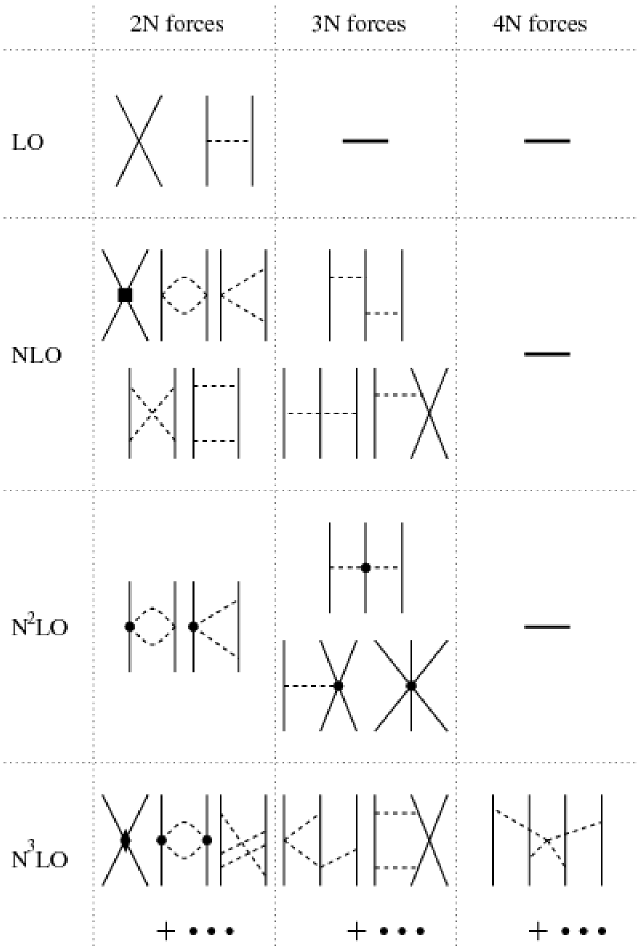
2N forces
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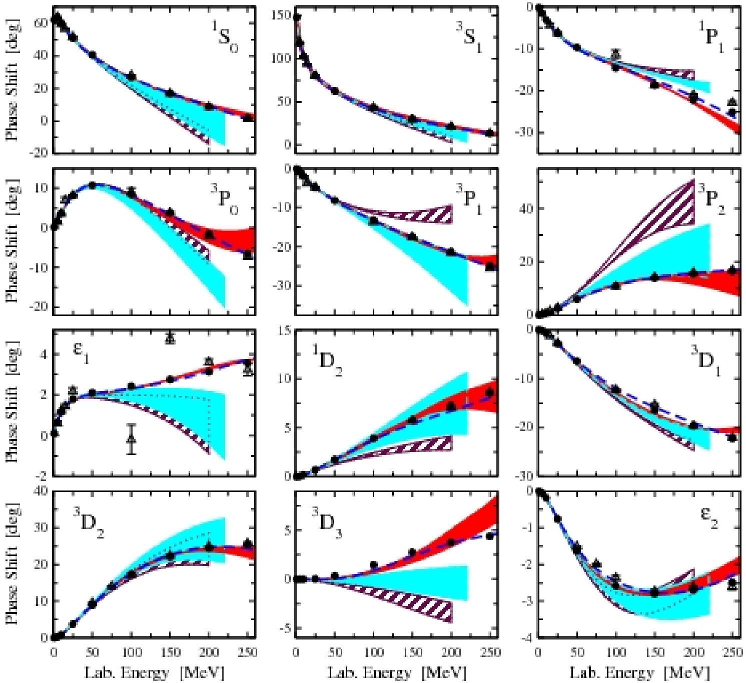
– Approach works very well in practice:

