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Newport News, VA 23606

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TITLE: Study of quasi-particle orbits in closed shell nuclei with (e,e'p)

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EDDYO @ UIUCNPL

THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

/X/ YES
/ / NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

Study of quasi-particle orbits in closed shell nuclei with (e,e'p)

ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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Proposal Received Nov. 6 '89

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contact: Offermann

Study of quasi-particle orbits in closed shell nuclei with $(e,e'p)$

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Abstract

We propose to pursue experimental investigations of correlations in the nuclear many-body problem using the $(e,e'p)$ probe. The high resolution spectrometers in hall A at CEBAF will offer an ideal experimental tool for the pursuit of such studies. The scope of the envisioned program, the instrumental requirements, the kinematic parameters are presented in this proposal.

1. Preamble

While limits of the mean field description of nuclear many-body systems have been seen clearly [1,2], the nature and the importance of higher-order corrections is still the subject of intense theoretical debate. We propose to investigate the limitations of the mean-field approximation and to try to elucidate the nature of these corrections with the $(e,e'p)$ observables. The available data are too limited in accuracy and dynamic range to provide guidance to nuclear theory on this subtle and yet fundamental many-body question. The determination of the momentum content of given orbitals to momenta up to $\sim 2k_f$ will provide additional valuable, since it is now well recognized that mean-field phenomenology can reproduce easily a given charge density or momentum distribution but not both. [3]

While the charge distributions of nuclei are known with high accuracy, [4] the same claim cannot be made about momentum distributions. Experiments at Saclay, [5] and at NIKHEF, [6] have contributed a great deal to our understanding of the $(e,e'p)$ probe and of momentum distributions in nuclei. However, results to date are limited by the low duty factor of available accelerators and their low-incident energies. The high quality beam of the CEBAF accelerator, with its high duty factor and high beam energies, coupled with the high-resolution spectrometers planned for Hall A, will allow the extension of available $(e,e'p)$ data to higher momenta. The kinematic flexibility (due to the high beam energies) will be essential to control and check the influence of final state interactions.

We are particularly interested in pursuing such measurements on medium and heavy doubly-closed shell nuclei like ^{40}Ca, ^{90}Zr and ^{208}Pb. These nuclei offer the best possibility for isolating many-body effects from the effects of the nuclear surface. The separation between bulk and surface effects, as has recently been demonstrated [7], can be pursued effectively through the study of multi-nodal orbitals (e.g. $3s_{1/2}$, $2p_{1/2}$ etc.) in heavy systems. In this letter of intent we outline the scope of the experimental program. For the case of ^{208}Pb we examine several questions at some detail to provide an example of the issues and the ways we intend to address them. In particular, we discuss the case of the $3s_{1/2}$ orbital in ^{208}Pb. It is most demanding from an experimental point of view and it thus helps to establish the necessary experimental parameters for the pursuit of this program that has been the object of several recent theoretical and experimental investigations.

2. Theoretical Motivation

In nuclear many-body theory the mean-field description is only the leading contribution in a series expansion in terms of multi-particle correlations. This approximation implies that a closed-shell nucleus can be described by a finite Slater determinant, i.e. it has a step-function occupation probability distribution with occupation numbers equal to unity for orbits below the

Fermi energy and zero above it. As simple as this approximation is, it allows considerable flexibility in choosing the radial shape of the wavefunctions [1]. The fact that a truly microscopic calculation is intractable for all but the lightest nuclei (where the concept of mean-field is poorly defined) means that the issue of establishing the degree of validity of the mean-field approximation is an experimental one.

The accurate determination [7] of the radial shape of the $3s_{1/2}$ orbit of ^{206}Pb has demonstrated that while the concept of a single-particle orbit in the middle of a saturated nuclear medium is valid, phenomenological mean-field theories such as density-dependent HF overpredict its strength in the center of the nucleus. The systematic overprediction of single-particle strength is also apparent in many inelastic excitations throughout the periodic table, especially in the lead region. Transitions to states having a simple microscopic composition, such as stretched-configuration states in ^{208}Pb or neutron hole states in ^{207}Pb, exhibit an almost universal 30% quenching relative to mean-field predictions. Similar quenching factors have also been observed [8] in high momentum transfer magnetic scattering from ^{207}Pb, ^{205}Tl and ^{209}Bi.

