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THE NEW FRONTIERS OF ELECTRON SCATTERING AT INTERMEDIATE ENERGY

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Recent advances in experimental techniques have produced a new generation of electron scattering data. This paper explores the frontiers of this field and shows how our prospects for the future may be modified. Nuclear structure has been determined with an unprecedented accuracy defining clearly the limits of the most advanced theoretical descriptions. Large meson exchange currents are measured quantitatively with precision. Recent data on the electrodisintegration of deuterium at threshold and on the magnetic form factor of ^{3}He and tritium show that the pionic exchange current is well understood. There is no satisfactory theoretical description of shorter range processes.

1. INTRODUCTION

Nuclear physics is now in a period of profound change. For a long time it was thought of as a field of low energy processes where only nucleonic degrees of freedom should play a role. We now realize that this is not true. We are faced with the impossibility of explaining even static properties of the few nucleon systems in a description limited to nucleons. Whenever we try to interpret nuclear data quantitatively we stumble on the lack of knowledge of the short range part of the nucleon-nucleon interaction.

The central question is then : "What are the relevant degrees of freedom needed for nuclear theory?"

The nucleon and meson picture is difficult to carry very far. The strong couplings involved make the calculations unreliable. One never knows for sure when to stop in a diagrammatic expansion. Even more troublesome is the problem of determining the coupling constants and the form factors needed at each vertex. Today, with the present knowledge of quantum chromodynamics, it is not possible to believe in the validity of heavy meson exchanges between two nucleons. How could the substructure of two nucleons remain intact when they overlap almost completely in a ρ-meson exchange.

A different theoretical approach must therefore be found...

At present one of the most active areas in theory is to try to link the quark and gluon description to the classical nucleon and meson picture. In this framework Isgur and Llewellyn Smith[1] have calculated recently the proton and the pion form factors. By determining with quark model wave functions the possible range of asymptotic normalizations, they conclude that the perturbative QCD limit is not reached even at very high Q^2. The perturbative QCD regime is relegated in the "asymptopia" of infinite Q^2. Such a result does not necessarily imply that one cannot observe perturbative effects in deuterium or in heavier nuclei. These effects could be factorized out for some kinematical conditions. But it means that the whole description of nuclear processes does not reach a perturbative QCD regime even at very large Q^2. The nuclear medium has still very distinctive features although it has rarely been envisaged as such by particle physicists. This makes the understanding of quark dynamics in a nuclear medium of very special interest. It is one of the most unexpected by-products of the discovery of the EMC effect described in the two previous talks : particle physicists are discovering that a nucleus is not just a collection of nucleon targets moving with a Fermi motion. The main difficulty is that we do not know how to describe nuclear dynamics at the quark level. This is one of the most exciting challenges of the future.

In order to build this new description of nuclear physics, it is imperative to understand at a quantitative level the present limits of our knowledge. For this task, electromagnetic data are the most accurate source of present information. The experimental results are directly interpretable in the framework of a genuine theory (QED), where theoretical hypotheses are well controlled by gauge invariance, i.e. conservation of charge and current. Ten years ago the experimental investigations were limited to a very small domain of the nuclear response function $R(Q^2,\nu)$ shown in Figure 1. Today this situation is completely changed. A systematic program of electron scattering experiments at intermediate energy, a few experiments at very high Q^2, and very deep inelastic muon scattering have considerably expanded our knowledge of $R(Q^2,\nu)$. Since the last conference held at Versailles in 1981, technical efforts have produced very exciting results, clarifying some existing problems and raising new questions.

This talk will explore the new advances of this field.

2. THE NUCLEAR MEDIUM

2.1. Deep inelastic scattering, y-scaling and the nucleon radius

A striking difference is observed between elastic scattering from a proton and quasi-elastic scattering from a nucleon in a nucleus. This difference is primarily due to the Fermi motion which causes Doppler broadening. However, there are much more interesting effects related to the behavior of a nucleon in the nuclear medium. At very high momentum transfers the nuclear response function $R(Q^2,\nu)$ does not depend on the momentum transfer and the energy loss

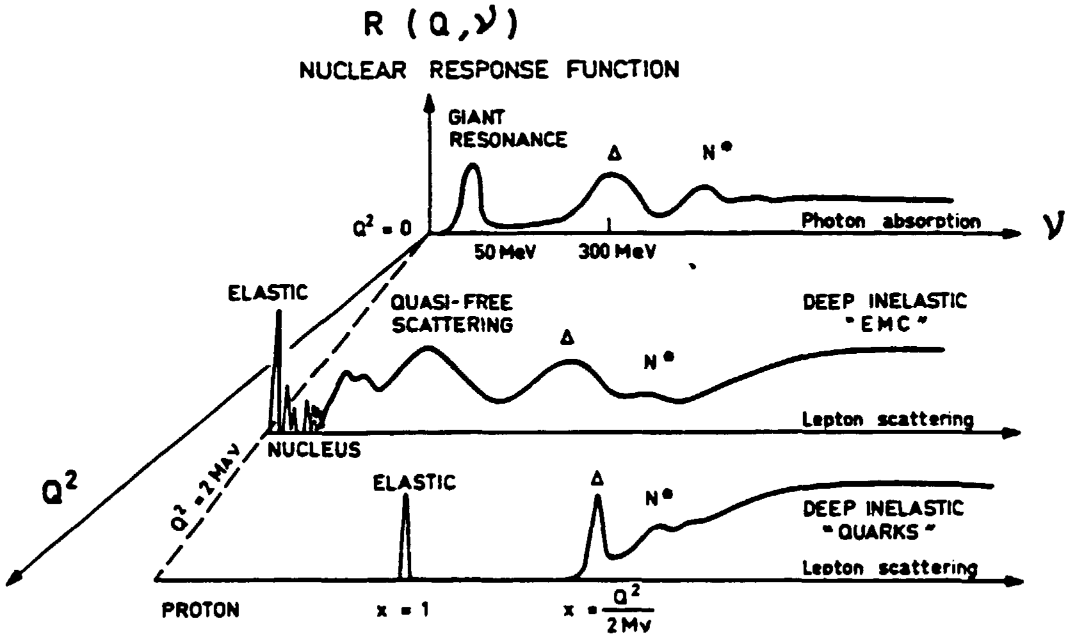


FIGURE 1
Schematic representation of the nuclear response function to electromagnetic probes. Q^2 is the four vector momentum transfer defined by $Q^2 = \vec{q}^2 - \omega^2$ and ν is the energy transfer $\nu = E - E'$ ($\nu \equiv \omega$). The absorption of real photons ($Q^2 = 0$) is a purely transverse excitation dominated by the giant resonance below the pion threshold and by the data resonance above the pion threshold. For lepton scattering ($Q^2 > 0$) the absorbed photon is virtual. This enables not only to vary $\vec{q}$ and ω independently, but also to have longitudinal and transverse excitations. Lepton scattering on both a nucleus and a proton has been represented. This comparison stresses the modification of the response function due to the nuclear medium. The very deep inelastic region is the region where both Q^2 and ν are extremely large. In this region scaling effects are observed giving clear evidence of the presence of quarks. Differences in the scaling behavior of heavy nuclei such as the observations of the European Muon Collaboration (EMC) are interpreted as modifications of quark dynamics in the nuclear medium.

independently. West[3] predicted about ten years ago that the response function should then depend only on the variable y, defined by $y = \vec{k}\,\frac{\vec{q}}{|q|}$. This variable is the component of the momentum $\vec{k}$ of the knocked out nucleon parallel to the momentum transfer $\vec{q}$. The experimental data plotted as a function of y all lie on the same curve representing the scaling function $F(y)$. This can be used to map out momentum distributions at very high momentum transfers provided that final state interactions and relativistic effects are understood. Only two experiments at SLAC on deuterium[4] and ^3He [ref.[5]] have reached the very the very high momentum region where the condition of validity $q >> k_F$ is satisfied. Both show clearly this scaling behavior. At present none of the three body calculations based on a nucleon picture can reproduce this scaling behavior in ^{3}He. This is a short-range effect which is associated with a lack of high momentum component in the theoretical prediction. Pirner and Vary[7] obtain a reasonable agreement with experimental data by taking into account quark cluster effects.

Figure 2 shows the ^{3}He(e,e') cross sections[5] together with the scaling function F(y) [ref.[8]]. F(y) has been obtained with the free nucleon kinematical parameters. Thus the perfect scaling observed in the nucleonic region of the quasi-elastic peak is strong evidence that the reaction mechanism is a one nucleon interaction. This explains why no such scaling is observed in the Δ region. Thys y-scaling effect is very sensitive to the kinematical variables in particular to the mass and the radius of the nucleon. Sick[8] has shown that this scaling behavior is destroyed by a 15 % increase in the nucleon radius in ^{3}He. Jaffe et al.[9] have predicted that quarks might occupy a large volume in nuclei than in a nucleon isolated in vacuum. One has to wait for the new experiments planned at SLAC on heavy nuclei to know whether it is possible to measure this effect experimentally. This should be within the reach of the sensitivity of the y-scaling and would be a very exciting experimental result.

