Proton ground-state correlations in 40Ca studied with the reaction 40Ca(e,e'p)39K

PROTON GROUND-STATE CORRELATIONS IN ^{40}Ca STUDIED WITH THE REACTION ^{40}Ca(e, e'p)^{39}K

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The spectral function of the reaction ^{40}Ca(e, e'p)^{39}K was measured with special emphasis on the knockout of protons from the $1f_{7/2}$ and $2p_{3/2}$ orbits above the Fermi level. Particularly for the transition to the $3/2^-$ state two-step processes were found to be not negligible. The spectroscopic strength for the 1f and 2p knockout, integrated up to 10 MeV excitation energy, is much less than the missing strength in the $1d_{3/2}$ and $2s_{1/2}$ orbits, but it agrees with values expected from calculations involving ground-state correlations.

In recent (e, e'p) experiments [1–3] on medium heavy and heavy nuclei it was found that the spectroscopic factors, deduced from these experiments, are surprisingly low. If taken at face value 50% of the proton strength for states just below the Fermi level (ε_F) is missing compared to the independent-particle shell model (IPSM). However, there exists only scarce information from the (e,e'p) reaction on the strength residing in normally unoccupied states, i.e. ground-state correlations. For ^{40}Ca Gerace and Green [4,5] already showed that the inclusion of n-particle–n-hole configurations in the ground state improved the calculated electromagnetic transition probabilities in the light Ca isotopes. The most direct experimental evidence for correlations in the ground state of ^{40}Ca, in which $1d_{3/2}$ and $2s_{1/2}$ protons from below the Fermi level are promoted to the $1f_{7/2}$ and $2p_{3/2}$ orbitals above the Fermi level, involves an accurate determination of spectroscopic factors (S) for picking up $1f_{7/2}$ and $2p_{3/2}$ protons or stripping protons into $1d_{3/2}$ and $2s_{1/2}$ holes. In both cases the reactions involve "small" components of the ground-state wave function. With the (d, ^{3}He) reaction [6,7] pick-up from orbitals above the Fermi level has indeed been observed but spectroscopic factors for these weak transitions differ up to a factor of two. For reactions initiated with hadrons a reliable determination of spectroscopic factors for such small components in the nuclear wave function is difficult for the following reasons: (i) the presence of two-step processes hampers unambiguous assessment of the direct part of the transfer, (ii) there is a strong dependence on the choice of the geometry of the bound-state well [8,9] and (iii) different optical-model potentials for the incoming and outgoing particles can lead to appreciable differences in spectroscopic factors [10]. The (e, e'p) reaction is a much better tool for studying these small components, since two-step processes are relatively small [11] and the radius of the bound-state well is deduced experimentally from the measured momentum distributions [3], while the proton optical potential is reasonably well known from proton scattering data [12].

Various theoretical estimates have been given for the occupancy $n = \sum S/2j+1)$ of states above the Fermi level. Early RPA calculations [13] for ^{40}Ca

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predicted 10% (4%) occupancy for the $1f_{7/2}$ ($2p_{3/2}$) orbitals, while recent $2\hbar\omega$ shell-model calculations [14] yield a $1f_{7/2}$ nucleon occupation number of (5–7%) in the ground state of ^{40}Ca. Other calculations employing a dispersion-relation approach [15] find values of 13% (9%) for the $1f_{7/2}$ ($2p_{3/2}$) occupancy. These values are obtained when the strength is integrated over the total knockout part of the calculated spectral function (i.e. from $-\infty$ to ϵ_F).

In this paper we present a study of the reaction ^{40}Ca(e, e'p)^{39}K leading to the first four states in ^{39}K. In the IPSM these four states result from proton knock-out from the $1d_{3/2}$, $2s_{1/2}$, $1f_{7/2}$ and $2p_{3/2}$ orbits. The experiment has been performed with the electron accelerator MEA and the dual spectrometer setup [16] at NIKHEF-K. A natural calcium foil of 14.3 mg/cm^2 was used as target. The (e, e'p) cross sections were obtained in parallel kinematics in which the proton with momentum $\boldsymbol{p}'$ is detected in the direction of the momentum transfer $\boldsymbol{q}$. The outgoing proton kinetic energy was 100 MeV. Data were taken in the missing-momentum range from 0–270 MeV/c. From the measured incoming and outgoing electron and proton momenta one determines, using energy and momentum conservation, the missing momentum $\boldsymbol{p}_m (=\boldsymbol{q}-\boldsymbol{p}')$ and the missing energy E_m. A mapping of the measured cross section, divided by the off-shell electron–proton cross section [17], onto the two-dimensional E_m, $|\boldsymbol{p}_m|$ plane yields the distorted spectral function $S(E_m, p_m)$, from which momentum distributions $\rho(p_m)$ were deduced for transitions to the discrete final states [3]. The shape of the momentum distribution is related to the shape of the bound-state wave function, while the strength is proportional to the spectroscopic factor of the transition.

