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Abstract. The development of theoretical photonuclear physics over the last 40 years is illustrated by a few selected examples highlighting a number of important issues like collective motion in nuclei, the role of subnuclear degrees of freedom, relativity and meson production.

1. Introduction

In this talk, which I dedicate to the memory of Michael Danos, I would like to give a brief overview on a number of important issues in the field of photonuclear physics which have deepend considerably our understanding of nuclear structure over the past 40 years. It is not possible to give here a comprehensive review, and I had to make a selection which is governed by the scientific work of Danos, who has made many important contributions to nuclear photoreactions, and also by my own research interests. A very good representation of benchmark papers in this field may be found in \cite{1}. Let me remind you that in nuclear physics the electromagnetic probe has always been a very important tool. This is illustrated by a few highlights from the early development of nuclear physics:

- 1909: Coulomb scattering of $\alpha$-particles from a gold foil by Geiger and Marsden \cite{2} from which Rutherford concluded in 1911 that most of the mass of an atom is concentrated in a tiny, almost pointlike nucleus in its center \cite{3}.
- 1934: Photodisintegration of the deuteron by Chadwick and Goldhaber \cite{4} marks the beginning of photonuclear physics.
- 1947: Discovery of the giant dipole resonance by Baldwin and Klaiber \cite{5} as a collective phenomenon almost exhausting the Thomas-Reiche-Kuhn dipole sum rule completely.
2. The dynamic collective model of the giant resonances

The collective phenomenon of the giant dipole resonance (GDR) can well be explained in the framework of the hydrodynamical model of Steinwedel and Jensen as an oscillation of a proton fluid against a neutron fluid. In particular, the dependence of the position of the GDR on the mass number is governed by the fact that for a spherical nucleus the eigenfrequency is proportional to the nuclear radius. It was the important observation of Danos (and independently of Okamoto) that for an axially symmetric deformed nucleus the GDR will be split into two peaks corresponding to oscillations along and perpendicular to the symmetry axis.\cite{8}

In view of the additional collective surface degrees of freedom, Danos and Greiner\cite{9} developed in 1964 a unified dynamic collective model of the giant resonances (DCM) which includes in particular the coupling between the rotation-vibration and the giant resonance d.o.f. leading to additional dynamic effects. A comparison between the predictions for the total $\gamma$-absorption cross section and experimental data is shown in Fig.\,1 for $^{165}$Ho including the giant quadrupole resonance contributions. The very good agreement is evident.

![Fig. 1. E1 and E2 photoabsorption cross section for $^{165}$Ho (from \cite{10}). Experimental data from \cite{11}.](image)

An important consequence of this dynamic coupling is the considerably strong dipole transition strength from the GDR states to the low lying rotational and vibrational states leading to sizeable Raman scalar and tensor scattering into these states (see Fig.\,2, left panel) as experimentally observed by Fuller and Hayward\cite{1}. Another interesting feature of the DCM is the fact that a deformed nucleus with a nonvanishing ground state spin...
becomes optically anisotropic (nonvanishing tensor polarization) and thus its absorption and scattering cross sections depend on the nuclear orientation. This is shown in the right panel of Fig. 2 for $^{165}$Ho with spin $I = 7/2$. A review may be found in [12]. Subsequently,

**Fig. 2.** Left panel: Calculated elastic and inelastic photon scattering cross sections at $140^\circ$ for $^{166}$Er (from [13]). Right panel: Elastic photon scattering cross sections for $^{165}$Ho (from [14]): unoriented target: solid curve, aligned target: (a) perpendicular to scattering plane: dashed curve, (b) parallel to scattering plane and perpendicular to incoming beam: dash-dot curve.

**Fig. 3.** Dipole strengths and photon absorption cross sections, low energy spectra and potential energy surfaces for an axially symmetric prolate (A), oblate (B), and triaxially deformed nucleus (from [15]).
the DCM was further developed in order to describe a much more general class of potential energy surfaces for the low energy collective d.o.f. allowing a unified description of the GDR for nuclei with quite different collective characteristics \cite{16}. An example is shown in Fig. 3.

