Quasielastic $^{40}Ca(e,e'p)$ cross sections in a many-particle self-consistent Hartree model

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A fully distorted partial-wave calculation is presented for the reaction $^{40}Ca(e,e'p)^{39}K$ which uses relativistic self-consistent Hartree wave functions for both the target nucleus and the residual nucleus. The final state interaction of the knocked-out nucleon is described by an optical potential and the Coulomb distortion of the electron wave functions is also included. We assume standard values for meson coupling constants and masses in the Hartree calculations and the optical potential used comes from global fits to elastic proton scattering; hence, this calculation is a description of $(e,e'p)$ reactions with no free parameters. We examine the proton knocked-out from the $d_{3/2}$ state of ^{40}Ca which leaves the residual nucleus ^{39}K in its ground state. Agreement with the experimental data of NIKHEF is good and the calculated spectroscopic factor agrees very well with the one extracted from experiment. There seems to be no need to make the assumption that the $d_{3/2}$ state is appreciably depleted. We also calculate the $(e,e'p)$ cross section from the $2s_{1/2}$ and $1f_{7/2}$ orbitals. For the $2s_{1/2}$ orbital the shape does not agree so well with the experimental data. The $f_{7/2}$ orbital leads to approximately the correct shape and we extract a spectroscopic factor of 3.7%.

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I. INTRODUCTION

Analyses of $(e,e'p)$ reactions in the quasielastic region to study the shell structure of nuclei have attracted great interest over the past decade [1–6]. If one takes the view that one is knocking a proton out of a particular bound state of a target nucleus, the $(e,e'p)$ reaction should allow one to study the momentum distribution of the initial bound state and to extract the spectroscopic factor. Over the past few years such experiments have been carried out on ^{40}Ca, ^{90}Zr, ^{208}Pb, and some other nuclei at NIKHEF, Amsterdam [7–9], and more data are expected in the future. However, when it comes to extracting information about the target nucleus, particularly the spectroscopic factors of the initial proton states, there have been some conflicting results; most commonly the spectroscopic factors extracted are anomalously low. Some of this must be due to the choice of nuclear models and appropriateness of simplifications used in the analysis.

The simplest set of assumptions is the plane-wave impulse approximation (PWIA). The electron is presumed to interact with one proton only, which is initially bound in the nucleus, and raise it to a free (plane-wave) state. Evidently, taking $\mathbf{p}_p$ as the outgoing proton momentum and $\mathbf{q}$ as the momentum transferred by the electron, the so-called missing momentum

$$\mathbf{p}_m = \mathbf{p}_p - \mathbf{q} \tag{1}$$

must have been the initial momentum of the proton. Thus, knowing the electron-proton cross section (which must necessarily be off shell), one can extract the momentum distribution in the initial proton state:

$$\rho_m(\mathbf{p}_m) = \frac{1}{pE\sigma_{ep}} \frac{d^3\sigma}{dk'_0 d\Omega_{k'} d\Omega_p}. \tag{2}$$

In Eq. (2), k_0 and $\mathbf{k}'$ refer to the outgoing electron energy and momentum. The off-shell cross section is not uniquely defined, but the deForest cross section σ^{cc1} [10] is commonly used (and will be used here). This cross section has a particularly simple form when $\mathbf{p}_m$ is parallel to $\mathbf{q}$, and consequently it is popular to set the proton detectors in that configuration, called parallel kinematics, which is used in all the experiments quoted here. In this analysis the measured cross section has only to be reduced by the factor $pE\sigma_{ep}$ as in Eq. (2), and the spectroscopic factor S may be extracted in principle by integrating ρ_m over $\mathbf{p}_m$. More practically, S can be extracted by comparing theoretical calculations of ρ_m to the experimental data as discussed below.