2.2. The Δ resonance

Inelastic cross sections have been recently measured in the Δ resonance at Saclay[10,11] and MIT-Bates[12] laboratory. Barreau et al.[10] and Meziani et al.[11] have studied the momentum dependence of the cross section for ^{12}C, ^{40,48}Ca and ^{56}Fe. They find that the Δ peak is in qualitative agreement with theory but its shape is not accurately reproduced by any calculation. In the region between the quasi-elastic peak and the Δ peak, called the dip" region, the theoretical strength is much too weak even when meson exchange currents are taken into account. This is a region where two body correlations also play an important role. Koch et al.[13] try to explain the ^{12}C data[10,12] in the Δ-hole formalism. The best agreement is obtained above the Δ peak. The lower energy side of the Δ resonance is very poorly reproduced showing that the phenomenological approach of a spreading potential is not sufficient. The theoretical difficulties met are at the level of the non resonant terms, the meson exchange currents and the two-body correlations. Laget[27] has developped a diagrammatic approach which has the advantage of obtaining separately the different contributions to the cross section. His calculations show that the Δ resonance part seems to be well understood. New data presented at this conference by Marchand et al.[14] show that the calculations of Laget[27] are in better agreement for ^{3}He. This indicates that the disagreement observed in heavier nuclei might be due to the approximations used. In ^{3}He the correlations between nucleons are

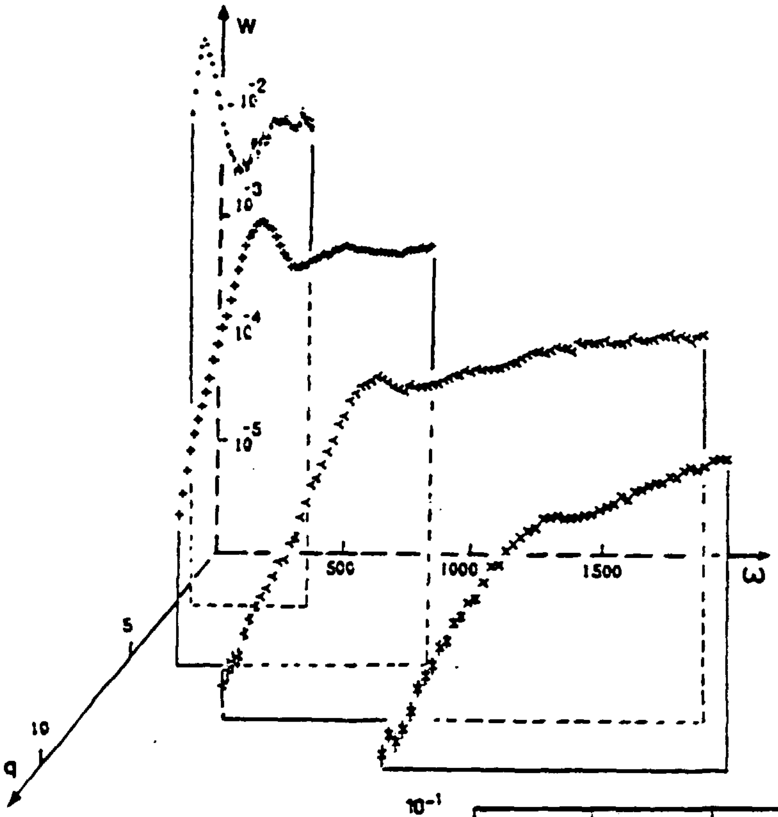
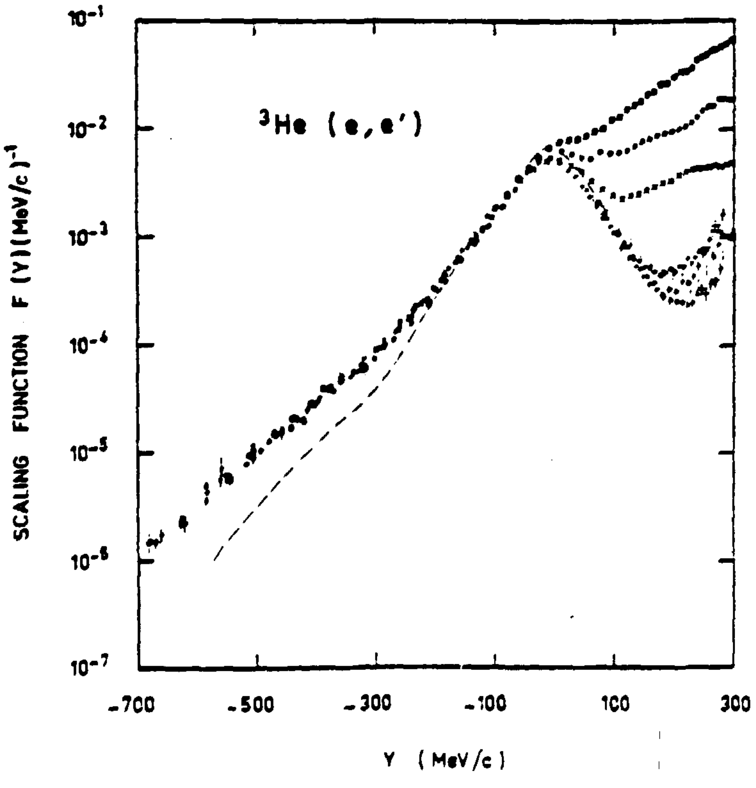


FIGURE 2
a) ^{3}He(e,e') total structure function[5] in the quasielastic region.
b) Scaling function F(y). The curve is a typical three-body calculation [ref.[8]].



calculated by Laget with three-body wave functions, while in heavy nuclei a quasideuteron assumption is made. The basic mechanisms are understood, but one now has to perform coincidence experiments to measure the effects of correlations and final state interactions. This is demonstrated by recent ^{3}He(e,e'd) measurements[41].

O'Connell et al.[12] have recently studied at MIT-Bates laboratory the Δ resonance in kinematical conditions close to the real photoabsorption, $q = \omega$ ($Q^2 = 0$). Data have been obtained on various light nuclei up to ^{16}O. The cross section is found to vary linearly with A which means that the cross section per nucleon is constant (Figure 3). This agrees with recent experimental results obtained by real photon absorption[19] (Figure 4). In particular a new method, which can be used for both light and heavy nuclei, confirms this linear dependence. Tamas et al.[19] present these data at this conference, obtained with an incident monochromatic photon beam by a tagged positron annihilation. The total photoabsorption is measured by a nearly 4π detector. This linear dependence of the cross section as a function of A can be understood simply in terms of sum rules[18].

2.3. Quasi-elastic scattering

At momentum transfers of the order of the Fermi momentum k_F, the total quasi-elastic scattering cross section is usually described by a Fermi gas model. Measurements performed at Stanford by Whitney et al.[20] at 500 MeV and a scattering angle of 60° showed a good agreement with this simple model. Moniz et al.[21] have extracted from these data the two parameters of the Fermi gas model, the Fermi momentum k_F and the average nucleon binding energy ε. The position of the quasi-elastic peak determines ε while its width determines k_F. The Stanford data and the new data on ^{12}C measured by Barreau et al.[10] are also in good agreement with the very complete calculation of Horikawa et al.[22]. This calculation has estimated the final state interactions with the attenuation of flux in the one nucleon channel and the excitation of the multinucleon ones.

This excellent agreement between experiment and theory for the total quasi-elastic cross section suggests that there should not be any theoretical difficulty to describe separately the longitudinal and transverse response functions. It turns out that a series of measurements[10,11,15,23] have definitely shown that this is fortuitous. There is in the total cross section a cancellation of overestimate of the longitudinal contribution and of underestimate of the transverse contribution.

If two body correlations are small, then the closure relation requires that at sufficiently high q, i.e. $q \approx 2\ k_F$ the integrated longitudinal cross section must contain all the charge strength. At 550 MeV/c the Coulomb sum rule is

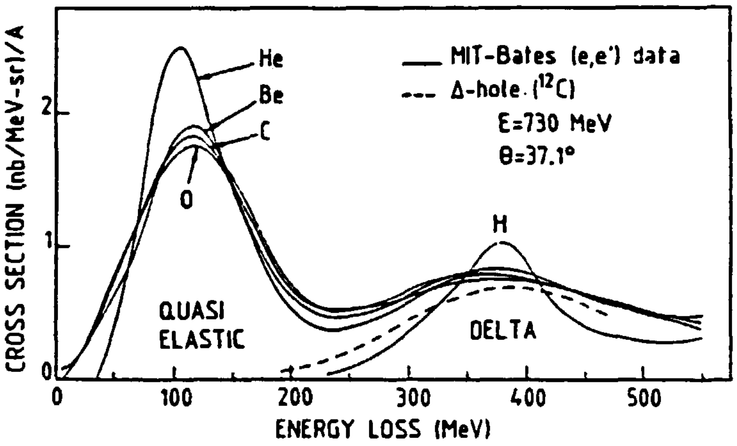


FIGURE 3
Deep inelastic electron scattering cross sections for light nuclei measured by O'Connell et al.[15]. The dashed line is a Δ-hole model prediction.

