New approach to the nuclear in beam γ spectroscopy of neutron rich nuclei at N=20 using projectile fragmentation

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Abstract : The structure of nuclei far from stability around ^{32}Mg have been recently investigated by means of a novel method. In-beam γ-decay spectroscopy of a large number of exotic neutron-rich nuclei produced by projectile fragmentation of a ^{36}S projectile has been performed, using coincidences between the recoil fragments collected at the focal plane of SPEG spectrometer and γ-rays emitted at the target location. Preliminary results on both the population mechanism and the decay of excited states in nuclei around ^{32}Mg are presented.

I- Introduction :

One of the most challenging goals of nuclear structure is to determine how the structure of atomic nuclei changes far away from stability line. 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 (N=20) and ^{44}S (N=28), where a large collectivity has been found [Mo95, Sc96, Gl97], have brought some evidence for such shell-gap weakening at large neutron excess. The present work deals with the N=20 shell closure for neutron rich nuclei far from stability. The ^{32}Mg lies just at this neutron shell closure and therefore is expected to be spherical. Nevertheless, evidences of nuclear deformations for nuclei exhibiting large neutron excess have been pointed out by some experimental works [Th75, Or91, De78]. In ^{32}Mg, only half of the $d_{5/2}$ sub-shell is occupied by the protons. This could account for the increase of collectivity and deformation in this nucleus as it is the case for many nuclei in which this proton sub-shell is not completely filled [Te96, Gi98]. Theoretical calculations including sd-shell configurations for neutrons and protons are unable to explain anomalous behaviours in the binding energies of neutron-rich Na [Th75, Or91] and Mg [De78, Or91] isotopes around N=20. Also, the large quadrupole excitation probability B(E2) of ^{32}Mg [MO95] can only be understood in the frame of a larger configuration space, including f-d shell excitations for neutrons [Wa81, Po87, Wa90, Fu92, Po94]. The crossing of the downsloping $1f_{7/2}$ level with the $2d_{5/2}$ level at prolate deformation may explain the breaking of this magicity. The large measured B(E2) [Mo95] value in ^{32}Mg could originate from vibrational and/or rotational degrees of freedom. In order to bring a clearer insight on the nature of the measured collectivity, the $E^*(4^+_1)$ / $E^*(2^+_1)$ ratio of the excited states should be determined, as for axially symmetric rotational nucleus this ratio should be close to 3, whereas a vibrational nucleus should exhibit a ratio closer to 2.

II- Experimental Technique :

The fragmentation of a ^{36}S beam has demonstrated that the production of neutron-rich nuclei around N=20 is clearly enhanced as compared to the use of other primary beams [Ta98]. A ^{36}S beam, with a 15 nAe intensity was impinged onto a thin a 2.77 mg/cm^2 Be target at an energy of 77.4 MeV/u. The target was located at the entrance of the SPEG spectrometer at GANIL. The Bρ setting of the spectrometer (3.444T.m.) was set to optimize the transmission of the entire ^{32}Mg momentum distribution within the SPEG focal plane. The experimental set-up is shown in Fig 1. It is fairly known that projectile fragmentation produces nuclei with relatively high excitation energy and spins up to 10 h. For example the isomeric 10$^+$ state at 6.5 MeV excitation energy in ^{54}Fe has been populated using the projectile fragmentation of a ^{112}Sn beam onto a ^{nat} Ni target (Eighteen percent of the ^{54}Fe were produced in this isomeric state) [Gr95]. In the present experiment, many neutron rich light nuclei have been produced in excited states and transmitted for a given spectrometer setting. The produced fragments deexcite in flight down to the ground state by the emission of a cascade of γ-rays. The γ-rays have been detected in coincidence with the recoil fragments, in an event by event basis. The fragment were identified in an event by event basis by means of time of flight and energy loss measurements. The energy loss was measured in an ionization chamber at the focal plane of the SPEG spectrometer, whereas the time of flight of the fragments was given by the time-difference between the RF pulse from the accelerator and the signal from a plastic scintillator located at the focal plane of SPEG. The 'Chateau de cristal' array composed of 74 BaF2 crystals was used around the Be target in order to detect the γ-rays. The total and photopeak efficiencies for a 1.33 MeV γ-ray were found to be 60% and 30% respectively. In addition to the BaF2 array, four 70% high resolution Ge detectors were used at the most backward angles. Fragment-γ as well as fragment-γ-γ coincidences were performed. The large Doppler broadening of the measured γ-rays energies due to the important recoil velocity of the fragments (β=v/c 38%) as well as the large expected X-rays and γ-rays background coming from the various reactions of the incoming beam in the target are as many difficulties in such in-beam γ-spectroscopy experiment. After gating on the proper fragment and on the true fragment-γ coincidences (subtracting the random coincidences contribution), Doppler corrected γ-spectra were obtained.