3. Subnuclear degrees of freedom

In his 1961-Lectures Danos had already alluded to the possibility that a nucleon, in view of its extended internal structure, could be slightly deformed in a nuclear medium. Indeed, at the end of the 60s several groups, including Danos, H.T. Williams and myself, were developing a phenomenological model of such modifications by admixing into the nuclear wave function configurations, where one or several nucleons are internally excited, say as a $\Delta(1232)$-resonance \cite{17}. Such wave function components have been coined "nuclear isobar configurations" (IC). Reviews may be found in \cite{18,19}. The characteristic features of these IC is that they possess small probabilities and a short range structure. Examples are shown in Fig. 4.

![Fig. 4. Left panel: Normal and $\Delta\Delta$-component of the deuteron ($P_{\Delta\Delta} = 97\%$) (from \cite{20}). Right panel: Relative two-particle wave functions of IC in $^4$He (from \cite{21}).](image)

These subnuclear d.o.f., as manifest in isobar admixtures in nuclear wave functions,
contribute also to the e.m. interaction. Alternatively, their contribution may be described by effective two-body exchange currents involving IC as shown diagrammatically in the left panel of Fig. 5 together with similar current contributions (MEC) from meson d.o.f. mediating the strong interaction, shown in the right panel for $\pi$-exchange. The largest MEC effects are found in $E1$-transitions which, however, are largely covered by the Siegert operator [22]. Particularly strong MEC contributions to $M1$ are found in deuteron electrodisintegration near threshold, for which I show the inclusive cross section in Fig. 6. One readily notices the sizeable increase of the cross section by MEC and IC, particularly dominant at higher momentum transfers (see also [23, 24]).

**Fig. 6.** Left panel: Inclusive cross section for $d(e, e')$ as function of energy $E_{np}$ (from [25]); Right Panel: Inclusive cross section for $d(e, e')$, averaged over $E_{np} = 0 - 3$ MeV, as function of momentum transfer $q^2$ (from [23]).

As last example for the importance of subnuclear d.o.f. I show in Fig. 7 differential cross sections of deuteron photodisintegration in the $\Delta$-resonance region, where $\Delta$-d.o.f. dominate. For a long time, the most sophisticated theoretical approaches were unable to describe properly the experimental date in this energy region. Only recently, a careful analysis has shown, that a proper treatment of meson retardation is absolutely necessary for a satisfactory description of experimental data [27].

### 4. Relativistic effects in the GDH sum rule

The Gerasimov-Drell-Hearn sum rule (1965/66) links a ground state property, the anomalous magnetic moment, to the energy weighted integral from threshold up to infinity over the spin asymmetry $\sigma^P(k) - \sigma^A(k)$, the difference of the total photoabsorption cross sections for circularly polarized photons on a target with spin parallel and antiparallel to the
spin of the photon, i.e.

$$
\int_0^{\infty} \frac{dk}{k} \left( \sigma^p(k) - \sigma^A(k) \right) = 4\pi^2 \kappa^2 \frac{e^2}{M_t^2} I,
$$

where $I$ denotes the spin of the particle, $M_t$ its mass, and $\kappa$ its anomalous magnetic moment, defined by the total magnetic moment $\vec{M} = (Q + \kappa) \frac{e}{M_t} \vec{S}$, with $e$ as its charge and $\vec{S}$ its spin operator. An important consequence is, that a particle has to possess an internal structure if $\kappa \neq 0$.

