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Probing shell structure in neutron-rich nuclei with in-beam γ-spectroscopy

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Abstract. The structure of neutron-rich light nuclei around $N = 20$ and 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. 23.20.Lv Gamma transitions and level energies – 23.20.En Angular distribution and correlation measurements – 25.70.Mn Projectile and target fragmentation – 27.30.+t $20 \le A \le 38$

1 Introduction

From the study of the structure of light neutron-rich nuclei, it has been recently suggested that some shell structure changes will occur 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 these large quadrupole collectivities 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 high excited states, through projectile fragmentation reactions, and on the detection of their in-beam γ-decay. Such experiments have been recently performed at GANIL.

2 In-beam γ-spectroscopy using fragmentation reactions

In a first experiment aiming at studying neutron-rich nuclei around ^{32}Mg, a ^{36}S beam, at 77 MeV/u was used on a 2.77 mg/cm^2 Be target. The second experiment used a ^{48}Ca beam at 60 MeV/u on the same Be target in order to study nuclei around ^{44}S and ^{46}Ar. The target was located at the entrance of the SPEG spectrometer which was used to analyze the different fragments produced in

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the reaction. Many neutron-rich nuclei have been produced and identified in a time of flight *versus* energy-loss plot. Gamma-spectroscopy for all the produced fragments is obtained by performing coincidences with γ-rays emitted in flight during the decay of the fragments to their ground state. For that purpose, a highly efficient (25% at 1.33 MeV) γ array consisting of 74 BaF_2 crystals, was used around the target covering symmetrically the upper and lower hemispheres (roughly 80% of the solid angle around the target is covered). This array is supposed to provide γ-fragment as well as γ-γ-fragment coincidences. The latter is needed to build up a level scheme for each fragment. It is worth having in mind that all γ-rays of interest are emitted from projectile fragments with their full velocities (about 40% of the speed of light). Typical Doppler-corrected spectra from the BaF_2 detectors exhibit gamma-lines with FWHM varying from 200 keV at 1 MeV up to 500 keV at 3 MeV. In addition to the BaF_2 array, two different Ge detectors setups have been used in the two different experiments in order to help identifying more complex gamma-spectra. In the first experiment performed with the ^{36}S beam, four 70% high-resolution Ge detectors were used at the most backward angles with an efficiency of $1.2 \cdot 10^{-3}$ at 1.3 MeV. Typical Doppler broadening of γ-lines detected in these Ge detectors is 30 keV at 1.3 MeV. In the second experiment with the ^{48}Ca beam, 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. Utilizing the possibilities provided by this type of Ge detectors, we could enhance the efficiency by using the add-back method (the overall photopeak efficiency for this system is more than one order of magnitude higher than the efficiency of the 4 coaxial Ge detectors used for the first experiment), and reduce the Doppler broadening by using the segments information (a FWHM of 35 keV has been obtained for a typical 1.5 MeV γ-ray emitted at 35% of the speed of light). With the used Be target and typical 15 nAe beam intensity, production rates going from few 100/s (for the most populated fragments) to 0.1/s (for fragments very far from stability such as ^{28}Ne and ^{44}S). In these conditions, individual Ge crystal counting rates of the order of 10 to 15 kHz have been obtained. After gating on the proper fragment and on the true γ-fragment coincidences (subtracting the random coincidences contribution), Doppler-corrected γ-spectra are produced together with γ-γ matrices for coincidence analysis. Typical γ-spectra from Ge and BaF_2 detectors have been presented in previous publications [4–6]. In the following, there will be a presentation of the general properties and features of this new method based on in-beam γ-spectroscopy with fragmentation reactions as well as a discussion of some of the results related to the structure of neutron-rich nuclei in the $N = 20$ and $N = 28$ isles of inversion.

This is the first time that in-beam γ-spectroscopy combined with projectile fragmentation reactions at intermediate energies has been used [4]. Some general features could be extracted from the analysis of the feeding intensities of different excited states in different fragments, from the use of the 74 BaF_2 detectors as a multiplicity filter and from the analysis of the angular distributions of different γ transitions. These features, that will be summarized as follows, have been used, in addition to coincidence relationships and intensity arguments, to propose level schemes for many of the populated neutron-rich fragments:

i) In all cases, the obtained gamma-spectra exhibit the same properties. Namely, an exponential background with few discrete γ-lines. States with spin values up to 4 have been populated in most of the cases.
ii) In all known cases, the yrast states were found to be favored among all other states in the population mechanism of the different fragments. This supports the idea that after the fragmentation-like reactions have occured, different primary fragments undergo statistical decay. For example, in the case of ^{20}O, where low-lying excited states are known from previous studies, the first 2^+ and 4^+ excited states are more populated than the second-excited 2^+ and 0^+ states.
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. This indicates, 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) 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 is suggesting that the orientation of the fragment angular momenta is not large enough to allow, within the resolving power of

