The importance of subnuclear degrees of freedom in photon absorption and electron scattering by nuclei is discussed. After a short introduction into the basic properties of one-photon processes and a very brief survey on the nuclear response in the various regions of energy and momentum transfers, the particular role of subnuclear degrees of freedom in terms of meson and isobar degrees of freedom is considered. Their importance is illustrated by several reactions on the deuteron which are currently under study at c.w. electron machines like MAMI in Mainz.

1 Introduction

Since the beginning of nuclear physics, when the existence of the atomic nucleus was deduced by Rutherford from the famous experiments of α-particle scattering on a gold foil by Geiger and Marsden up to the deep inelastic scattering experiments at Stanford by Friedman, Kendall and Taylor revealing the parton substructure of nucleons, the electromagnetic probe has always played an outstanding role in the study of nucleon and nuclear structure

One of the major goals of present day research in this field is to clarify the role of subnuclear degrees of freedom (d.o.f.) in the structure of nuclei as well as their relation to the underlying quark-gluon dynamics of QCD. In this talk I will concentrate on the manifestation of meson and isobar degrees of freedom in electromagnetic processes where they contribute as two-body meson exchange currents (MEC) and via nuclear isobar configurations (IC). The latter are nuclear wave function components containing internally excited nucleons (isobars).

2 Properties of the Electromagnetic Probe

The special role of the electromagnetic interaction in unravelling the microstructure of the world is due to the fact that (i) its properties as a classical field are well known, (ii) the electromagnetic interaction fulfills the basic requirements of a fundamental interaction incorporating relativity and representing the simplest case of a gauge theory, and (iii) the electromagnetic interaction is

* Dedicated to Walter Greiner on the occasion of his 60th birthday
weak enough to allow lowest order perturbation treatment resulting in simple and unique interpretations of experimental results. However, this weakness constitutes also a disadvantage since the cross sections for photoreactions and electron scattering are considerably smaller than for pure hadronic reactions.

The lowest order processes are the one-photon processes like photon absorption (or emission) and electron scattering which is governed by the exchange of one virtual photon. The main differences between photoabsorption and electron scattering or real and virtual photon processes, respectively, are:

(i) For real photons one has a fixed relation between energy and momentum transfer ($q^2 = \omega^2$) while for the exchange of a virtual photon in electron scattering the four momentum is space-like ($q^2 \geq \omega^2$) allowing an independent variation of energy and momentum transfer within the spacelike region.

(ii) Real photons have only transverse polarization so that only the transverse current density contributes while virtual photons have both, transverse and longitudinal polarization allowing also the charge density to contribute.

Qualitatively one may distinguish different regimes of the nuclear response to photo absorption. At low energies below particle emission threshold, one finds sharp resonances corresponding to the excitation of bound excited nuclear states. Above particle emission threshold for photon energies of about 10 to 30 MeV the dominant feature is the giant dipole resonance. It is a collective nuclear mode which exhausts almost one classical TRK-sum rule. It can be described in a phenomenological two-fluid model as an oscillation of the proton against the neutron fluid or in a microscopic description as a coherent superposition of one-particle one-hole excitations. Increasing the energy, one enters the domain of short-range correlations or the so-called quasi-deuteron region, where the leading process is the absorption by a correlated two-nucleon pair emitted mainly back to back. Here, the major contributions come from MEC. Above pion production threshold, the dominant mode of absorption is the isobar excitation of a nucleon to a $\Delta$ or to higher nucleon resonances.

In electron scattering one can explore the same dynamical regions but with the additional possibility of independent variation of the momentum transfer. It allows, for example, in the elastic process “cum grano salis” the determination of ground state charge and magnetization densities.

3 Subnuclear Degrees of Freedom in Deuteron Break-up

Now I will turn to the discussion of subnuclear d.o.f. in deuteron disintegration by photons and electrons. These subnuclear d.o.f. are described in terms of meson exchange currents (MEC) and isobar configurations or currents (IC). The special role of the electromagnetic deuteron break-up is a consequence of
(a) the simple structure of the two-body system allowing exact solutions at least in the nonrelativistic domain, and (b) the specific features of the electromagnetic probe as discussed in the preceding section. The continued interest in this process has persisted over more than sixty years because the two-body system is in fact a unique laboratory, in particular for the study of subnuclear d.o.f.

One may summarize the evidence for MEC and IC in $\gamma(\gamma^*) + d \to p + n$ as follows:

(i) The strongest MEC contributions appear in $E1$ in $d(\gamma, N)N$, but they are mostly covered by the Siegert operator.

(ii) A clear signature of MEC is furthermore observed in $M1$ in $d(e, e'np)$ near break-up threshold at higher momentum transfers.