In fig. 1 a typical excitation-energy spectrum is shown. Knockout from the $1d_{3/2}$ and $2s_{1/2}$ orbits resides in two strong transitions, while the missing-energy resolution of 130 keV allowed for the first time to observe knock-out from the $1f_{7/2}$ (at 2.814 MeV) and $2p_{3/2}$ (at 3.019 MeV) orbits. In fig. 2 the momentum distributions for the strong transitions to the $3/2^+$ states are displayed, while in figs. 3 and 4 those to the $7/2^-$ and $3/2^-$ states are shown. In the figures only statistical errors on the data are displayed. A careful estimate of all the systematic errors results in a 4% systematic uncertainty on the momentum distributions [3].

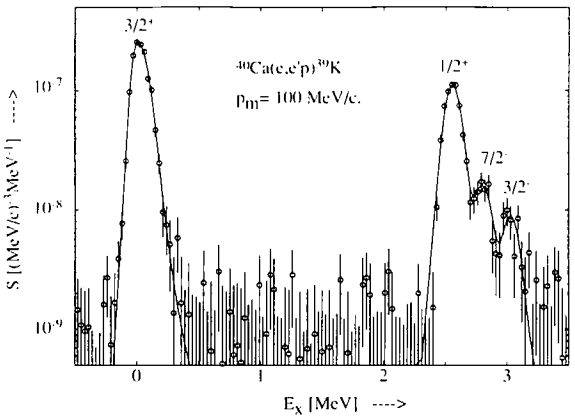

Fig. 1. Excitation-energy spectrum for the reaction ^{40}Ca(e, e'p)^{39}K at a missing momentum of 100 MeV/c. The curve is a fit to the data.

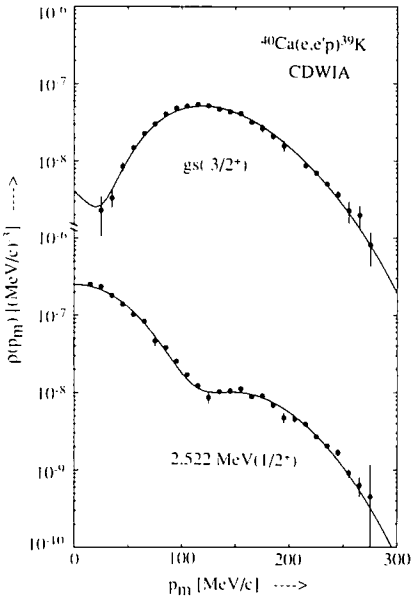

Fig. 2. Measured momentum distributions for the first two strong transitions in the reaction ^{40}Ca(e, e'p)^{39}K. The curves represent the CDWIA calculations as mentioned in the text.

In order to extract spectroscopic factors from the data CDWIA calculations have been performed with the code DWEEPY [18] which accounts for both the electron and proton distortions. The electron distor-

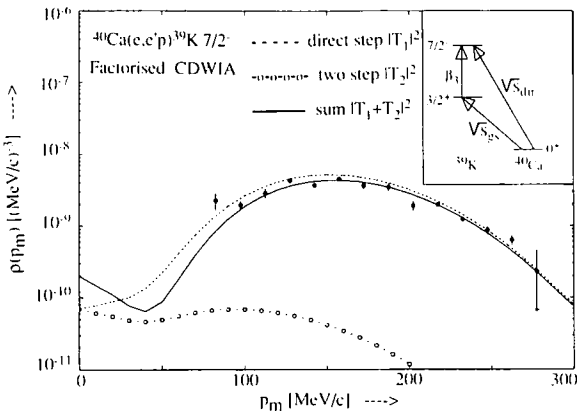

Fig. 3. Measured momentum distribution for the transition to the $7/2^-$ state at 2.814 MeV in the reaction ^{40}Ca(e, e'p)^{39}K. The dashed curve represents direct $1f_{7/2}$ knock-out, the dash-dotted the two-step contribution, while the coherent sum is shown by the full curve. In the inset the channels used in the calculation are shown.