Recently, additional evidence has been emerging from coincident probes. High resolution $(e,e'p)$ measurements [8,9] on ^{206}Pb, ^{208}Pb and ^{205}Tl have derived absolute spectroscopic factors that are in agreement with the results from inclusive measurements and theoretical estimates. Re-examination [10] of Gamow-Teller resonance data also shows that the missing strength in these experiments can be explained by assuming an occupation number distribution similar to the one needed to account for the electron scattering measurements.

The natural next step in the investigation of the validity of the mean-field approximation is the determination of the nuclear wavefunctions. Available $(e,e'p)$ data have been analyzed using HF wavefunctions. An important question to be answered experimentally is: how realistic is this uncorrelated HF basis ?. In terms of the Distorted Wave Impulse Approximation (DWIA) the six-fold differential $(e,e'p)$ cross sections can be written as

$$\frac{d^6\sigma}{d e d \mathbf{p}} = K\sigma_{ep} S^D(\mathbf{p}_m, E_m, \mathbf{p}) \quad ,$$

where the distorted spectral function is given by

$$S^D(\mathbf{p}_m, E_m, \mathbf{p}) = \left[\int \chi_p^*\langle\psi_{A-1}|a_\alpha|\psi_A\rangle\, e^{-i\mathbf{q}\cdot\mathbf{r}}\, d^3r\right]^2 \quad ,$$

and the distorted proton wavefunction is represented by χ_p, which can be identified with the quasi-hole orbital

$$\chi_h(\mathbf{r}_1) = \langle\psi_{A-1}|a(\mathbf{r}_1)|\psi_A\rangle = \int \psi_h^*(\mathbf{r}_2 \dots \mathbf{r}_A)\,\psi(\mathbf{r}_1, \mathbf{r}_2 \dots \mathbf{r}_A)\, d^3r_2 \dots d^3r_A \quad .$$

In this framework the quasihole wavefunction $<\psi_{A-1}|a_\alpha|\psi_A>$ can be calculated by Fouriertransforming the spectral function. In the Hartree-Fock basis $\chi_h(\mathbf{r})$ is represented by $\phi_\alpha(\mathbf{r})$ where α is a set of quantum numbers (nlj) specifying the bound-state wavefunction.

A recent theoretical study [11] of single-particle orbitals in quantum ^{3}He liquid drops with Monte Carlo techniques offers insight into differences between the quasi-hole orbital χ_i, and the mean-field orbitals, ϕ_i. Figures 1 and 2 show orbitals which were evaluated in a 70 particle drop of ^{3}He atoms for two distinct quantum states, $3s_{1/2}$ and $1g_{9/2}$. These states were selected because it appears that the shape differences of χ_i and ϕ_i are conspicuous for $n>1$ quantum orbitals. For the latter orbitals the probability of localization in the interior high-density region of the drop is appreciable. From Monte-Carlo studies of the ^{3}He liquid drop it has been deduced that the following approximate relation holds:

$$\chi_i = \sqrt{Z(\rho(r))}\,\phi_i \quad ,$$

where $Z(\rho(r))$ is the difference of occupation probabilities of hole states $(n(h))$ and particle states $(n(p))$ at the Fermi surface for a local nucleon density $\rho(r)$.

In the $(e,e'p)$ kinematics accessible with existing facilities these shape differences are not visible [9]. It turns out that the shape of the momentum distribution $\phi(p_m)$ corresponding to $\chi_i(r)$ is not distinguishable from the one corresponding to the mean-field orbital with a slightly adjusted radial extension in DWIA model studies of surface-localized orbitals (n=1). In the case of the $3s_{1/2}$ orbital, the momentum distribution is affected at large p_m ($\approx$200 MeV/c) as is shown in figure 3. The curves shown correspond to the ansatz $\chi_{3s}(r) = (1-c\rho/\rho_0)\phi_{3s}(r)$ for c=0 (HF) and 0.3. However, the accuracy of the the existing $3s_{1/2}$ data [8] does not permit the unambiguous discrimination of these wavefunction shapes. A reasonable value of c would be 0.15, a value corresponding to the depletion of single particle states calculated for nuclear matter ($\rho=\rho_0$).

Different calculations of the proton momentum distribution in the ^{208}Pb nucleus [3] are shown in figure 4. They correspond respectively to the uncorrelated case (HF), to long-range correlations (RPA) and to tensor and short, medium and long-range correlations (PPW+RPA). Note that a clear distinction can be made between all three models only at high proton momenta (k>1.5 fm^{-1}). This momentum range has not been explored for the different ^{208}Pb orbitals at NIKHEF. By extending the existing data to higher momenta in measurements at CEBAF, quasi-hole orbitals can be extracted with sufficient precision to distinguish between the different models. This would allow the extension of the precision $(e,e'p)$ probe by determining orbital functions deep into nuclear interior.

