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NUCLEAR CHARGE AND MAGNETIZATION DENSITIES OF SINGLE PARTICLE STATES

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ABSTRACT

High energy electron scattering data have recently determined the spatial distributions of nucleons in the center of nuclei with amazing accuracy. For the first time we have access to the structure of the nuclear interior throughout the periodic table. The spatial resolution achieved by high momentum transfer measurements is now sufficient to define clearly the present limits of nuclear theory. The experimental situation is briefly reviewed and the results interpreted in the framework of self-consistent field theory. The shapes of single particle distributions in the nuclear interior are found to be in surprisingly good agreement with the predictions of mean field theory. The effects of correlations are discussed.

FOREWORD

After Ben Mottelson's evocation of the early developments of nuclear physics and of the major role played by Niels Bohr, it is not easy to jump right into technical matters. Physics is quite a challenge when one is preceeded by such giants who have so increased our understanding in just a century. We all know that each new generation has to take the torch of knowledge from its predecessors, but sometimes it is a formidable task to carry it further. So it seems to me appropriate to remember the words written during the Middle-Ages not very far from Saclay, by Bernard de Chartres, Chancellor of Chartres cathedral :

> "We are dwarfs mounted on the shoulders of giants,
> so that we can see more and further than they ; yet not
> by virtue of the keenness of our eyesight,
> not through the tallness of our stature, but because we
> are raised and borne aloft upon that giant mass".

Thus, it is a great pleasure for me to participate in the celebration of the Niels Bohr Centennial and to thank the organizers of this meeting for their kind invitation to present recent high energy electron scattering data. Very exciting results have been obtained in this field, some of them in the tradition of the work of Niels Bohr.

1. INTRODUCTION

The atomic nucleus is a remarkable and unique form of matter. It is the only quantum system in which a limited number of strongly interacting fermions is condensed in such a small region of space. Nucleons are nearly overlapping in the interior of the nucleus, but they behave almost as independent particles in a mean field. In the interior of a highly dense and correlated system such as the nucleus the concept of an independent particle wave function can be verified to an high degree of accuracy by measuring charge and magnetization densities in the interior of the nucleus. The recent data that I am going to present in this talk show that we are beginning to a have a clear and coherent picture of the nuclear ground state.

For many years the nuclear interior eluded our grasp and we had no experimental information to which we could cling. Pions, protons, alpha particles and other hadronic projectiles, which are easy to use, are too strongly absorbed at he nuclear surface. Multiple scattering effects are difficult to disentangle in processes induced by a strong interation. So, the situation was quite frustrating because the nuclear interior was always just out of our reach.

In order to study the single particle distributions in the center of the nucleus, one needs a probe which penetrates without absorption in nuclear matter. Its interaction must be sufficiently weak so that multiple scattering effects are negligible and a significant perturbation of the nucleus does not occur. The reaction mechanism must be well known and proceed by the exchange of virtual particles in order to be able to vary the momentum transfer to the nucleus independently of the energy transfer. This last condition is necessary to map out the spatial distributions of nucleons for a given state of the nucleus. Since the interaction must be weak, one needs to use the primary beam of an accelerator in order to have sufficient flux of particles. For a good spatial accuracy it is important to use a point particle.

Electrons are then the natural choice since they are the only particles which meet all these requirements. However it has taken a long time to harness the full power of this probe because considerable difficulties had to be overcome first. In order to have electrons of sufficiently small wavelength, a high energy is needed, typically 500 MeV for a heavy nucleus. This requires huge magnetic spectrometers of large solid angles and wide momentum acceptance. The difficulty is increased by the need to isolate specific nuclear excitations at such a high incident energy. An energy resolution $\Delta E/E = 10^{-4}$ is barely sufficient for nuclear studies. The measurement of angular distributions, which is the most efficient way of determining charge distributions, requires moving the 600 ton spectrometer and its shielding with an accuracy of 0.05°. Finally, one needs to map out nuclear form factors to sufficiently high momentum transfers to bring out the details of nuclear charge and magnetization densities. Since scattering cross section decrease rapidly as a function of momentum transfer, it is imperative to be able to measure very small cross sections without background.

Such experimental constraints led to the development of a completely new generation of equipment starting around 1970. The detection and data acquisition systems met the requirements about ten years later, permitting a full exploitation of the possibilities of single arm electron scattering. Various facilities around the world have developed specific areas of research in order to cover a broad range of subjects, from the study of meson exchange currents and single particle distributions to collective excitations in heavy nuclei.

The aim of this talk is to present some of the recent data on nuclear charge and magnetization densities and their impact on our understanding of the nuclear ground state.

2. THE GROUND STATE CHARGE DISTRIBUTIONS OF MAGIC NUCLEI

The charge distribution of a spin 0 nucleus can be determined from the elastic electron scattering cross section. The experiment is the standard example given by textbooks of the measurement of nuclear sizes and shapes. The situation in 1975 was summarized in a review by Friar and Negele[1]. The interior charge densities of medium and heavy nuclei had not been determined with sufficient accuracy. This is precisely the area in which major progress has been made in the last ten years. High momentum transfer data have mapped out the fluctuations of the charge densities in the nuclear interior. The precision of lower momentum transfer data has been considerably increased. These new electron scattering data, combined with the very precise measurements of muonic x-ray transitions, have decreased the experimental uncertainty of charge densities to negligible values in the interior of the nucleus. Figure 1 shows that for magic nuclei the experimental error, which is of the order of 1 %, is now barely perceptible. This is one of the most precise pieces of information on the structure of the ground state of the nucleus. The experimental data[2] were taken at Amsterdam, Darmstadt, Mainz, NBS, Stanford and Saclay over a period of 35 years.