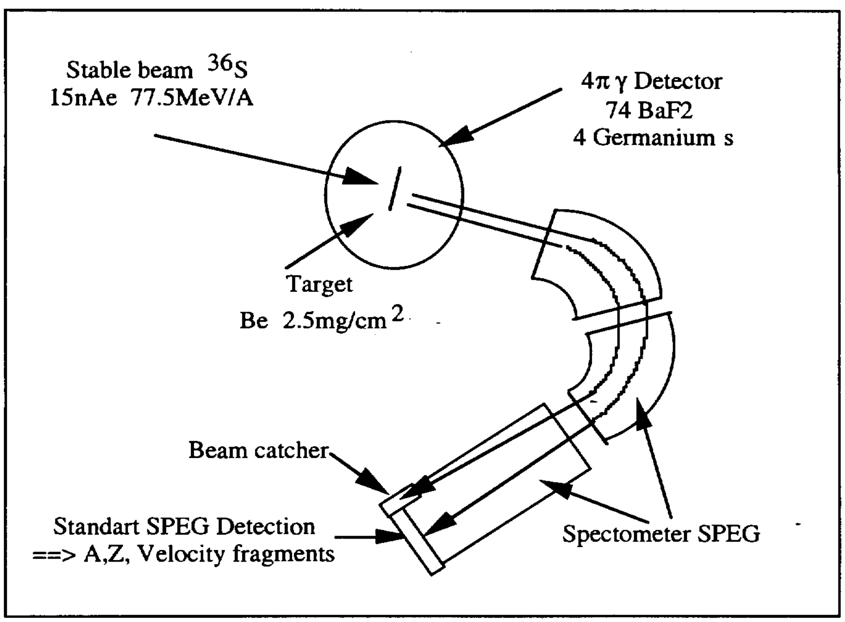

Fig.1: Schematic view of the experimental set-up.

III- Population of excited states by projectile fragmentation

Very little information is known on the population mechanism of exotic nuclei by projectile fragmentation at intermediate energy. Most of it comes from isomer decay studies in laboratories such as GANIL [Da99]. The study of the projectile fragmentation mechanism is essential in order to understand how and to what extend associated in-beam γ-spectroscopy is could be used to study the structure of nuclei far from stability. For that purpose, the Château de Cristal was used as an energy sum and multiplicity spectrometer in order to deduce the excitation energy and spin distribution

