Shell model studies of neutron rich nuclei

E. Caurier\textsuperscript{a} F. Nowacki\textsuperscript{b} and A. Poves\textsuperscript{c}

\textsuperscript{a}Institut de Recherches Subatomiques, IN2P3-CNRS-Université Louis Pasteur, F–67037 Strasbourg Cedex 2, France
\textsuperscript{b}Laboratoire de Physique Théorique, Université Louis Pasteur, 3-5 rue de l’Université, F–67084 Strasbourg Cedex, France
\textsuperscript{c}Departamento de Física Teórica C–XI, Universidad Autónoma de Madrid 28049 Madrid, Spain

Abstract

We discuss the present status of the description of the structure of the very neutron rich nuclei, in the framework of modern large scale shell model calculations. Particular attention is paid to the interaction related issues, as well as to the problems of the shell model approach at the neutron drip line. We present detailed results for nuclei around N=20 and, more briefly, we discuss some salient features of the regions close to N=8, 28 and 40. We show that most experimental features can be understood in a shell model context.

Key words: Neutron rich nuclei. Large scale shell model calculations.
PACS: 21.60.Cs, 21.60.-n, 21.10.Hw, 21.10.Ky

1 Introduction

Our knowledge of the properties of the nuclei lying far from the valley of stability has increased a lot in the last decade, thanks to the work carried out at the isotope separators on line (ISOL) and fragment separators. In some cases, mostly in light nuclei, the neutron and/or proton drip lines have been reached. The situation will be much improved with the advent of the new generation of Radiactive Ion Beam facilities that will be discussed at length in other papers of this volume. These experimental advances have been accompanied

\* Work supported in part by Nato CRG 970196, DGES-Spain PB96-53 and the IN2P3.CICYT agreements.
by intense developments in nuclear structure theory. In the region of medium-light nuclei, the shell model description in large valence spaces, that gives the most complete and reliable picture, has become available. A novelty in the very neutron rich side, is that the situation at the Fermi surface resembles that of the heavy nuclei at the valley of stability, with the proton and neutron Fermi levels sitting at different major shells. This represents a new challenge for the shell model approach, because two contiguous major shells have to be included in the valence space, in contrast with the usual calculations in a single major shell. This brings in new problem; on one side the size of the calculations can become very large, demanding novel shell model codes or new techniques; on the other, the effective in medium interaction is richer and therefore more difficult to keep under control. Besides, very close to the neutron drip line, where the physical states are only slightly bound and the wave functions may exhibit very long tails, the validity of an approach based in a Fock space representation may appear at first sight dubious, because of the entanglement of configuration space and Fock space degrees of freedom.

The predictive power of the shell model descriptions in these new regions is seriously hindered by the lack of an “universal” shell model interaction. Whereas it has been demonstrated that one can obtain a fully reliable multipole hamiltonian from modern G-matrices, the monopole hamiltonian is usually incorrect [1]. The monopole hamiltonian contains all the terms depending on the number of particles and on the isospin. The isospin dependent terms of the spherical mean field play a dominant role in the location of the different configurations far from stability and therefore determine which dynamical aspects will be manifest in each regime. Unfortunately, the experimental knowledge of the spherical mean field close to the valley of stability is, in general, not sufficient to move safely far out. The success of the large scale shell model calculations depends crucially on the correctness of the monopole hamiltonian, that’s why the experimental information on some “simple” (closed shells plus or minus one nucleon) exotic nuclei is invaluable.