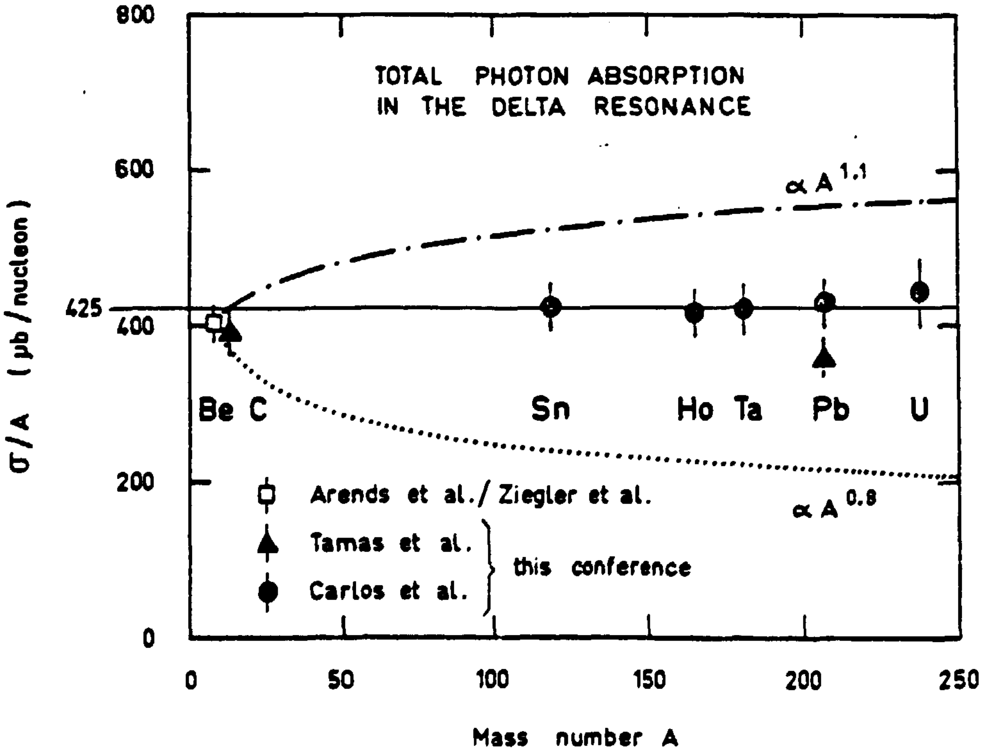


FIGURE 4
Total photon absorption cross section in the delta resonance divided by the number of nucleons.

very well satisfied[10,11]. However a large disagreement between the experimental and theoretical predictions is observed in the shape of the longitudinal response function even at 550 MeV/c. Therefore this sum rule is not at all a measure of the agreement between experiment and theory. One must make a direct comparison of the shape of the longitudinal response function.

A few years ago Rosenfelder[24] calculated the total cross section in a relativistic model. He noticed that it was no longer necessary to introduce an energy shift to reproduce the position of the quasi-elastic peak. Recently a similar approach has been used for the longitudinal and the transverse response functions by De Forest[25], and Do Dang and Giai[26]. Excellent agreement is obtained both for the longitudinal and transverse contributions at 410 MeV/c. Figure 5 shows that at 550 MeV/c the longitudinal response function is in perfect agreement with the data, while there is a significant lack of strength for the transverse response function. By examining the results of Laget[27] one finds that at 550 MeV/c meson exchange effects and pion production are important in the transverse part. Though it has only an indicative value, one can add the estimate of Laget[27] for these processes to the calculation of Do Dang and Giai[26]. This brings the theoretical prediction into excellent agreement with the data. This is now a theoretical problem. Why does this Dirac phenomenology works so well while everything else fails for the longitudinal response? One should notice that Do Dang and Giai have[26] used the same scalar and vector potentials used so successfully by Clark et al.[28] for proton scattering. This might be an important warning that a relativistic equation is needed to describe nuclear dynamics properly.

Following a suggestion of M. Ericson, Meziani et al.[11] have examined the imaginary part of the polarization propagator $\pi(\vec{q},\omega)$. This imaginary part is obtained directly from the transverse response function by dividing out the effect of nuclear matter density and the magnetic form factors of the nucleons One observes for ^{40,48}Ca and ^{56}Fe at 410 MeV/c a universal function for $\pi(\vec{q},\omega)$ (Figure 6). This shows that the transverse response function determines the bulk properties of nuclear matter.

3. NUCLEAR STRUCTURE

Real breakthroughs have been made in this domain. High energy resolution, usually better than 10^{-4}, is now standard. Very low cross sections, as small as 10^{-39} cm^2/sr can be measured without background. These technical achievements have enabled the form factors of a large number of nuclear excitations to be mapped out. I have selected here only a few examples chosen for their illustrative value. Further references can be found in the recent review

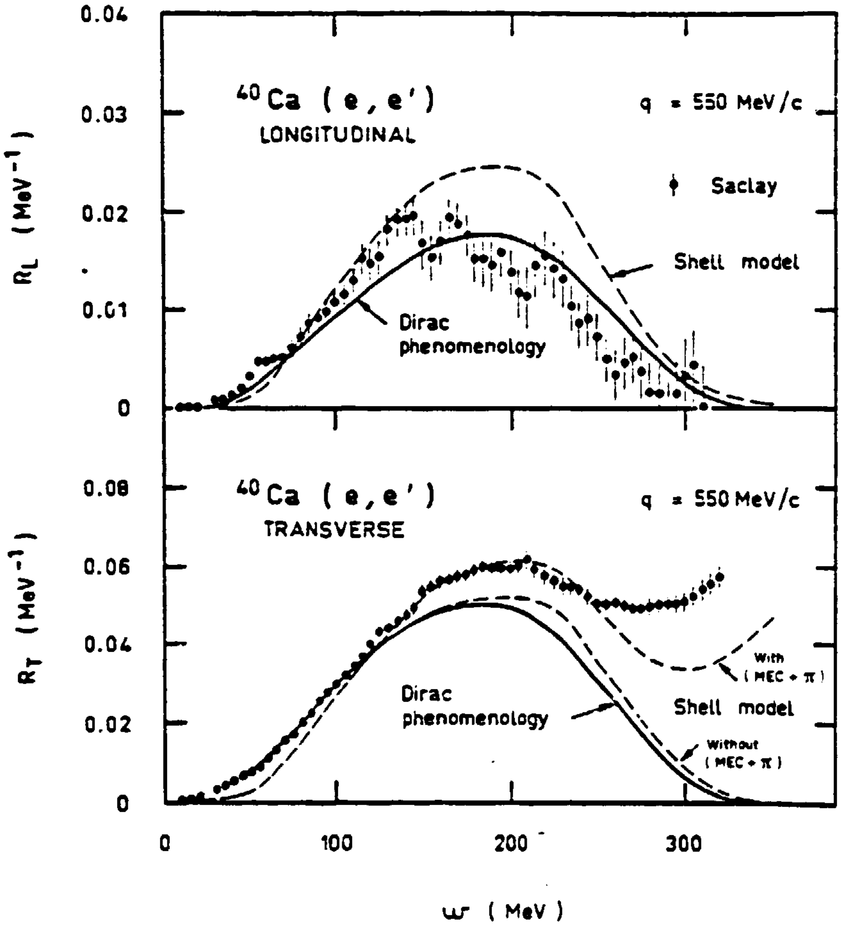


FIGURE 5
Longitudinal and transverse response functions for ^{40}Ca measured by Meziani et al.[11]. The solid curve is a Dirac phenomenology prediction by Do Dang and Giai[26] with the scalar and vector potentials of Clark et al.[28]. The dashed curves were calculated by Laget[27].

article of Donnelly and Sick[29] for magnetic elastic scattering, Richter[30] for inelastic scattering at low energy, Heisenberg and Blok[31] for inelastic scattering at intermediate energy, Frullani and Mougey[32] for (e,e'p) coincidence experiments.