3. Experimental Methods and Requirements

3.1 Data taking

Data will be taken mostly at high missing momentum (p_m > 250 MeV/c). Low p_m data are already available from NIKHEF; additional low p_m data can be collected at CEBAF in a very short amount of time. In order to perform a "model-independent" analysis of the measured momentum distributions (to arrive at a reliable quasi-particle orbital reconstruction in the nuclear interior) the region between p_m = 300 and 400 MeV/c is indispensable. For the study of correlations one wants to go as high as 500 MeV/c. Based on experience with the NIKHEF machine (duty factor = 1%, E_{max} = 500 MeV) we know that data at p_m = 300 MeV/c are just measurable for an energy resolution of 100 keV and a timing resolution of 1 nsec with real/accidental ratio smaller than 1. Since the momentum distribution drops two orders of magnitude between 300 and 500 MeV/c, good energy resolution and timing resolution (and therefore accurate flight-path reconstruction!) will be needed in addition to 100% duty factor.

In Table 1 we present some count rate estimates for the $3s_{1/2}$ ground state transition in the reaction ^{208}Pb$(e,e'p)^{207}$Tl. The values of the momentum distribution $\rho(p_m)$ between 250 and 350 MeV/c were derived from existing NIKHEF data [12]. Also at the momentum range region (p_m < 250 MeV/c) explored at NIKHEF substantial improvement can be expected. Superior data will emerge because of the superb quality of the CEBAF beam, the superior instrumentation at hall A and the reduced influence of final state interactions (FSI) due to the better control on the kinetic energy of the outgoing proton. Sufficient improvement on the quality of the anticipated data will allow the detection of the small but very important deviations (see Fig. 3) from the mean-field description. For higher momenta we used the calculations involving short-range correlations by Ciofi degli Atti [13]. This work predicts that the correlations show up at about 350 MeV/c for a range of nuclei (^{4}He to ^{40}Ca) at a level of $n(k)$=1 (GeV/c)$^{-3}$ for the *total* momentum distribution. Hence, at p_m = 350 MeV/c we may expect for the *two* $3s_{1/2}$ protons in ^{208}Pb a contribution 2/82 = 0.02 (GeV/c)$^{-3}$ due to correlations (see Table 1). For the present count rate estimates we have used Ciofi degli Atti's values of $n(k)$ scaled by 2/82. Clearly this ansatz is very optimistic, if not outright unrealistic, since most of the excess strength is expected to be at higher missing energies. However, taken as such, it provides a useful recipe for count rate estimates for setting the scale of the experimental program and the values of the various experimental parameters. In practice, we expect to map the momentum distribution of all accessible orbitals up to the limit of detection of the CEBAF system which should occur earlier than the above ansatz implies.

3.2 Experimental requirements

The experiment requires an energy resolution of about 125 keV. This requirement originates from the need to separate the low-lying discrete transitions. For the nuclei of interest we list some relevant energy differences:

^{208}Pb :	350 keV between $3s_{1/2}$ and $2d_{3/2}$ state, 330 keV between $1h_{11/2}$ and $2d_{5/2}$ state
^{90}Zr :	250 keV between $2p_{3/2}$ and $1f_{5/2}$ state
^{40}Ca :	300 keV between $2s_{1/2}$ and $1f_{7/2}$ state, 200 keV, between $1f_{7/2}$ and $1d_{3/2}$ state

Clearly, one should aim at 125 keV missing-energy resolution. This requires e.g.:

monochromatic beam resolution	3×10^{-5}	at 1000 MeV	yields 30 keV
electron spectrometer	1×10^{-4}	at 800 MeV	yields 80 keV
proton spectrometer	1×10^{-4}	at T_p=200 MeV	yields 40 keV

For a 2 GeV beam one needs a 5×10^{-5} momentum resolution in the electron spectrometer. The dispersion matching technique will be mandatory unless the total beam-energy resolution can be made as small as 3×10^{-5}. The missing momentum resolution of the proposed experiment is not crucial. A value of 5 MeV/c entails a few mrad angular resolution for the spectrometers.

