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The Atomic Nucleus and the Short Range Structure of Nuclear Matter

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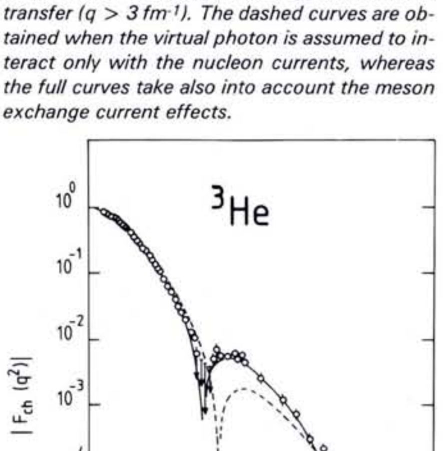
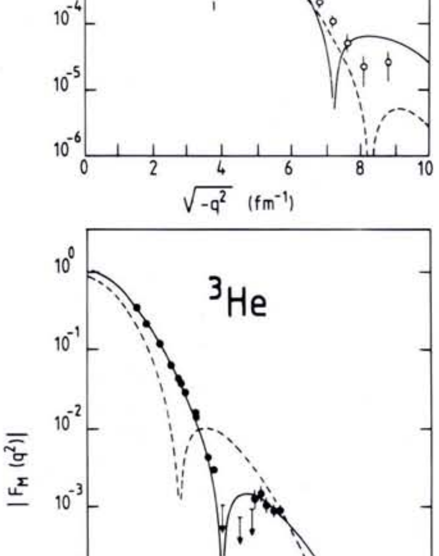
Fig. 1 — The charge and the magnetic form factors of ^3He are plotted against the momentum of the virtual photon. The charge form factor was measured at Stanford and the magnetic form factor at MIT for low momentum transfer ($q < 3\ fm^{-1}$) and at Saclay for high momentum transfer ($q > 3\ fm^{-1}$). The dashed curves are obtained when the virtual photon is assumed to interact only with the nucleon currents, whereas the full curves take also into account the meson exchange current effects.





Over more than half a century, the complementary use of electromagnetic and hadronic probes has led us to a very accurate description of the atomic nucleus. Studies of the systematics of nuclear masses revealed a greater stability when the nucleon number approached given values — the magic numbers — and this gave rise to the shell model, in which nucleons fill shells of well defined energies. When one is complete, the interaction between the nucleons is strongest and the nucleus is more stable. At the same time, the scattering of nuclear fragments (nucleons, deuterons, helium, nuclei, etc.) by nuclei indicated another degree of freedom: the collective states. While, in the shell model, each nucleon is moving independently in a mean effective potential created by its neighbours, nuclear states, where all the nucleons are moving coherently, also exist. The nucleus can be permanently deformed, or its surface can oscillate around a spherical equilibrium shape.

More complex models have been constructed to reconcile these two extreme pictures and to explain the richness of nuclear spectra revealed by the reactions induced by nuclear fragments. However, definitive tests can only be made by comparing their predictions with the electromagnetic properties of nuclei, as the interaction between a nuclear fragment and a nucleus is basically the same as the force which binds together the nucleons: the reaction mechanism and the nuclear structure effects are strongly interconnected.

In contrast, the electromagnetic interaction is very well known and weak enough to be treated as a small perturbation, although, because the cross sections are small, the corresponding experiments are time-consuming.

A systematic study of the electromagnetic properties of nuclei became possible only with the advent of high energy and high intensity modern electron accelerators which provided electromagnetic radiation of smaller and smaller wave length. Now, charge and magnetisation densities as well as the transition charge densities of nuclei have been accurately determined, and we have gained a precise knowledge of the nuclear shape and of the motion of each nucleon inside the nucleus. This has brought us to the frontier between nuclear physics and elementary particle physics, as the nucleons can no longer be regarded as inert, but objects with an internal structure.