3.1. To what extent can a nuclear wave function be approximated by an independent particle wave function?

The charge distributions of the ground states of magic nuclei from ^{4}He to ^{208}Pb are now determined with an overwhelming precision The experimental uncertainty in the central region of the nucleus is hardly perceptible, as a direct

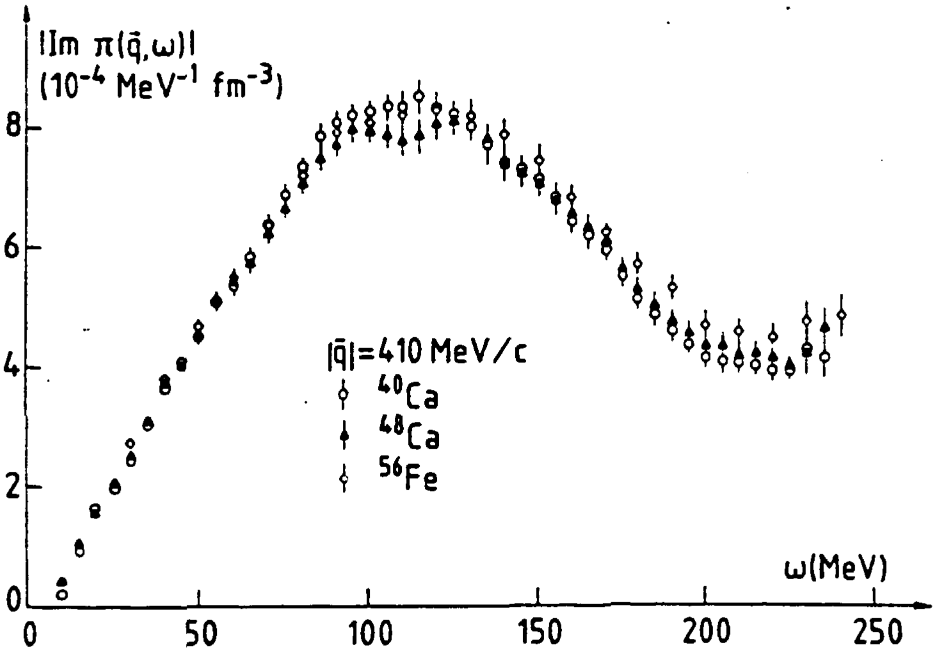


Figure 6

The polarization propagator for ^{40,48}Ca and ^{56}Fe extracted from the transverse quasielastic response function with k_F = 1.32 fm^{-1} [ref.11].

result of 30 years of technical efforts both in electron scattering and in muonic X-ray measurements.

The comparison with the best mean field calculations shows that there is a systematic overestimate of the shell oscillations in the center of the nucleus. In the independent particle description, the charge distribution of the nucleus is simply the sum of the squares of the proton wave functions in the ground state. Electron scattering provides here a measurement of the observable which is the most closely related with the nuclear wave function. Quite paradoxically the disagreement is most important in ^{208}Pb [ref.33] which a priori seems the most appropriate for a description in terms of a mean field. The experimental result is essentially without structure (Figure 7) while all the most refined theoretical calculations produce a bump at the center of ^{208}Pb. Relativistic calculations performed in the Dirac phenomenology approach[34] have exactly the same problem. The results of Serot[35] in the Hartree approximation presented in Figure 7 show that the lower components have very little smoothing effects.

The narrow structure in the center of ^{208}Pb can be attributed only to the 3s protons which occupy the valence orbit. Residual correlations either deform the radial structure of the 3s wave function or modifying the occupation of the 3s

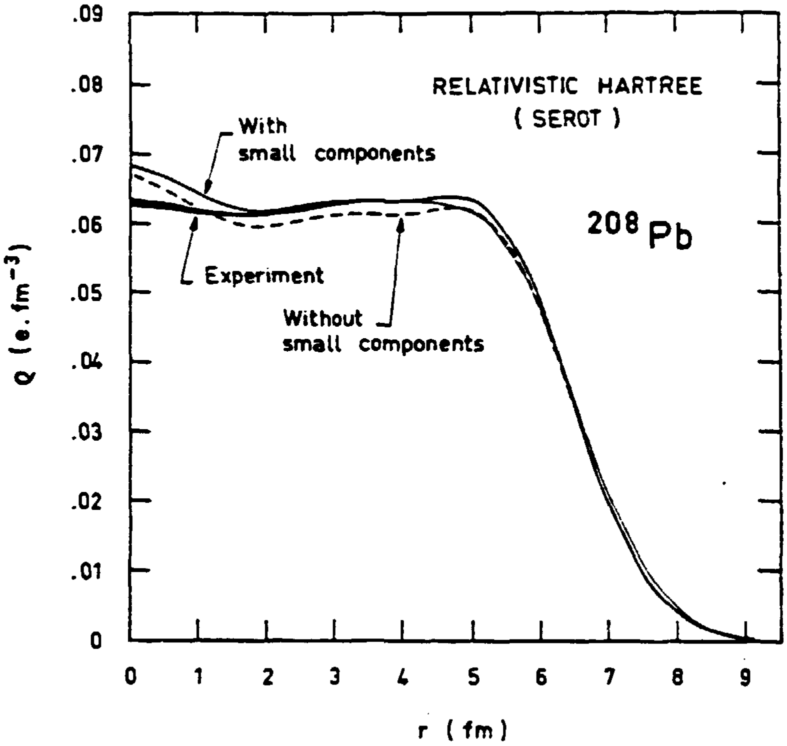


FIGURE 7
The charge density of the ground state of ^{208}Pb. The shaded area is the total experimental uncertainty[33]. The solid and the dashed curves are the predictions of the Dirac phenomenology[35].

state. A comparison of the charge density of ^{206}Pb and ^{205}Tl has shown that the oscillations predicted by the mean field theory is in remarkable agreement with experiment (Figure 8). However an almost uniform reduction of their amplitude is observed. This reduction is of the order of 30 to 35 % and can be directly observed in the experimental cross section ratio[36,37] (Figure 9). The very small experimental uncertainty reflects the precision attainable now in electron scattering experiments. This has allowed the unambiguous observation of the very characteristic effects of the 3s orbit. It is the first time that one can visualize how a particle is distributed in a quantum orbit. The reduction observed experimentally is just the natural consequence of the interactions between the nucleons at the Fermi surface. But at present there is no complete microscopic calculation for a finite nucleus. Pandharipande, Papanicolas and Wambach[38] have shown in a recent paper that short range, tensor and RPA calculations are needed to explain such a reduction. These correlations which go beyond the mean field approximation might explain the reduction observed in all the single-particle transition.

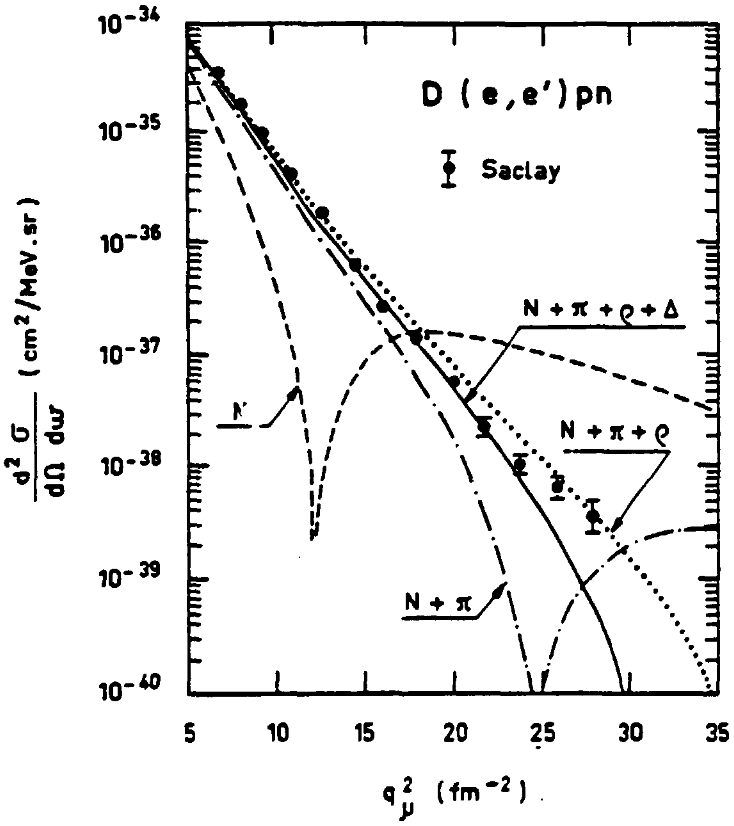


FIGURE 14
Electrodisintegration cross section of deuterium at threshold. The new data of Clemens et al. have been represented with the theoretical predictions of Mathiot[59].

F_1. At 25 fm^{-2} the sum of nucleon and pion currents vanishes, the cross section is almost exclusively due to the ρ and Δ currents. A reasonable agreement with the experimental results is found by Matniot[59] when the $\pi + \rho + \Delta$ currents are taken into account with a πNN form factor of 1.25 GeV and F_1 for the nucleon current. However similar results are found by considering only the currents associated with he presence of "soft pions" i.e. bare pions without form factor. This is a puzzling problem which is a clear example of the serious theoretical difficulties that we have now. A reasonable description of the experimental results can be found but short range processes are taken into account only in a phenomenological way.