3.3 Kinematics

We propose to measure data in parallel kinematics, i.e. q//p, q<p (see Table 1). Choosing a beam energy of 750 MeV and a proton energy of 250 MeV we find that the range p_m = 250-450 MeV/c yields electron spectrometer angles larger than 10° and typical count rates of 10-100 counts/hr. Going to a beam energy of 1500 MeV yields an order of magnitude larger count rates, but the high p_m data require extremely forward electron angles. This may be cured by employing larger proton energies, as exemplified by the entry T_p = 400 MeV, E_0 = 2000 MeV in Table 1. However, such a choice of kinematics will require extremely good momentum resolutions for both spectrometers (see sect. 3.2). In principle it would be possible to change to antiparallel kinematics (q>p), which implies much less forward angles. However, in that case other difficulties will arise as shown by the entry T_p = 250 MeV, E_o = 2000 MeV in Table 1. In the interesting p_m region (300-500 MeV/c) typical count rates are below 1 count/hr. As shown in Table 1, going to 4000 MeV does not alleviate this problem substantially. The region p_m = –300 to 0 MeV/c is easily measurable at these energies.

In order to separate the nuclear structure information from the reaction mechanism and distortion effects one should check the dependence of the data on proton energy (i.e. FSI), on electron energy (i.e. Coulomb Distortion) and on virtual photon polarization ε. The latter point requires a longitudinal-transverse (L/T) separation with a sufficiently large difference in ε. For this purpose one should go as low as 500 MeV beam energy, as shown in Table 1. An investigation of the FSI can be carried out by studying the same region of the spectral function at various proton energies e.g. 150, 200, 250 MeV. This yields similar kinematics and count rates. The Coulomb distortion effects are expected to be well controlled at high beam energies.

The kinematic range of the proposed measurements follows from the acceptances of the spectrometers. For $\delta p/p$ = 10 % and $\Delta\Omega$ = 10 msr for both spectrometers one has a span in missing energy of up to 100 MeV and in missing momentum of about 100 MeV/c. Note that the count rates listed in Table 1 are *integrated* over this p_m range, but that they correspond to the g.s. transition (E_m = 8 MeV) only. Obviously the data automatically contain the momentum distributions of all other quasiparticle orbitals down to the $1s_{1/2}$ orbital at E_m = 60 MeV. It is proposed to perform an angular-momentum decomposition of these data up to large values of E_m.

An interesting observable can also be obtained by summing the observed strength found up to a given excitation (missing) energy as a function of missing momentum. This "sum rule" can be compared directly with theoretical calculations and can help establish the minimum of correlations needed to achieve a reasonable description of a heavy nucleus. Such data are simply unavailable at this point due to the lack of high-energy c.w. electron beams.

4. Beam time request

We base our beam time request for the measurements at high p_m (300-500 MeV/c) on a statistics of 100 counts per 25 MeV/c p_m bin. The study of the final state interactions requires a similar amount of beam time for each different T_p. The low p_m data can easily be obtained with an accuracy of <5 %. The L/T separation requires a large amount of beam time due to the low count rates in the "transverse" kinematics. In summary we request a total of 420 hours of beam time for the first studies on ^{208}Pb. This time will be spent as detailed in Table 2. Studies of the requirements for extending this work to ^{40}Ca and ^{90}Zr are in progress and will be presented at a later time.

Table 1: $^{208}Pb(e,e'p)^{207}Tl$, $3s_{1/2}$ g.s. transition for t = 30 mg/cm^2, I = 30 μA, Ω_e = 10 msr, Ω_h = 10 msr, $dp/p\,|_e$ = 10 % and $dp/p\,|_h$ = 10 %.