Nucleon-Nucleon Interaction

At large distances ($r > 1$ fm), the interaction between two nucleons is well described by the exchange of the lightest meson (the pion), and at intermediate distances ($0.5 < r < 1$ fm) by the exchange of two correlated pions, whose total charge is zero. At shorter distances ($r < 0.5$ fm) the exchange of heavier mesons (ρ and ω) also plays a role and at very short distances (r ~

Contents

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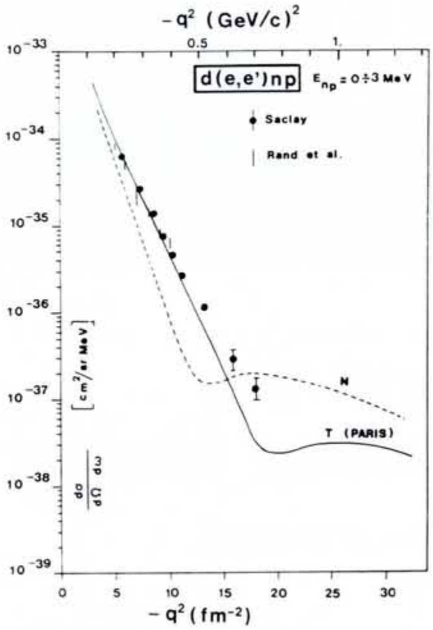

Fig. 2 — The cross section of the deuteron electrodisintegration at backward angle is plotted against the square of the momentum of the virtual photon as recently measured at Saclay. The dashed curve is obtained when the virtual photon is assumed to interact only with the nucleon current, whereas the full curve takes also into account the meson exchange current effects.

0.1 fm) the internal structure of the nucleons becomes important. While nucleon-nucleon interactions at long and intermediate range are now reasonably well understood, the study of short range interactions is still a field of active research.

Elastic scattering of electrons of few body systems has made it possible to "see" those mesons which are travelling between nucleons and which ensure the binding of nuclei, because an electron passing close to a nucleus exchanges a virtual photon with any of the constituents with a finite charge or magnetic moment. In Fig. 1 the charge and magnetic form factors, which are nothing but the Fourier transform of the corresponding spatial distributions, are plotted against the momentum of the exchanged virtual photon ($q = 2E \sin \theta/2$, where E is the energy of the incoming electron and θ the scattering angle) for ^{3}He.

When the virtual photon is assumed to interact only with the nucleon currents, it is impossible to reproduce correctly the experimental data. This is really significant, since we know how to solve numerically the three-body problem starting with the actual two-body interaction, and predict the effects of its short range part on the three nucleon form factors. An example is the minimum near $q = 3$ fm^{-1} which is a direct consequence of the strong repulsion between two nucleons below 0.5 fm.

Good agreement with experiment is, however, achieved when the coupling of the virtual photon to the mesons is also taken into account — not with the two correlated pions responsible for the intermediate range part of the nucleon-nucleon interaction (which are not seen by the virtual photon as their total charge is zero), but the currents associated with the exchange of a single charged meson (pion or ρ). These currents ensure the binding of the nucleus and are called the "meson exchange currents".

Meson Exchange Currents

Meson exchange currents appear also in other reactions, and a main part of the research programme at modern electron accelerators has been, and still is devoted to their systematic study.

The most striking example is the electrodisintegration of the deuteron just above threshold:

$$e + d \rightarrow e' + p + n.$$

The deuteron is broken up, but the transferred energy is small enough (of the order of 3 MeV) to prevent the emitted nucleons going too far away from each other. For a fixed electron scattering angle, the momentum of the virtual photon increases (its wave length decreases) as the energy of the incoming electron increases. The experimental points with $\theta = 155°$ are shown in Fig. 2. Here again a fair agreement with theory is only possible when the contribution due to the meson exchange currents is also considered.

The same is true in reactions induced by real photons as in deuteron photodisintegration ($\gamma + d \rightarrow p + n$) the cross section of which is plotted in Fig. 3 against the incoming photon energy. The value reaches a second maximum when the photon energy rises towards 300 MeV; it is here that two new phenomena appear.

Creation of Real Pions

First, real pions are created when the photon energy exceeds their rest mass ($m_\pi = 140$ MeV). Virtual pions, which were confined in the deuteron at lower energies, receive enough energy to become real and can escape: they no longer ensure the coherence of the nucleus which breaks up when the pion is emitted. This channel dominates the cross section in this energy range.

Second, when the energy is close to 300 MeV, the photon transforms the nucleon into its first excited state. The nucleon is not an inert object, but like the nucleus has a spectrum of excited states. However, the energy scale is not the same. While the spacing between the nuclear levels is of the order of a few MeV, the levels of the nucleon are separated by a few hundred MeV. The first is called the Δ resonance, and its mass is some 300 MeV larger than the nucleon mass. It is unstable and soon decays to the ground state by emitting a pion. Its very short lifetime (10^{-23} s) prevents our knowing the mass accurately, the width of about 100 MeV being a direct consequence of the uncertainty principle. This resonance is responsible for the bump which dominates the pion photoproduction reactions and which appears near 300 MeV in Fig. 3. Pions which are emitted when the resonance decays can also, of course, be re-absorbed by the other nucleon in the deuteron, but this channel represents only 5 - 10% of the total cross section near 300 MeV even though it dominates below the pion emission threshold.

