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Spectroscopy of nuclei far from stability at GANIL: Recent experiments

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Abstract. The structure of neutron-rich light nuclei around $N = 20, 28$ has been investigated at GANIL by means of in-beam gamma spectroscopy using fragmentation reactions of ^{36}S and ^{48}Ca beams on a Be target. Gamma decay of relatively high-lying excited states have been measured for the first time in nuclei around ^{32}Mg and ^{44}S. Level schemes are proposed and discussed for a large number of these neutron-rich nuclei around $N = 20$ and $N = 28$.

PACS. 27.30.+t $20 \leq A \leq 38$ – 21.10.-k Properties of nuclei; nuclear energy levels

1 Introduction

From the study of the structure of light neutron-rich nuclei, it has been recently suggested that some major shell-gaps are weakened when large isospin values are encountered. The typical cases of ^{32}Mg and ^{44}S, where a large quadrupole collectivity has been found [1–3] have brought some evidence for such a shell-gap weakening at large neutron excess. Though, information on the excitation energies of the first 2^+ states and on the $B(E2)$ values of the 0^+ to 2^+ transitions is not sufficient to fully understand the structure of these nuclei. For instance the measurement of higher-lying excited states and for example the $E(4^+)/E(2^+)$ ratio should shed some light on the origin of the large quadrupole collectivity observed. In order to bring more spectroscopic information on nuclei around ^{32}Mg and ^{44}S, a novel experimental method has been used. This method is based on the production of very neutron-rich nuclei in relatively higher excited states, through the projectile fragmentation process and on the detection of their in-beam γ-decay. Two experiments have been recently performed at GANIL with the SPEG spectrometer. The first one aiming at the production of neutron-rich nuclei around $N = 20$ used the fragmentation of a ^{36}S beam, the second aiming at the study of nuclei in the region $N = 28$ a ^{48}Ca beam. Numerous isotopes have been produced in the two experiments and identified in a time of flight *versus* energy-loss plot. Gamma spectroscopy for all the produced fragments is obtained by performing coincidences between the analyzed fragments and γ-rays emitted in flight during their decay to the ground state. For that purpose in both experiments a highly efficient (25% at 1.33 MeV) γ array consisting of 74 BaF_2 crystals was used around the target. In addition in the first experiment, four 70% high-resolution Ge detectors were used at the most backward angles to help identifying more complex gamma spectra. In the second experiment three segmented clover detectors have been used at about 20 cm from the target and at three different angles 85 degrees, 122 degrees and 136 degrees with respect to the beam axis.

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2 Method of in-beam γ spectroscopy with fragmentation reactions

By using in-beam γ spectroscopy combined with projectile fragmentation reactions at intermediate energies [4], it has been possible to extract general behaviours from the analysis of the intensities feeding the different excited states in the fragments, from the data provided by the 74 BaF_2 detectors of the Chateau de Cristal as a multiplicity filter and from the analysis of the angular distributions of different γ transitions:

i) The obtained gamma spectra exhibit an exponential background with few discrete γ lines. States with spin values up to 4 have been populated in most of the cases.
ii) The yrast states were found to be favored among all other states in the population mechanism of the different fragments, supporting the idea that after the fragmentation-like reactions occur, different primary fragments undergo statistical decay.
iii) A clear correlation has been found between the number of fired BaF_2 detectors (related to γ multiplicity) and the fragment position in the focal plane of the SPEG spectrometer, indicating for instance that low-velocity fragments are correlated to more dissipative collisions and consequently to higher excitation energy and angular momentum. The comparison of spectra with high BaF_2 multiplicity (low-velocity fragments) and low BaF_2 multiplicity (higher-velocity fragments)