The experimental charge densities are compared in Figure 1 with the prediction of a mean field calculation by Dechargé and Gogny[3] with a finite range density-dependent effective force. An extensive review of mean field theory has been published recently by Negele[4]. One finds here a systematic overestimate of the shell oscillations in the center of the nucleus. The disagreement is the most important in ^{208}Pb, which a priori seemed the most favourable case for a mean field description. Electron scattering definitely shows that it is not possible to completely describe the structure of the ground state of magic

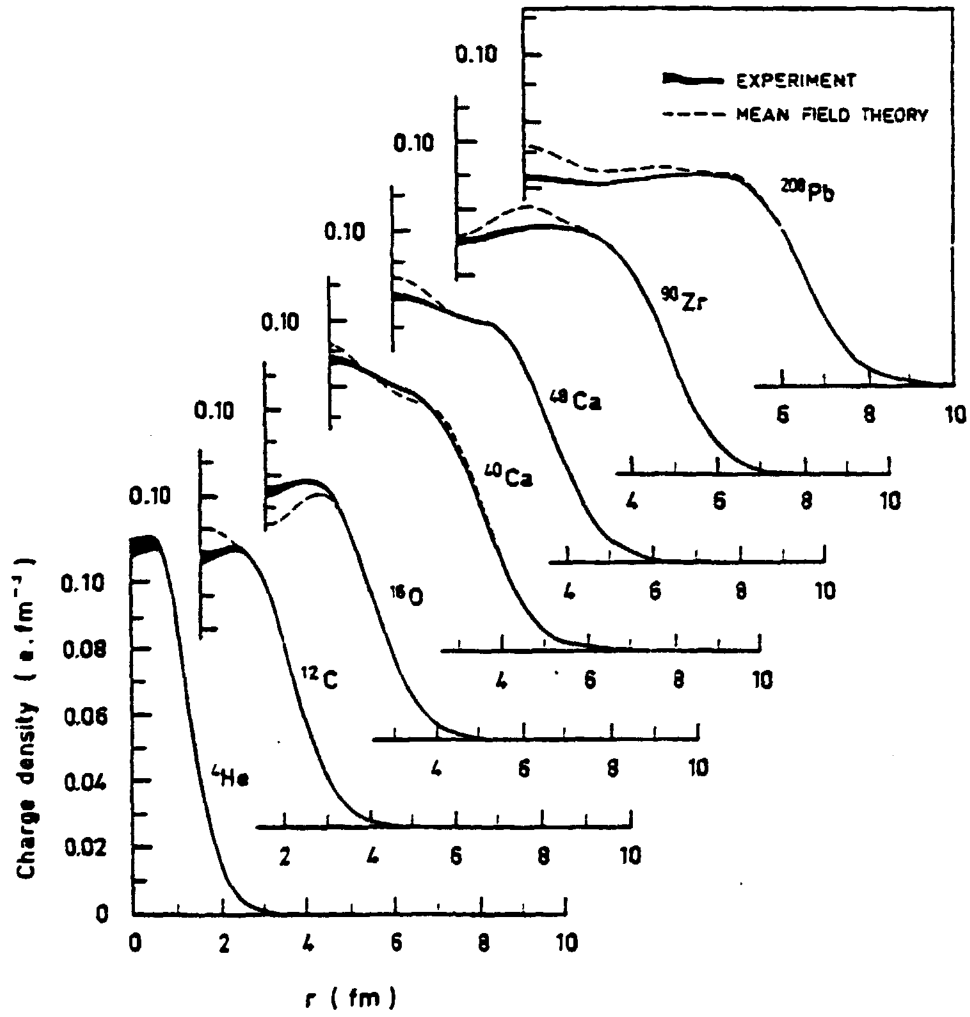

Figure 1
The ground state charge densities of magic nuclei.

nuclei in the Hartree-Fock approximation. It is obvious, that the deviations are small and that modern self consistent calculations are a very reasonable approximation. Nevertherless the new generation of electron scattering data is so precise that one has a quantitative estimate of the correlations[5] which are required beyond the Hartree-Fock approximation. In the mean field approach the sum of the interactions of a nucleon with all the other nucleons is approximated by an effective potential. The effects of short-range correlations are taken into account by a density dependence in the effective nucleon-nucleon potential. The Pauli principle tends to neutralize short-range interactions since nucleons cannot scatter into states that are already occupied, explaining why mean field theory is able to reproduce so well experimental data. However the effect of long-range correlations is not taken into account. The interaction between nucleons in the vicinity of the Fermi surface will tend to deplete the occupied orbits via a dynamical effect associated with the energy of the mean field. These residual interactions can be parametrized by an effective mass, a technique to be discussed at this conference by Mahaux. The first order correction is the coupling to low lying excitations. To be reliable, such corrections must be made self consistently with a finite range force. This has been done for particle hole excitations via the RPA. A 10.6 % depletion of the 3s orbit is predicted [6]. This takes into account the effects of vibrations at the surface but not the volume effects. Figure 2 shows the effect of these RPA ground state correlations in the calculated charge densities of ^{40,48}Ca, ^{90}Zr and ^{208}Pb. The fluctuations in the central region of the nucleus are considerably reduced and there is a better agreement with the experimental densities, but it is not sufficient to explain completely the shape of the charge density of ^{208}Pb.