Coincidence electrodisintegration experiments have been performed in the Δ region by Turck-Chieze et al.[60] at Saclay and by Mehnert et al.[61] at Bonn. The

These results modify the usual concept of a magic nucleus. Such nuclei are considered as having closed shells. Electron scattering data give us a quantitative and absolute estimate of the limits of validity of this picture.

Magnetic elastic scattering has provided a very accurate method for the measurement of the radius of valence orbitals[39]. Meson exchange and core polarization effects introduce a small theoretical uncertainty which when folded with the experimental uncertainty gives a total error of ± 1.5 % for the radius of the $1f_{7/2}$ and $1g_{9/2}$ proton and neutron orbits. Platchkov et al[39] have shown that the experimental result agrees with mean field calculations within this uncertainty. This result confirm that mean field calculations are able to predict the shape of valence wave functions to a good accuracy. Magnetic elastic electron scattering enables also allows a very interesting and complementary information the 3s orbit to be obtained. One has a direct information on core polarization by the quenching of the single particle current. Papanicolas et al.[40] have measured the magnetic form factor of the ground state of ^{205}Tl by elastic scattering at 180° at MIT-Bates laboratory. At present only high momentum transfer data are available. But the preliminary results are exciting. The experimental reduction of the 3s magnetic form factor is approximately 65 % which is twice the reduction observed in charge scattering. Additional measurements are required in order to determine as completely as possible this magnetic form factor. The rather surprising result is the complete absence of agreement with the calculations which explain the magnetic form factor of ^{207}Pb (which has a valence neutron hole instead of a valence proton hole).

The new 500 MeV electron scattering facility available at Amsterdam NIKHEF-K has considerably improved the resolution in missing mass for (e,e'p) coincidence experiments. An example of experimental spectrum for ^{208}Pb is shown in Figure 10 [ref.[41]]. The separation of the different hole states is a major experimental achievement. With 10Q keV it will be possible for the first time to have access to informations on deep holes and two body correlations in heavy nuclei. This is discussed by Lapikas at this conference. In the case of ^{208}Pb it is of special interest to complement the informations on charge and current densities by (e,e'p) measurements. One can determine both the spectroscopic strength and the momentum distribution of the 3s orbit.

3.2. Low lying collective excitations of deformed nuclei

Microscopic calculations are able to predict reasonably well the properties of magic nuclei. A much more ambitious task is to describe nuclear dynamical deformations. From the experimental point of view deformed nuclei are very difficult to study because their excited states are separated by much smaller energies. Detectors able to achieve energy resolutions lower than 10^{-4} have

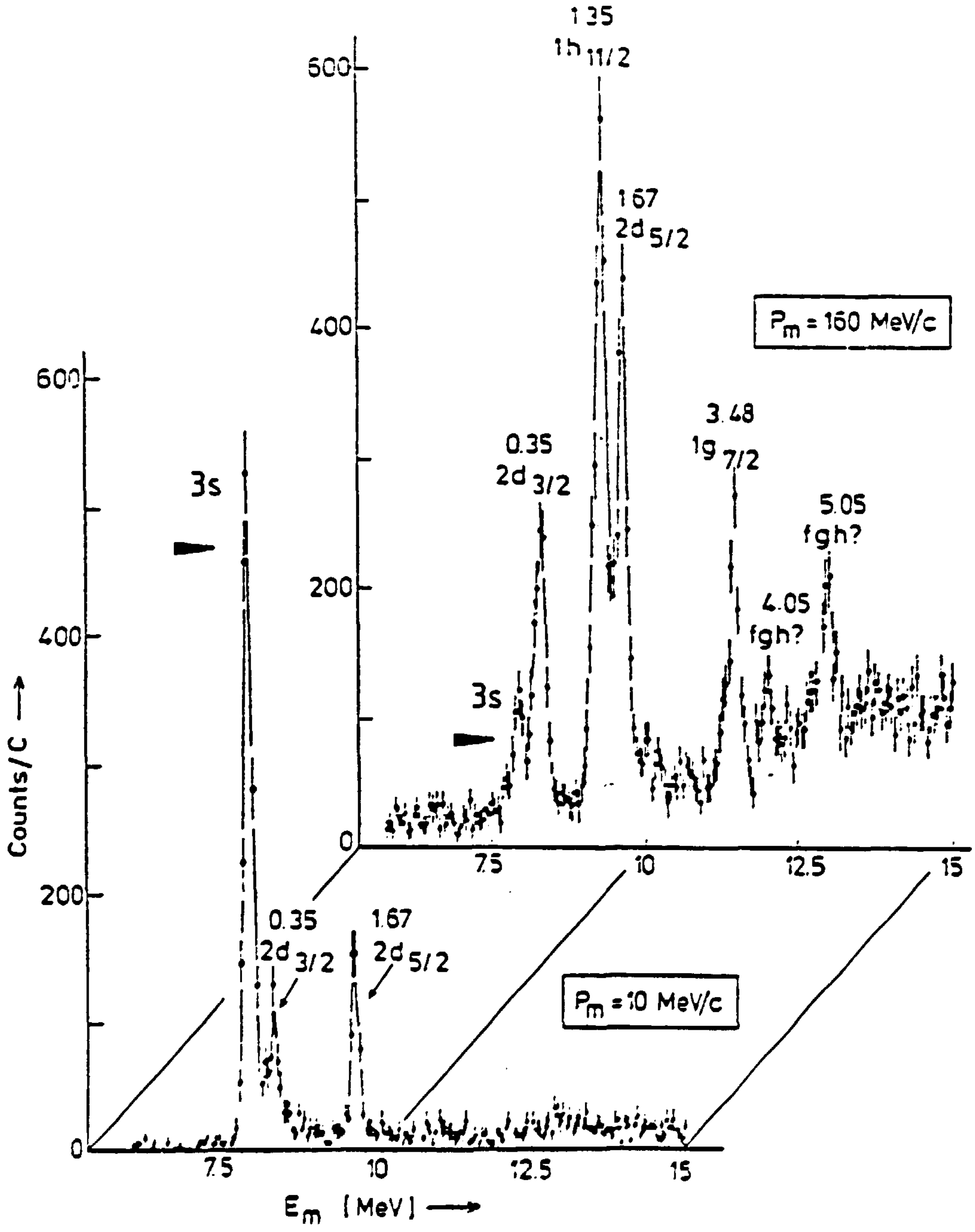


FIGURE 10

^{208}Pb (e,e'p) reaction measured with the new experimental facility of NIKHEF-K.

have only been available recently. Corrections for kinematic broadening and spectrometer aberrations have been performed with multiple wire chambers and arrays of scintillators. This has enable Hersman et al.[42] to measure at MIT-Bates laboratory the form factors of three 2^+ states in ^{154}Gd, interpreted as the first rotational, the β and γ vibrational states. The shape of the experimental transition densities of these three states is shown in Figure 11. The locations of the peaks of the β and γ vibrations correspond to the geometric picture of a β vibration along the deformation axis and a γ vibration perpendicular to the deformation axis. The γ vibration peaks inside of the rotational state while the β vibration peaks outside. The understanding of these transitions at a more profound level requires a microscopic calculation of dynamical deformations.

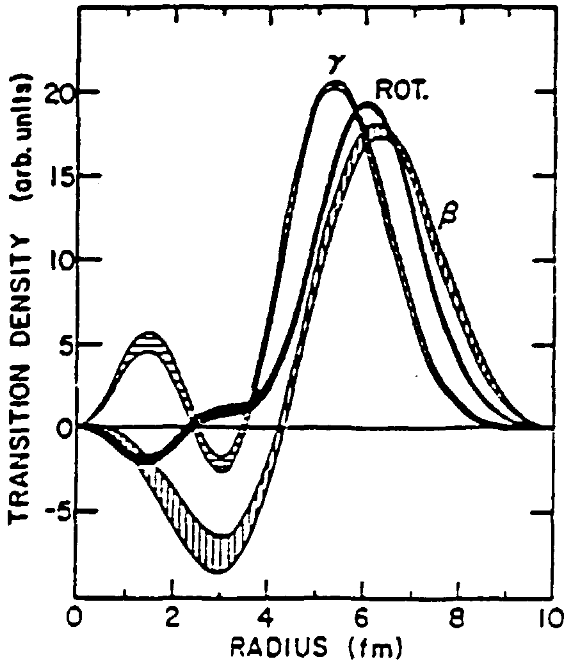


FIGURE 11
^{154}Gd 2^+ transition charge densities measured by Hersman et al.[42].

Hersman et al.[42] have shown that there is not a linear relation between these three form factors predicted by the Interacting Boson Model IBM-1. This is the early version of the model which does not make a distinction between neutron and proton bosons. The failure observed by Hersman et al.[42] for ^{154}Gd is the failure of an approximation valid only for an extreme case. It is not a check by electron scattering of the general validity of the model. It shows that this simplest form of symmetry possible in the Interacting Boson Model does not exist in ^{154}Gd and does not imply that this limit is not possible in other nuclei. In order to find this limit, De Jager et al.[43] have studied Pd isotopes at the new high energy resolution electron scattering facility of NIKHEF. Three 2^+ have been found in ^{110}Pd which follow the prediction of IBM-1. This shows that one needs further systematic studies of deformed nuclei by electron scattering to reach definitive conclusions on the limits of the Interaction Boson model.