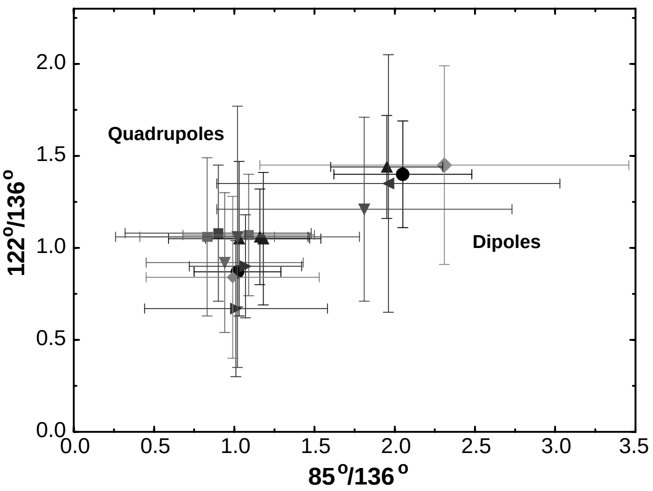

Fig. 1. Systematics of measured γ-ray intensity ratios between the two angle pairs of segmented clover Ge detectors for known transitions. Two groups of measured values for dipole and quadrupole transitions are clearly visible.

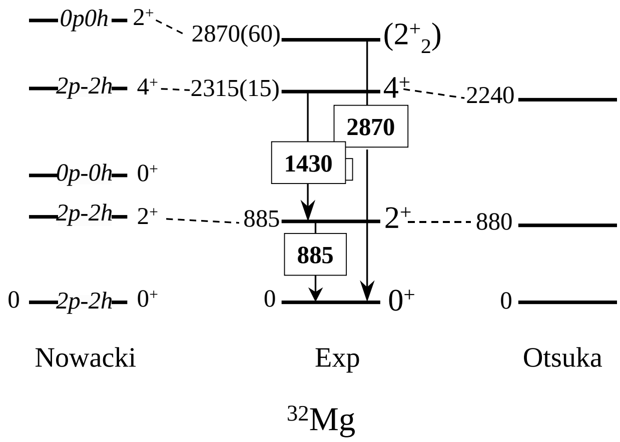

Fig. 2. Level schemes of ^{32}Mg from shell model calculations by Utsuno *et al.* [9] (right) and Nowacki *et al.* [10] (left). The proposed level scheme from the experiment is also shown (middle).

conditions was used in many cases in order to help establishing the position of a given γ-ray in the level schemes.

iv) The analysis of the gamma-ray angular distributions using the BaF_2 detectors was found, within the error bars, to be independent of the multipolarity of known gamma-rays from the data. This suggests that the orientation of the fragment angular momenta is not larger then 15%. Thus from the first experiment (that used ^{36}S beam) no information on the multipolarity of the γ transitions could be extracted.

The second experiment using three segmented clover Ge detectors placed at three different angles allowed to study angular correlation. As shown in fig. 1, the observed γ-ray intensity ratios at different angles are fairly different for typical $\Delta L = 1$ and $\Delta L = 2$ γ transitions allowing multipolarity assignments. Despite a very low degree of orientation of the fragment angular momenta, this has been made possible because of the much higher resolving power of segmented clover Ge detectors compared to the BaF_2 detectors.

3 Structure of neutron-rich nuclei around N = 20

The fragmentation of the ^{36}S beam into a Be target produced numerous neutron-rich nuclei of Mg isotopes up to $A = 32$, of Na isotopes up to $A = 31$, of Ne isotope up to $A = 28$, of F isotopes up to $A = 25$ and $A = 22$ for O isotopes. Many of the obtained gamma spectra have already been shown and discussed elsewhere [4–6]. In the following the discussion will be focused on some of the obtained level schemes and their comparison to shell model calculations. In agreement with the β-decay study of ^{32}Na [8], the two lines: the 885 keV (the well known 2^+ to 0^+ transition in ^{32}Mg [7]) and the 1430 keV, were found to be in coincidence. In the second experiment that used the fragmentation of ^{48}Ca beam it was also possible to study ^{32}Mg. The analysis of the angular distributions of the two gamma-rays detected in the segmented clovers allowed to deduce their nature. Both are of quadrupole character. An other weaker γ line have also been observed at 2870(40) keV. The analysis of the intensity dependence with BaF_2 multiplicity suggests that the 2870 keV γ transition corresponds to the direct decay of an excited state to the ground state. Based on these observations a level scheme is proposed (see fig. 2). Shell model calculations including the fp shell in the valence space [9,10] are in very good agreement with the experimental level scheme. Both calculations suggest that the yrast states (up to spin 4) of ^{32}Mg are deformed. The calculations by Nowacki *et al.* [10] also show that some excited states, such as the second 0^+ and 2^+ states, are spherical. From the proposed level scheme one can find a candidate for an excited spherical 2^+ state. This can be taken as an indication that deformed and spherical states co-exist in ^{32}Mg.

