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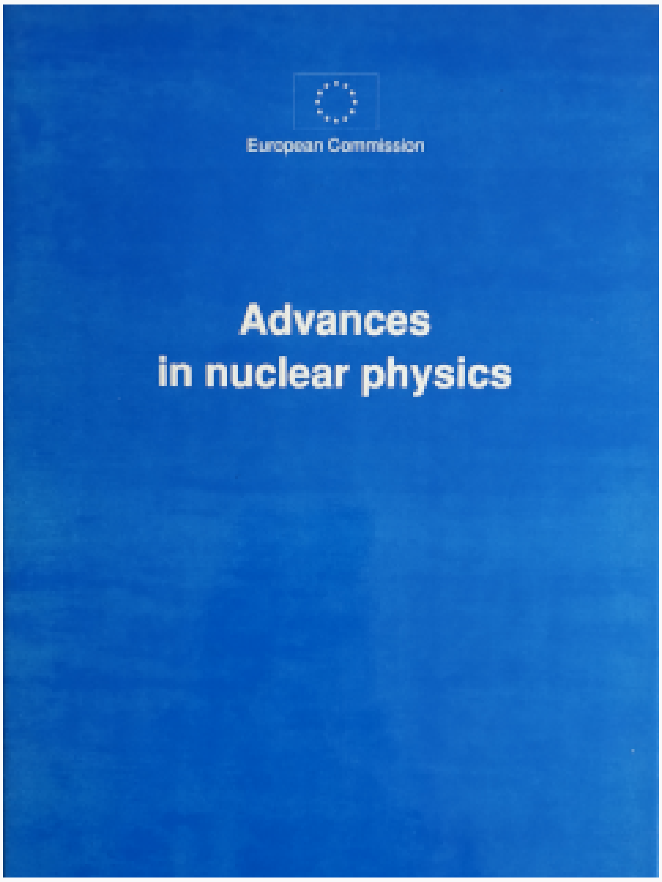

The influence of state dependent short range correlations on the depletion of the nuclear Fermi sea

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The influence of state dependent short range correlations on the depletion of the nuclear Fermi sea.

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Abstract

The inlfuence of state dependent short range correlations on the occupation numbers of the single particle shell model orbits of the doubly closed shell nuclei ^{16}O and ^{40}Ca is examined. The study shows that the effect of the state dependence of the short range correlations is rather small. The total depletion of the nuclear Fermi sea changes slightly compared with the one calculated by considering state independent short range correlations.

1 Introduction

In a series of papers [1-3] a simple method was proposed for the introduction of short range correlations (SRC) in the ground state nuclear wave function for nuclei in the region $4 \leq A \leq 40$. This method offers the possibility to obtain closed form expressions for the correlated charge form factors F_{ch}(q) of s-p and s-d shell nuclei and the corresponding correlated proton density distributions ρ_{cor}(r). The correlations were of the Jastrow type [4] and the correlation parameters were determined by fitting the charge form factor experimental data.

Recent high resolution (e,e'p) experiments have shown significant deviation from the mean field picture [5-9]. The quantum states, especially those near the Fermi sea [5] appear to be depleted and this clearly demonstrates that the single particle orbits are partially occupied because of nucleon-nucleon correlations [8].It is noted, however, that in such experiments only a part of the spectroscopic strength is measured and therefore it is expected that the occupancy of the single particle orbits is larger (e.g. a value of about 80% is reported for the occupation probability of $3s_{1/2}$ in lead [10], while an analysis of (e,e'p) data yields a spectroscopic strength of about 50% [11,12]).

In very recent publications [13,14] we used ρ_{cor}(r) derived in the way described above as input in a method for the determination of fractional occupation probabilities, where the natural orbital representation (NOR) [15] is employed, by imposing the condition $\rho_{cor}(r) = \rho_{n.o}(r)$, where $\rho_{n.o}(r)$ is the density distribution constructed by natural orbitals. Thus, one can make a systematic study of the effect of SRC on the occupation numbers of the shell model orbits and the depletion of the nuclear Fermi sea in light nuclei. However, SRC used so far were assumed to be state independent, i.e. the correlation parameters are the same for all states of the relative motion.