In practice, the PWIA is inadequate, but it has left an indelible stamp on the way experiments are designed and results are presented. It also contains the essential expectation that one may hope to extract the single-particle wave function (or momentum distribution) for the bound proton and the spectroscopic factor. More generally, any calculation of the differential cross section is bound to make some assumption about the effective single-particle wave function for the proton orbital. Successfully reproducing the *shape* of the cross section is then a measure of the model's success, but reproducing the *magnitude* of the cross section requires the spectroscopic factor which, if not a product of the calculation, can nevertheless be inferred by reducing the calculated cross section by the factor S to fit the measurement. In all models of the $(e,e'p)$ problem one is dealing with the interaction of an electron current and a nuclear current, which is not to imply that the cross section will break up into two factors as in PWIA, but the two parts do call for rather different sets of assumptions.

In the nuclear part, because we are assuming quasielastic conditions, the nuclear matrix element breaks up

into two parts: a single-particle part, which involves an electromagnetic transition current between a bound proton state and a continuum wave function, and a second part, which consists of the overlap of the wave function of the initial target nucleus with a hole (corresponding to the knocked-out proton) and the wave function of the residual nucleus, which is clearly related to the spectroscopic factor.

For the single-particle part of the transition we use simple nuclear wave functions consistent with known data on their respective states, and the free nucleon current operator (the operator $j^{(1)}$ of Ref. [11]). This combination does not give a strictly conserved current, and Ref. [11] furnishes some estimates of the consequences of this shortcoming. Our best estimate of the lack-of-conservation uncertainty is around 5%, but while there are many possible schemes for modifying the current to conform, a compelling case to adopt one of these has yet to appear. We have to accept that there are two-body and mesonic components discarded in the impulse approximation, and it would be unreasonable to demand a conserved current in such a case.

We use relativistic Hartree wave functions, which can reproduce many physical observables of finite nuclei, to describe both initial and final nuclei, and we use a relativistic optical potential, which can account for all elastic proton-scattering observables [12], to describe the final-state interaction of the outgoing proton and residual nucleus. Since we are using many-particle wave functions for the nuclei, we can calculate the effective single-particle wave function and the spectroscopic factor within one framework. One must acknowledge, however, that different optical potentials fitted to elastic proton scattering can result in wave functions which differ in the nuclear interior because any phase-equivalent potential may be used. It may be that the $(e,e'p)$ reaction can help remove this ambiguity since it is sensitive to the wave function in the nuclear interior.

An alternative approach is to use a random phase approximation (RPA) model to calculate the nuclear states and thereby avoid the use of an optical potential. A nonrelativistic continuum RPA has been used by Ryckebusch *et al.* [2–4], [13] by Cavinato, Marangoni, and Saruis [5], and by Saruis and Clemente [6] and in each case employs a Skyrme-type residual interaction which serves well to reproduce the resonance region of nuclear reactions and which has been extended to the quasielastic region [3]. Since this leads to many different outgoing channels, including any residual collective-type absorption, the model contains elements of the absorptive part of the optical potential and some features not described thereby. As a result it has great promise, especially in the region of overlap between resonance absorption and single-particle interaction. But the method entrusts a great deal to a residual interaction which not only provides the final-state interaction for the proton; it also rearranges the nuclear (initial and final) bound states. Yet it is generally a phenomenological force not tuned to the particular phenomena or energy region considered here.

By contrast to the difficult job of defining the nuclear current, the electron side of the calculation is unambiguous and can be refined more or less indefinitely: Here the needed elements are the correct electron wave functions and the treatment of the electromagnetic interaction. In most previous analyses of quasielastic scattering, the potential arising from the electron current has been evaluated using electron plane waves (the plane-wave Born approximation) or by using various approximations of Coulomb distortion which nevertheless use the plane-wave formalism as a basis.