Epelbaum



dashed: NLO, blue: N^{2}LO, red: N^{3}LO

3.2. The energy domain beyond pion threshold

- Possible reactions in the two-nucleon sector below pion threshold:

$$\begin{aligned} \text{hadronic:} \quad & NN \to NN \\ \text{electromagnetic:} \quad & \gamma^{(*)}d \to NN, \quad ed \to ed, \quad \gamma d \to \gamma d, \\ & NN \to NN\gamma \end{aligned}$$

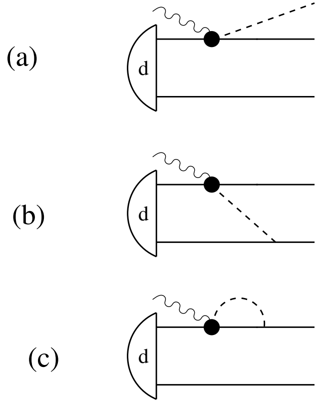
- Beyond pion threshold, large number of new inelastic reactions:

$$\begin{aligned} \text{hadronic:} \quad & NN \to \pi d, \pi NN, \pi\pi d, \ldots \\ \text{electromagnetic:} \quad & \gamma^{(*)}d \to \pi d, \pi NN, \\ & \gamma^{(*)}d \to \pi\pi d, \ldots \end{aligned}$$

- Different reactions are linked by **unitarity**:

$$\begin{aligned} \operatorname{Im} T(NN \to NN) &\sim \sigma_{tot}(NN \to NN, \pi d, \pi NN, \ldots)\,, \\ \operatorname{Im} T(\pi d \to \pi d) &\sim \sigma_{tot}(\pi d \to NN, \pi d, \pi NN, \ldots)\,, \\ \operatorname{Im} T(\gamma d \to \gamma d) &\sim \sigma_{tot}(\gamma d \to NN, \pi d, \pi NN, \ldots)\,, \end{aligned}$$

- Consequence: **unified** description of all possible reactions necessary!
- Intuitively:

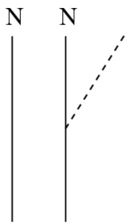


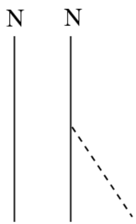
(a) Contribution to $\gamma^{(*)}d \rightarrow \pi NN$

(b) MEC to $\gamma^{(*)}d \rightarrow NN$

(c) pion cloud contribution to anomalous magnetic moment of a (bound) nucleon

- Construction of corresponding model recently realized
  - Hadronic interaction given by XNN vertices ($X \in \{\pi, \rho, \omega, \sigma, ...\}$) and $\pi N\Delta$ vertex





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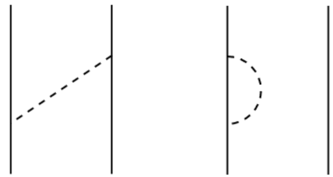
– Iteration of iteration of vertices via Lippmann-Schwinger equation

$$T(z) = V + V G_0(z) T(z)$$

generates NN-Potential which is consistent with meson production operator



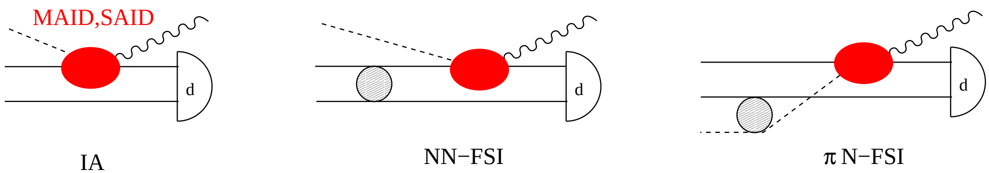
– nonperturbative treatment of Δ isobar

– Consistent electromagnetic current operators by minimal substitution

Interesting results, for example in

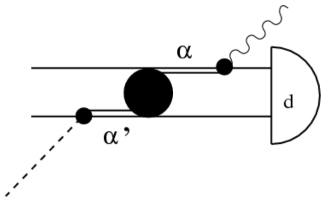
incoherent pion photoproduction: $\gamma d \to \pi N N$