The aim of the present paper is to estimate the effect of state dependent SRC on the occupation numbers. We expect that in this way, we will be able to reproduce better the experimental data for F_{ch}(q) especially at large momentum transfers, obtaining thus better correlated densities ρ(r) at small r and describing better the particle states in NOR. The paper is organized as follows : In section 2 closed form expressions for the correlated F_{ch}(q) are presented for the case of ^{16}O and ^{40}Ca. In section 3 the method for the determination of occupation numbers is outlined and finally in section 4 numerical results are reported and certain comments are made.

2 Closed form expressions for the correlated charge form factor F_{ch}(q) of ^{16}O and ^{40}Ca.

The factor cluster expansion of Ristig, Ter Low and Clark [16] as reviewed by Clark [17] was employed [18] to derive a general expression for the charge form factor F_{ch}(q) of light closed shell nuclei. The method was simplified [1] using normalized correlated wave functions of the relative motion of the form:

$$\psi_{nlS}(r) = N_{nlS}[1 - exp(-\lambda_{nlS} r^2/b^2)]\phi_{nl}(r) \tag{1}$$

where N_{nlS} are the normalisation factors, $\phi_{nl}(r)$ are the harmonic oscillator wave functions and $b = \sqrt{2}b_1$ ($b_1 = \sqrt{\hbar/m\omega}$) is the harmonic oscillator (HO) parameter for the relative motion.Thus an expression for F_{ch}(q) of ^{16}O was derived in closed form (expression (30) of [2]) :

$$\begin{aligned} F_{ch}(q) &= f_p(q) f_{CM}(q)\times \\ &\{\tfrac{1}{16}e^{-y}\sum_{S=0,1}[6(7-6y+y^2)A^{00S}_{00S}(j_0) + 4(3-y)(\delta_{S0}+9\delta_{S1})\times \\ &A^{01S}_{01S}(j_0) + 15A^{02S}_{02S}(j_0) + 3A^{10S}_{10S}(j_0) - 4y(\delta_{S0}+9\delta_{S1})A^{01S}_{01S}(j_2) \\ &-2\sqrt{6}yA^{10S}_{00S}(j_0) - 4\sqrt{15}A^{02S}_{00S}(j_2)] - 14e^{-2y}(1-y)\} \end{aligned} \tag{2}$$

where

$$A^{n'l'S'}_{nlS}(j_k) = < \psi_{nlS}|j_k(qr/2)|\psi_{n'l'S'} > \tag{3}$$

and f_p(q) and f_{CM}(q) are the corrections due to the finite proton size [18] and the center of mass motion [19] respectively.

In an extension of the above work the following formula was derived for the F_{ch}(q) of ^{40}Ca in the Born approximation:

$$F_{ch}(q) = f_p(q) f_{CM}(q)[F_1(q) + F_2(q)] \tag{4}$$

where

$$F_1(q) = \frac{1}{A}4\sum_{n_i l_i}(2l_i+1) < n_i l_i|j_0(qr_1)|n_i l_i > = (1 - 2y + \frac{4}{5}y^2)e^{-2y} \tag{5}$$

is the contribution of the one body term to F_{ch}(q) while the contribution of the two body term to F_{ch}(q) is

$$F_2 = \overline{F}_2(q) + \overline{\overline{F}}_2(q) \tag{6}$$

where

$$
\begin{aligned}
&\overline{F}_2(q) = \\
&\tfrac{1}{40}\{12[(\tfrac{185}{8} - 40y + \tfrac{83}{4}y^2 - 4y^3 + \tfrac{1}{4}y^4)A_{00}(j_0) + (\tfrac{175}{8} - \tfrac{50}{3}y + \tfrac{31}{12}y^2)A_{02}(j_0) \\
&+\tfrac{27}{8}A_{04}(j_0) + (\tfrac{35}{8} - \tfrac{10}{3}y + \tfrac{2}{3}y^2)A_{10}(j_0) + \tfrac{15}{8}A_{12}(j_0) + \tfrac{3}{8}A_{20}(j_0) \\
&+(-\tfrac{10}{3}y + \tfrac{20}{21}y^2)A_{02}(j_2) + \tfrac{9}{7}y^2A_{02}(j_4)] + 20[(30 - 35y + 11y^2 - y^3)A_{01}(j_0) \\
&+(\tfrac{21}{2} - \tfrac{7}{2}y)A_{03}(j_0) + (\tfrac{9}{2} - \tfrac{3}{2}y)A_{11}(j_0) + (-\tfrac{25}{2}y + 8y^2 - y^3)A_{01}(j_2) \\
&-\tfrac{9}{10}yA_{11}(j_2) - \tfrac{7}{5}yA_{03}(j_2)]\}e^{-y} - 39(1 - 2y + \tfrac{4}{5}y^2)e^{-2y}
\end{aligned}
\tag{7}
$$