In earlier work [14,15] we described a distorted-wave Born approximation analysis which treats the electron Coulomb distortion arising from the Coulomb potential of the target through partial-wave analysis, and found significant differences with the approximate treatment of Coulomb distortion. For medium and heavy nuclei, the electron Coulomb distortion is very important and a full distorted-wave analysis is required. If one uses an approximate treatment of Coulomb distortion, the information extracted can be misrepresented. The problem of low spectroscopic factors extracted from $(e,e'p)$ as compared with other probes is, in part, due to the electron Coulomb distortion not being treated correctly. Another electron distorted-wave calculation [16] of $(e,e'p)$ has appeared, but as reported in Ref. [15], we find serious disagreements with this calculation, whereas we are in tolerable agreement with other calculations (nonrelativistic or plane wave) in the appropriate limits. Furthermore, the size and direction of Coulomb distortion effects shown in Ref. [16] are not consistent with our experience in investigating these effects.

In calculations reported in this paper we combine the same formalism as Ref. [15] for the electron distorted-wave Born approximation with the relativistic Hartree framework for the nuclear part of the matrix element. Whether or not this can describe the experimentally observed cross section can help us assess the validity of the Hartree wave functions. We examine the cases of proton knockout from the $d_{3/2}$ state of ^{40}Ca leaving the residual nucleus in the ground state of ^{39}K and proton knockout from the $2s_{1/2}$ state leaving ^{39}K in an excited state. Proton knockout from the $f_{7/2}$ shell in ^{40}Ca is also considered.

In Sec. II we present the formalism and discuss the calculation of spectroscopic factors in the Hartree model. In Sec. III we relate our calculations of the reduced cross section to experimental data from NIKHEF. We will discuss the spectroscopic factors for three orbitals in ^{40}Ca, and finally in Sec. IV we give our conclusions.

II. FORMALISM

In the first Born approximation, the interaction Hamiltonian for quasielastic electron scattering is well known from electrodynamics:

$$H_{\rm int} = -\langle \Psi_f | J^\mu A_\mu | \Psi_i \rangle, \tag{3}$$

where J^μ is the nucleon transition current operator and A_μ is the potential generated by the electron transition current j_μ. The operator J^μ is a one-body operator and

in this model only operates between single-particle states. We assume the single-particle state for the knocked-out proton $|\phi_f\rangle$ is determined by an optical potential and that the entire final state $|\Psi_f\rangle$ is a direct product of the residual nucleus and the knocked-out proton. Then we can write Eq. (3) as

$$H_{\rm int} = -\langle\phi_f|J^\mu A_\mu|\Phi_i\rangle, \tag{4}$$

where Φ_i is an effective single-particle state for the initial bound proton and is defined, for the case of ^{40}Ca as the target, by taking the overlap of the remaining 39 nucleons:

$$\Phi_i = \langle{}^{39}\mathrm{K}|{}^{40}\mathrm{Ca}\rangle. \tag{5}$$

The effective single-particle state is neither a ^{39}K nor a ^{40}Ca single particle state, and to calculate it we have to know the wave functions for both.

Of course, one expects that a doubly closed shell nucleus with A nucleons is spherical, but the neighboring odd nucleus with $A-1$ nucleons will in general not be spherical. Thus one has to do a deformed Hartree calculation for the residual nucleus in order to get realistic Hartree states. We use ψ_κ to represent the single-particle wave functions of the target nucleus (^{40}Ca) and $\phi_{\kappa'}$ to represent the single particle wave functions of the final residual nucleus (^{39}K). If both nuclei are in the ground state, then in both cases the nuclei have all their levels completely filled up to the Fermi level. Then we can write the effective single particle wave function as an expansion in terms of initial spherical single-particle wave functions:

$$\begin{aligned}\Phi_i &= \langle{}^{39}\mathrm{K}|{}^{40}\mathrm{Ca}\rangle \\ &= \langle{}^{39}\mathrm{K}|{}^{40}\mathrm{Ca}(d_{3/2})^{-1}\rangle\psi_{d_{3/2}} \\ &\quad + \langle{}^{39}\mathrm{K}|{}^{40}\mathrm{Ca}(2s_{1/2})^{-1}\rangle\psi_{2s_{1/2}} + \cdots \\ &= \sqrt{S_{d_{3/2}}}\psi_{d_{3/2}} + \sqrt{S_{2s_{1/2}}}\psi_{2s_{1/2}} + \cdots,\end{aligned} \tag{6}$$