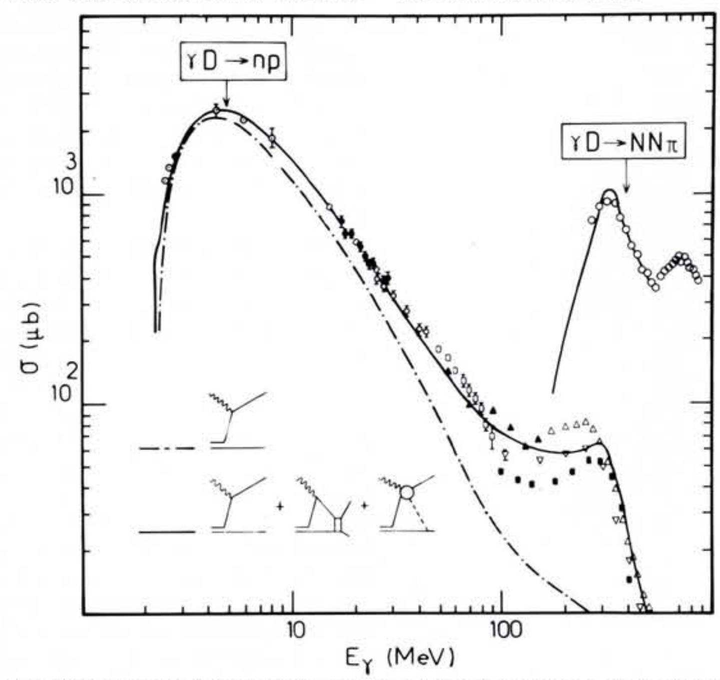

Fig. 3 — The deuteron total photoabsorption cross section is plotted against the energy of the incoming photon. Below the pion production threshold ($E_\gamma = 140$ MeV), it is dominated by the two-body photodisintegration channel. The dashed curve does not take into account the meson exchange current effects which are included in the full curve. Above threshold, the pion photoproduction channels dominate the cross section. The bump which appears around $E_\gamma = 300$ MeV is due to the creation of the Δ resonance.

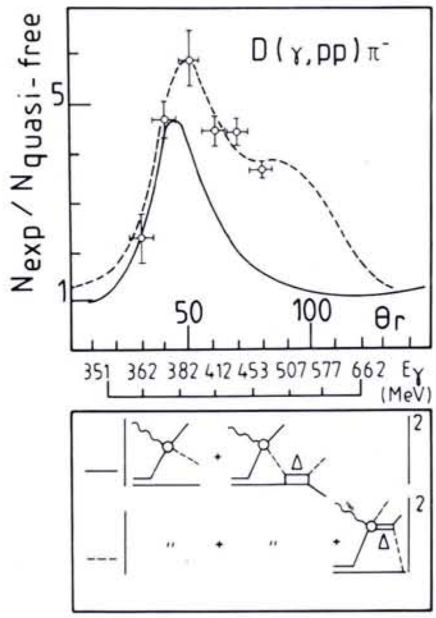

Fig. 4 — Pion reproduction: the angular distribution of the proton which is emitted with a constant momentum (p = 400 MeV/c) is plotted against its angle θ_R (or against the energy of the incoming photon). The experimental cross section has been normalized to the theoretical cross section which would have been obtained if one of the two nucleons were a mere spectator (quasi-free pion photoproduction mechanism). The full line takes into account the pion rescattering mechanisms. The dashed line takes also into account the photoproduction of two pions, one of which is reabsorbed by the other nucleon. This experiment was performed at Saclay.

Propagation of the Δ Resonance in the Nucleus

Particular attention has been devoted, during the past ten years, to the creation and propagation of this Δ resonance in the nucleus. The excited states of the nucleon are unstable particles, and it is as important to study their mutual interaction as to understand the two-nucleon interaction, which is, in fact, a special case of a more general problem.

The difficulty lies in its short-life. It is impossible to produce a beam as the Δ will travel only a distance of 1 fm before decaying. This is precisely the mean distance between two nucleons in the nucleus, and the only way to study its interaction with the nucleon is to create it inside a nucleus, and to look at the final state interactions.

In principle any probe may be used provided the transferred energy is high enough, but with nuclear fragments, or even pion beams, it would hardly be possible to disentangle the creation from the propagation mechanism, since their nature is basically the same. Again, the electromagnetic probe is the cleanest.