The first extensive survey of neutron rich nuclei in the shell model context is due to Wildenthal, Curtin and Brown [2] using their fitted USD interaction [3] to compute energy spectra and beta decay properties of all the neutron rich nuclei in the sd-shell. However, some years before, similar calculations by Wildenthal and Chung, when compared with the experimental data of $^{31}$Na, had led these authors to entitle his paper “The collapse of the shell model ordering in the very neutron rich isotopes of Na and Mg” [4]. This was a word of warning on the weird behaviour to be expected when exploring the far from stability land. Later, more experimental findings confirmed this premonitory view, and, nowadays, expressions like “new phases of nuclear matter” or “vanishing of shell closures” are part of our current jargon.
The neutron rich side of the \(p\)-shell has since long provided us with the most dramatic example of intruder state; the ground state \(1/2^+\) in \(^{11}\text{Be}\). The expected \(0\hbar\omega\) “normal” state lies at 300 keV. The shell model description of such inversion requires obviously two major shells. The mechanism of this inversion is common to other cases that we will study later and can be schematically understood as consisting of two major ingredients:

1) The monopole hamiltonian that gives the “unperturbed” or spherical Hartree-Fock energy of the different distributions of the valence particles among the valence orbits (configurations). Far from stability, the energy gaps between these configurations may be eroded because of the small binding of the orbits at the top of the well.

2) The multipole terms (mainly pairing and quadrupole) that mix the components belonging to each configuration, produce different levels of coherence and different energy gains relative to the centroid for different configurations, depending on the structure of the spherical mean field. They can even invert the energy ordering of the configurations given by the monopole terms.

There is a very nice application of this scheme to the \(^{11}\text{Be}\) case by B. A. Brown in ref. [5]. He examines first the \(p-sd\) gap evolution towards the neutron rich side, concluding that it is reduced, but still 4 MeV wide. Promoting a particle across the gap cost therefore 4 MeV. However, it opens the possibility for neutron pairing correlations (gain \(\sim 2\) MeV) and also allows for the quadrupole coupling of the \(^{10}\text{Be}\) \(2^+\) with the \(1d_{5/2}\) neutron (gain \(\sim 2\) MeV). Summing up all those contributions the intruder wins. Notice the subtle balance between spherical mean field properties and correlations, the latter depending very much on the detailed location of the orbits around the Fermi level. When many particles many holes excitations are at play, the monopole effects are more involved, as discussed by A. Zuker [6] in the case of the \(4p-4h\) \(0^+\) excited state of \(^{16}\text{O}\) at \(\sim 6\) MeV and clustering (mainly \(\alpha\) correlations) effects are surely present in the physical solution.

These calculations and a few similar ones [7,8], have provided a solid shell model interpretation to the behaviour of the nuclei in the region, in agreement with or confirmed by subsequent experiments. A most prominent member of this region is \(^{11}\text{Li}\), which sits at the drip line and has a very small (\(\sim 200\) keV) two-neutron separation energy. The last two neutrons have a very large spatial extension, forming what is called a neutron halo [9]. In spite of the exotic matter distribution and of the closeness of the continuum, the shell model picture can still cope with many of the structural properties of \(^{11}\text{Li}\). The calculations predicted a ground state of \(^{11}\text{Li}\) dominated by a configuration with two
neutrons in the $2s_{1/2}$ orbit. Indeed, the most recent experimental information confirms this extreme [10]. Another fingerprint of the dominance of intruder configurations in $^{11}$Li was provided by a classical beta decay experiment, measuring its lifetime and the branching ratio of its decay to the first excited $1/2^-$ state in $^{11}$Be. The results were only compatible, by large, with the assumption of $s$-wave dominance [8]. Very recent experimental work at MSU, has shown that a similar situation happens in $^{12}$Be. The expectedly semi-magic isotope of Berilium (N=8) turns out to be dominated by the intruder configuration with two neutrons in the $sd$-shell [11]. With this, it joins its forerunner cousin $^{32}$Mg in the realm of the intruders.