where the notation $|{}^{40}\mathrm{Ca}(d_{3/2})^{-1}\rangle$ means the initial target nucleus (^{40}Ca) wave functions with a hole in the $d_{3/2}$ state, and $S_{d_{3/2}}$ is the spectroscopic factor.

Specifically, if we are knocking a proton out of the $d_{3/2}$ state from ^{40}Ca leaving the residual nucleus in the ground state of ^{39}K, it turns out that only one term ($S_{d_{3/2}}$) in Eq. (6) is dominant and all the others can be neglected. The spectroscopic factor $S_{d_{3/2}}$ is then given by

$$S_{d_{3/2}} = \left|\langle{}^{39}\mathrm{K}|{}^{40}\mathrm{Ca}(d_{3/2})^{-1}\rangle\right|^2. \tag{7}$$

To calculate the spectroscopic factors, we use a relativistic self-consistent Hartree model for both the initial ^{40}Ca nucleus and the residual ^{39}K. The model has its origins in the relativistic one-boson-exchange description of the NN interaction [17] and Walecka model [18], and is fully described in Ref. [19]; we give a short description below.

We start from an effective local Lagrangian density which couples a nucleon (ψ) to four mesons with the following spin-parity and isospin quantum numbers (J^π, T):

$$\sigma(0^+,0),\quad \omega(1^-,0),\quad \pi(0^-,1),\quad \rho(1^-,1). \tag{8}$$

We have also included electromagnetic interactions (A^μ). The interaction part of the Lagrangian density can be written as [19]

$$\begin{aligned}\mathcal{L}_I &= g_\sigma\bar\psi\sigma\psi - g_\omega\bar\psi\omega^\mu\gamma_\mu\psi - \frac{f_\pi}{m_\pi}\bar\psi\gamma_5\gamma^\mu\boldsymbol{\tau}\psi\partial_\mu\boldsymbol{\pi} \\ &\quad - g_\rho\bar\psi\boldsymbol{\rho}^\mu\boldsymbol{\tau}\gamma_\mu\psi - e\bar\psi\gamma^\mu\tfrac{1}{2}(1+\tau_3)A_\mu\psi,\end{aligned} \tag{9}$$

where g_σ, g_ω, etc., are coupling constants for the corresponding mesons. We consider all these coupling constants to be fixed by other calculations [19].

Having defined the Lagrangian, one can write down the Hamiltonian and carry out a variational procedure on the basis of Hartree or Hartree-Fock wave functions to obtain the single-particle equations. For spherical nuclei one obtains the Dirac equation for a single particle in central scalar and timelike vector mean-field potentials. The mean-field potentials and the nucleon wave functions are coupled, and a solution is obtained by using an iteration method until self-consistency is achieved.

For odd-A nuclei, because of lack of symmetry, there are more components in the meson mean fields and also the system may find a minimum in a deformed state. The single-particle wave functions are thus defined in the intrinsic frame of the nucleus. In our calculation, we consider an axial and space-reflection symmetric system, so that the angular momentum j is not a good quantum number; however, m (third component of angular momentum), π (parity), and t_3 (third component of isospin) are still good quantum numbers and there is still a principal quantum number n. To solve for the single-particle particle wave functions we expand the wave functions in a complete orthogonal set of basis functions. In principle, one can use any complete orthogonal set, but we choose the wave functions from the nearby spherical nucleus; in our case we expand the ^{39}K wave functions in terms of the ^{40}Ca wave functions:

$$\phi_\alpha = \sum_i C_{\alpha i}\psi_i, \tag{10}$$

where we have used the label α to represent the quantum numbers (n, t_3, π, m) for ^{39}K, and i represents the set (n, t_3, π, j, m) for ^{40}Ca.