Very low statistics have been obtained for ^{31}Na. Only information from the BaF_2 spectrum could be obtained. This spectrum has mainly three gamma lines at 770 keV, 2470 keV and 2850 keV. Because of its intensity, the lowest-energy γ-ray transition (770 keV) could correspond to the decay of the lowest excited state in ^{31}Na. Though, recently a Coulomb excitation experiment performed at MSU [11] has reported that the lowest excited state is at 350 keV. Because of the high-energy threshold (approximately 300 keV) of the BaF_2 detectors, such a low-energy γ-ray transition could not be observed. Therefore the 770 keV transition would be very likely followed by the 350 keV in the level scheme of ^{31}Na.

A level scheme of ^{26}Ne was built from the collected data. It is shown in fig. 3 together with shell model calculations [12] including only the sd shell in the neutron valence space. The agreement between the experimental and the theoretical level schemes indicates that ^{26}Ne is

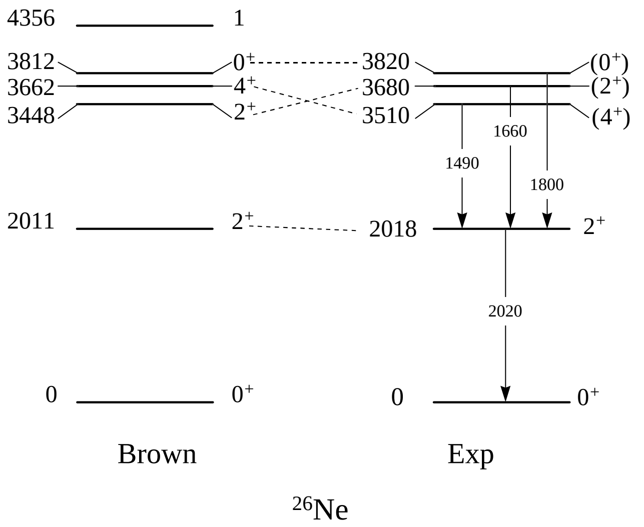

Fig. 3. Theoretical and experimental level schemes of ^{26}Ne.

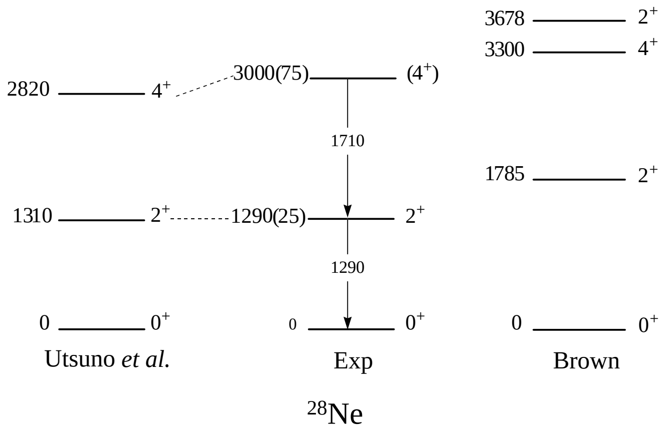

Fig. 4. Theoretical and experimental level schemes of ^{28}Ne.

spherical and is not yet situated in the so-called "island of inversion".

Gamma-ray spectra have been obtained for both ^{25}Ne and ^{27}Ne. In contrast with ^{25}Ne the partial level scheme proposed for ^{27}Ne was found to be in total disagreement with shell model calculations including only the *sd* shell [12]. This is also suggesting that in neon isotopes deformation may already start at $N = 17$ and that the neutron *fp* shell has to be included in the valence space in order to reproduce the data.