3 N=20: Intruders

It was in this region were the massive breaking of a semi-magic closure far from stability was first detected, in what is known as “the island of inversion” around $^{31}$Na. The anomalous experimental data on the mass and the spin of $^{31}$Na [12] were attributed to a transition from spherical to prolate shape at N=20 [13]. Later, the measures were extended to other Neon, Sodium and Magnesium isotopes [14] and were interpreted in a shell model context as due to the inversion of the neutron closed shell configuration and a 2p-2h intruder configuration, intrinsically deformed [15]. The intrusion mechanism, that works as we have explained in section 2, was already sketched in ref. [15]. The N=20 quasiparticle gap diminishes when the neutron rich area is approached. For instance, its experimental value for $^{40}$Ca is $g=7$ MeV, for $^{36}$S is $g=5.6$ MeV and for $^{34}$Si is $g=5.1$ MeV. $^{34}$Si is a good reference because it is clearly semi-magic, as we shall discuss later, and very neutron rich. Extrapolating smoothly these numbers one should expect $g \sim 4.6$ MeV for $^{32}$Mg, whereas experimentally $g=3.6$ MeV. This difference may be actually due to the onset of deformation. A two particle-two hole neutron excitation across the N=20 closure, would accordingly cost $\sim 7$ MeV, much less than what it takes in $^{40}$Ca. When the calculations are performed, it turns out that the gain in correlation energy of the intruder state overshoots the monopole gap by 1.5 MeV, producing the famous inversion. Most of the intruder’s gain in correlation energy is quadrupole, because of the presence of open shell $sd$ protons and open shell $pf$ neutrons. When we move to $^{34}$Si, the gap becomes larger and the quadrupole correlation is hindered due to the closure of the $1d_{5/2}$ proton subshell. As a result, the neutron closed shell is now the ground state and the intruder becomes an excited state.

Different groups have made calculations in this region. In ref. [16] the diagonalizations were supplemented with a weak coupling approximation to delineate the contour of the “island of inversion”. More recently [17,18] similar calculations have been undertaken using different truncations of the $sd$-$pf$ space.
In ref. [19] the full sd-shell for neutrons and the full pf-shell for neutrons is considered. The calculations allow up to two particle jumps from the sd-shell to the pf-shell. Besides, it turns out that the cross shell proton excitations are irrelevant in this zone. There is a good level of agreement between the results of these groups, in particular they share the same strong and weak points. One of the strong points is the description of the structure of the isolated intruders as well as its location relative to the normal states for nuclei N=20. Another common strong point concerns the predicted limits in Z of the island of inversion; in all the calculations only Ne, Na and Mg belong to it, while F and Al sit at its very edge. In the weak side are the limits in N of the region. Different choices of the monopole hamiltonian produce small shifts in the borders. As a consequence, N=19 and N=22 are inside or outside depending on the calculation. Also in the weak side is the amount of mixing between normal and intruder states. Very recently, the Quantum Monte Carlo diagonalization method has been also implemented in this region, using as valence space the sd-shell plus the two lower pf-shell orbits, 1f7/2 and 2p3/2 [20]. The effective interaction employed in this reference has been adjusted to produce a 1d3/2–fp gap that decreases rapidly between 34Si (g=4.4 MeV) and 28O (g=1.2 MeV), whereas in our case these figures are 4.7 MeV and 3.4 MeV respectively. It is evident that this choice results in an enhancement of the intruder mixing and in an enlarged “island of inversion”.

We shall now present some of our latest results. We use the same valence space we had in ref [19] and essentially the same effective interaction. A modification has been forced by the recent experimental measure at Isolde [21] of the excitation energy of the 3/2− state in 35Si (1 MeV). In order to fix the monopole terms of the cross shell interaction in the sd-pf valence space this information is vital. In our old interaction we had taken the conservative view and had put the 3/2− state at 2 MeV (as in 41Ca). The effect of this change on the results of ref. [19] is not dramatic and amounts to enhance moderately the quadrupole correlations, increasing the binding energy and the deformation of the intruders. Besides, this modification binds 31F, in agreement with the most recent experimental result [22]. In what follows we compare the structure of the normal and intruder states in the different nuclei of interest and give our predictions for their relative position.