Using the orthogonality of the basis functions (^{40}Ca wave functions), the spectroscopic factor can be expressed in terms of the coefficients $C_{\alpha i}$, for example,

$$\sqrt{S_{d_{3/2}}} = \det|C_{\alpha i}|, \tag{11}$$

where in Eq. (11) the indices α,i range over the 39 occupied states of ^{39}K and those of ^{40}Ca excluding the $d_{3/2}$. Strictly speaking, one needs to project the intrinsic single-particle state from the intrinsic frame to the laboratory frame before one can use them to do overlap calculations. However, for nuclei with only one nucleon more or less than a spherical nucleus, one finds that, in the expansion (10), one component is dominant and we believe that the projection cannot produce a very large effect. However, we can only calculate the overlap using wave functions defined in the intrinsic frame. This caveat should be kept in mind when examining our results.

To calculate an excited state of the residual nucleus, we constrain the nucleus to have the required third component of angular momentum, and self-consistently iterate the Dirac equation as we did for the ground state. Although the variational procedure will produce candidate wave functions for low-lying excited states, they are not strictly orthogonal to the ground state; but it is still interesting to see what kind of cross sections and spectroscopic factors one obtains from this procedure.

Now if we use the electron DWBA calculation for single-particle knockout using the effective wave function of Eq. (6), knowing that the first term is dominant, then the result naturally splits into two factors, the calculated cross section using a normalized wave function $\psi_{d\frac{3}{2}}$ and a spectroscopic factor $S_{d\frac{3}{2}}$ calculated from Eq. (11). The combination gives us the cross section $d^3\sigma/dk_0' d\Omega_{k'} d\Omega_p$ found in Eq. (2); we are therefore able to compare directly with experimental data which is presented in the form of ρ_m.

III. RESULTS AND DISCUSSIONS

The $d_{3/2}$, $2s_{1/2}$, and $f_{7/2}$ states from ^{40}Ca are the surface state (last filled), the first state below, and the first state above the Fermi surface, respectively. Experimentally, one observes proton knockout from all three of these states, the identification being made on the basis of energy and the shape of the extracted cross section as a function of p_m. For a perfectly filled Fermi sea, one should, of course, observe nothing for the $f_{7/2}$ state. Kramer [8] analyzed these three reactions using a computer code DWEEPY [1], which is a nonrelativistic single-particle calculation with electron Coulomb distortion treated approximately. The spectroscopic factors deduced, by scaling the calculations to the experimental data, are 58%, 66%, and 5%, respectively. And the occupation probabilities obtained through these analyses are 74%, 80%, and 28%, respectively, obtained by integrating the corresponding spectral function over all excitation energies.

We note two things about these results. First, ^{40}Ca is a double-magic nucleus, which means there is a large energy gap (about 6 MeV) between the last filled level and the next empty level. The 28% occupancy of the $f_{7/2}$ means we should expect 28% $\times$ 8 = 2.24 protons in the $f_{7/2}$ state. Second, spectroscopic factors deduced from other experiments, using hadrons as probes, are generally larger than the corresponding ones obtained from $(e,e'p)$ experiments [20]. With these results in mind, we used our relativistic calculation to evaluate the single-particle transition cross section and to calculate the spectroscopic factor.

In Fig. 1 we show our calculation for ρ_m for knocking out a proton from the $d_{3/2}$ state as compared with the experimental data from Amsterdam. The curve, as we mentioned before, is from a parameter-free calculation, yet we can see it agrees with experiment very well. Our calculated spectroscopic factor for this state is 81%, which is larger than the one obtained by Kramer. This suggests that the single-particle wave function we used has the right components. In fact, we cannot improve the fit by scaling the calculation as is normally done. In other words, the curve in Fig. 1, which contains no variable parameters, is as good as our "best" fit. Since in our model we assume the $d_{3/2}$ state is completely filled, the agreement between our calculation and the experimental data suggests that we do not need partial occupancy for the $d_{3/2}$ state. Of course, there are some uncertainties in our model arising from the possibility of using different phase-equivalent optical potentials and the choice of deformed basis for evaluation of the spectroscopic factor, but we do not expect these uncertainties could cause more than a 10%–20% difference in apparent occupancy.