and

$$
\begin{aligned}
&\overline{\overline{F}}_2(q) = \\
&\tfrac{1}{40}[\sqrt{6}(-25y + 16y^2 - 2y^3)A_{00}^{10}(j_0) + \tfrac{3}{5}\sqrt{30}y^2A_{00}^{20}(j_0) - 5\sqrt{14}yA_{02}^{12}(j_0) \\
&+4\sqrt{10}(-5y + y^2)A_{01}^{11}(j_0) - 2\sqrt{5}yA_{10}^{20}(j_0) + \sqrt{15}(-50y + 32y^2 - 4y^3)A_{00}^{02}(j_2) \\
&+12\sqrt{\tfrac{15}{14}}y^2A_{00}^{12}(j_2) + \tfrac{40}{\sqrt{35}}(-21y + 6y^2)A_{01}^{03}(j_2) + 4\sqrt{10}(4y + y^2)A_{01}^{11}(j_2) \\
&-\tfrac{108}{\sqrt{7}}yA_{02}^{04}(j_2) + \tfrac{20}{7}\sqrt{14}yA_{02}^{12}(j_2) - 4\sqrt{2}yA_{02}^{20}(j_2) + 2\sqrt{10}(8y - y^2)A_{02}^{10}(j_2) \\
&+12\sqrt{14}yA_{03}^{11}(j_2) - 2\sqrt{35}yA_{10}^{12}(j_2) + 36\sqrt{\tfrac{3}{35}}y^2A_{00}^{04}(j_4) + \tfrac{240}{\sqrt{35}}y^2A_{01}^{03}(j_4)]e^{-y}
\end{aligned}
\tag{8}
$$

where

$$y = b_1^2q^2/8 \tag{9}$$

and

$$A_{nl}^{n'l'}(j_k) =< \psi_{nl}|j_k(qr/2)|\psi_{n'l'} > \qquad A_{nl}^{nl}(j_k) = A_{nl}(j_k) \tag{10}$$

In previous work [2-3] "approximate" expressions were used for F_{ch}(q) of ^{16}O and ^{40}Ca which are quite satisfactory and allow us to make a systematic study for light nuclei ($4 \leq A \leq 40$). By "approximate" we mean that an expansion of the coefficients $a_i(\lambda)$,$\beta_i(\lambda)$, $\gamma_i(\lambda)$ was made in powers of λ and the terms beyond $\lambda^{-3/2}$ were neglected (see relations (10) of [2]). In the present work we use "exact" expressions, i.e. the above approximation is not used.

Closed form expressions for ρ_{cor}(r) of ^{16}O and ^{40}Ca can be easily derived [2,3] with the aid of the formulae for F_{ch}(q) written above and are used as input to the theoretical method described in section 3.

In the case of ^{40}Ca in order to reduce the number of adjustable parameters we assume that the wave functions of the relative motion are the same in singlet and triplet states i.e. $\lambda_{nl0} = \lambda_{nl1}$ for all n,l. Otherwise the number of parameters appearing in formulae (7) and (8) would be large and we would not be able to determine them by fitting the experimental data. Hence, there is no spin dependence of the matrix elements $A_{nl}^{n'l'}(j_k)$ in (7) and (8).

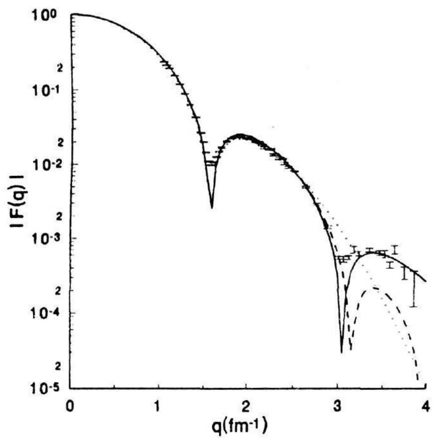

Fig. 1. The charge form factor of ^{16}O (for details see text)