A good example from the systematic studies performed at Saclay is the reaction:

$$\gamma + d \rightarrow \Delta + p \rightarrow (p + \pi) + p,$$

where the created Δ decays into a correlated pion-nucleon pair.

The two mechanisms, which dominate the interaction between a nucleon and the Δ resonance, appear clearly in Fig. 4. In the first, a high energy pion, emitted at one nucleon, creates another Δ resonance from the second nucleon. This interaction looks very much like a two-nucleon interaction in which a virtual pion is exchanged. The only difference is that this pion can now be real, since the available energy is larger than the pion creation threshold. The contribution of this mechanism to the cross section is highest when the probability of exchanging a real pion is highest and it is therefore possible to enhance it by carefully selecting the kinematical conditions of the experiment. This accounts for the violent variation of the cross section in Fig. 4. In the second mechanism, a pion is created at the same time as a Δ resonance which subsequently decays by emitting another pion which is re-absorbed by the second nucleon.

An unstable particle can thus keep its identity and elastically scatter on a nucleon, but it can also loose it, in which case it is possible to observe the transition between this nucleon-resonance system and the two-nucleon system. As a result, the treatment of the interaction between the Δ and the nucleon is much more complicated than for two nucleons at lower energies. It is absolutely necessary to take into account the coupling between the two corresponding channels: this is a complex problem which is still a field of active research and needs a systematic experimental study. However we are now near the limits of the capabilities of modern electron accelerators, and we must ask ourselves what we shall learn by studying nuclear systems at shorter distances. As a guide, we have the progress made in our understanding of the internal structure of the nucleon.

Quarks Inside the Nucleus

We have just seen that the nucleon is not a rigid body, but has several excited states, the first of which, the Δ resonance, is really the analogue of a collective nuclear state. Before being emitted, when the Δ decays, the pion may interact many times with the nucleon and remain in its neighbourhood during a time which is considerably larger than the time necessary to cross the nucleon volume. In a nucleus, all the nucleons may oscillate as a whole and can be compared to the oscillations of such a nucleon and the pion cloud which surrounds it.

This analogy between the structure of the nucleon and the nucleus can be pushed farther. The particles, which we used to call elementary, are made of quarks as the nuclei are made of nucleons. The difference is that it is impossible to see free quarks: the energy, which is necessary to extract them from the nucleon, is larger than the mass of the lightest mesons, which they prefer to create rather than escape. This difference comes from the fact that the corresponding interaction increases with the distance, contrary to the two-nucleon interaction which decreases quickly. Quarks are therefore confined in the nucleon volume, but they move independently when they are very close to each other.

It is precisely this property which has made it possible to "see" them with an electromagnetic probe. Deep inelastic scattering of 20 GeV electrons at the Stanford Linear Accelerator Center (SLAC) has shown that they interact as point-like and independent objects with a non-integer electric charge. They have also been a very powerful tool in understanding and analysing the reactions induced between two hadrons at high energy and high momentum transfer, where it has been possible to treat the relatively weak quark-quark interactions as a first order perturbation through Quantum Chromo-Dynamics (QCD) which, at short distances, looks very much like Quantum Electro-Dynamics (QED).

At lower energies, this treatment is no longer possible, as the interaction becomes too strong. It has therefore been necessary to build phenomenological models in order to take into account quark confinement — the bag models, where it is assumed that the elementary constituents (three quarks for a nucleon and two quarks for a meson) are trapped inside an impermeable cavity, whose volume is close to the volume of the particle which is described. This is a brute approach to the problem of confinement, which takes into account the fact that a free quark has never been seen, but which leads to other problems: more particularly, the coupling between the pion and the nucleon.

However, pion exchange mechanisms dominate the low energy and low momentum transfer reactions between elementary particles. The pion-nucleon coupling is very strong and cannot be treated in a perturbative way. But the smallness of the pion mass (one seventh of the nucleon mass) makes it possible to use a conservation law, which appears to impose a strong constraint on the dynamics of low energy reactions: the conservation of the Axial Current. It is coupled to the pion field in the same way the Electromagnetic Current is coupled to the photon field. As in Quantum Electrodynamics where the Electromagnetic Current is conserved because the mass of the photon (the carrier of the force) is zero, in a theory of strong interactions, where the mass of the pion (the carrier of the long range part of the force) would vanish, the Axial Current would also be conserved. As the mass of the pion is, in practice, finite, this conservation law is only partially obeyed, but its smallness makes it possible to treat in a quantitative way the corresponding deviations.