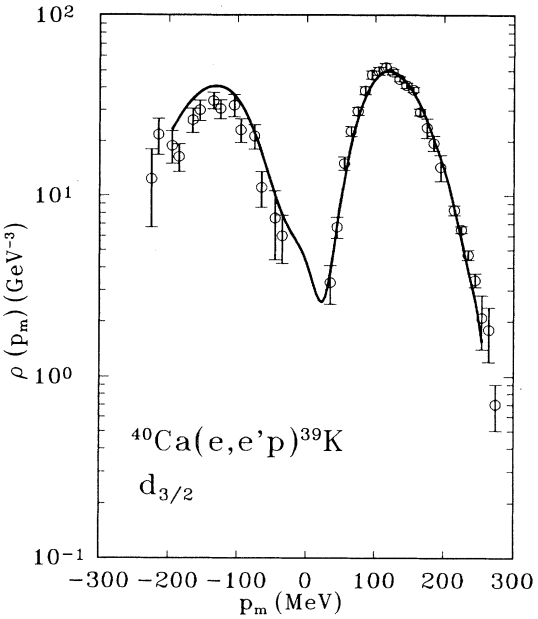

FIG. 1. Parallel kinematics calculation (shown by the solid line) for the $d_{3/2}$ state in ^{40}Ca. The outgoing proton energy is 100 MeV in the laboratory system, and the momentum is along the $\mathbf{q}$ direction. The beam energy is k_0 = 460 MeV, and each value of p_m corresponds to a different momentum transfer in the range of 250 < $|\mathbf{q}|$ < 650 MeV, consistent with the condition of parallel kinematics. Tables of kinematic values are given in Ref. [8], and the data are from Refs. [8] and [9].

We performed the same calculation for knocking a proton from the $2s_{1/2}$ state of ^{40}Ca. The calculated spectroscopic factor is (although independently calculated) also 81%. We show this calculation along with the experimental data in Fig. 2. The agreement is not nearly as good as for the $d_{3/2}$ case. The most obvious difference is that the shape produced from the Hartree $2s_{1/2}$ wave function is different in the range 0 < p_m < 150 MeV/c from the experimentally observed one. This suggests that the Hartree $2s_{1/2}$ orbital may not be the effective single-particle wave function for this transition. Nevertheless, if one were to use our calculation of the shape of ρ_m and normalize the curve to the data by least-squares fitting, shown by the dashed line in Fig. 2, the extracted spectroscopic factor would be 55%. Thus one would estimate the $2s_{1/2}$ occupancy to be about 70%.

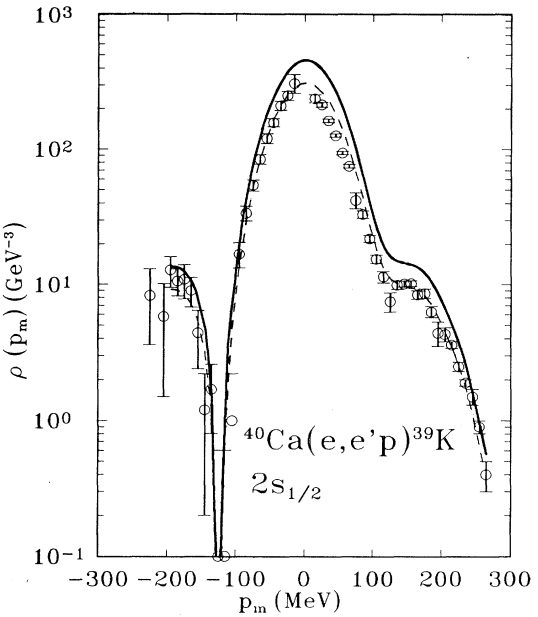

FIG. 2. Same as Fig. 1 but for the $2s_{1/2}$ state. The dashed line corresponds to the best fit with the spectroscopic factor as discussed in the text.