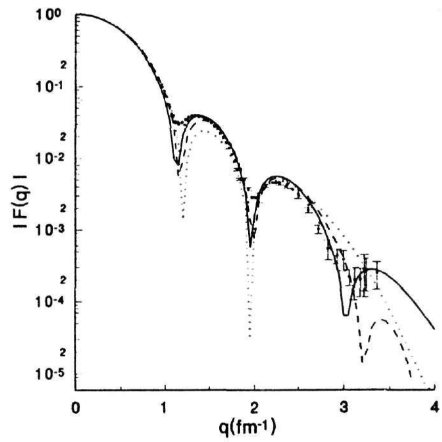

Fig. 2. The charge form factor of ^{40}Ca (for details see text)

3 The theoretical method

Here we present very briefly the main points of our method [13-14]. The connection with the short range correlations is done by employing the natural orbital representation [15]. The natural orbital approach has already been applied in the past for nuclear structure studies [20-22]. Recently this approach was also employed [23] within a varionational Jastrow-type correlation method to study quantum liquid drops such as Fermi liquid ^{3}He and Bose liquid ^{4}He. It is the most suitable way of keeping the simplicity and the visuality of the single particle description while the effect of short range correlations is taken into account in an effective way by expressing the ground state wave function in terms of the occupation probabilities of the single particle orbits.

In our approach it is assumed that the radial part of the single particle wave functions of a harmonic oscillator potential can be identified with "natural orbitals" in a way similar to [21-24,25] (see also [26]). It is noted that proper linear combinations of harmonic oscillator wave functions could be used instead, (see for example [27]). In such a case, however, the method loses its simplicity.

The determination of the occupation probabilities and the size parameter b_1(n.o) is made by assuming that $\rho_{cor}(r) = \rho_{n.o}(r)$, where $\rho_{n.o}(r)$ in the case of spherical symmetric systems takes the simple form:

$$\rho(r) = \frac{1}{4\pi} \sum_{nl} (2j+1) n_q |\phi_q(r)|^2 \tag{11}$$

where n_q is the occupation probability ($n_q \leq 1$) of the q(=nlj) state. In addition we demand that for the proper model space

$$< r^k >_{cor} = < r^k >_{n.o} \tag{12}$$

Our previous results for the occupation numbers (see tables II-IV of [13]) lead to a total depletion of the nuclear Fermi sea which apart from ^4He is about 32%.

The merit of this approach is that, in some way, it establishes a relationship of fractional occupation probabilities with short range correlations. The effect of short range correlations is taken into account in an effective way and is absorbed in the values of the calculated occupation numbers and the size parameter b_1(n.o).

It should be noted, however, that this relationship is not completely clear because we are not able to distinguish the corrections to the charge form-factor $F_{ch}(q)$ for large values of q because of short range correlations from the ones due to meson exchange currents.

Another point which we think that it is worthy for further investigation and it is the aim of the present work is the fact that in [13] the oscillator parameter b_1(n.o) was taken state independent. Specifically, b_1(n.o) was considered the same for all states within and above the Fermi sea. This is a rather rough approximation and it might lead to an overestimate of the total depletion.

The low energy ($k < 2fm^{-1}$) experimental electron scattering data e.g. charge density distributions, elastic form-factors, proton momentum distribution e.t.c are in general satisfactorily described by the mean field approximation. However, this is not the case at higher energies where mostly short range correlations manifest themselves and therefore deviations from the mean field picture are expected. Because of them hard colllisions between nucleons at small distances ($\leq 0.5fm$) may result in a scattering of nucleons into states of higher energy above the Fermi sea, which thus appear to be partially occupied. Preliminary experimental estimates for fractional occupation probabilities [9] support this idea. Having this in mind it seems reasonable for one to assume that states above the Fermi sea with non zero occupancy mainly reflect the short range correlations effect. In addition since such states describe short range effects at high momenta it is expected to be characterized by smaller root mean square radii. In other words they restrict themselves in the interior of the nucleus where the density has significant values. In our approach this corresponds in expressing them by "natural orbital" wave functions having a smaller size parameter. The method was improved [14] by considering different oscillator parameters for the hole states and those above the Fermi sea. In other words $\rho_{n.o}(r)$ is divided in two parts :

$$\rho_{n.o}(r) = \rho_{n.o}^{<F.S}(r) + \rho_{n.o}^{>F.S}(r) \tag{13}$$

where each part is expressed by a harmonic oscillator basis characterized by the oscillator parameters b and $\tilde{b}$ respectively. In addition it is assumed that for $\rho_{n.o}^{<F.S}(r)$ the occupancy of the states above the Fermi sea is practically zero, while for $\rho_{n.o}^{>F.S}(r)$ only the states above the Fermi sea have occupation probabilities which appreciably differ from zero [14].

