SHELL MODEL AND NUCLEAR STRUCTURE FAR FROM STABILITY*

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We describe the properties of neutron-rich nuclei around $N = 28$ and $N = 20$ in the shell model framework. The valence space includes the *sd* shell for protons and *pf* shell for neutrons without any restrictions. Good agreement is found with the available data and the $N = 28$ shell closure is shown to be persisting. Then we perform calculations in the $N = 20$ region where the valence space is enlarged to include intruder states. We are able to account for the vanishing of the $N = 20$ neutron shell and the dominance of the intruders explains the collective features experimentally found in this region.

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1. Introduction

The exploration of the behaviour of the nucleus under extreme conditions: high spin, vicinity of the drip lines, finite temperature, *etc*, is a major source of new insight into nuclear structure. One of the most important questions raised by the study of the drip lines is whether the basic shell order evolves with the neutron (proton) excess. In particular, long chains of isotopes from Ne to Ar are presently under experimental investigations and give us unique opportunity of exploring the behaviour of several magic closures in one single isotopic chain. Recently, there has been an increase of interest in the $N = 28$ isotones, motivated by the possible existence of anomalies in the shell closure as already observed in $N = 20$. Sorlin *et al.* [1]

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undertook the study of β decay and β-delayed neutron emission probability for ^{44}S and $^{45-47}$Cl. Their measured half-lives were found much shorter than those predicted by TDA [2] or QRPA [3] calculations. These discrepancies were attributed to unexpected shape transitions in the region. Similar conclusions have been drawn by Werner *et al.* [4]. Relativistic and non-relativistic mean field calculations using Skyrme forces produce flat energy surfaces for sulphur isotopes, with several minima separated by energy barriers of just a few hundred keV. Such an effect was accounted for $1f_{\frac{7}{2}} \to fp$ core breaking.

2. $N = 28$ region

The natural valence space for the protons is *sd* shell and *fp* shell for neutrons. The effective interaction used here is composed of the standard *sd* interaction USD [5] , standard *fp* shell interaction KB3 [6] and monopole corrected *sd–fp* G matrix for cross-terms. The mass trends and the two neutron separation energies are well reproduced [7].

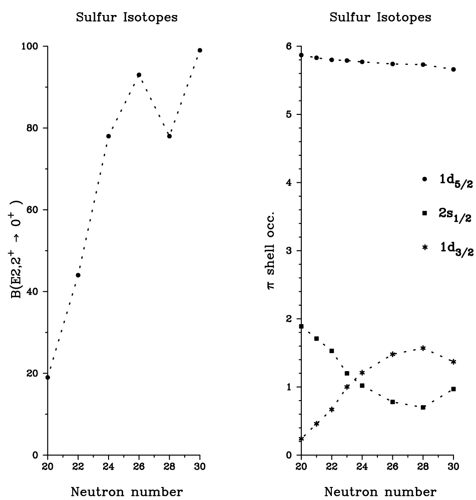

Fig. 1. Proton occupation numbers and increase of collectivity in Sulfur chain.

We show in Fig. 1 the increase of BE2's along the sulfur chain. This raise in collectivity is associated to the filling of proton orbitals and the interplay between $s_{1/2}$ and $d_{3/2}$ shells. The $d_{5/2}$ shell remains almost closed and for light sulfur isotopes, the protons fill essentially the $s_{1/2}$ shell. But as the number of neutrons increases, the filling of the $d_{3/2}$ raises. The maximum of quadrupole coherence is reached when $s_{1/2}$ and $d_{3/2}$ are degenerate, leading to a pseudo-SU3 proton space. This occurs precisely for $N = 26, 28$. Nevertheless, we can rather speak here of strongly correlated closed shell than no shell closure at all: the leading configuration in ^{44}S is $(1f_{7/2})^8$ with 50% and the average occupancy of $1f_{7/2}$ shell is 6.95 compared to the maximum value 8.0. The energy of 2^+ increases relative to $N = 26$ and $N = 30$ and the BE2 slightly decreases compared to $N = 26, 30$. Therefore, even if strong correlations are present we do not think the $N = 28$ shell closure has disappeared. Our calculated values agree with the recent experiments at MSU [8, 9] and GANIL [1].