We start the tour with the even Mg isotopes with N=18, N=20 and N=22. Our results are gathered in table 1. In 30Mg the configuration with normal filling gives clearly the best reproduction of the (scarce) existing experimental data [23]. Notice however, that the 2p-4h intruder is very collective, actually as much as the intruder in 32Mg. We can therefore conclude that 30Mg is outside the inversion zone. In 32Mg the situation is the opposite. Our calculation places the 2p-2h intruder well below the closed shell configuration. The differences between both are manifest, and the excellent agreement between the properties of the calculated intruder and the experimental data (the 2+ excitation
Table 1
Properties of the even magnesium isotopes. N is for normal and I for intruder. Energies in MeV, BE2’s in e²fm⁴ and Q’s in efm² in all the tables

|        | ³⁰Mg |        | ³²Mg |        | ³⁴Mg |
|--------|------|--------|------|--------|------|
|        | N    | I      | EXP  | N      | I    | EXP  |
| ΔE(0⁺) | +3.1 |        |      | -1.4   |      | +1.1 |
| 0⁺     | 0.0  | 0.0    |      | 0.0    | 0.0  |      |
| 2⁺     | 1.69 | 0.88   | 1.48 | 1.69   | 0.93 | 0.89 |
| 4⁺     | 4.01 | 2.27   | 2.93 | 2.33   | 0.89 | (2.29)|
| 6⁺     | 6.82 | 3.75   | 9.98 | 3.81   | 3.52 | 3.50 |
| BE2    |      |        |      |        |      |      |
| 2⁺ → 0⁺| 53   | 112    | 59(5)| 36     | 98   | 90(16)|
| 4⁺ → 2⁺| 35   | 144    | 17   | 123    | 88   | 175  |
| 6⁺ → 4⁺| 23   | 140    | 2    | 115    | 76   | 176  |
| Q_{spec}(2⁺) | -12.4 | -19.9 |      | -11.4  | -18.1 |      |

energy [24], the 0⁺ → 2⁺ BE2 [25] and the 4⁺ excitation energy [26]) make it possible to assign this configuration unambiguously. Data and calculations suggest, at low spin, a prolate deformed structure, certainly perturbed, with β ~ 0.5. But, what about the mixing between different np-nh configurations? Indeed, the true physical state must be mixed to a larger or smaller extent. However, in view of the excellent agreement of our fixed 2p-2h solution with the experiment, it is clear that any mixing would deteriorate it. The way out of this dilemma --to mix or not to mix-- refers to the effective interaction. The sd-shell and pf-shell parts of our effective interaction are well suited for 0hω calculations, and contain implicitly part of the effects of the cross shell mixing. Thus, in a mixed calculation one has to take care of properly unrenormalising the interaction. With this caveat, the mixed results may come back to agree with the experiment. In ³⁴Mg the normal configuration that contains two pf neutrons, is already quite collective. It can be seen in the table that it resembles very much the intruder configuration in ³²Mg. Its own 4p-2h intruder is even more deformed (β ~ 0.6) and a better rotor. Therefore, it is more difficult to make a sharp distinction between them both and their different mixed combinations. In our calculation the normal state is 1 MeV below the intruder. However, it is by no means excluded that they could be much closer or even than the intruder would come below. We have put in parenthesis the very recent and preliminary results from Riken [27] that seem to favour the intruder option. Let’s mention however, that results equivalent to those given by the intruder configuration alone, can be also obtained with a 50% mixed solution, provided the pf-shell pairing is reduced. In the QMCD calculations
Table 2
Properties of the even neon isotopes. N is for normal and I for intruder.