Two gamma lines were observed in the BaF_2 spectrum of ^{28}Ne. From intensity arguments, the γ line at 1320 keV is assigned to the 2^+ to 0^+ transition which shows for the first time that, approaching $N = 20$, the 2^+ energies in the Ne isotopes decrease dramatically. This result has been interpreted [9] as due to an increase of deformation in neutron-rich Ne isotopes similar to the one already observed in the Mg isotopes. This has been recently, confirmed by Pritychenko *et al.* [13] in a Coulomb excitation experiment at MSU. The obtained level scheme for ^{28}Ne is shown in fig. 4. Monte Carlo shell model calculations including both the *sd* and *fp* neutron shells [9] are in excellent agreement with the data.

The γ spectra obtained for the first time in ^{22}O from both the BaF_2 and Ge detectors indicate that the γ line at 3200 keV represents the 2^+ to 0^+ transition which extends the systematics of the 2^+ transition energies of oxygen isotopes up to $N = 14$. One can see from this systematics that oxygen isotopes exhibit a rapid increase of the 2^+ energy at $N = 14$. This appearance of a spherical shell effect at $N = 14$ has been recently confirmed by a Coulomb excitation experiment at MSU [14]. The increase in the oxygen isotopes of the 2^+ energy at $N = 14$ is very similar to the one observed in the neon and magnesium isotopes.

This together with the fact that ^{26}O and ^{28}O isotopes seem to be unbound [15–17], is suggesting that a similar shell effect weakening is maybe developing at $N = 20$ for oxygen isotopes. The measurement of the 2^+ excitation energy in ^{24}O (provided it is particle bound) is therefore very crucial. The obtained level schemes from the data for ^{23}F and ^{25}F seem to suggest that ^{22}O and ^{24}O would have their first 2^+ state at about the same excitation energy, just like ^{24}Ne and ^{26}Ne do. The experimental level schemes for both ^{23}F and ^{25}F (see figs. 5 and 6) are in very

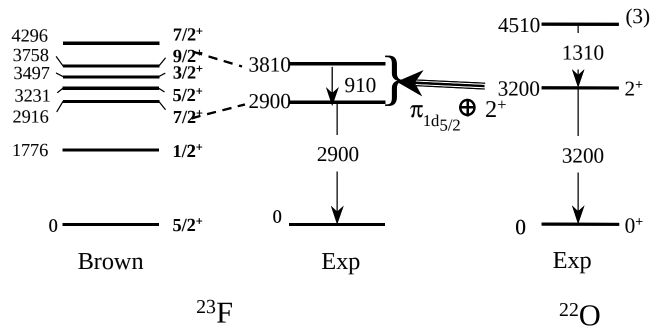

Fig. 5. Level schemes of ^{23}F from experiment (middle) and from shell model calculations including only the *sd* neutron valence space [12] (left). For comparison the experimental level scheme of ^{22}O is also shown (right).

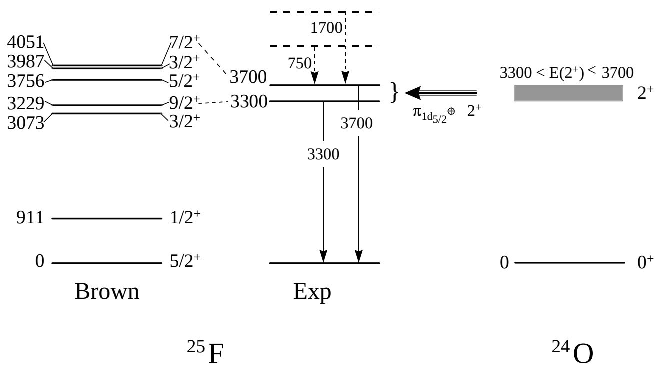

Fig. 6. Level schemes of ^{25}F from experiment (middle) and from shell model calculations including only the *sd* neutron valence space [12] (left). A suggestion of what would be the level scheme of ^{24}O is indicated (right).