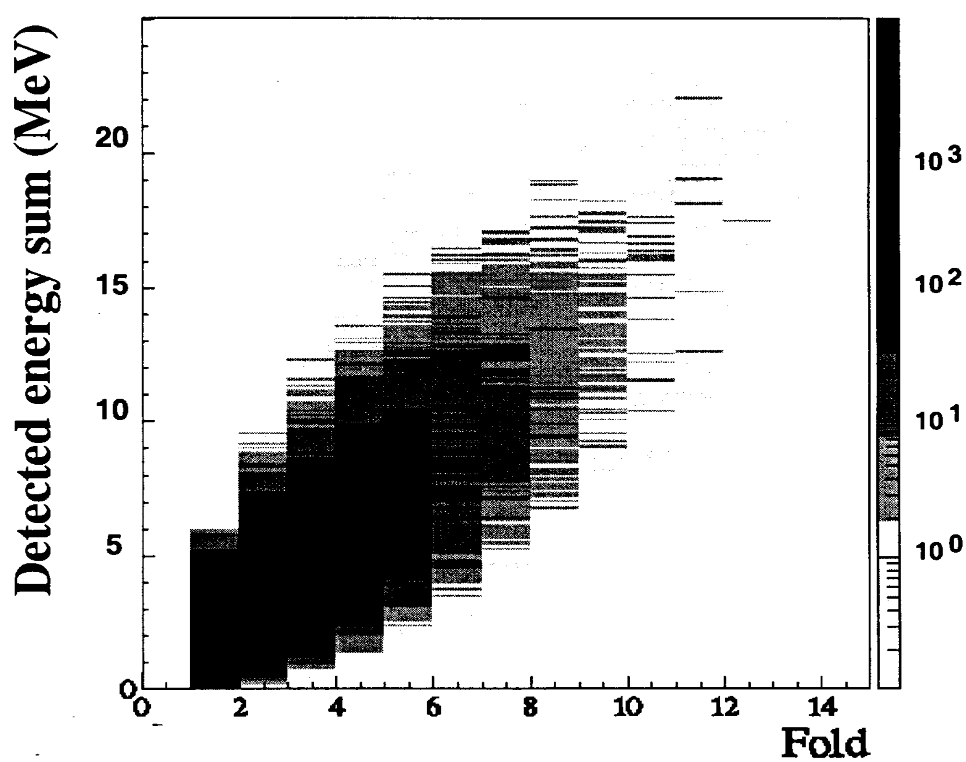

Fig.2 : The BaF2 detected energy sum versus the BaF2 detected fold for ^{32}Mg fragments. This experimental spectrum is not corrected for the detector efficiency and neutrons contribution. Only the background corresponding to random coincidences was subtracted. The detected average fold and energy sum are respectively 2 units and 2.91 MeV (see text).