(iii) In the $\Delta$-region one finds a strong manifestation of IC.

3.1 MEC and relativistic effects in electrodisintegration

First, I will consider the inclusive process $d(e, e')pn$, where no analysis is made of the hadronic final state. The threshold region is dominated by the excitation of the antibound $^1S_0$ resonance in NN scattering at very low energies. It is the inverse process to thermal n-p radiative capture, which proceeds via $M1$ transition and where MEC and IC give about a 10 percent enhancement.
The advantage of electron scattering in having the momentum transfer at one's disposal becomes now apparent since the relatively small effect of subnuclear d.o.f. in the real photon process can be amplified considerably. The reason for this lies in the fact that with increasing momentum transfer the one-body contribution drops rapidly due to a destructive interference of S- and D-wave contributions and thus the distribution of the momentum transfer onto both nucleons via the two-body operators becomes more favourable. This can be seen in Fig. 1 where the transverse form factor is shown as obtained from the Rosenbluth separation. While the longitudinal form factor is well described by the classical theory supporting the Siegert hypothesis, that the charge density is little affected by exchange effects, one finds a large discrepancy in $F_T$ which is only resolved if MEC and IC are added.

The situation for higher momentum transfers is shown in Fig. 2 where the inclusive cross section is plotted at backward angles for moderate momentum transfers. One readily sees the strong enhancement due to MEC, but in addition one notes sizeable relativistic contributions. It is clear from this result that already at low excitation energies relativistic effects may become important and have to be considered in a quantitative comparison of theory with experiment. One has to keep in mind that relativistic contributions appear both in the current operators and in the wave functions. For the latter case one may distinguish between (i) the internal dynamics of the rest frame wave function and (ii) the boost operation transforming the rest frame wave function into a moving frame. It is obvious that for a conclusive interpretation one has to include all corrections of the same order consistently. In this work, presented in Fig. 2, where we have adopted a $(p/M)^2$-expansion starting from a covariant approach, all relativistic terms are included consistently.

Fig. 3: Inclusive cross section for $d(e,e')$ for PWBA and with FSI, MEC, IC, and RC (from §).

Fig. 4: Coincidence structure function $f_{LT}$ as function of the missing momentum without and with relativistic corrections (from §).
In Fig. 3 we show for higher energy and momentum transfer another comparison of experimental data for \( d(e,e') \) with a realistic calculation including FSI, MEC, IC and the dominant relativistic contributions (RC) and a comparison to the pure plane wave Born approximation (PWBA). One notes that the relativistic contributions improve considerably the agreement between theory and experiment. Furthermore, the comparison to the PWBA shows that off the quasi-free region interaction effects are important.

As last example of relativistic effects, I show in Fig. 4 the longitudinal-transverse interference structure function \( f_{LT} \) appearing in the exclusive process \( d(e,e'p)n \). The comparison with recent experimental data is significantly improved if relativistic contributions are included. The relative size of the RC is shown in the inset as ratio of nonrelativistic (nr) to relativistic (r) result.

3.2 Signature of a \( \Delta\Delta \) component in the deuteron

![Fig. 5: Contribution of the \( \Delta\Delta \) component to the longitudinal structure function \( f_L \)](image)

![Fig. 6: Longitudinal structure function in the \( \Delta \) region for \( E_{np} = 240 \) MeV and \( q^2 = 5 \) fm\(^2\) without (dashed) and with (full) \( \Delta\Delta \) component.](image)

One important consequence of the internal nucleon dynamics is the presence of small wave function components where one or more nucleons are internally excited into an isobar state. These isobar configurations (IC) are rather small and thus their presence is difficult to detect. In any case, evidence for them will only be indirect since they are not directly observable. However, under certain favourable conditions they may lead to sizeable effects. I would like to show one example for the double \( \Delta \)-component in the deuteron.

In view of the fact, that the charge excitation of a \( \Delta \) which has to proceed via \( C2 \) is largely suppressed, the only contribution of IC to the longitudinal structure function \( f_L \) comes from the double \( \Delta \)-component as sketched in the diagram of Fig. 5. At low momentum transfer, the contribution is negligible. However, with increasing momentum transfer its relative importance is
enhanced considerably because of the much shorter ranged structure of the isobar configurations compared to the normal ones. This behavior is shown in Fig. 6. It also illustrates nicely the advantage of varying the momentum transfer independently in electron scattering.