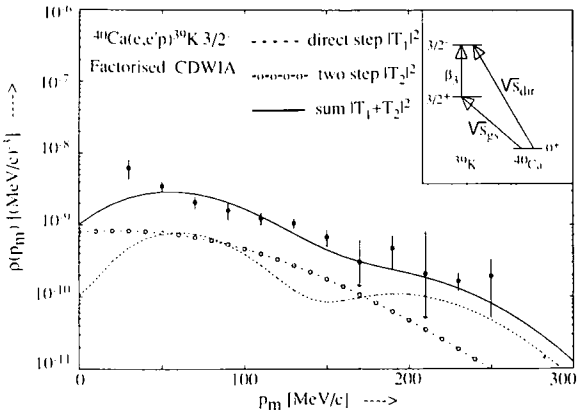

Fig. 4. The same as fig. 3, but for the transition to the $3/2^-$ state at 3.019 MeV.

tions were treated in the first order eikonal approximation [18]. The proton distortions were calculated using a Woods–Saxon type optical potential with parameters obtained from the parametrization of Schwandt et al. [12]. Earlier work [3,19] on ^{51}V has shown that the uncertainty due to different parametrizations of the proton-optical model potential is 2.5% for the extracted radii and 6% for the spectroscopic factors. These uncertainties have been included in the quoted errors. The bound-state wave function (BSWF) was calculated in a Woods–Saxon potential well with parameters as listed in table 1. Its radius r_0 was deduced individually for each subshell from a fit to the momentum distributions, while the depth of the potential-well V_0 was adjusted to get the correct separation energy. Non-locality corrections ($\beta=0.85$ fm) were applied to both the optical-model wave function and the bound-state wave function according to the prescription of Perey [20].

The transition to the $3/2^+$ ground state of ^{39}K is described by $1d_{3/2}$ proton knock-out. The value of $r_0=1.295(47)$ fm is larger than the one employed in the analysis of the (d, ^{3}He) reactions, in which r_0 values of 1.20–1.25 fm were assumed [6,7] and moreover no non-locality corrections were applied. The spectroscopic factor for the ground-state transition is 2.58(26). None of the other known $3/2^+$ states [21] were observed in this experiment. The transition to the $1/2^+$ state at 2.522 MeV is due to proton knock-out from the $2s_{1/2}$ orbit. From the CDWIA calculation a spectroscopic factor of 1.02(10) and a radius $r_0=1.276(59)$ fm are extracted. A second $1/2^+$ state at 4.095 MeV was observed in this experiment containing about 4% of the strength of the first $2s_{1/2}$ transition.

Once we know that the strong $2s_{1/2}$ and $1d_{3/2}$ transitions are adequately described by the chosen optical and bound-state potentials we now turn our attention to the weak transitions. For that purpose the $3/2^-$ and $7/2^-$ states are described as members of the weak-coupling multiplet [22], so two-step processes of the type indicated in the inset of figs. 3 and 4 may be important. We performed two-step calculations with the code CHUCK [23] according to the prescription of ref. [24] to establish the size of the direct

Table 1
Bound-state parameters [a] and spectroscopic factors.

E_x [MeV]	J^π	V_0 [MeV]	r_0 [b] [fm]	r_{RMS} [b,c] [fm]	S [b]
0.000	$3/2^+$	51.6	1.295(47)	3.69(10)	2.58(26)
2.522	$1/2^+$	55.5	1.276(59)	3.72(10)	1.02(10)
2.814	$7/2^-$	61.0	1.348(67)	4.07(12)	0.38(4)
3.019	$3/2^-$	65.0	1.40 [d]	4.17	0.010(2)

[a] Diffuseness $a=0.65$ fm, Thomas spin–orbit parameter $\lambda=25$, $r_c=1.30$ fm.
[b] Errors include systematic uncertainties.
[c] r_{RMS} in proton–^{39}K system.
[d] Parameter fixed.

and the two-step contribution. The latter consists of direct proton knock-out to the $3/2^+$ ground-state in ^{39}K followed by inelastic excitation. The results are shown in figs. 3 and 4. The employed values of β_3 for the strength of the inelastic excitation were taken from ref. [22], while the $1d_{3/2}$ transition strength to the ground state was taken from the present experiment (table 1). These parameters fix the strength of the two-step process completely. The amplitude of the direct process was varied to get the best description of the measured momentum distribution.