PARALLEL KINEMATICS : T_p = 250 MeV

E_o MeV	p_m MeV/c	q MeV/c	θ_e deg	θ_p deg	$K\sigma_{ep}$ fm^{2}MeV^{2}sr^{-1}	cnts hr^{-1}	ρ (GeV/c)$^{-3}$	eps
500.0	250.0	479.8	71.14	-28.43	4.398e+0	18.16	1.0	0.410
500.0	300.0	429.5	59.15	-28.87	8.234e+0	3.96	0.1	0.498
500.0	350.0	379.2	47.07	-27.81	1.657e+1	1.95	0.02	0.586
500.0	400.0	328.9	34.06	-24.31	3.695e+1	0.98	0.01	0.671
500.0	450.0	278.6	17.31	-14.97	1.129e+2	1.99	0.005	0.753
750.0	250.0	479.8	38.89	-40.01	1.865e+1	86.28	1.0	0.740
750.0	300.0	429.5	32.82	-38.33	3.469e+1	17.24	0.1	0.786
750.0	350.0	379.2	26.43	-35.24	6.874e+1	7.51	0.02	0.829
750.0	400.0	328.9	19.31	-29.62	1.497e+2	9.34	0.01	0.869
750.0	450.0	278.6	9.89	-17.64	4.371e+2	17.33	0.005	0.904
1000.0	250.0	479.8	27.15	-44.83	4.268e+1	230.58	1.0	0.859
1000.0	300.0	429.5	22.98	-42.37	7.929e+1	46.04	0.1	0.885
1000.0	350.0	379.2	18.55	-38.47	1.565e+2	19.87	0.02	0.910
1000.0	400.0	328.9	13.58	-31.97	3.389e+2	24.22	0.01	0.931
1000.0	450.0	278.6	6.97	-18.84	9.776e+2	42.57	0.005	0.950
1500.0	250.0	479.8	17.03	-49.28	1.201e+2	789.60	1.0	0.941
1500.0	300.0	429.5	14.44	-46.13	2.228e+2	155.94	0.1	0.952
1500.0	350.0	379.2	11.67	-41.49	4.388e+2	66.11	0.02	0.963
1500.0	400.0	328.9	8.56	-34.18	9.470e+2	78.30	0.01	0.972
1500.0	450.0	278.6	4.40	-19.97	2.712e+3	129.69	0.005	0.980

Table 1 continued.

PARALLEL KINEMATICS : T_p = 400 MeV

E_o MeV	p_m MeV/c	q MeV/c	θ_e deg	θ_p deg	$K\sigma_{ep}$ $fm^2MeV^2sr^{-1}$	cnts hr^{-1}	ρ $(GeV/c)^{-3}$	eps
2000.0	250.0	705.8	18.55	-45.82	3.936e+0	380.82	1.0	0.926
2000.0	300.0	655.5	16.51	-43.60	6.577e+1	66.60	0.1	0.936
2000.0	350.0	605.1	14.36	-40.71	1.137e+2	24.26	0.02	0.945
2000.0	400.0	554.8	12.07	-36.85	2.056e+2	23.32	0.01	0.953
2000.0	450.0	504.5	9.51	-31.41	3.994e+2	24.39	0.005	0.961

ANTI-PARALLEL KINEMATICS: T_p = 250 MeV

E_o MeV	p_m MeV/c	q MeV/c	θ_e deg	θ_p deg	$K\sigma_{ep}$ $fm^2MeV^2sr^{-1}$	cnts hr^{-1}	ρ $(GeV/c)^{-3}$	eps
2000.0	-250.0	982.9	29.44	-60.43	2.316e+0	12.16	1.0	0.871
2000.0	-300.0	1033.2	31.09	-60.38	1.592e+0	0.82	0.1	0.858
2000.0	-350.0	1083.5	32.75	-60.26	1.105e+0	0.11	0.02	0.845
2000.0	-400.0	1133.9	34.42	-60.08	7.734e-1	0.04	0.01	0.832
2000.0	-450.0	1184.2	36.08	-59.83	5.458e-1	0.01	0.005	0.818
4000.0	-250.0	982.9	14.08	-67.71	1.044e+1	74.34	1.0	0.968
4000.0	-300.0	1033.2	14.85	-68.08	7.141e+0	4.99	0.1	0.965
4000.0	-350.0	1083.5	15.63	-68.38	4.929e+0	0.68	0.02	0.962
4000.0	-400.0	1133.9	16.40	-68.61	3.431e+0	0.236	0.01	0.958
4000.0	-450.0	1184.2	17.18	-68.79	2.408e+0	0.08	0.005	0.954

Table 2: Summary of the beam-time request for $^{208}Pb(e,ep')^{207}Tl$.

item	E_o [MeV]	p_m-range [MeV/c]	beam time [hrs]
parallel	750	0 to 300	30
antiparallel	2000	-250 to 0	50
high p_m	750	300-500	70
FSI	750	300-500	70
L/T separation	500	300-500	200
		total	420

Figure Captions

Fig. 1 Shapes of a $3s_{1/2}$ quasi-particle orbital (solid curve) and a mean-field orbital (dot-dash) in a 70 particle ^{3}He drop. The quasi-particle orbital obtained in a local density approximation is a good approximation to the Monte Carlo result shown by points with error bars. (Figure adapted from Ref. 11)

Fig. 2 Idem for the $1g_{9/2}$ orbital.