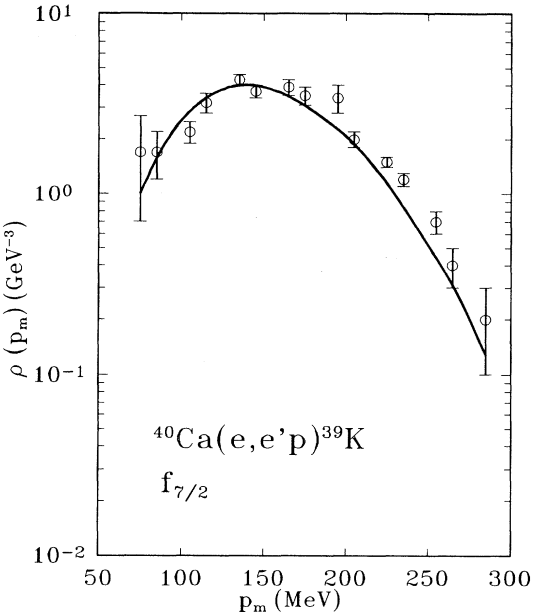

FIG. 3. Same as Fig. 1 but for the $f_{7/2}$ state.

However, there remains a discrepancy in the shape and we are of the opinion that no reasonable modification of the model wave function would produce a cross section of the right shape. It is more likely that the correct $2s_{1/2}$ state may contain two-particle–two-hole contributions which are outside our model space, or perhaps the experimental data between $0 < p_m < 150$ MeV/c are not correctly normalized.

It is also interesting to see what spectroscopic factor one extracts for the $f_{7/2}$ state if our Hartree single-particle wave function is used. In Fig. 3 we show our single-particle calculation compared with the data. The curve requires a spectroscopic factor of 3.7% which is obtained by least-squares fitting and is a little smaller than the value of 5% quoted by Kramer. A theoretical calculation of the spectroscopic factor for this state requires a calculation beyond the Hartree or Hartree-Fock, which we have not done.

IV. CONCLUSIONS

We presented a fully distorted partial-wave calculation which uses relativistic self-consistent Hartree wave functions for both the initial state of the target nucleus (^{40}Ca) and the final state of the residual nucleus (^{39}K). The final-state interaction of the knocked-out nucleon is described by an optical potential, and the Coulomb distortion of the electrons is also included. Since all the meson coupling constants and masses are fixed in the mean-field calculations, the model gives a parameter-free description of the $(e, e'p)$ reactions. For the proton knocked out from the $d_{3/2}$ state of ^{40}Ca which leaves the residual nucleus in the ground state of ^{39}K, the comparison of the calculation to the experimental data is very good and the calculated spectroscopic factor agrees very well with the one extracted by scaling the single-particle transition to fit the experiments. There seems no need to make the assumption that the $d_{3/2}$ state is appreciably depleted in order to describe the experimental data. We did the same calculation for the $2s_{1/2}$ state. The calculation overestimates the experimental data, and the shape of the calculated reduced cross section is somewhat different from the experimental one, which, assuming the experimental data are correct, suggests that the $2s_{1/2}$ Hartree state alone is not the effective single-particle state. Finally, we used the Hartree $f_{7/2}$ bound-state wave function to fit the $f_{7/2}$ experimental data and found a spectroscopic factor of 3.7%, which suggests only a few percent of occupancy in the $f_{7/2}$ state and is consistent with our treatment of ^{40}Ca as a largely uncorrelated Fermi sea.

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