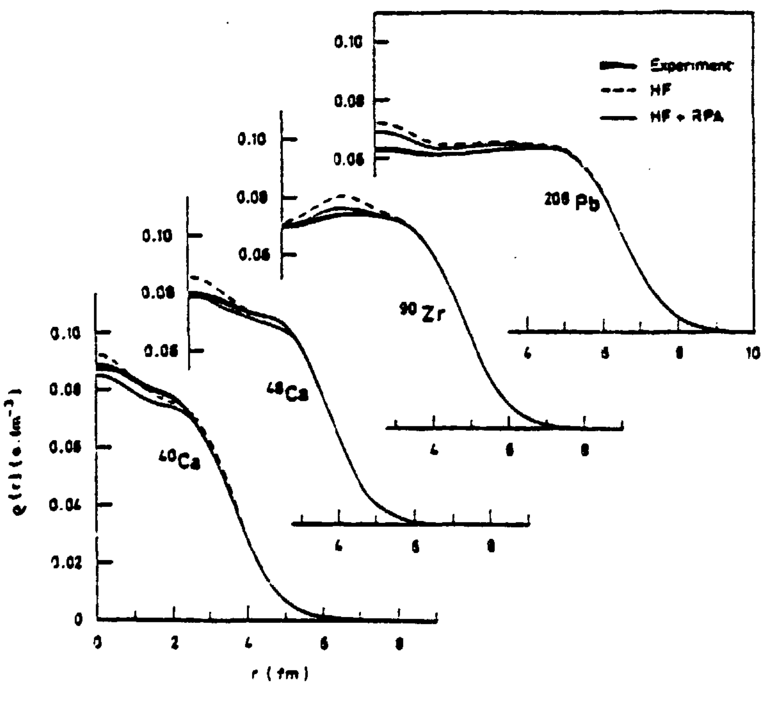

FIGURE 2
Effects of RPA ground state correlations[6].

Recently a detailed study of the charge densities of ^{90}Zr and ^{140}Ce [ref.[7]] has shown that for specific cases extensions of mean-field beyond the Hartree-Fock approximation improve the agreement with experiment in a very convincing way. In the case of ^{90}Zr it is the RPA correlations which deplete the $2p_{1/2}$ shell and populate the $1g_{9/2}$ shell. A small fraction of the charge in the vicinity of 2 fm leaves the interior of the nucleus to populate the surface of the nucleus. In ^{140}Ce the pairing correlations[3] deplete the $1g_{7/2}$ orbit. 2.6 protons leave this orbit at the surface of the nucleus to go in the central region of the nucleus in the $2d_{5/2}$ and $2d_{3/2}$ orbits. The pairing field is treated self-consistently in the Hartree-Fock Bogolyubov framework without introducing any new parameters. The migration of the nuclear charge due to long range correlations both from the surface to the interior and vice-versa is amazingly well predicted by the extensions of the mean field theory.

The central question is then : "Do correlations change the shape of the single particle wave functions in the nuclear interior ?". A priori a correlated wave function and an independent particle wave function have no reason to be identical. The answer to this question has been found recently by a detailed study of the Pb region which is discussed in the next section.

3. THE SHAPE OF SINGLE PARTICLE DISTRIBUTIONS

3.1. The Pb region

In the independent particle description, the charge distribution is simply the sum of the squares of the proton wave functions in the ground state. Electron scattering provides the possibility of measuring the observable which is the most closely related to a single particle wave function. The narrow structure in the center of ^{208}Pb can be mainly related to the two 3s protons which occupy the valence orbit. Correlations could deform the radial structure of the 3s wave function or modify its occupation probability. Figure 3 shows the variation of the ratio of the cross sections of ^{205}Tl to ^{206}Pb (which differ by a 3s proton) as a function of the momentum transferred to the nucleus. The experimental data were taken at Mainz[8] and Saclay[9]. Due to the very special shape of the 3s orbit, which has a narrow structure similar to a spherical Bessel function jo (qr), the contribution of the 3s proton can be isolated without ambiguity. The prediction of mean field theory is a peak of large amplitude totally different from the usual small fluctuations between neighboring nuclei. The experimental result and the theoretical prediction have very similar behavior ; the phase and the shape of the oscillations predicted by the theory are in remarkable agreement with the experimental result, but an almost uniform reduction of their amplitude is observed. This reduction is of the order of 30 to 35 %. A detailed analysis[9] of the various contributions to the ratio of the cross sections of

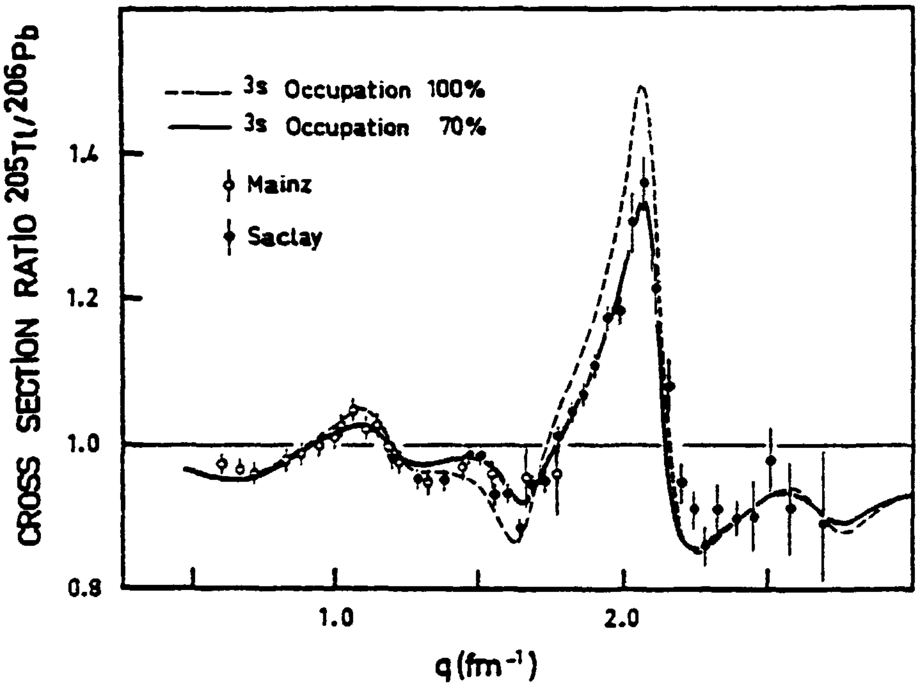

FIGURE 3
Cross section ration $^{205}Tl/^{206}Pb$. The solid curves are mean field predictions.