Fig. 3 Momentum distributions of the $3s_{1/2}$ orbital calculated with the local density approximation for values $c = 0$ and $c = 0.3$ in DWIA (parallel kinematics), 70 MeV proton energy and an optical appropriate for ^{208}Pb. (figure adapted from Ref. 6)

Fig. 4 Proton momentum distribution in the ^{208}Pb nucleus. They respectively correspond to the uncorrelated case (HF), to long-range correlations (RPA) and to tensor and short, medium and long-range correlations (PPW+RPA). (figure adapted from Ref. 3)

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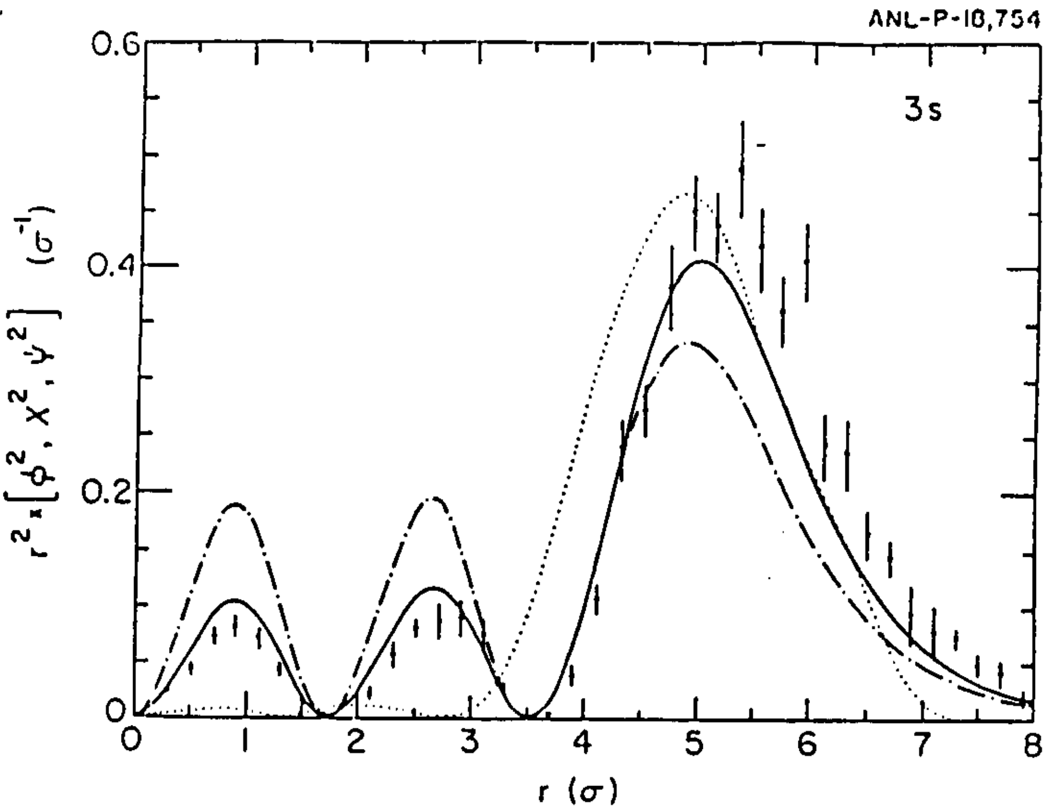
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3s
$r^2 \times [\phi^2, \chi^2, \psi^2]$ (σ^{-1})
r (σ)
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0.2
0.4
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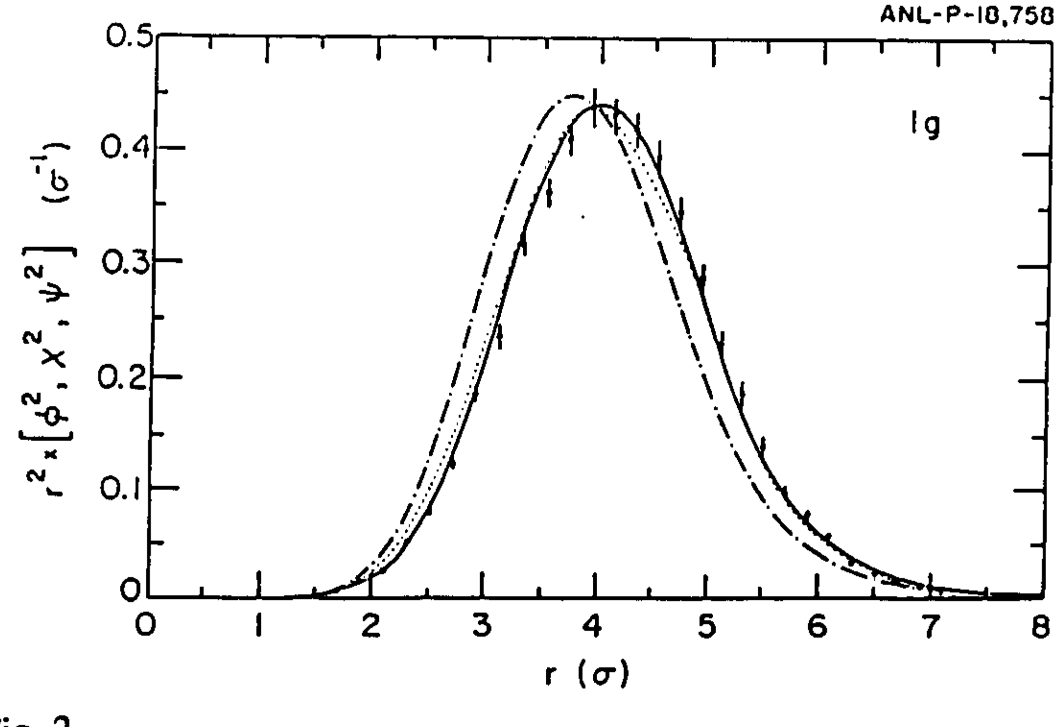
0 1 2 3 4 5 6 7 8