The transition to the $7/2^-$ state at 2.814 MeV can proceed through knockout from the $1f_{7/2}$ orbit and via the two-step process mentioned above. The β_3 used for this transition is 0.159(10) [22]. The relative sign between the two paths was chosen to be positive because when the other sign is used, we can only fit the measured momentum distribution with unrealistic parameters for the bound-state well ($r_0 = 1.1$ fm, $V_0 = 80$ MeV). A comparison between the measured momentum distribution and a pure two-step calculation revealed that the dominant contribution for this transition is the direct path. This allows a rather accurate determination of the BSWF and spectroscopic factor for this transition. From the coherently added one- and two-step contribution a spectroscopic factor of 0.38(4) was deduced, which corresponds to 5% of the strength of a completely filled $1f_{7/2}$ shell. From an l-decomposition [3] of the spectral function we conclude that up to 10 MeV excitation energy there is less than 0.08 additional $1f_{7/2}$ strength. The radius of the BSWF well was found to be 1.348(67) fm, which is significantly larger than the radii deduced for the orbits below the Fermi level. Such a difference for states that are far from their unperturbed energy was predicted by Pinkston and Satchler [25] who stressed that if an effective one-body potential is used to generate the BSWF it is not sufficient to vary only its depth, but changes in shape, particularly in the radius, must be considered. For proton knock-out from the $1f_{7/2}$ shell above the Fermi level, one expects that the r_0 of the potential should be increased to take into account the residual interaction. This is in agreement with our finding. We remark that our value for r_0 is much larger than the one that has been used in the analysis of (d, ^{3}He) experiments [6,7].

The $3/2^-$ state at 3.019 MeV can be populated by a direct $2p_{3/2}$ proton knock-out, but the measured momentum distribution shown in fig. 4 does not show the well known shape [3] expected for a 2p transition. However, taking the coherent sum of the direct and the two-step process we were able to reproduce the shape of the measured momentum distribution. These processes shown in fig. 4 are of the same magnitude but of different shape. The β_3 of 0.285(10) was taken from ref. [22]. The relative minus sign between the two paths was determined from the shape of the experimental momentum distribution, because the positive sign gave an appreciable deepening of the minimum at $p_m = 140$ MeV/c, in disagreement with the experimental data. Because the direct knock-out process is not dominant it was not possible to fit the value of r_0 for the $2p_{3/2}$ orbit so we chose $r_0 = 1.40$ fm which gave a well depth (65 MeV) close to the value for the $1f_{7/2}$ orbit. This choice is based on the prediction of Pinkston and satchler [25] mentioned before and on the more recent surface-peak method [26]. The deduced spectroscopic factor for the direct $2p_{3/2}$ knock out is 0.010(2) where the error includes the small sensitivity to the choice of the radius. Additional $2p_{3/2}$ strength (0.03)(1)) was found in the transition to the state [21] at 5.826 MeV. From an l-decomposition of the spectral function we deduced an upper limit of 0.04 for further 2p strength up to 10 MeV excitation energy.

We conclude that the total observed 1f and 2p strength in the excitation energy region from 0 to 10 MeV ((5–6)% and (1–2)%, respectively) is much less than the missing strength for the $1d_{3/2}$ and $2s_{1/2}$ orbits (35% and 45%, respectively). Also, the observed 1f and 2p strength is smaller than RPA predictions [13] (10% and 4%), but in these calculations it was not specified over which energy domain the strength is spread. Recently, Mahaux et al. [15] have calculated the distribution of spectroscopic strength in the dispersion-relation approach, which effectively includes both short- and long-range correlations. By integrating this distribution over the presently studied energy interval we find 3% and 2% for the 1f and 2p strength, respectively, in reasonable agreement with the measured values.

Summarizing, we have quantitative evidence for ground-state correlations in ^{40}Ca, deduced from proton knockout from orbitals above the Fermi level. For the description of the corresponding experimental

momentum distributions the inclusion of two-step processes and the use of BSWF parameters different from the ones for normally occupied orbitals, were found to be necessary. The observed strength agrees with calculations in which both long- and short-range calculations are taken into account.

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