^{205}Tl to ^{206}Pb has shown that the 3s proton difference has an effect completely decoupled in {q} space from polarization effects. The other neighboring orbits d, g, h, etc... have a completely different radial structure and do not contribute significantly in the region of momentum transfer where the 3s creates a large peak. Polarization effects produce a very smooth variation of small amplitude which does not alter the shape of the 3s peak. This shape does not depend on the details of the force used or on pairing effects. One finds almost exactly the same shape for different mean field calculations with or without pairing. This peak in the ratio of cross sections of ^{205}Tl to ^{206}Pb is the signature of the shell-model. Figure 4 shows the charge difference between ^{206}Pb and ^{205}Tl. The very small experimental uncertainty reflects the precision attainable now in electron scattering experiments. The very characteristic shape of the 3s orbit is observed. It is the first time that we have isolated the way a particle is distributed in a quantum orbit. Experiment and theory have also the same remarkable similarity in configuration space as in momentum space. An additional piece of information appears in configuration space. Because charge is conserved we can see that the fraction of charge which has left the center of the nucleus is found at its surface : for $r > 5$ fm, the experimental charge density is higher than the theoretical prediction.

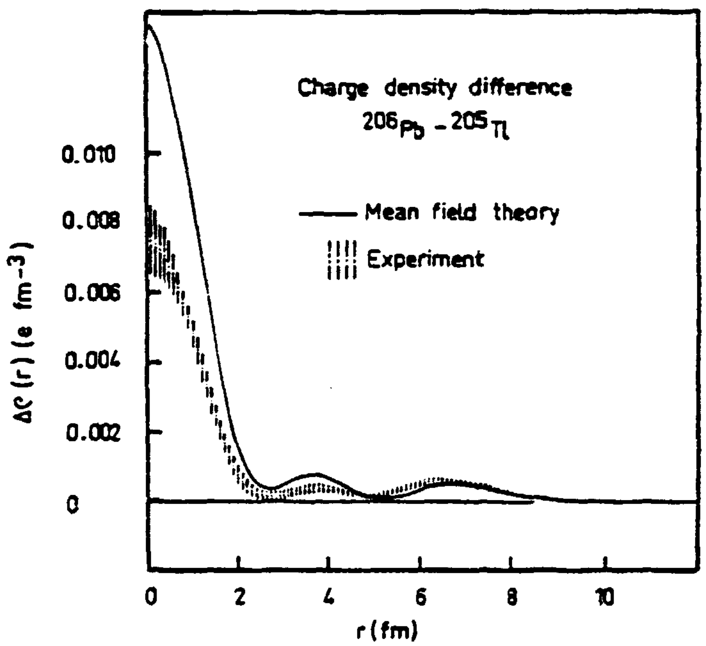

FIGURE 4
Charge density difference between ^{206}Pb and ^{205}Tl.

This experiment shows the validity of the concept of independent particle orbit to an unexpected degree. Modern self-consistent field calculations have reached quantitative agreement with the experimental shape of single particle distributions in the center of the nucleus, a feat that is truly impressive. The remaining problems which must be understood concern occupation probabilities and core polarization effects.

There does not seem to be any problem associated with the theoretical description of polarization effects induced by neutrons. Figure 5 shows the charge density differences between ^{207}Pb and ^{208}Pb, ^{206}Pb and ^{208}Pb, ^{204}Pb and ^{208}Pb. The experimental data were taken at Mainz[8] and Saclay[10]. The Hartree-Fock Bogolyubov (HFB) prediction[4] is in excellent agreement with the experimental result, while a Hartree-Fock calculation without pairing[15] is unable to reproduce the shape of the experimental charge density differences. These differences between Pb isotopes have been discussed in detail by Martorell and Sprung[11]. We find here that the HFB approximation is able to reproduce perfectly the differences of the charge densities of Pb isotopes. This means that mean field theory can handle very well the relative change of single particle distributions induced by removing up to 4 neutrons from ^{208}Pb.