– Standard approach, also applied in η-, kaon-physics):

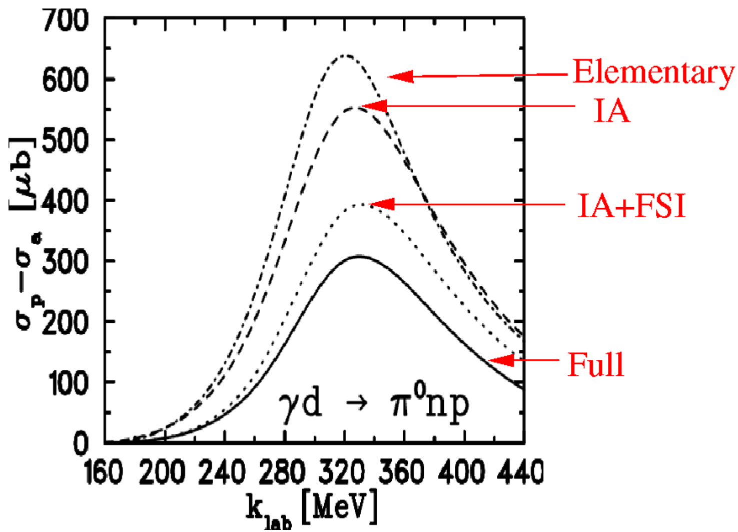


– Problems:

* Unitarity, gauge invariance?
* Insufficient consideration of two-body production operators ($\alpha, \alpha' \in N, \Delta$):



Spin asymmetry for $\vec{\gamma}\vec{d} \to \pi^0 pn$



Example shows urgent need for unified approach!

Example for open problems: Proton polarization $P_y(90°)$ in deuteron photodisintegration

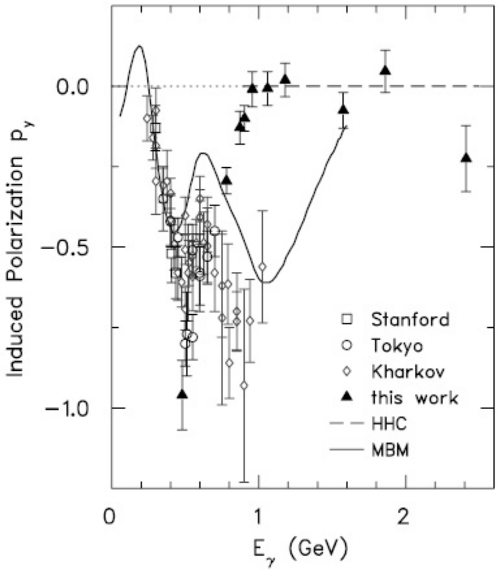


FIG. 1. Induced polarization p_y in deuteron photodisintegration at $\theta_{\rm c.m.} = 90°$. Only statistical uncertainties are shown. The curves are described in the text.

JLAB experiment (Wijesooriya et al.)

- very strong negative polarization around $E_\gamma = 500 - 600$ MeV
- data not consistent
  $\longrightarrow$ TJNAF-Experiment E05-103
- serious problem for any existing approach which is based solely on "standard" degrees of freedom (nucleons, mesons, resonances)
- speculations in 70s and 80s: signature for nonstandard degrees of freedom (dibaryons)?
  $\longrightarrow$ signature for "new physics"?
- Essential task: to push the effective picture toward its limits

The Gerasimov-Drell-Hearn sum rule

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

$$\int_0^\infty \frac{dk}{k}\Big(\underbrace{\sigma^P(k) - \sigma^A(k)}_{\text{spin asymmetry of total absorption cross section}}\Big) \;=\; 4\pi^2\kappa^2\frac{e^2}{m^2}S$$

- eQ = charge of particle
- m = mass of particle
- κ = anomalous magnetic moment, i.e., magnetic moment operator

$$\mathbf{M} \;=\; (Q+\kappa)\frac{e}{m}\mathbf{S}$$

Note: GDH sum rule links a ground state property – the anomalous magnetic moment – to the whole internal excitation spectrum

$$\kappa \neq 0 \;\longrightarrow\; \text{particle possesses internal structure}$$