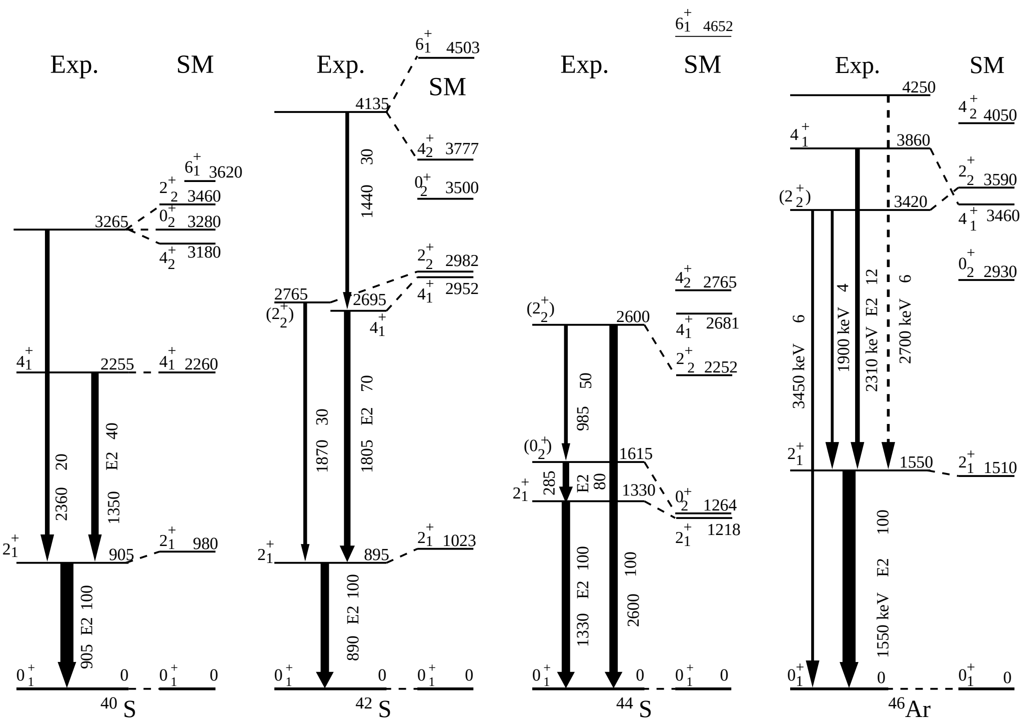

Fig. 7. Proposed level scheme for ^{40,42,44}S and ^{46}Ar extracted from the in-beam γ spectroscopy method using the fragmentation of ^{48}Ca beam on a Be target. For comparison level schemes from shell model calculations [10] are also shown.

good agreement with the *sd* shell model calculations [12] (again one has to keep in mind that only yrast states are populated in the reaction we used). This is indicating that both odd fluorine isotopes are spherical. Furthermore the excited states in ^{23}F can be interpreted as due to the weak coupling of the $1d_{5/2}$ single proton to the 2^+ phonon state in ^{22}O. If we assume that the same weak-coupling picture holds for ^{25}F, then the first 2^+ state in ^{24}O should be expected to have about 3.5 MeV excitation energy. From the tendency that has been seen when going from Mg isotopes to Ne isotopes, namely that neon isotopes start to be deformed earlier (at $N = 18$) than the magnesium isotopes (at $N = 20$), one also could expect oxygen isotopes to start to be deformed even earlier. This tendency does not seem to be followed by oxygen nuclei. In that case the $Z = 8$ strong spherical shell gap would be responsible of not allowing deformation in oxygen isotopes. This could also explain why oxygen isotopes are particle unbound so early (at $N = 18$). In other words, in the case of Ne and Mg isotopes, deformation could push further the neutron drip line whereas in the case of O isotopes it stays where it should be for spherical nuclei. Nevertheless, the question whether there is a weakening of the $N = 20$ spherical shell gap in oxygen isotopes is still an open question. It may be answered in a near future by the study of the spectroscopy of ^{23,24}O isotopes. It is worth noting that in the fluorine chain, ^{31}F is bound [18] and that adding one proton to oxygen can bind six more neutrons.