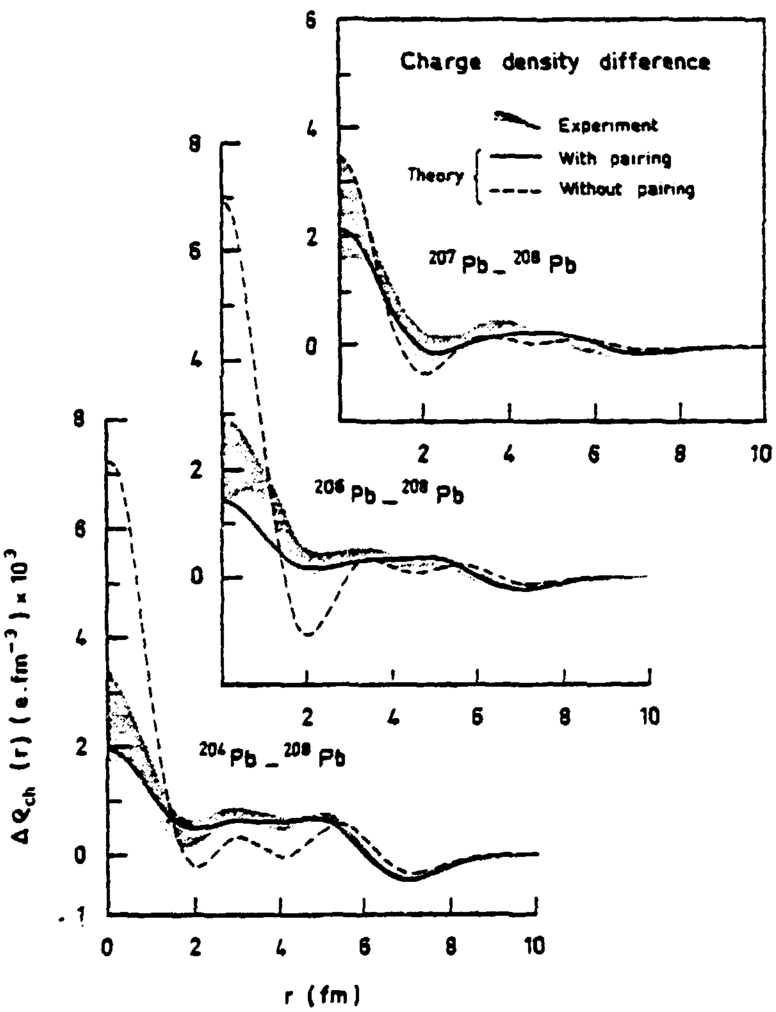

FIGURE 5
Charge density differences of Pb isotopes.

Figure 6 is the magnetic form factor of the 3s proton measured by 180° scattering at MIT-Bates laboratory[12]. A strong reduction due to core polarization effects is observed much larger than in the charge difference Pb-Tl. The data disagree completely with core-polarization calculations[13,14] which explained the M1 magnetic form factor of the $3p_{1/2}$ valence neutron hole in ^{207}Pb. This is most likely due to the fact that ^{206}Pb is *not* as *good* a closed shell nucleus as ^{208}Pb. The 3s single hole strength is strongly *affected* by open-shells[15] which are superposed on long range correlations present in ^{208}Pb. The strong reduction observed here is compatible with the predictions of Pandharipande et al.[3].

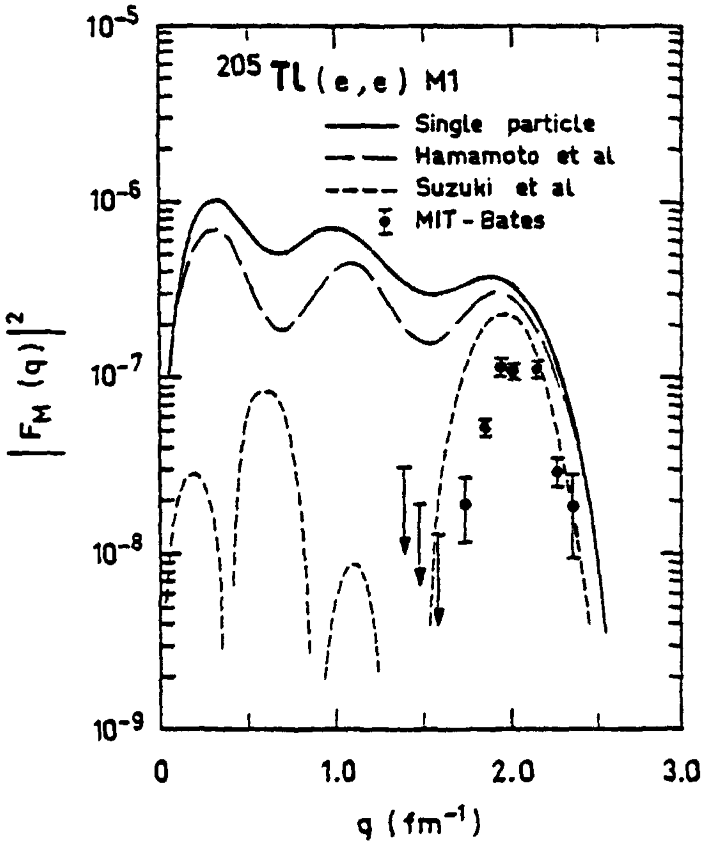

FIGURE 6
M1 magnetic form factor of ^{205}Tl.

An important piece of information is still missing, it is the link with the results of one-nucleon transfer reactions such as (d,^{3}He). These reactions probe with great precision the tail of the 3s distribution around 10 fm, but the occupation number deduced from these experiments is highly model dependent. One hopes now that by combining information from electron scattering and one-nucleon transfer data, it will be possible to have a much more precise determination of the absolute spectroscopic factors. The new electron scattering at Amsterdam NIKHEF-K laboratory will bring very valuable information through a study of (e,e'p) reactions which determines the momentum distribution of the 3s orbit as well as its spectroscopic factor. The missing mass resolution achieved at NIKHEF-K is a real breakthrough. A value of 100 keV is typical, enough to distinguish clearly the various shells. Preliminary data[17] are shown in Figure 7. They will be analyzed together with (d, ^{3}He) data measured with very high reso-