The most difficult challenge to our understanding comes from transitional nuclei which are very easily deformed such as the germanium isotopes. These nuclei have been studied for many years with hadronic probes. Their complexity has been shown in particular by transfer reactions. Various theoretical hypotheses been proposed to explain the strange behavior of their spectroscopic data.

"How could electron scattering be used to solve such a problem"?

In order to answer to this question, Goutte et al.[44] have measured at Saclay the form factors of all the low lying excitations in ^{70,72,74,76}Ge. The large momentum transfer range and the small experimental uncertainties of the data have pinned down the details of the transition densities in the interior of the nucleus (Figure 12). The ground state charge densities have been determined by muonic X-ray measurements at SIN[45] and a combination of low-q measurements at Mainz[45] and high-q measurements at Saclay. These ground state charge densities are reasonably well reproduced by microscopic calculations. However it is not possible to describe the structure of the 2_1^+ and 2_2^+ state. A microscopic description of these soft nuclei is still an open problem even with the best calculations including triaxial degrees of freedom.

Goutte et al.[43] have shown that the strange behavior observed in the Germanium isotopes is perfectly explained at a phenomenological level by the Interacting Boson Model IBM-2. This version of the model treats explicitly the neutron and proton degrees of freedom. Duval, Goutte and Vergnes[47] have calculated the parameters of the model by fitting energy levels and reduced probabilities of transition. They explain these spectroscopic data of the germanium isotopes by a mixing of two interacting boson configurations. Goutte et al.[44] have compared the eight quadrupole transition charge densities for the 2_1^+ and 2_2^+ states of the four isotopes to the predictions of the Interacting Boson Model. A radial shape for the $\alpha(r)$ and $\beta(r)$ boson densities have been extracted from experimental data in ^{72}Ge and ^{76}Ge [ref.[45]]. With these boson densities and the matrix elements obtained in ref.[44], a theoretical prediction was made for the transition charge densities of the 2_1^+ and 2_2^+ in ^{70}Ge and ^{4}Ge. All the calculated densities are in good agreement with the experimental data including a very

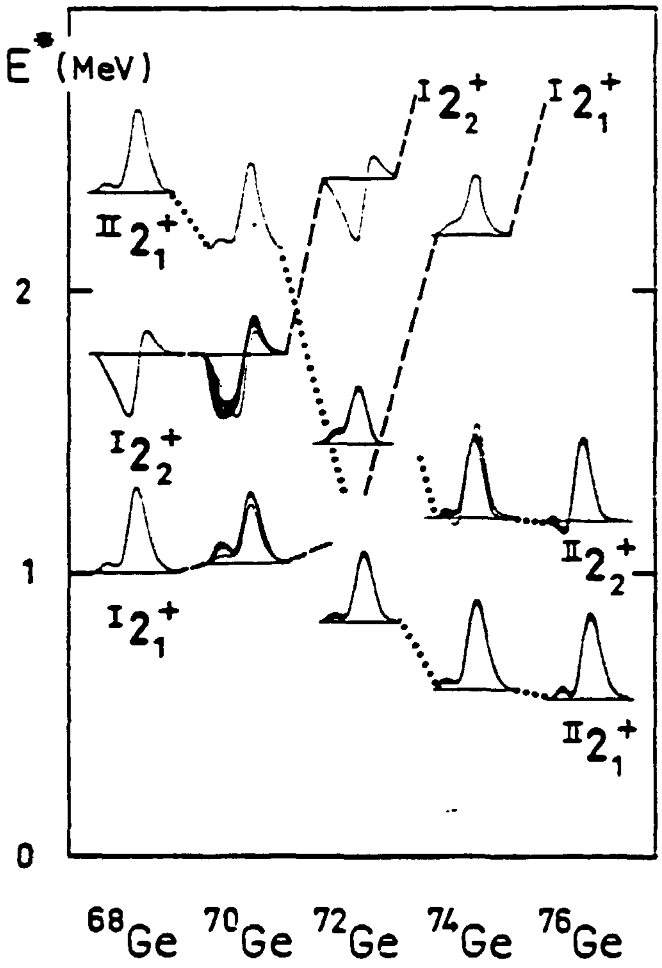


FIGURE 12
Low lying 2^+ transition charge densities of ^{70,72,74,76}Ge. The thin solid line indicate the predictions of the Interacting Boson Model. The shaded areas indicate the experimental results. The agreement for the ^{70}Ge 2_2^+ state is remarkable.

"strange" 2_2^+ in ^{70}Ge. This transition charge density has a very different radial behavior from the other 2^+ state with a strong oscillation in the nuclear interior. This shape is an excitation of the first IBM configuration which appears at higher energies in $^{72-76}$Ge.

In the absence of knowledge on the difference of shape between proton and neutron boson densities Goutte et al.[44] have assumed that they have the same shape. The agreement with the experimental results indicates that this is a reasonable approximation. This is also justified by recent results by Papanicolas et al.[48] who have found very similar shapes for the transition charge densities of proton and neutron 2^+ transitions in the Pb region.

The phenomenological approach of the Interacting Boson Model with the configuration mixing technique appears as an elegant and powerful guide to describe these complex low lying excitations. The next step is to use this guide to find a microscopic description of soft nuclei.

4. FEW-NUCLEON SYSTEMS

The electromagnetic structure of few-nucleon systems is of particular interest for nuclear theory. It is the testing ground of the description of the fundamental nucleon processes.

4.1. Deuterium

For the first time the tensor polarization of deuterium t_{20} has been measured by Schulze et al.[49] at MIT-Bates laboratory. This is an ideal experiment to separate F_F and F_Q the charge and the quadrupole form factors of deuterium. F_Q is sensitive to the tensor part of the N-N interaction and cannot be isolated without polarization measurements. t_{20} is directly proportional to the ratio F_Q/F_C. From this ratio the isoscalar electric nucleon form factor cancels out. Two data points have been measured at $q = 1.74$ and $2.03\ fm^{-1}$. They were obtained by scattering an unpolarized electron beam from an unpolarized deuterium target with the detection of the polarization of recoil deuterons. The experimental results are in good agreement with predictions of "reasonable" models of the deuteron. The region sensitive to the differences between theoretical calculations has not been reached yet because of experimental difficulties. In order to have access to higher momentum transfers, experimental techniques must be improved. An experiment using a polarized target is planned at Bonn this fall while the Alberta-SATURNE collaboration is developing a new polarimeter with a much higher figure of merit. Holt[50] has also discussed the feasibility of performing this experiment with a polarized internal target in an electron storage ring. The recent developments of laser-driven polarized targets appear to be the most promising approach to reach very high momentum transfers.

The magnetic form factor of deuterium can be isolated by a combination of forward and backward elastic scattering measurements. At angles near 180°, the magnetic contribution dominates the cross section. One measures experimentally $B(Q^2)$ the magnetic structure function which is proportional to F_M. Recent measurements at Saclay[51] and Bonn[52] have determined $B(Q^2)$ precisely up to 33 fm^{-2} (Figure 13). This represents a considerable progress. Previous data available only up to 12 fm^{-2} were not sensitive to the difference between different the theoretical approaches. There is a considerable difference between various calculations and the experimental data. The best agreement is obtained with the non-relativistic calculations of Gari[53] which includes a large contribution of the $\rho\pi\gamma$ and of the pair meson exchange current. However this agreement might not be meaningful because of the large theoretical uncertainties associated to isoscalar meson exchange currents and relativistic effects.