Fig. 1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1g
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r (σ)
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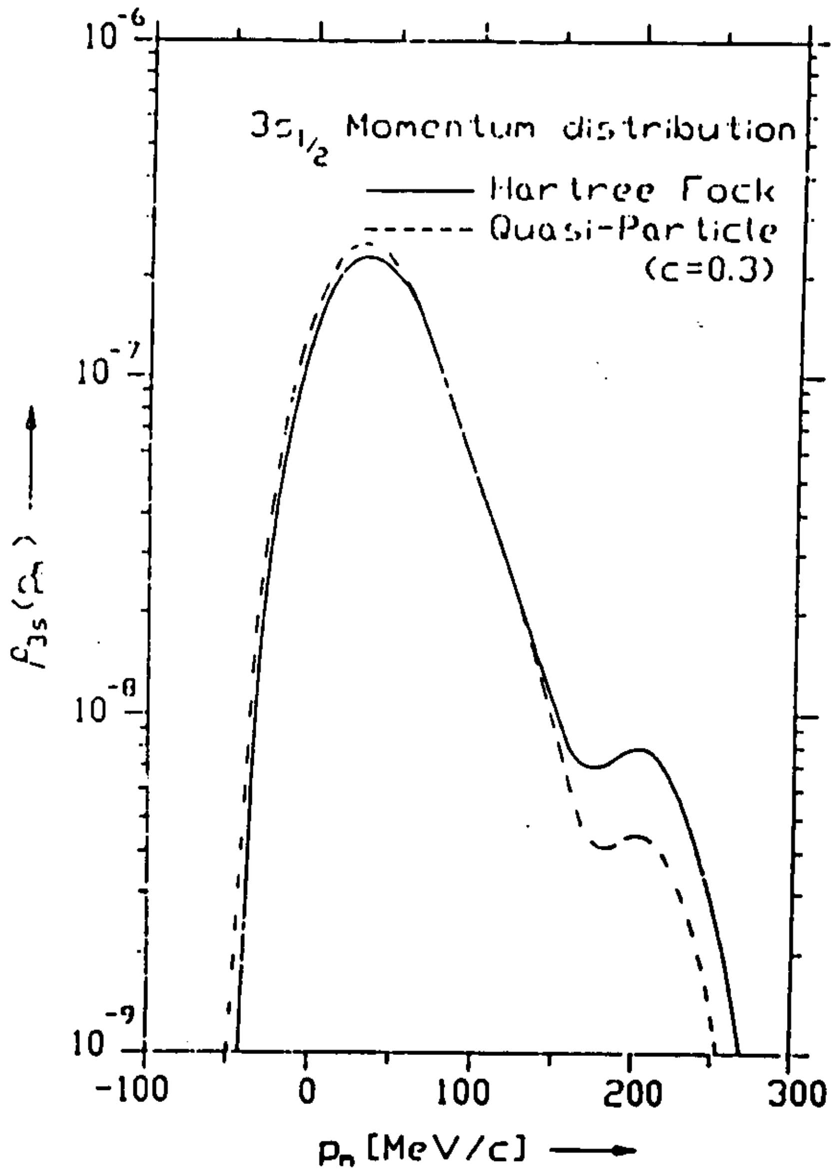
0.3
0.4
0.5
0 1 2 3 4 5 6 7 8