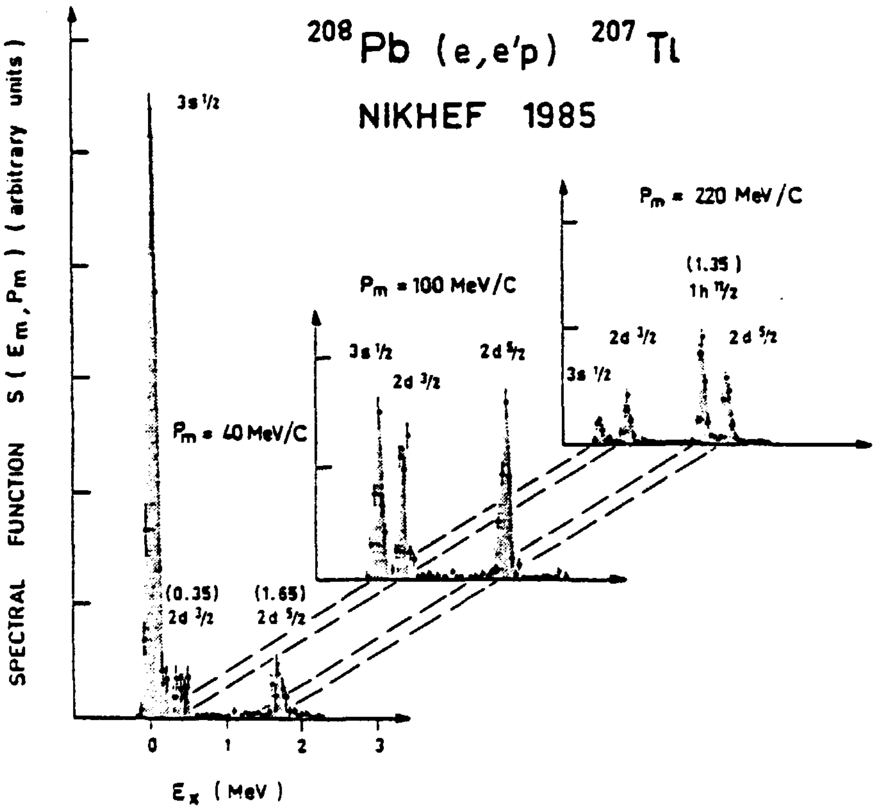

FIGURE 7
Spectral function ^{208}Pb (e,e'p).

lution obtained recently by two groups from Tubingen[13] and Indiana[19]. At present a complete comparison between ^{208}Pb, ^{206}Pb and ^{205}Tl is planned. The analysis of these data together with charge and magnetic electron scattering data should enable us to reach definitive conclusions. It is worth noting that the measurement of the momentum distribution will bring a new type of information because one expects it to be much more sensitive to the details of the short range correlations than the ground state charge density. In particular Jaminon et al.[33] have stressed that in a mean field approach it is not possible to reproduce simultaneously the charge and the momentum distribution.

3.2. The radii of the $f_{7/2}$ and $g_{9/2}$ valence orbits

Magnetic elastic scattering has provided a very accurate method for the measurement of the radii of valence orbitals. Platchkov et al[20] have measured the size of the proton and neutron valence orbits in the $1f_{7/2}$ and $1g_{9/2}$ shells.

These measurements have a very small uncertainty ± 1.5 % including the uncertainty due to the theoretical evaluation of core-polarization and meson-exchange effects. The results agree with the predictions of the most complete mean-field calculations (HFB) within this uncertainty ; however, large differences are observed between the predictions of these and other calculations. A complete review of magnetic scattering has been published recently[21]. Figure 8 shows the magnetic form factor of ^{51}V. One observes M1, M3, M5, M7 multipoles. The M7 multipole is the only one which can be isolated at high momentum transfer. It is entirely due to the spin-current of the unpaired $f_{7/2}$ proton. The change of the shape of this multipole due to meson-exchange currents and core polarization effects has a small effect on the radius of the single particle orbit[20,22,24].

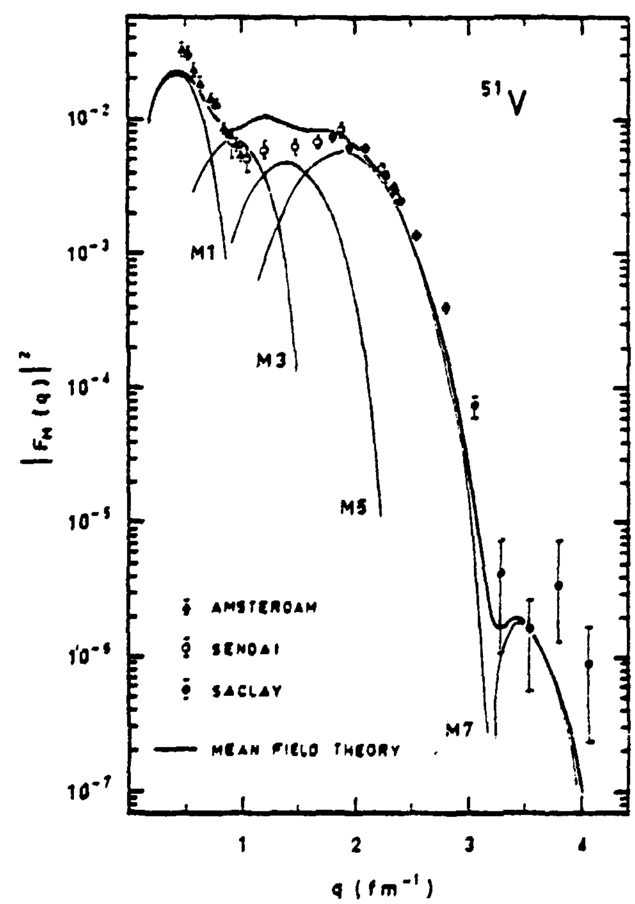

FIGURE 8
The magnetic form factor of ^{51}V.

This explains why it provides such precise information on the radius of the $f_{7/2}$ valence orbit. The experimental data[22,23] have been taken at Amsterdam, Sendai and Saclay. The Hartree-Fock Bogolyubov prediction of Dechargé and Gogny[3] are in very close agreement to the data. The data beyond 3 fm^{-1} have been found to be very sensitive to details of the wave function. In particular the predictions of the DME of Negele and Vautherin[25] and the GO force of Campi and Sprung[16] are an order of magnitude too low in the region of the second diffraction maximum of the M7 multipole.