3.3 \( N\Delta \) dynamics in \( d(\gamma,p)n \) in a coupled channel approach

Deuteron photodisintegration is fairly well understood at low energies in the framework of nucleon, meson and isobar d.o.f.\(^{11}\) whereas at higher photon energies between 200 and 450 MeV, where the \( \Delta \)-excitation dominates the reaction, the theoretical description is much less well settled.\(^{2}\) Often the \( \Delta \)-excitation is treated in the impulse approximation (IA). It turns out, however, that it is important to include the \( N\Delta \) dynamics in a coupled channel approach.\(^{12,13}\) Here I will present an improved coupled \( NN-N\Delta \) channel approach which includes in addition explicit pion d.o.f.\(^{14}\). In this calculation, the dominant magnetic dipole excitation of the \( \Delta \) has been fitted to the experimental \( M_{1+}(3/2) \) multipole of pion photoproduction on the nucleon. Details can be found in Ref.\(^{14}\).

I first show in Fig. 7 the total cross section for \( \gamma d \rightarrow pn \) in comparison with experiment. Complete calculation (full), IA (dotted) and complete calculation with modified \( \gamma N\Delta \)-coupling (dashed) as described in the text (from Ref.\(^{14}\)).

![Fig. 7: Total cross section for \( \gamma d \rightarrow pn \) in comparison with experiment. Complete calculation (full), IA (dotted) and complete calculation with modified \( \gamma N\Delta \)-coupling (dashed) as described in the text (from Ref.\(^{14}\)).](image-url)
7. Since in this case the Born terms are effectively incorporated in the modified coupling we are led to the conclusion that the framework of static $\pi$-exchange currents, containing in principle the Born terms, gives a poor description of them in this energy region.

Differential cross sections and photon asymmetries for three energies are shown in Fig. 8. In addition to the IA and the complete calculation with modified $\gamma N\Delta$-coupling, we show results where the $\gamma N\Delta$-coupling has been modified in the M1 multipole only. Despite the good description of the total cross section, problems in the angular distributions still remain. At the lower energy our calculation does not show such a strong decrease at the backward angles as the data. Furthermore, a dip around $90^\circ$ appears, in particular at the highest energy, which clearly contradicts the experimental shape. The occurrence of this dip structure is also reported in [13]. The photon asymmetry in Fig. 8 is quite satisfactory although at the higher energies it appears to be more asymmetrical around $90^\circ$ than the experiment. At even higher energies this trend continues so that the model clearly fails to reproduce the data.

### 3.4 Unitary ambiguity in the resonance multipoles for $\gamma + N \rightarrow \Delta$

From the foregoing it is clear that for a reliable description of $\Delta$ excitation in nuclei one needs to know their multipoles fairly well. Consequently, there
is considerable experimental effort in measuring the corresponding $E_{1+}$ and $M_{1+}$ isospin 3/2 multipole amplitudes for photoproduction of pions on the nucleon. However, all realistic pion photoproduction models show that both multipoles, in particular $E_{3/2}^{1+}$, contain nonnegligible nonresonant background contributions. Unfortunately, their presence complicates the isolation of the resonant parts. Basically two different approaches are used in order to extract these transition amplitudes. The first one is an effective lagrangian approach, in which the $\pi N$ scattering is not treated dynamically and thus different unitarization schemes are used. These introduce some model dependence.

Fig. 9: Real and imaginary parts of the $M_{3/2}^{1+}$ multipole as function of the photon laboratory energy $E_\gamma$. Dashed, dotted and dash-dotted curves are bare multipoles corresponding to transformation angles $\tilde{\alpha} = 0^\circ$, $10^\circ$ and $-10^\circ$, respectively. The solid curves show the total multipoles which are representation independent (from 15).

In the second approach, the $\pi N$ interaction is treated dynamically and thus unitarity is respected automatically. However, also the latter approach contains considerable model dependence of the resonance properties because of an inherent unitary ambiguity. The reason for this unitary freedom is that the separation of a resonant $\Delta$ contribution corresponds to the introduction of a $\Delta$ component into the $\pi N$ scattering state which vanishes in the asymptotic region. It is known that the explicit form of a wave function depends on the chosen representation, and can be changed by means of unitary transformations. Consequently, the probability of a certain wave function component is not an observable, since it depends on the representation, whereas any observable is not affected by a change of the representation. We have demonstrated this fact in a simple model where the unitary transformation mixes resonant and background $\pi N$ interactions 15. I show in Fig. 9 the effect of such unitary transformations (governed by a parameter $\tilde{\alpha}$) on the $M_{3/2}^{1+}$ multipole. One notices a considerable variation of the bare resonance multipole with $\tilde{\alpha}$ while the total one is unchanged.
With this I would like to close the brief review in which I could give only
a very cursory survey on the many interesting facets of present day research in
current electromagnetic physics programs at various c.w. electron machines.

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