All together these results show that ^{32}Mg is not an isolated case with regard to the 2^+ excitation energy when approaching $N = 20$ and that shape coexistence as it has been recently suggested [19] is responsible for the structure of these nuclei in the so-called island of inversion. Why does for these neutron-rich nuclei the $N = 20$ deformed shell effect become more effective than the $N = 20$ spherical shell effect? This is still an open question. Revisiting the region of nuclei around $N = 20$ will benefit from the multipolarity determination made possible by the use of segmented clover Ge detectors in this experiment. The analysis of this experiment is still in progress [20].

4 Structure of neutron-rich nuclei around N = 28

The fragmentation of ^{48}Ca allowed the population of many of the neutron-rich nuclei around $N = 28$ and also nuclei around $N = 20$ such as ^{32}Mg. Though, very interesting results on S and Ar isotopes have been already obtained. Using the relative intensities of the γ-rays and energy balance, level schemes for ^{40,42,44}S and ^{46}Ar have been proposed. The assignment of spins and parities have been based on the measured multipolarities of the transitions. The energies of the previously known first 2^+ excited states in ^{40,42,44}S and ^{46}Ar [2,3] as well as the energy of the second excited state in ^{40}S are confirmed. Several new states such as 4^+ states and excited 2^+ and 0^+ states have been identified in many of these nuclei. The proposed level schemes are shown in fig. 7 in comparison with recent shell model calculations [10]. It can be seen from the $E(4^+)/E(2^+)$ ratios that although the ground state and the first excited 2^+ in these nuclei are suggested by shell model calculations [10] to be deformed, only ^{42}S has a value that corresponds to a rotor-like behavior. The same shell model calculations suggest that the second excited 2^+ and 0^+ have spherical shapes. The overall nice agreement between the experimental and theoretical level schemes should be taken as a strong indication of shape co-existence in these nuclei. While their ground and first excited states are deformed, they exhibit spherical higher-lying excited states.

5 Conclusion

The important results obtained on neutron-rich nuclei around $N = 20$ and 28 show that the in-beam γ spectroscopy from fragmentation reactions is a very promising tool for exploring nuclear structure far from stability. It also highlights that a dedicated gamma detection system with a high efficiency, a good resolution and a better Doppler broadening reduction is needed. These are the basic requirements for which EXOGAM [21] was built. It will soon become the ideal gamma detection system for such experiments.

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References

1. T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995).
2. H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).
3. T. Glasmacher *et al.*, Phys. Lett. B **395**, 163 (1997).
4. F. Azaiez *et al.*, in *Proceedings of the International Conference Nuclear Structure 98, Gatlinburg, 1998* (AIP, New York, 1999).
5. F. Azaiez, in *Proceedings of the International Conference ENPE99, Sevilla, Spain* (AIP, New York, 1999).
6. M. Belleguic *et al.*, Phys. Scr. T **88**, 122 (2000).
7. C. Detraz *et al.*, Phys. Rev. C **19**, 164 (1979).
8. G. Klotz *et al.*, Phys. Rev. C **47**, 2502 (1993).
9. Y. Utsuno *et al.*, Phys. Rev. C **60**, 054315 (1999).
10. F. Nowacki, private communication.
11. B. Pritychenko *et al.*, in *Proceedings of the International Conference ENPE99, Sevilla, Spain* (AIP, New York, 1999).
12. B.A. Brown, private communication.
13. B.V. Pritychenko *et al.*, Phys. Lett. B **467**, 309 (1999).
14. B.P.G. Thirolf *et al.*, Phys. Lett. B **485**, 16 (2000).
15. D. Guillemaud-Mueller *et al.*, Nucl. Phys. A **426**, 37 (1984).
16. M. Fauerbach *et al.*, Phys. Rev. C **53**, 647 (1996).
17. O. Tarasov *et al.*, Phys. Lett. B **409**, 64 (1997).
18. H. Sakurai *et al.*, Phys. Lett. B **448**, 180 (1999).
19. P.-G.Reinhard *et al.*, Phys. Rev. C **60**, 014316 (1999).
20. D. Sohler *et al.*, in *Proceedings of the International Conference ENS2000, Debrecen, Hungary*, Acta Phys. Hung, **12**, 241 (2000).
21. F. Azaiez, W. Korten, Nucl. Phys. News, Vol. **7**, No. 4 (1997).