It is worth noting that there is a difference between the magnetic density in a Hartree-Fock calculation and a Hartree-Fock Bogolyubov calculation due to the different time reversal properties of particles and quasi-particles. Pairing correlations create a slight difference between the radii deduced from charge and the one deduced by magnetic scattering.

4. DEFORMED NUCLEI

Nuclear deformations can be also handled in a self-consistent microscopic approach by performing calculations with constraint on the deformation parameters. Electron scattering can determine the precise shape of the nucleus by measuring not only the ground state charge density but also the transition charge densities of the ground state rotational band. A detailed study of several deformed nuclei was performed at MIT-Bates laboratory with very high energy resolution. A summary of these results was presented by Bertozzi[26] a few years ago. So I shall discuss very briefly some recent results. Hersman et al.[27] have studied ^{154}Gd, which is a deformed heavy rotor, by electron scattering at MIT-Bates laboratory. They have measured the charge density and the transition charge densities of the ground state rotational band. Their results have been compared with the deformed Hartree-Fock calculations of Negele and Rinker [28]) which assume axially symmetric rotation. The theoretical predictions are in reasonable agreement for the ground state and the first 2^+ state, but do not agree with the 4^+ and 6^+ transition densities.

The ground state rotational band of ^{152}Sm is at present the most well known one. It has been studied at NBS, Mainz and Saclay[29]. The resulting densities for the 0^+, 2^+, 4^+, 6^+ states are shown in figure 9 together with the predictions of a deformed Hartree-Fock-Bogolyubov calculation[30] with constraints on the particle numbers and the deformation parameters β, γ (investigating the effects of triaxial degrees of freedom). In this calculation dynamical effects are described by a collective wave function in the Bohr-Mottelson model. The agreement with all the experimental densities is reasonably good. Figure 9 includes two calculations with a slight modification of the pairing properties of the effective force. The best agreement is obtained with the force D1A, which reproduces more closely the experimental neutron separation energies in the tin isotopes. This study of the ground state rotational band of ^{152}Sm demonstrates the need for a fully dynamical treatment of nuclear deformation which takes into account correctly nuclear superfluidity in a self-consistent way.

It is worth noting that a microscopic description of low energy fission dynamics can be similarly obtained. Berger, Girod and Gogny[31] have shown recently that the fission barriers of ^{240}Pu can be very well reproduced, this provides a stringent test of the surface properties of the effective force.

Thus we have now a reasonable description of the nuclear ground state in spherical and deformed shapes. But at present there are still some difficulties in reproducing the strong variations observed in chain of very soft isotopes such as Germanium. Girod[30] has shown that it is possible to reproduce correctly the static deformation, the ground-state and the 2_1^+ densities, but it is not yet possible to reproduce the 2_2^+ densities. An explanation of their apparent strange variation has been proposed by Bazantay et al.[32] in terms of IBM-2.

5. CONCLUSIONS

Nuclear charge and magnetization densities now can be determined quite accurately in the central region of the nucleus. In 1985 the measurement of high momentum transfer data from ^{90}Zr completes the study of the charge densities of magic nuclei. The experimental uncertainty is now of the order of 1 % in the nuclear interior. This uncertainty is sufficient to allow us to see the effects of correlations beyond mean field description and to guide theoretical research.

The measurement of the charge distribution of the 3s proton orbit has demonstrated that modern self-consistent calculations are able to predict almost perfectly the shape of single particle orbits. Nevertheless it is clear that obtaining this agreement has required the use of a phenomenological density dependent effective interaction. The fundamental problem is that only nuclear matter can be calculated from a realistic two body interaction without introducing phenomenological adjustments. However major theoretical progress has been made in that once the parametrization of the force is achieved, the same force is used from ^{16}O to ^{240}Pu without any other adjustment. It is a fully self-consistent essentially parameter free theoretical description. This description can extend beyond Hartree-Fock, to include the small amplitude fluctuations due to RPA collective excitations, but also dynamical deformations in transition regions. The pairing correlations are found to be important, and recent results show that the Hartree-Fock-Bogolyubov calculations are in excellent agreement with the experimental data.