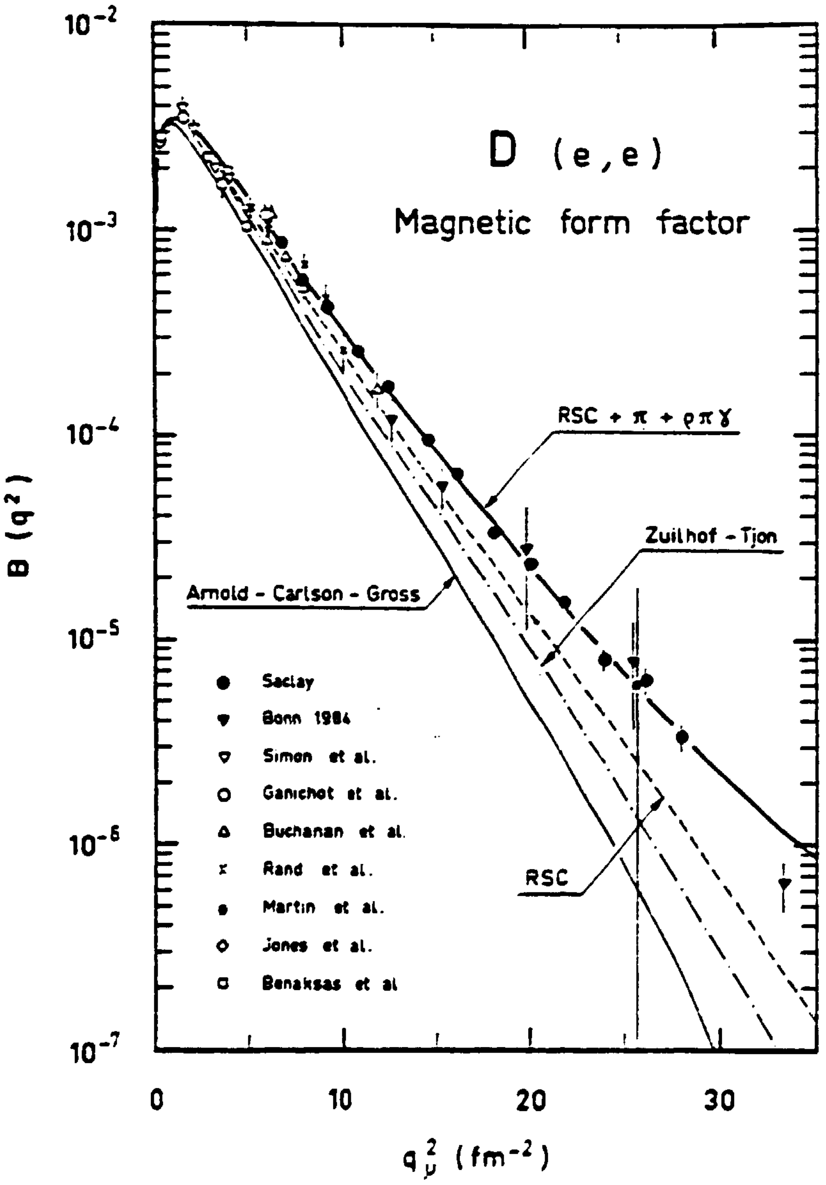


FIGURE 13
The magnetic factor of deuterium.

In the magnetic form factor of deuterium meson exchange currents are isoscalar. They are relativistic corrections of second order ($1/M^2$), so one should also correct the wave functions at the same order. Two groups, Arnold-Carlson-Gross[54] and Zuilhof-Tjon[55] have developed a fully relativistic approach. Their results are in complete disagreement with the experimental data. A possible source of this disagreement is the $\rho\pi\gamma$ exchange which has been neglected by these two groups. Gari finds in the non relativistic approach it is a major contribution to the cross section. A complete and reliable relativistic calculation is now needed.

The electrodisintegration of deuterium at threshold is a much simpler case for theory. At backward scattering angles it is essentially an M1 isovector transition. Meson exchange currents are very large and are much simpler to understand because of their isovector nature. They appear only as first order corrections ($1/M$) and one does not need relativistic corrections for the wave functions. Furthermore their theoretical description is constrained by low energy theorems which do not exist for isoscalar processes. The electrodisintegration at threshold is the inverse of the radiative capture of thermal neutrons ($n + p \rightarrow d + \gamma$) where Riska and Brown[56] have shown that meson exchange currents contribute about 10 % of the cross section. In the electrodisintegration one can study these meson exchanges directly in the nucleus instead of looking at asymptotic modifications. The various currents which contribute to the cross section have strong destructive interferences which occur successively at different momentum transfers. Thus measurements at specific momentum transfers single out the different contributions of the meson exchanges. Electron scattering serves as a microscope which looks at an object with larger and larger magnification. With the very high momentum transfers measured recently by Clemens et al.[57] (Figure 13), the short range part of the nucleon-nucleon interaction is now the major part of the effects observed. At $Q^2 \approx 12$ fm^{-2} a destructive interference between the ^3D-^1S and ^3S-^1S transitions leads to a complete cancellation of the nucleonic contribution to the cross section which reflects almost entirely the presence of pion exchanges.

At Versailles three years ago experimental data were available only up to 18 fm^{-2}. Clemens et al.[57] have extended the momentum transfer range to 27 fm^{-2} where the cross sections are of the order of neutrino cross sections ($\approx 10^{-39}$ cm^2/sr). This represents an improvement in the measurements by two orders of magnitude. These new data disagree completely with a calculation of Leidemann and Arenhövel[58] using the Sachs form factor G_E for the nucleon. Figure 14 is a comparison of th data of Clemens et al. to recent calculations of Mathiot[59]. A reasonable agreement is obtained by using the Dirac form factor

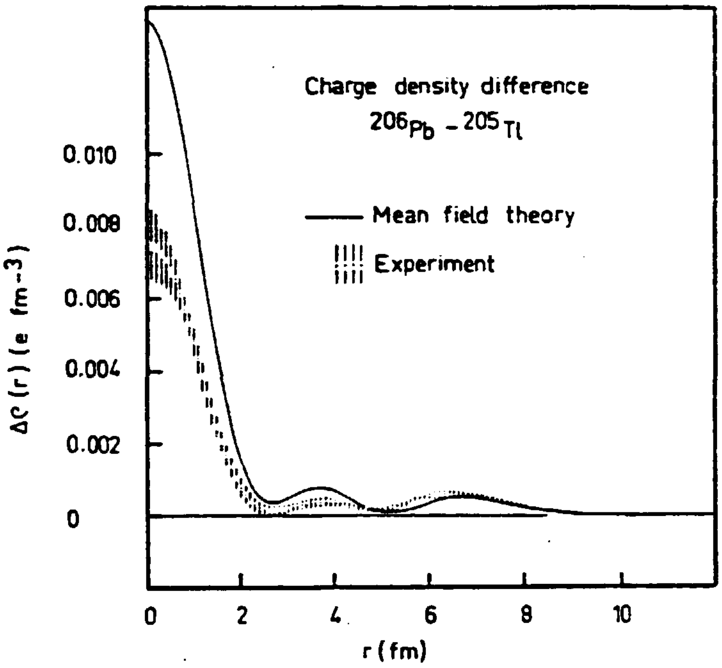


FIGURE 8
Charge density difference between ^{206}Pb and ^{205}Tl.

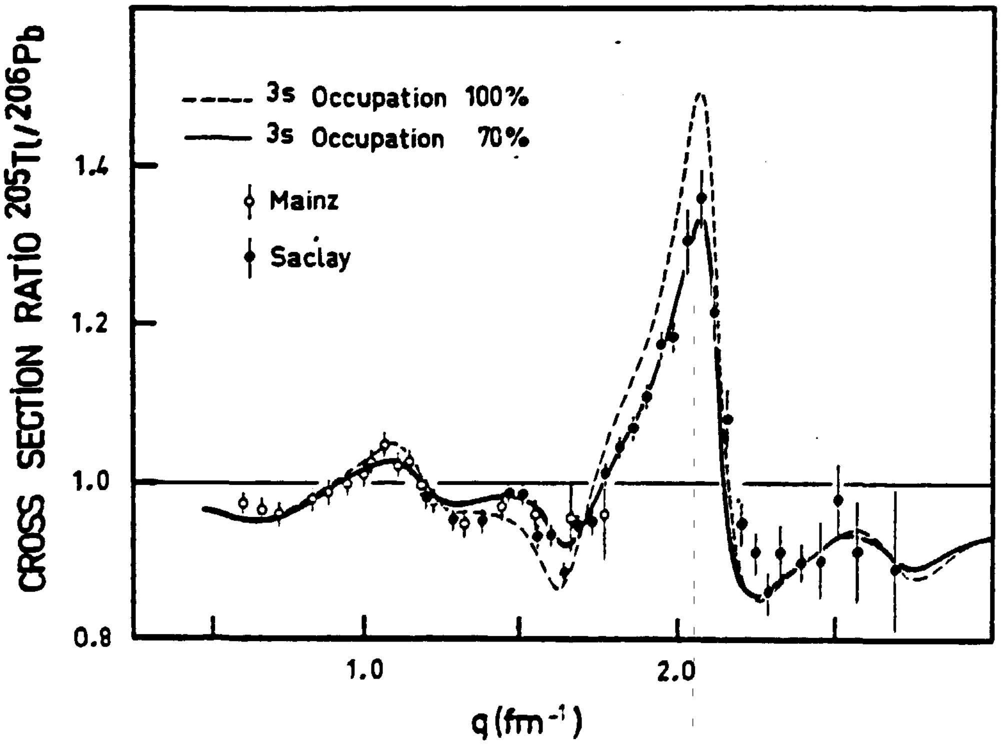


FIGURE 9
Experimental cross section ratios ^{205}Tl/^{206}Pb together with mean field predictions.

final state interactions are large. One cannot use the impulse approximation where the momentum distribution of the bound proton can be factorized out. Leidemann and Arenhövel[62] have made calculations with three different potentials. A renormalized version of the Reid Soft Core (RSC) and two new types of NN potential[6], V_{14} a purely nucleon-nucleon potential and V_{28} potential which takes into account explicitly the Δ degrees of freedom in a coupled channel model. In this potential the ρ-meson exchange is simulated by a cut-off for the π-exchange. Leidemann and Arenhövel find for both the Saclay and Bonn experiment that the results are more sensitive to the model used to describe the Δ than to the nuclear potentials.