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Forward
Quit

(i) Brief Derivation

(a) **Low energy theorem** for forward elastic photon scattering amplitude (Lorentz and gauge invariance, unitarity, crossing)

$$T_{\lambda\lambda} = \underbrace{-e^2 \frac{Q^2}{m}}_{\text{Thomson term}} + \underbrace{\lambda\kappa^2 \frac{e^2}{m^2} \langle \mathbf{S} \cdot \mathbf{k} \rangle}_{\text{spin term (relativistic order)}} + \mathcal{O}(\mathbf{k}^2)$$

(b) **Unsubtracted dispersion relation** (causality)

$$\Re f(k) = \frac{\mathcal{P}}{\pi} \int_{-\infty}^{\infty} dk' \frac{\Im f(k)}{k' - k}$$

for difference of scattering amplitudes for photon and particle spins parallel and antiparallel

$$\begin{aligned} f(k) &= T_{\lambda\lambda}(k,\, S_P) - T_{\lambda\lambda}(k,\, S_A) \\ &= 2\kappa^2 \frac{e^2}{m^2} k\, S + \mathcal{O}(k^2)\,. \end{aligned}$$

(c) **Crossing and optical theorem →**

$$\Re f(k) = \frac{k}{2\pi^2}\mathcal{P}\int_0^\infty dk' k' \frac{\sigma^P(k') - \sigma^A(k')}{k'^2 - k^2}$$

(d) Derivative at $k = 0$ yields GDH sum rule.

(ii) GDH sum rule for the nucleon and the deuteron

Definition of finite **GDH** integral:

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

- GDH sum rule values for proton, neutron and deuteron

$$\begin{aligned} I_p^{GDH}(\infty) &= 204.8\,\mu\mathrm{b}\,,\\ I_n^{GDH}(\infty) &= 233.2\,\mu\mathrm{b}\,,\\ I_d^{GDH}(\infty) &= 0.65\,\mu\mathrm{b}\,. \end{aligned}$$

- Explicit evaluation?
  Absorptive processes for proton
  (analogously for neutron)

$$\begin{aligned} \gamma + p &\longrightarrow p + \pi^0\,,\\ \gamma + p &\longrightarrow n + \pi^+\,,\\ \gamma + p &\longrightarrow N + \pi + \pi\,,\ \text{etc.} \end{aligned}$$

Experimental results for **proton** available (MAMI, ELSA)

An important question is:

What is the spin asymmetry of the neutron?

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For that, one basic assumption must be fulfilled:
The spin asymmetry on the deuteron has to be 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.

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A consequence of this assumption would be

$$I_d \approx I_p + I_n$$

which is largely wrong by almost three orders of magnitude!

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

$$\begin{array}{rcll} \gamma + d & \rightarrow & \pi d & \text{coherent } \pi\text{-production} \\ \gamma + d & \rightarrow & \pi NN & \text{incoherent } \pi\text{-production} \\ \gamma + d & \rightarrow & NN & \text{Photodisintegration} \end{array}$$

Strong anticorrelation between different channels in case of deuteron target:

	np	π	$\pi\pi$	η	$\sum$	sum rule
$n+p$		315.33	175.95	-14.54	476.74	437.94
d	-381.52	263.44	159.34	-13.95	27.31	0.65

Consequence: Deuteron not suitable as effective neutron target for extraction of GDH on neutron, but spin asymmetry for itself very interesting quantity

4. Summary and outlook

- Deuteron constitutes the "hydrogen atom" of nuclear physics
- two-nucleon physics important for
  - Investigation of neutron properties
  - Investigation of fundamental reaction mechanisms in nuclear physics
- Basic requirement for future studies: **Unification**

The deuteron constitutes a "fundamental" object of nuclear physics

5. References for further reading

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