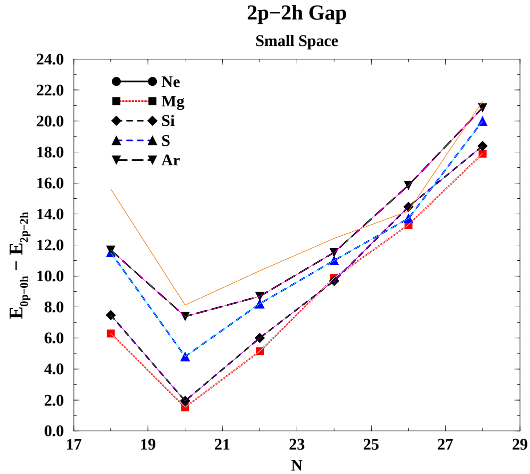

Fig. 2. Energy of the $2p$–$2h$ intruders relative to the normally filled states from $N = 18$ to $N = 28$ (neutron restricted space).

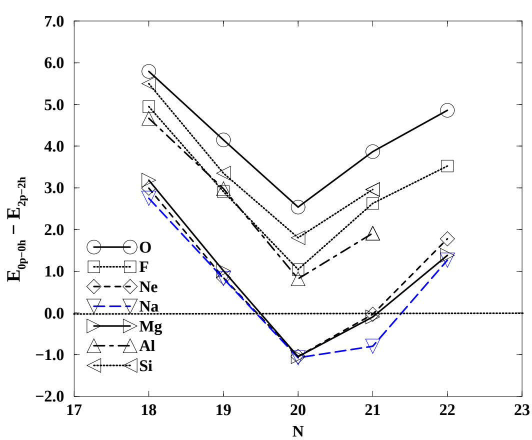

Fig. 3. Energy of the $2p$–$2h$ intruders relative to the normally filled states (full space).

The conclusion concerning the previous situation is that the $N = 28$ shell closure is eroded by the correlations and collective aspects show up in some cases, but this do not imply the vanishing of $N = 28$ shell closure. The occurrence of intruders configurations is excluded as confirmed by the $2p2h$–$0p0h$ gap in Fig. 2. Here, the neutron space is restricted to $(f_{7/2}p_{3/2})$ orbitals. The energy shift caused by this restriction can be estimated by comparison with Fig. 3 and is about 2 MeV.

3. Island of inversion around $N = 20$.

We can also remark on the previous figure, that things change radically when we move to the neutron rich isotopes of neon, sodium and magnesium with $N = 20$. It was pointed out many years ago that data on masses and ground state spins were incompatible with persistence of the $N = 20$ closure. Subsequent spectroscopic studies confirmed this hypothesis in particular because of the very low 2^+ in ^{32}Mg (0.89 MeV) [10] and its enhanced E2 decay (450 $e^2.fm^4$) corresponding to deformation parameter of β=0.5 .

We use the same shell model interaction as previously but include now the 2p2h intruder configurations [11]. In Fig. 3, we see that the intruder configurations appear to be more bound in Ne, Na and Mg at $N = 20$. Let us focus now on ^{32}Mg: the theoretical results with $N = 20$ closed are $\delta E = 1.71$ MeV and BE2$\uparrow$= $150\, e^2.\mathrm{fm}^4$. For the intruder state these values are $\delta E = 1.01$ MeV and BE2$\uparrow$= $500\, e^2.\mathrm{fm}^4$. The agreement is very good and if we mix properly the intruder and the normal configuration, the percentage of closed shell in the ground state is about 20% and we are entitled to speak about shell closure breaking. This produces also a small reduction of the E2 transition.

Then we can wonder whether intruders play a dominant role when neutrons are added or not. The answer is already seen in Fig. 3 where the intruders are not favoured energetically beyond $N = 21$.

4. Conclusion

We have shown the possibility to produce very detailed spectroscopic calculations in the $N = 20$ and $N = 28$ regions where two different kind of behaviour can be observed: in the former region, the vanishing of the $N = 20$ closure due to intruder effects and in the latter, enhanced collectivity especially in the sulphur chain due to reordering in the filling of proton orbitals. The descriptive power of these calculations allows also confidence in predictions such as the highly deformed nature of ^{40}Mg as detailed in [11].

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