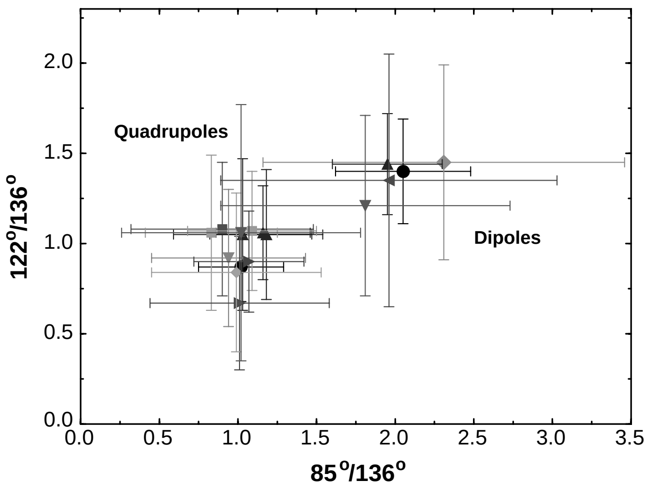

Fig. 1. Systematics of the measured γ-ray intensity ratios between the two angles pairs of segmented clover Ge detectors. Note the significantly different clustering of the measured values for dipole and quadrupole transitions.

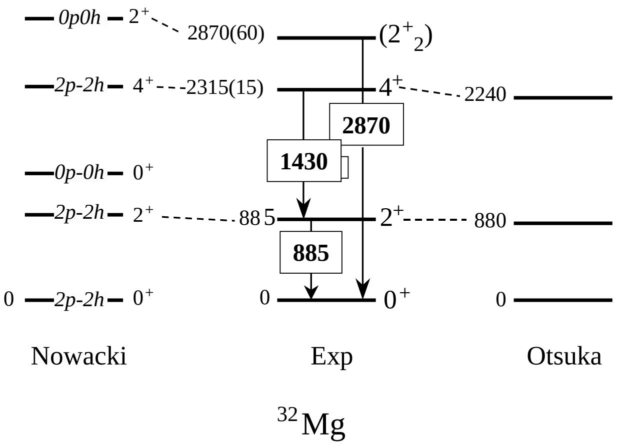

Fig. 2. Level schemes of ^{32}Mg from shell model calculations by Utsuno *et al.* [7] (right) and Nowacki *et al.* [8] (left). The proposed level scheme from the experiment is also shown (middle).

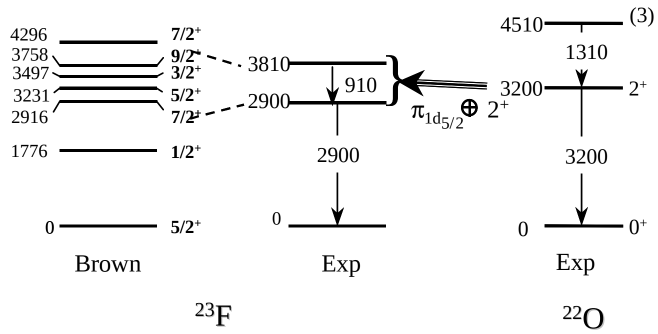

Fig. 3. Level schemes of ^{23}F from experiment (middle) and from shell model calculations including only the *sd* neutron valence space [9] (left). For comparison the experimental level scheme of ^{22}O is also shown (right).

the BaF_2 detectors, to extract γ-ray multipolarities. 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 (that used ^{48}Ca beam) had the advantage of using three segmented clover Ge detectors placed at three different angles suitable for angular correlation measurements. As shown in fig. 1, the observed γ-ray intensity ratios are fairly different for typical $\Delta L = 1$ and $\Delta L = 2$ γ transitions allowing multipolarity assignments. Despite a relatively 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 a big number of neutron-rich nuclei up to $A = 32$ for Mg isotopes, $A = 31$ for Na isotopes, $A = 28$ for Ne