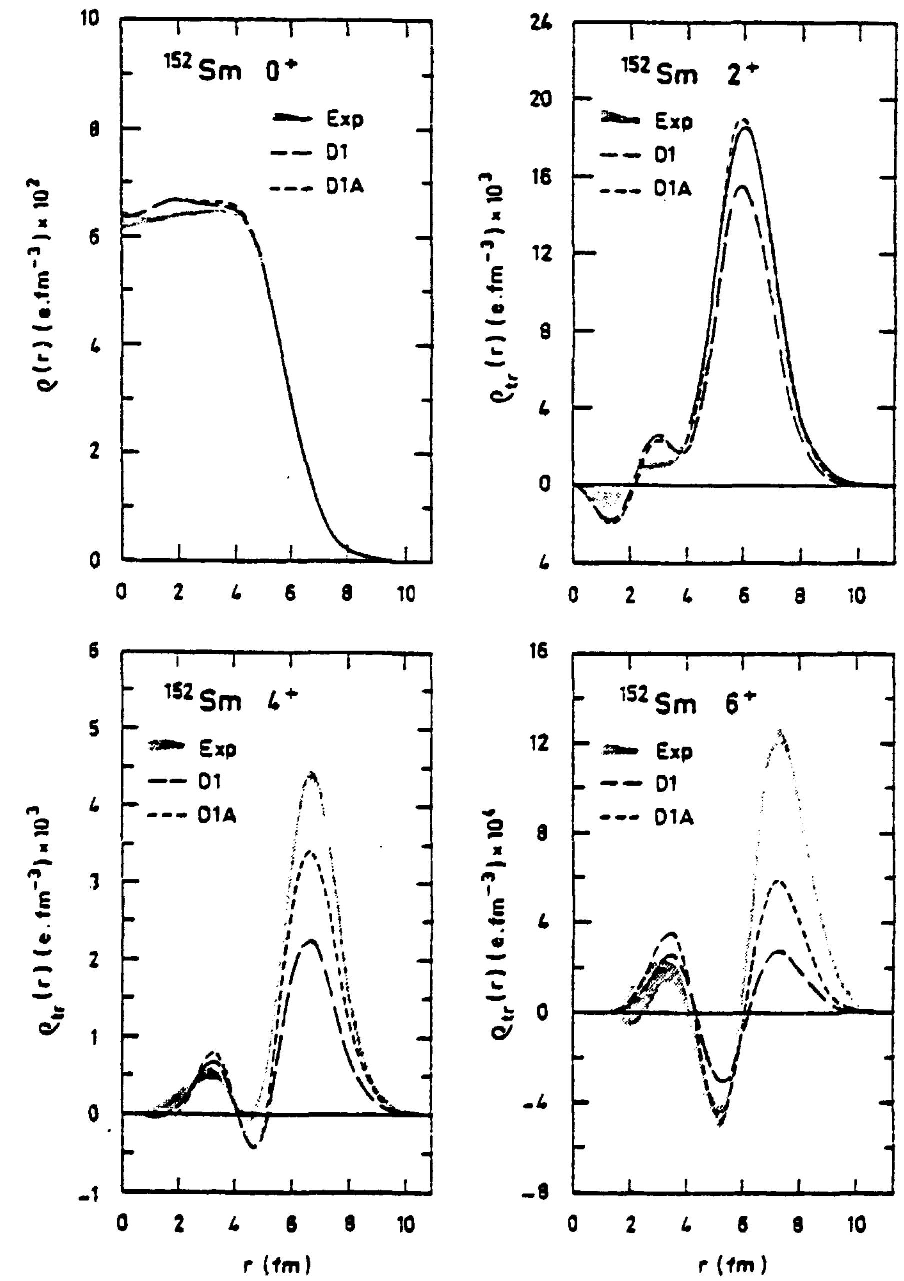

FIGURE 9
Charge densities of the ground state rotational band of ^{152}Sm.

High multipole magnetic scattering has provided very accurate information on the size of valence orbits. A direct comparison of the radii of neutron and proton orbits in the $f_{7/2}$ and $g_{9/2}$ shells has been possible. An agreement with Hartree-Fock Bogolyubov calculations is found at the 1 % level. Magnetic scattering from low multipoles is found to be very sensitive to core polarization effects which are not at present well understood. The magnetization densities of the $3s_{1/2}$ proton and $3p_{1/2}$ neutron probe these core polarization effects in the central region of the nucleus.

One major problem which remains is to understand absolute spectroscopic factors. It is hoped that a detailed study of (e,e'p) reactions in the Pb region will shed some light on this problem. This is not an easy task since one has to understand sufficiently well the reaction mechanism to obtain a quantitative answer, but it is now mainly a question of theoretical effort.

Thus, the accuracy in the nuclear interior achieved by these new electron scattering data represents considerable progress. Since the measurements are quantitative, they give us direct insight to the nature of the improvements needed in the theory.

The deviations observed between experimental results and modern self-consistent calculations can be viewed as a measurement of the correlations that are not taken into account in a mean field approach, such as the ones calculated by Pandharipande et al.[5].

A different explanation has been proposed recently by Celenza et al.[34] in terms of a modification of the size of the nucleon in a nucleus. The same increase of the size of the nucleon would reconcile[35] experiment and theory for the EMC effect, the longitudinal/transverse separation of the nuclear response function in the quasi elastic region[36], the charge density of ^{208}Pb and the ^{206}Pb-^{205}Tl charge density difference[3]. To get this agreement Celenza et al.[34] use a soliton model for the nucleon and relativistic mean field nucleon distribution[37] to which they add RPA correlations[6]. It is too early to draw final conclusions but this is an interesting possibility that needs further investigations.

The role of electron scattering in nuclear physics can be nicely illustrated by one of the thoughts[38] of Blaise Pascal.

"Those who judge a work without any rule stand with regard to others as do those who have no watch with regard to those who have one. One man says : "Two hours ago", another says : "It is only three-quarters of an hour". I look at my watch and tell the first : "You must be bored", and the second : "You hardly feel the time passing", because it is an hour and a half ago. I take no notice of those who tell me that time must hang heavily on my hands and that I am judging it according to my own fancy.

They do not know that I am judging it by my watch".

The future of electron scattering is well defined. There is a crying need for experimental data on correlations and nuclear interactions at very short distances. This is virgin territory, because no high energy electron accelerator has a sufficient duty cycle to perform the necessary coïncidence experiments. Different proposals exist now. The most ambitious project is the Continuous Electron Beam Accelerator Facility (CEBAF) proposed by United States in Virginia which will have 4 GeV and 100 % duty cycle. This project is at present the highest priority of Nuclear Physics in USA. Other projects exist at somewhat lower energies, E ~ 1 GeV and 100 % duty cycle, at Mainz, MIT-Bates laboratory, Saclay and Sendaï. Such developments are for the future the equivalent of those which have been conceived twenty years ago and which are yielding now the present generation of data.

These improvements constitute the next necessary step in furthering our understanding of the dynamics of strongly interacting particles in the nucleus.

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