Fig. 2


3s1/2 Momentum distribution
Hartree Fock
Quasi-Particle
(c=0.3)
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10^-7
10^-8
10^-9
-100
0
100
200
300
pn [MeV/c]

Fig. 3

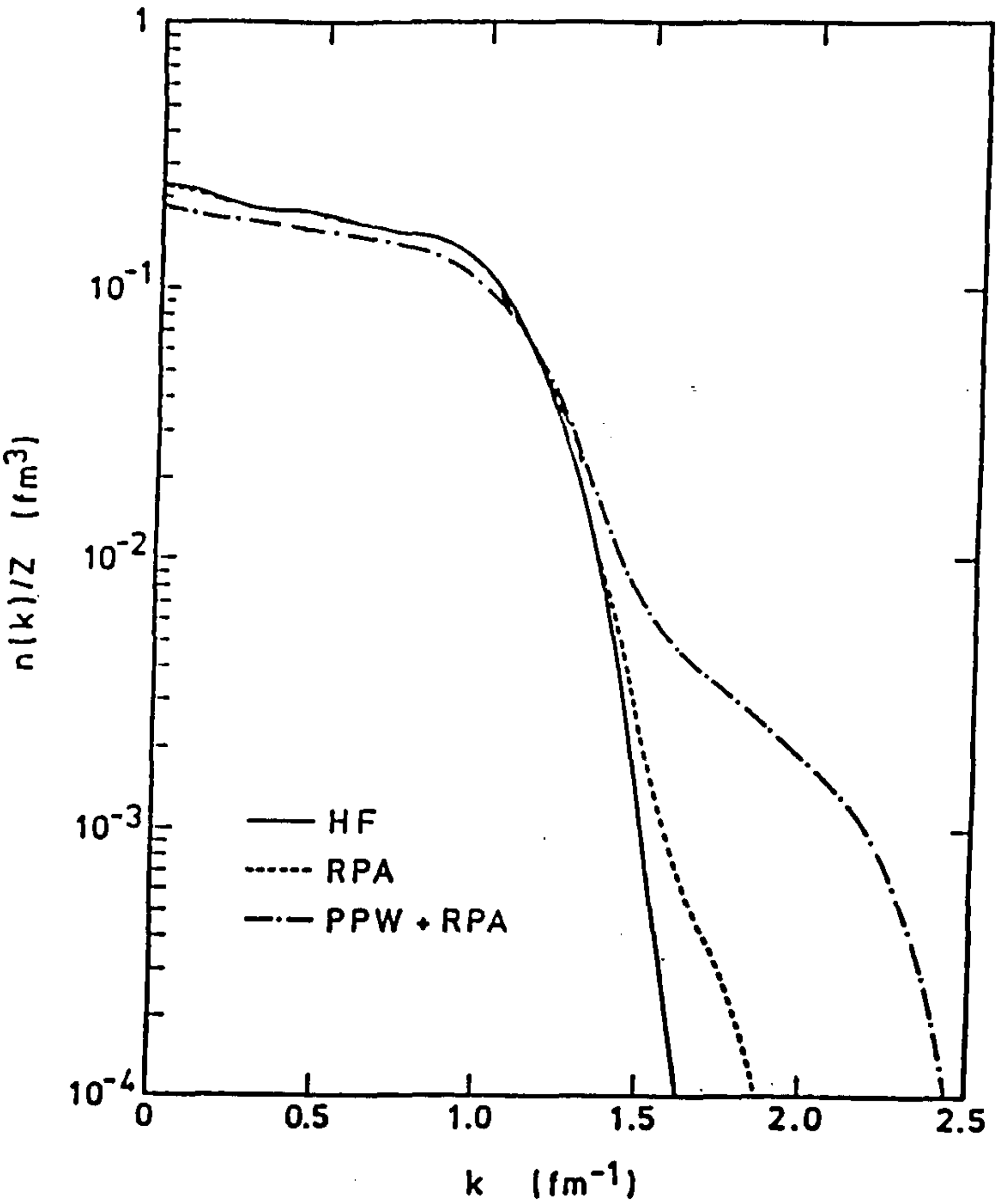

Fig. 4