Here, we give the expressions of the two parts of the density for ^{40}Ca and for a model space containing three major shells:

$$\rho_{n.o}^{<S.F.}(r) = \frac{1}{Z}\frac{1}{(\sqrt{\pi}b)^3}[N_1 + N_2\frac{r^2}{b^2} + N_3\frac{r^4}{b^4}]exp(-r^2/b^2) \tag{14}$$

and

$$\rho_{n.o}^{>F.S.}(r) = \frac{1}{Z}\frac{1}{(\sqrt{\pi}\tilde{b})^3}[\tilde{N}_1\frac{r^2}{\tilde{b}^2} - \frac{4}{5}\tilde{N}_1\frac{r^4}{\tilde{b}^4} + \tilde{N}_2\frac{r^6}{\tilde{b}^6}]exp(-r^2/\tilde{b}^2) \tag{15}$$

where

$$\begin{aligned} N_1 &= 2n_{1s} + 3n_{2s} \quad N_2 = 4n_{1p} - 4n_{2s} \qquad N_3 = \tfrac{8}{3}n_{1d} + \tfrac{4}{3}n_{2s} \\ \tilde{N}_1 &= 10n_{2p} \qquad \tilde{N}_2 = \tfrac{16}{15}n_{1f} + \tfrac{8}{5}n_{2p} \end{aligned} \tag{16}$$

The various moments $< r^k >_{n.o} = < r^k >_{n.o}^{<S.F.} + < r^k >_{n.o}^{>S.F.}$ are written

$$\begin{aligned} < r^k >_{n.o}^{<S.F.} &= \tfrac{2}{Z\sqrt{\pi}} b^k [N_1\Gamma(\tfrac{k+3}{2}) + N_2\Gamma(\tfrac{k+5}{2}) + N_3\Gamma(\tfrac{k+7}{2})] \\ < r^k >_{n.o}^{>S.F.} &= \tfrac{2}{Z\sqrt{\pi}} \tilde{b}^k [\tilde{N}_1\Gamma(\tfrac{k+5}{2}) - \tfrac{4}{5}\tilde{N}_1\Gamma(\tfrac{k+7}{2}) + \tilde{N}_2\Gamma(\tfrac{k+9}{2})] \end{aligned} \tag{17}$$

Similar expressions are derived in the same way for the other nuclei which possess spherical symmetry in the region $12 \leq A \leq 40$ [14]. The two parts somehow reflect nuclear characteristics which are sensitive to the low and high momentum component of the charge form factor $F_{ch}(\mathrm{q})$ respectively. It was shown that this modification leads to a significant reduction of the total depletion [14]. Finally it is noted that in a very recent publication Stoitsov et al [28] study by means of natural orbital representation the influence of short-range correlations on the single particle wave functions and occupation probabilities. The authors propose a decomposition of the one-body density matrix which reflects both the low and high momentum components of the correlated ground state. They also used Jastrow type short range correlations which, however, were taken state independent. Their study corroborates our conclusions in [14].

4 Numerical results and comments

The structure of expression (2) implies that the parameters λ_{nlS} for n,l fixed should be taken equal in the singlet and triplet states i.e. $\lambda_{nl0} = \lambda_{nl1}$, except in the case n=0, l=1 where $\lambda_{010} \neq \lambda_{011}$. The correlation parameter λ_{nlS} and the HO parameter b_1 were determined by fitting the experimental values of $F_{ch}(\mathrm{q})$ of ^{16}O. See third row of table 1 of [1] where there is, however, a misprint: b_1=1.632 must be replaced by b_1=1.708. In this work we repeated the fit for ^{16}O by removing the condition $\lambda_{010} \neq \lambda_{011}$, that is we considered the case $\lambda_{010} = \lambda_{011}$. Thus the values λ_{nlS} are taken to be the same in singlet and triplet states for every pair nl, in order to work on equal footing with the case where no spin dependence of λ is taken into account for ^{40}Ca (relations (7) and (8)). The parameters were again determined by fitting the experimental values of F_{ch}(q) of ^{40}Ca. The results are shown in table 1. It is noted that the results for ^{16}O are quite similar with the ones of [1].