Here I will consider the GDH sum rule and in particular the spin asymmetry for the deuteron [28] in order to illustrate the fact, that even at low energies relativistic effects can become quite important in certain polarization observables. Application of the GDH sum rule to the deuteron reveals a very interesting feature. On the one hand, one expects a very small anomalous magnetic moment for the deuteron, because the deuteron has isospin zero ruling out the contribution of the large nucleon isovector anomalous magnetic moments to the deuteron magnetic moment. In fact, the experimental value is $\kappa_d = -0.143$ resulting in a GDH prediction of $I^{GDH}_d = 0.65 \mu b$, which is more than two orders of magnitude smaller than the nucleon values. On the other hand, one has the following absorptive processes: (i) photodisintegration $\gamma + d \rightarrow n + p$, (ii) single pion production (coherent: $\gamma + d \rightarrow d + \pi^0$, and incoherent: $\gamma + d \rightarrow N + N + \pi$), (iii) two pion production etc. The processes (ii) and (iii) are dominated by quasifree production and, therefore, one may estimate from them a positive GDH contribution of the order of the sum of proton and neutron, namely $I^{GDH}_p(\infty) + I^{GDH}_n(\infty) = 438 \mu b$. In order to obtain the small total deuteron GDH value one, therefore, needs a large negative contribution of about the same size for cancellation.

Indeed, from the photodisintegration channel, which is the only photoabsorption process below the pion production threshold, a sizeable negative contribution arises at very low energies near threshold from the $M1$-transition to the resonant $^1S_0$ state, because this state can only be reached if the spins of photon and deuteron are antiparallel, and is forbidden for the parallel situation. The photodisintegration channel has been evaluated within a non-relativistic framework but with inclusion of the most important relativistic contributions.
5. Eta photoproduction on the deuteron

Finally, I will briefly consider photoproductions of mesons on the deuteron. Meson photoproduction is the primary absorptive process on the nucleon and the interest of meson production on nuclei arises from the possibilities (i) to study the elementary neutron amplitude, (ii) to study the meson-nucleon interaction, (iii) to study medium effects, and (iv) to study nuclear structure.

As an example of recent interest, I will present some very new results on incoherent
Fig. 9. Total cross section for the reaction $\gamma d \rightarrow \eta np$. Notation of the curves: dotted: impulse approximation (IA), dashed: inclusion of first-order $\eta N$- and $NN$-rescattering, solid: full three-body calculation. The results obtained within the three-body approach with different sets of $\eta NN^\ast$ and $\pi NN^\ast$ couplings are presented as the solid curves “1” and “2”. The inclusive $\gamma d \rightarrow \eta X$ data are taken from Metag et al. (in preparation).

$\eta$-meson production on deuterium near threshold. It turns out that the simple impulse approximation fails badly to describe the experimental data. This is seen very clearly in Fig. 9 where the total cross section is shown. The strong enhancement by final state interaction (FSI) is most evident. In fact, it is so strong that the first order rescattering contribution underestimates FSI considerably close to threshold, thus making a three-body calculation necessary which leads to a much improved description, although not completely satisfactory.

Fig. 10. The $\eta$-meson spectrum for the reaction $\gamma d \rightarrow \eta np$ versus the total $\eta$ c.m. energy $\omega_\eta$ for two lab photon energies. Notation of the curves as in Fig. 9.
But in this calculation, FSI has been included in S-waves only. A more detailed test would be provided by a measurement of the meson spectrum shown in Fig. 10 which exhibits very clearly the signature of the virtual $^1S_0$-resonance of $NN$-scattering near threshold.

6. Concluding remarks

These examples should suffice for illustrating that the field of photo- and electronuclear physics has seen quite an impressive development both in breadth and depth over the past 40 years. This was made largely possible by the advent of new experimental tools and techniques and in theory by new ideas and the extraordinary progress in computing power. As a result, we have gained much deeper insights into the structure of hadrons, but still quite a few problems remain unresolved, in particular in the high energy regime, where a transition to quark-gluon dynamics is expected.

At present, the main research in this field is focused on the following topics:

- short range structure of nuclei, in particular, the nature of 2-body correlations,
- the size of relativistic effects in nuclear wave functions and operators,
- the role of subnuclear d.o.f. in terms of nuclear IC and meson exchange operators and their relation to the underlying quark-gluon d.o.f. of QCD,
- study of polarization observables,
- meson production on light nuclei.

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