|        | 28Ne |        | 30Ne |        | 32Ne |        |
|--------|------|--------|------|--------|------|--------|
|        | N    | I      | EXP  | N      | I    | EXP    |
| $\Delta E(0^+_I)$ | +2.6 | -1.4   | +1.5 |        |      |        |
| $0^+$  | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    |
| $2^+$  | 1.81 | 0.87   | (1.32)| 1.90   | 0.85 | 1.01   |
| $4^+$  | 3.34 | 2.21   | 2.87 | 2.08   | 2.09 | 1.82   |
| $6^+$  | 6.35 | 3.90   | 3.61 | 3.29   | 3.42 |        |
| BE2    |      |        |      |        |      |        |
| $2^+ \rightarrow 0^+$ | 36   | 78    | 54(27)| 29    | 72   | 100    |
| $4^+ \rightarrow 2^+$ | 31   | 105   |      | 22    | 97   | 137    |
| $6^+ \rightarrow 4^+$ | 15   | 104   |      | 89    | 60   | 133    |
| $Q_{spec}(2^+)$     | -1.2 | -17.8 | -1.1 | -16.4 | -13.7| -20.0  |

of ref. [20], the ground state band is dominantly 4p-2h; the $2^+$ comes at the right place but the $4^+$ is too high, making the solution to over-rotate. Clearly, $^{34}\text{Mg}$ is at the edge of the “island of inversion”, whether it is more on the inside or the outside is (theoretically) a matter of subtle arrangements that can only be decided by better experimental data.

In table 2 we have collected the results for the even Neon isotopes to which, *mutatis mutandis*, most of the arguments advanced in the discussion of the magnesiums apply. Now, the experimental information is even meagre than before. Let’s just comment on the $^{28}\text{Ne}$ case because it has been argued in ref. [20] that it could be substantially more mixed than its neighbour $^{30}\text{Mg}$. This claim originates in the comparison between the $sd$ prediction for the $2^+$ excitation energy (1.81 MeV using the USD interaction) and the experimental result (1.32 MeV [26]). However, there could be another explanation; that the discrepancy were due, instead, to a defect of the USD interaction, for the experimental $2^+$ excitation energy of $^{28}\text{Ne}$ (1.32 MeV) is only slightly lower than that of $^{30}\text{Mg}$, (1.48 MeV). The recent measure of the BE2 [23] does not settle the case yet, because its large error bar do not discards a low mixing scenario. In the N=19 isotones $^{29}\text{Ne}$ and $^{31}\text{Mg}$ the situation is even more complex, because the normal configurations are almost degenerate with the opposite parity 1p-2h intruders, while the 2p-3h intruders appear a bit above. The competition for the ground state is between $3/2^+$ and $3/2^-$ in both cases. The beta decay data from Isolde [28] favour the positive parity for the ground state of $^{31}\text{Mg}$. On its side, the calculation explains the occurrence of such a high level density at low excitation energy in the experiment. In the N=21
Table 3
$^{31}$Na level scheme. N is for normal and I for intruder.

\[ \Delta E(\text{intruder} - \text{normal}) = -1.6 \]

| 2J    | N  | 2J    | I(2p-2h) | 2J    | exp |
|-------|-----|-------|----------|-------|-----|
| $5^+$ | 0.0 | $3^+$ | 0.0      | $3^+$ | 0.0 |
| $3^+$ | 0.45| $5^+$ | 0.28     | $(5^+)$| 0.35(2) |
| $1^+$ | 3.18| $7^+$ | 1.06     |       |     |
| $7^+$ | 4.42| $1^+$ | 2.28     |       |     |

BE2($5^+ \rightarrow 3^+$) 62 BE2($3^+ \rightarrow 5^+$) 216

Table 4
$^{34}$Si level scheme. N is for normal and I for intruder.