4.2. Tri-nucleon form factors

The interpretation of the tri-nucleon form factors has been discussed recently by Friar et al.[64]. The charge and magnetic form factors of ^{3}H and ^{3}He give us a striking evidence of very large subnucleonic effects.

The charge form factor of ^{3}He has recently been measured at low momentum transfers with very small systematical uncertainties (< 1 %). These measurements have precisely determined the charge radius of ^{3}He. The values found by Dunn et al.[65] (1.935 ± 0.030 fm) and by Otterman et a.[66] (1.958 ± 0.18 fm) are in excellent agreement with the value predicted (1.95 fm) in the most complete calculation[68]. For the charge radius of tritium the value found by Beck et al.[67] (1.67 ± 0.05 fm) is significantly smaller than the prediction of Hajduk et al.[68] (1.78 fm).

The magnetic form factor of ^{3}He has been measured[16] up to $Q^2 = 32$ fm^{-2}. The diffraction minimum is shifted from $q^2 = 8$ fm^{-2} to 18 fm^{-2} by meson-exchange currents (Figure 15). A similar experiment is in progress for tritium at MIT and Saclay. The first results of the Saclay experiment are presented at this conference by Cavedon et al. The magnetic form factor of tritium has been mapped out to the diffraction minimum. Results at higher momentum transfer should be available before the end of 1984.

From a theoretical point of view, there is also considerable progress. New calculation techniques have been used, reaching a high degree of sophistication. Faddeev and variational calculations give similar results for the contribution of the two-nucleon force, but significant differences have been observed for the effect of three-nucleon forces. To understand these differences, Wiringa et al.[69] have used a Monte-Carlo method in conjunction with a three-body wave function obtained from Faddeev calculations. A 1.1 MeV additional attraction is found with this method. The differences between previous results can be attributed to the complex angular dependence of the three-body force which needs a large number of partial waves to be treated correctly by Faddeev techniques.

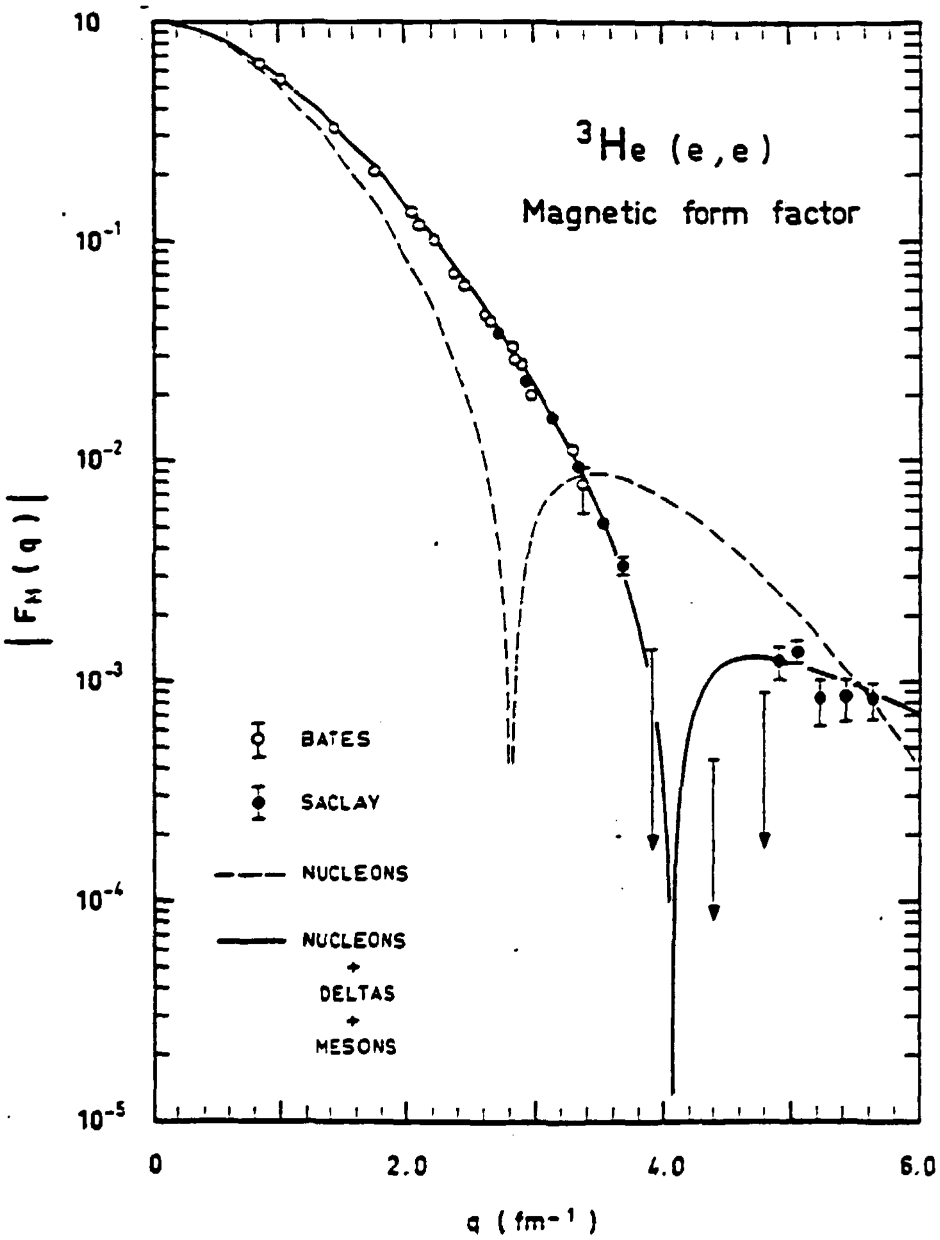


FIGURE 15
The magnetic form factor of ^{3}He [ref.[65,69,72]).

Hadjimichael et al.[17] and Hajduk et al.[68] have shown that the behavior of the charge form factor of ^{3}He is explained by meson-exchange currents, three-body forces and relativistic corrections, without creating a hole in the ^{3}He charge density. The wave functions of ^{3}He should also be corrected for relativistic effects. This has yet to be done and it is now a complex theoretical problem to determine if the present description is a reliable one. Furthermore the nature of the short range part of the three-body force remains poorly known.

The theoretical interpretation of the tri-nucleon magnetic form factors is more reliable because meson exchange currents are corrections of order (1/M). Thus relativistic corrections for the wave functions are of order ($1/M^2$) and can be neglected. The magnetic form factors of ^3H and ^3He are M1 isovector transitions similar to the electrodisintegration of deuterium at threshold. Over a wide momentum transfer range the cross section is issentially due to the π-exchange current. Recent calculations of Strueve et al.[18] show an excellent agreement with both ^3H and ^3He magnetic data. This shows that we have achieved a reasonable description of the pion exchange in isovector processes. It should be also noted that the ^3H and ^3He magnetic form factors can be reproduced only by using the F_1 form factor for the nucleon.

5. CONCLUSION

Electron scattering experiments have provided a wealth of information which has well defined the limits of the present phenomenological description of nuclear physics.

The concept of nucleons moving in a mean field has been verified in the nuclear interior to a surprising degree of validity. But residual correlations cannot be neglected even in a doubly magic nucleus. It is now a challenge to the most advanced many-body techniques to describe these correlations in a reliable way.

Are the properties of the nucleon modified in the nuclear medium? This is an intriguing problem which might be solved in the near future by studying y-scaling effects in heavy nuclei. Do we need a relativistic equation to describe the behavior of nucleons in the nuclear medium? This is a fundamental question which has now to be answered at the light of the new experimental results obtained both by electron and proton scattering.

The success of the Interacting Boson Model is impressive in the germanium region. It is an eloquent demonstration that nuclear physics is able to develop models which give simple representations of very complex dynamical problems.

Evidence of large π-exchange currents have been found in light nuclei. The comparison between ^3H and ^3He shows that this process is well understood. Heavier meson-exchange currents are much more difficult to isolate because there are large cancellations between the various processes. We have no choice now, we must build a more consistent theory of the short range part of the NN interaction in a more convincing approach. Measurements of exclusive processes by coincidence experiments will be a very powerful source of information. At present the duty cycle of existing accelerators is too small. A 100 % duty cycle is imperative to perform such experiments. At low energies $E < 200$ MeV, such accelerators exist already at the University of Illinois, Mainz and Sendaï. The feasibility of new type of experiments such as $(e,e'\gamma)$ [ref.[40]] has already been demonstrated. It is just a question of building accelerators of a sufficiently high energy to see short range mechanisms in the nuclear medium.

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