The constraints have led to improvements of the original bag model: the Axial Current is assumed to be carried by the pion outside the bag, by the quarks inside, and is continuous across the bag surface. This provides a solution to the problem of the pion-nucleon coupling, but the bag radius is still a parameter of the model which is chosen in an *ad-hoc* way. Moreover, the picture (pions outside and quarks inside the bag) seems to be artificial. An elegant solution to the problem of quark confinement has still to be found, and this is why much effort is devoted to its study.

To summarize: we know how to deal with mechanisms which occur at high energies (in the framework of Quantum Chromo-Dynamics) and those which involve low energies (by using the constraint due to the Partially Conserved Axial Current). But the "Gordian knot" is still the problem of quark confinement. It is very unlikely that a systematic study of the mutual interactions between free elementary particles alone will solve this complex problem and it is here that nuclear physics, which is the study of bound systems of particles, appears as an invaluable tool.

The short range interaction of two nucleons is strongly linked to their internal structure, as the quarks of each nucleon can interact directly. The study of high energy nucleon-nucleon scattering leads, of course, to strong constraints, but they are partial. If two nuclear fragments (made of several bound nucleons) are smashed together, the dynamical domain is considerably enlarged, since it is now possible to observe mechanisms which are strictly forbidden by the kinematics of a free nucleon-nucleon collision. This is the idea behind the study of reactions induced by relativistic ions, which is another field of active research. Nevertheless, while it is expected to lead to strong constraints on the quark confinement problem, it suffers from the same disadvantage as all reactions induced by nuclear fragments: it is not possible to disentangle the reaction mechanisms from those responsible for binding.

The alternative is to look at the atomic nucleus itself. This is an assembly of nucleons which are bound in a very small volume with interactions very different from those between two free nucleons. The most straightforward way of "seeing" how nucleons interact at shorter and shorter distances, and in kinematical conditions which are very different from those allowed to free nucleons, is to probe nuclear systems with electron beams of higher and higher energies.

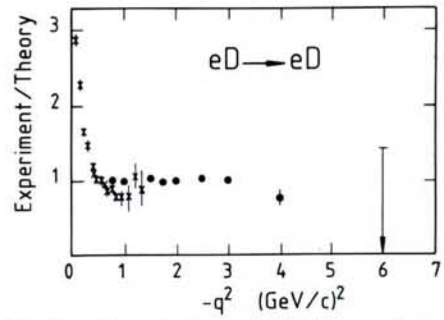

Fig. 5 — The ratio between the deuteron form factor and the prediction of the model in which the virtual photon (see Fig. 1) is assumed to interact directly with the quarks, is plotted against the square of the transferred momentum. Below 1 $(\mathrm{GeV}/c)^2$ the measurement was performed at Orsay, above 1 $(\mathrm{GeV}/c)^2$, at Stanford.

Pioneering experiments have already been performed at Stanford. As an example, Fig. 5 summarizes the analysis of the cross section of elastic electron scattering on deuterons when it is assumed that the exchanged virtual photon interacts directly with the quarks. Above $q \geq 1$ GeV/c, the ratio of experiment to theory is good.

Furthermore, nuclear systems provide us with the only way of studying complex multiquark states, in which more than three quarks are confined in the same volume. Their symmetries are different from those of normal nuclear states, which can be viewed as a collection of nucleons in which just three quarks are confined. Multiquark states might appear as small components in the nuclear wave functions, or as nuclear resonances. Their discovery and the study of their electromagnetic properties would certainly lead to strong constraints on the quark confinement problem.

Conclusions

The study of the short range properties of nuclear systems is today a field of active study. Nuclear physics has reached a frontier where it is still not possible to neglect "molecular effects", in which nucleons keep their identify and exchange mesons, yet it is already necessary to take into account their internal degrees of freedom. Experiments are now at the limit of the possibilities of modern electron accelerators, and we look forward to the new generation of machines, projects for which exist already in Europe and around the world.

The present high energy electron accelerators have made it possible to reveal that quarks are moving freely in a nucleus when their distance does not exceed 0.1 fm. Intermediate energy accelerators such as the 700 MeV at Saclay have revealed that nucleons exchange mesons when their distance is larger than 1 fm. The new generation of accelerators whose energy should lie between 2 and 4 GeV and with intensity high enough to allow the measurement of very small cross sections should allow us to build the bridge between these two extreme limits of nuclear matter.