|       | N | exp | I(2p-2h) | exp | I(1p-1h) | exp |
|-------|---|-----|----------|-----|----------|-----|
| $0^+$ | 0.0| 0.0 | 0.0      | (2.1)| 4$^-$    | 4.19| 4.38|
| $2^+$ | 4.86| 5.3 | 2$^+$    | 3.0 | 3$^-$    | 4.40| 4.26|
| $4^+$ | 7.92| 4$^+$| 4.7      | 5$^-$| 4.53     | 4.97|

isotones $^{31}$Ne and $^{33}$Mg the lowest configurations are the positive parity 2p-1h intruders and the negative parity 3p-2h intruders. Like in the N=19 case they are nearly degenerate and the ground state candidates are $3/2^+$ and $3/2^-$. In a recent experimental study of the decay of $^{33}$Na [29] it is found that the ground state is $3/2^+$. This agrees with our calculation that, in addition, predicts a $3/2^-$ at 300 keV. In table 3, we show the results for $^{31}$Na. In this nucleus the intruder configuration is clearly dominant and very distinct from the normal one. The calculation reproduces the occurrence of $3/2^+$ as spin of the ground state as well as the excitation energy of the $5/2^+$ state, recently measured at MSU [30]. In this reference, shell model calculations along the same lines than ours, although in a somewhat smaller valence space, are reported. They agree reasonably well with the present results.

Finally, in table 4, we move outside of the “island of inversion”. In its “normal” ground state $^{34}$Si is closer to doubly-magic than to semi-magic. The different intruders fit very nicely with the experimental data. Notice the not very frequent level scheme, with a $0^+$ as first excited state. It stems from the calculation that this state is oblate with $\beta \sim 0.4$. The band built upon it is not very regular, but the first couple of transitions are in accord with the rotor picture and are consistent with the value of the $2^+$ spectroscopic moment.
If we move towards the neutron drip line, the Mg isotopes continue being deformed; even the N=28, $^{40}$Mg, which sits at the drip line. Another candidate to shell closure disappearance! Experimentally N=28 has been reached for Z as low as 14 and there is a lot of debate on the physical interpretation of the data. In ref. [31] we studied the region. When the reduction of the $1f_{7/2} - 2p_{3/2}$ splitting in $^{35}$Si is plugged in the calculations, its main effect is to erode the N=28 shell closure, bringing the $2^+$ excitation energy and the BE2($0^+ \rightarrow 2^+$) in $^{44}$S and $^{46}$Ar into full agreement with the data [32]. In $^{42}$Si the excitation energy of the first $2^+$ drops by $\sim 1$ MeV. We can follow the behaviour of the sulphur isotopes in the same valence space crossing two magic numbers and fifteen units of mass. $^{36}$S is spherical, its N=20 neutron closure is reinforced by the proton $2s_{1/2}$ closure, resulting in a $2^+$ at 3.5 MeV. Adding neutrons, the $2s_{1/2}$ and $1d_{3/2}$ become degenerate and, at N=26, $^{42}$S is a nearly perfect prolate rotor. At N=28 the spherical and the deformed solutions appear at the same energy and mix at 50%. $^{43}$S could provide a nice example of shape coexistence and isomerism. Our calculation produces a $3/2^-$ deformed ground state, a low lying $7/2^-$ spherical isomer and another $7/2^-$ at higher energy, belonging to the ground state band. All these in full correspondence with the experimental results of ref. [33]. One could even attempt N=40, but realism advises to increase Z a few units. We suggested a few years ago that $^{64}$Cr could be another “semi-magic” prolate rotor, because of the strong quadrupole coherence of the intruder configurations with four $pf$ protons and four $gds$ neutrons. Preliminary evidence of such behaviour has been reported in its neighbour $^{66}$Fe [34]. For the moment no signs of weakening of N=50 in $^{78}$Ni have been found [35].