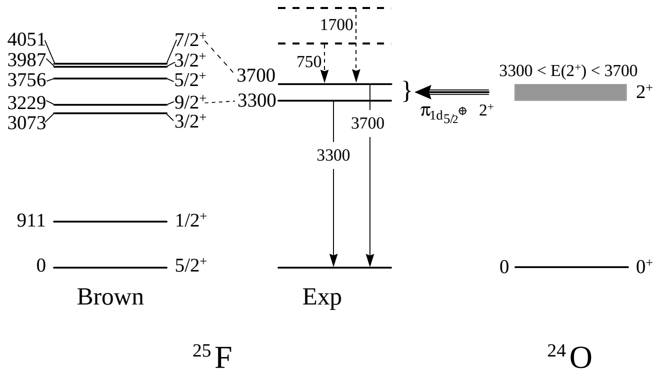

Fig. 4. Level schemes of ^{25}F from experiment (middle) and from shell model calculations including only the *sd* neutron valence space [9] (left). A suggestion of what would be the level scheme of ^{24}O is indicated (right).

isotopes, $A = 25$ for F isotopes and $A = 22$ for O isotopes. Many of the obtained gamma-spectra have been shown and discussed elsewhere [4–6]. In agreement with the β-decay study of ^{32}Na [10], the two lines: the 885 keV (the well-known 2^+ to 0^+ transition in ^{32}Mg [11]) and the 1430 keV, were found to be in coincidence. The second experiment that used the fragmentation of ^{48}Ca beam had also produced ^{32}Mg. The analysis of these two gamma-ray angular distributions from the collected data in the second experiment indicated that both are of quadrupole character. Another weaker γ-ray transition has also been observed 2870(40) keV. The analysis of the intensity dependence with BaF_2 multiplicity (point iii) of the previous section) 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). As is shown in this figure, the agreement with shell model calculations including the *fp*-shell in the valence space [7,8] is very good. Both calculations suggest that the yrast states (up to spin 4) of ^{32}Mg are deformed. The calculations by Nowacki *et al.* [8] also show that some excited states, such as the second 0^+ and 2^+ states, are spherical. From the proposed level scheme one can see 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 [12] 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.

Gamma-ray spectra have been obtained for both ^{25}Ne and ^{27}Ne. In contrast with ^{25}Ne, the partial level scheme