	λ_{00}	λ_{01}	λ_{02}	λ_{03}	λ_{04}	λ_{10}	λ_{11}	λ_{12}	λ_{20}
^{16}O	∞	9.737	3.862			5.590			
^{40}Ca	21.554	12.093	5.659	2.511	4.214	20.518	11.451	5.683	20.588

Table 1: The values of the SRC parameters in various states of ^{16}O and ^{40}Ca.

In table 2 the calculated size parameters b and $\tilde{b}$ together with the corresponding ones without taking into account the state dependence of the SRC parameters [14] (i.e. b(s.in), $\tilde{b}$(s.in)) as well as those which correspond to the pure harmonic oscillator (mean field) b_1(HO), the correlated case b_1(cor) and the parameters b_1(n.o) [13] are shown for the nuclei considered in this work. It is seen that the parameters b and $\tilde{b}$ are very close to the ones of [14] where the state dependence of SRC was ignored. In addition the same comment can be made as in [14] that is, SRC affect mainly the particle states.

	b_1(HO)	b_1(cor)	b_1(n.o)	b(s.in.)	$\tilde{b}$(s.in.)	b	$\tilde{b}$
^{16}O	1.786	1.705	1.597	1.697	1.529	1.726	1.473
^{40}Ca	1.950	1.894	1.785	1.886	1.728	1.932	1.728

Table 2: Comparison of b_1(HO), b_1(cor), b_1(n.o) of ref. [13] and b(s.in), $\tilde{b}$(s.in) from [14] (state independent (s.in) correlation parameters) with the harmonic oscillator parameters b and $\tilde{b}$ obtained in this approach.

In table 3 the occupation probabilities n_q of the single-particle states of ^{16}O and ^{40}Ca are displayed. The values in parentheses correspond to the occupation probabilities calculated in our previous study [14] where the SRC parmeters λ were taken state independent. It is seen that the values of n_{nl} do not differ much from those of the previous study.

	n_{1s}	n_{1p}	n_{1d}	n_{2s}	n_{1f}	n_{2p}
^{16}O	0.86 (0.87)	0.86 (0.80)	0.10 (0.14)	0.06 (0.06)		
^{40}Ca	0.82 (0.93)	0.72 (0.75)	0.72 (0.72)	0.52 (0.60)	0.38 (0.34)	0.10 (0.09)

Table 3: Occupation probabilities n_q for various nuclei obtained in this approach. The values in parentheses correspond to those calculated in [14] i.e. by considering state independent correlations

Finally in table 4 the occupation numbers $a_q = (2j+1)n_q$ for ^{16}O and ^{40}Ca calculated in this approach, the preliminary "experimental" values of [9] and thoses reported in [29] (see also [30]) along with the theoretical values from other studies [31-33] are shown for the sake of comparison. However, one should keep in mind the large uncertainties concerning the absolute determination of the occupation numbers as well as the model dependence of various analyses [8,30,34].

nucleus	nl	IPM	a_q	exp$^{[9]}$	exp$^{[29]}$	ref. [31,32]	ref. [33]
^{16}O	1s	2	1.72		1.6	1.45	1.84
	1p	6	5.16		3.6	4.06	5.44
	1d	0	1.00			0.87	0.25
	2s	0	0.12			0.12	0.03
^{40}Ca	1s	2	1.64	1.58	1.5	1.94	1.98
	1p	6	4.32	4.60	5.7	5.85	5.92
	1d	10	7.20	7.43	7.7	8.84	9.62
	2s	2	1.04	1.48	1.3	1.74	1.92
	1f	0	5.32	4.31		0.99	0.42
	2p	0	0.60	0.60		0.21	0.06

Table 4: Comparison of the occupation numbers a_q(n.o) for ^{16}O and ^{40}Ca calculated in this work with"experimental" and theoretical values from other studies.

Our analysis shows that in the case of ^{16}O we have a reduction of the total depletion from 18% to 14% while in the case of ^{40}Ca the total depletion is slightly increased from 26% to 29%. A firm conclusion for the effect of state dependent SRC could be made only by carrying out a systematic study for nuclei in the region $4 \leq A \leq 40$ as was done in [13] with state independent

SRC. However, this task is not easy because it is difficult to treat open shell nuclei with the technique of cluster expansion in the case of state dependent SRC. Hence we restricted ourselves to the study of two closed shell nuclei that is ^{16}O and ^{40}Ca. Our results indicate that the effect of state dependent SRC is rather small compared with the effect of state independent SRC.

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