References

[1] M Dufour and A. P. Zuker, Phys. Rev. C54 (1996) 1641.
[2] B. H. Wildenthal, M. S. Curtin and B. A. Brown, Phys. Rev. C28 (1983) 1343.
[3] B.H. Wildenthal, Prog. Part. Nucl. Phys. 11 (1984) 5.
[4] B. H. Wildenthal and W. Chung, Phys. Rev. C22 (1980) 2260.
[5] B. A. Brown, Proc. ENAM95 p. 451, M. de Saint Simon and O. Sorlin eds. Ed. Frontieres (France) 1995; T. Aumann et al., Phys. Rev. Lett. 84, (2000) 35.
[6] A. P. Zuker, “Contemporary Nuclear Shell Models” Lecture Notes in Physics 482, p. 93, Springer 1997.
[7] T. Suzuki and T. Otsuka, Phys. Rev. C50, (1994) R555.
[8] M. J. G. Borge, et al., Phys. Rev. C55, (1997) R8.
[9] I. Tanihata, et al., Phys. Rev. Lett. 55, (1985) 380; P. G. Hansen and B. Jonson, Europhys. Lett. 4 (1987) 409.
[10] H. Simon, et al., Phys. Rev. Lett. 83, (1999) 496.
[11] A. Navin, et al., Phys. Rev. Lett. 85, (2000) 266.
[12] C. Thibault, et al., Phys. Rev. C12 (1975) 193.
[13] X. Campi, H. Flocard, A. K. Kerman, S. Koonin, Nucl. Phys. A251 (1975) 193.
[14] C. Detraz, et al., Phys. Rev. C19 (1978) 171.
[15] A. Poves and J. Retamosa, Phys. Lett B184 (1987) 311. A. Poves and J. Retamosa, Nucl. Phys A571 (1994) 221.
[16] E. K. Warburton, J. A. Becker and B. A. Brown, Phys. Rev. C41 (1990) 1147.
[17] N. Fukunishi, T. Otsuka, and T. Sebe, Phys. Lett. B296 (1992) 279. T. Otsuka and N. Fukunishi, Phys. Rep. 264 (1996) 297.
[18] T. Siiskonen, P. O. Lippas and J. Rikovska, Phys. Rev. C60 (1999) 034312.
[19] E. Caurier, F. Nowacki, A. Poves, J. Retamosa, Phys. Rev. C58 (1998) 2033.
[20] Y. Utsuno, T. Otsuka, T. Mizusaki, M. Honma, Phys. Rev. C60 (1999) 054315.
[21] S. Nummela, et al., “Experimental Nuclear Physics in Europe” AIP Conf. Proc. 495 (1999) 55, B. Rubio, M. Lozano and W. Gelletly eds.
[22] H. Sakurai, et al., Phys. Lett. B448 (1999) 180.
[23] B. V. Pritychenko, et al., Phys. Lett. B 461 (1999) 322.
[24] D. Guillemaud, et al., Nucl Phys A246 (1984) 37.
[25] T. Motobayashi, et al., Phys. Lett. B346 (1995) 9.
[26] F. Azaiez et al., “Experimental Nuclear Physics in Europe” AIP Conf. Proc. 495 (1999) 171, B. Rubio, M. Lozano and W. Gelletly eds.
[27] K. Yoneda, et al., Proc. Int. Conf. RIB2000, Divonne (France), in press.
[28] G. Klotz et al., Phys. Rev. C47 (1993) 2502.
[29] G. Walter, et al., Proc. Int. Conf. RIB2000, Divonne (France), in press.
[30] B. V. Pritychenko, et al., MSU-NSCL preprint-1156, June 2000.
[31] J. Retamosa, E. Caurier, F. Nowacki, A. Poves, Phys. Rev. C55 (1997) 1266.
[32] T. Glasmacher, Annu. Rev. Nucl. Part. Sci. 48 (1998) 1.
[33] F. Sarazin, et al., Phys. Rev. Lett. 84 (2000) 5062; R. W. Ibbotson, et al., Phys. Rev. C59 (1999) 642.
[34] M. Hannawald, et al., Phys. Rev. Lett. 82 (1999) 1391.
[35] J. M. Daugas, et al., Phys. Lett. B476 (2000) 213.