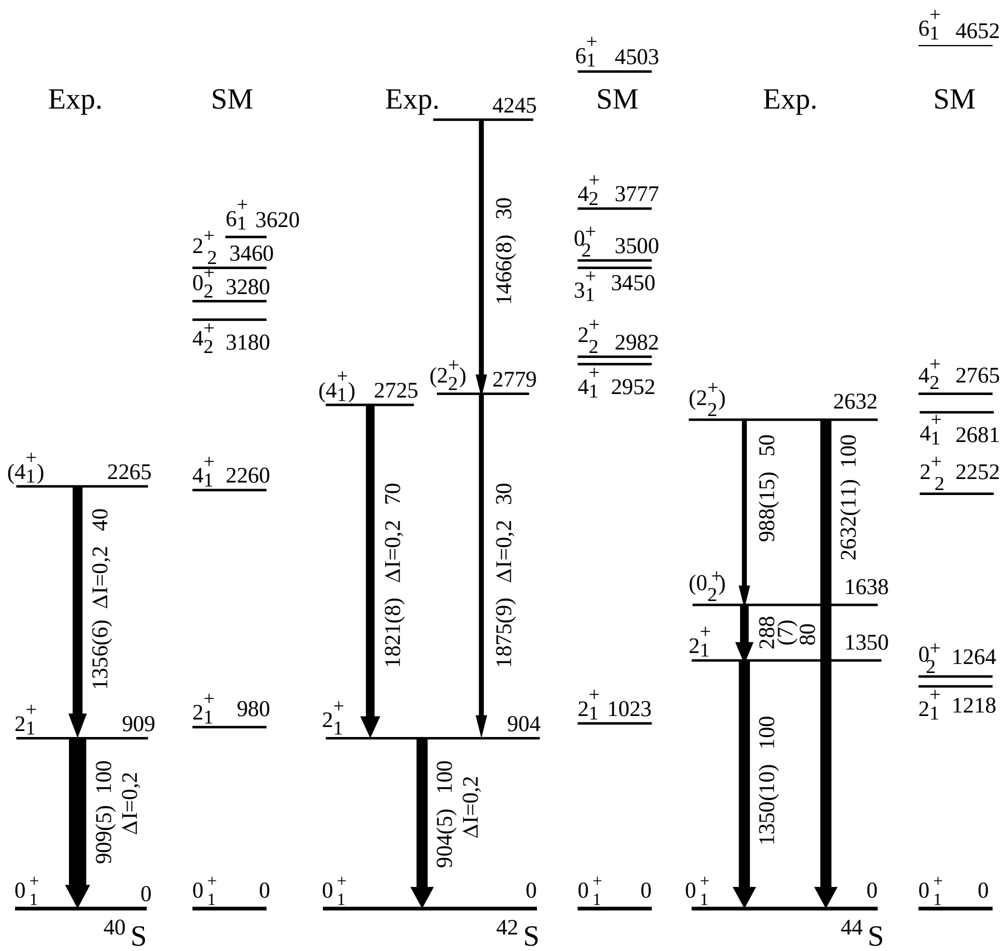

Fig. 5. Proposed level scheme for ^{40,42,44}S extracted from the in-beam γ-spectroscopy method using the fragmentation of ^{48}Ca beam on a Be target. For comparison, level schemes from shell model calculations are also shown.

suggested for ^{27}Ne was found to be in total disagreement with shell model calculations including only the sd-shell [9]. This is also suggesting that in neon isotopes deformation may already sets in 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 [7] 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. Moreover, another γ-line at 1710 keV has been observed in our experiment and assigned to the 4^+ to 2^+ transition. The overall obtained level scheme for ^{28}Ne is found to be in striking agreement with Monte Carlo shell model calculations including both the sd and fp neutron shells [7].

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 systematic 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 are presumably unbound [15–17], is suggesting that the spherical shell effect is moving from $N = 20$ to $N = 14$ and 16 in oxygen isotopes just as it does in Ne and Mg isotopes. The measurement of the 2^+ excitation energy in ^{24}O 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. 3 and 4) are in very good agreement with the sd-shell model calculations [9] (again, one has to keep in mind that only yrast states are populated in the used reaction). 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 lie around 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. If we assume what has just been suggested for ^{24}O, from the measured level scheme in ^{25}F, this tendency does not seem to be followed in the oxygen isotopes. 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 dripline, 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. Such study has been performed very recently at GANIL using in-beam γ-spectroscopy with fragmentation reactions induced by radioactive ^{26}Ne beam. 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 has been recently suggested [18], is responsible for the structure of these nuclei in the so-called island of inversion.

4 Structure of neutron-rich nuclei around N = 28

The second experiment that used 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. Revisiting the region of nuclei around $N = 20$ benefits from the multipolarity determination made possible by the use of segmented clover Ge detectors in this experiment. The analysis of this experiment revealed very interesting results on S and Ar isotopes [19]. 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 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. 5 in comparison with recent shell model calculations [8]. The $E_{4_1^+}/E_{2_1^+} = 2.5$ ratio in ^{40}S was found to be consistent with that of an anharmonic vibrator or a γ-soft rotor, the $E_{4_1^+}/E_{2_1^+} = 3.0$ and $E_{2_2^+}/E_{2_1^+} = 3.1$ ratios observed in ^{42}S are characteristic for a triaxial rigid rotor with $\gamma = 23°$ deformation, while a low-lying 0_2^+ state proposed for ^{44}S is supporting shape coexistence in this isotope. The results deduced for the individual nuclei as well as the trend in evolution of shapes from ^{40}S to ^{44}S are very much consistent with the erosion of the $N = 28$ spherical shell closure at $Z = 16$.

Beside the importance of the obtained results on neutron-rich nuclei around $N = 20$ and 28, both experiments showed that the in-beam γ-spectroscopy from fragmentation reactions is very promising for exploring nuclear structure far from stability. It also highlights the needs for a dedicated gamma detection system from the point of view of efficiency, resolution and Doppler broadening reduction. These three features are the basic requirements for which EXOGAM [20] was built and thus make it the ideal gamma detection system for such experiment.

The results discussed in this paper are from experiments performed at GANIL by a large team of physicists from many European laboratories. Both experiments using in-beam gamma-spectroscopy with fragmentation reactions benefit from the availability of ^{36}S and ^{48}Ca isotopes kindly provided by our colleagues from DUBNA and from the smooth running of the accelerator from the GANIL crew. The use of the segmented clover detectors was made possible thanks to the EXOGAM Collaboration. This work has been supported by the European Community contract No. HPRI-CT-1999-00019, and OTKA D34587, T30497.

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