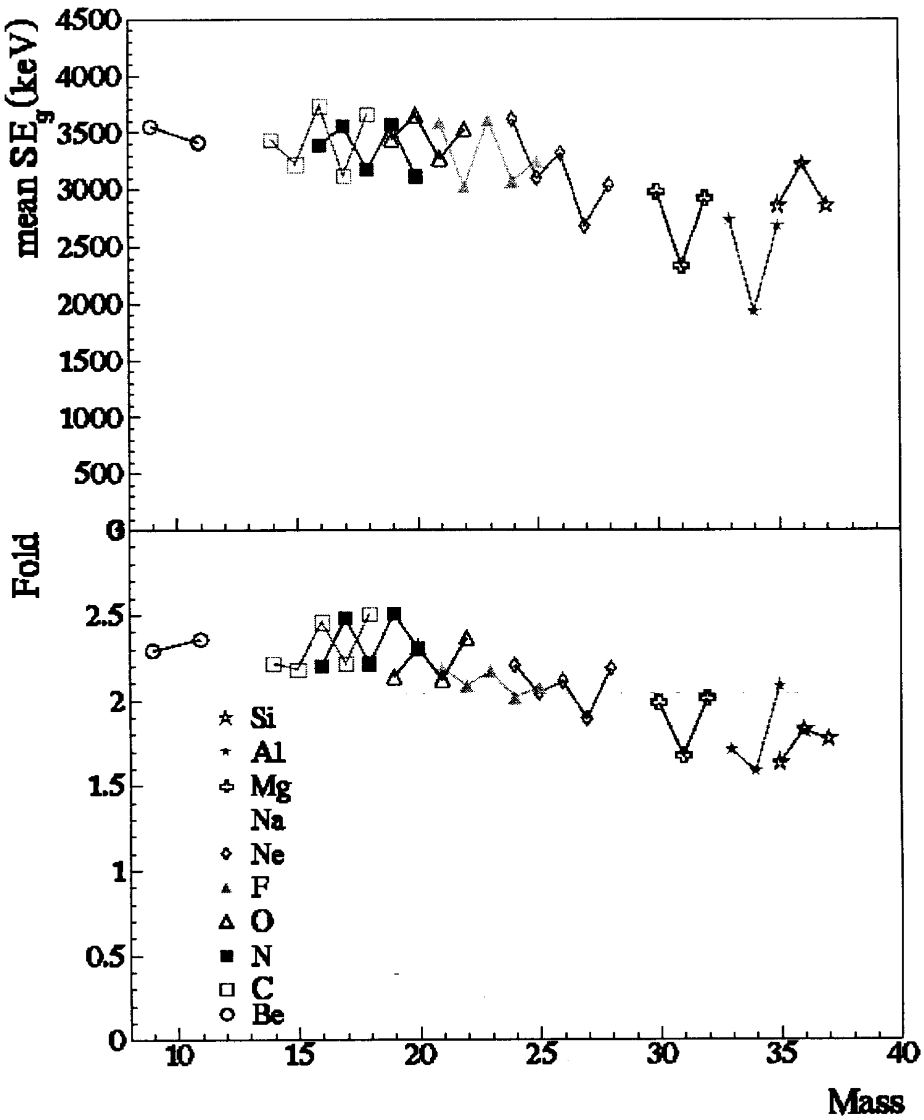

Fig. 3 : Dependence of the detected average BaF2 fold (lower part) and the detected average BaF2 energy sum (upper part) versus fragment products mass. These experimental spectra are not corrected by the detection efficiency. Only the background corresponding to random coincidences was subtracted (see text).

of the produced fragments. The excitation energy is given by the measurement of the total energy taken away from the fragments by γ-emission (γ-energy sum) whereas the spin is given by the measurement of the γ-multiplicity which is in turn deduced from the hit-pattern of the 74 BaF2 detectors (γ-fold). Typical plots (see figure 2), are examined for different fragments and different recoil energy in order to study the dependence of the spin and excitation energy with relevant parameters such as A/Z, velocity etc...

The figure 3 shows the dependence of the average BaF2 fold (upper part) and the average raw BaF2 energy sum (lower part) versus fragmentation products masses. One can see that both quantities slightly increase when going from fragments in the vicinity of the projectile to fragments well away from the projectile. These data are not still corrected for the detector efficiency and for the neutrons contribution. Only the background corresponding to random coincidences was subtracted. The Silicon fragments do not follow this trend because they are produced by a mechanism involving nucleons transfer instead of projectile fragmentation. Another point which are not yet understood is the fact that for ^{11}Be, the Baf2 fold and Baf2 energy sum are so high (M = 2.4 and E_{sum} = 3.5 MeV) . The E_{sum} value is in this case similar to that measured for other nuclei even if the one neutron separation energy of ^{11}Be (S_n= 508 keV) is extremely low. This means that not only the γ rays and γ continuum of projectile fragment are detected but also neutrons or other γ rays coming from nuclear reaction processes itself as target excitation etc. These effects can modify the tendencies shown in Figure 3. Furthermore, a odd-even staggering is clearly seen, reflecting the pairing energy contribution to the reaction Q values. It is worth reminding that the used parameters (fold and energy sum) are not unfolded with the château de cristal response function and therefore should not be taken as an indication of the absolute values of the excitation energy and spins.

IV - preliminary results on spectroscopy of ^{32}Mg and ^{26,28} Ne :

The main goal of this experiment was to get a new information on the structure of semi-magic ^{32}Mg and neighboring light neutron rich nuclei. After gating on the proper fragment (i.e. ^{32}Mg) and on the true fragment-γ coincidences, Doppler-corrected γ-spectra are presented in Fig. 4 (left part : BaF_2 detectors, right part : Germanium detectors). These spectra clearly show the presence of two lines : the first one is the well known 885 keV corresponding to the 2^+ to 0^+ transition in ^{32}Mg, the second one at an energy of 1.430 MeV. The γ-γ coincidences reveal that these two-γ-lines are in coincidence (Fig. 5). This 1.430 MeV line could be the line already observed by Klotz at al in radioactivity measurements [Kl93]. The γ angular distribution and directional correlation analysis are still in progress in order to determine the spin of this level. Though, it is likely to be either a 4_1^+ to the known 2_1^+ transition or a transition from a second 2_2^+ the known 2_1^+ state.

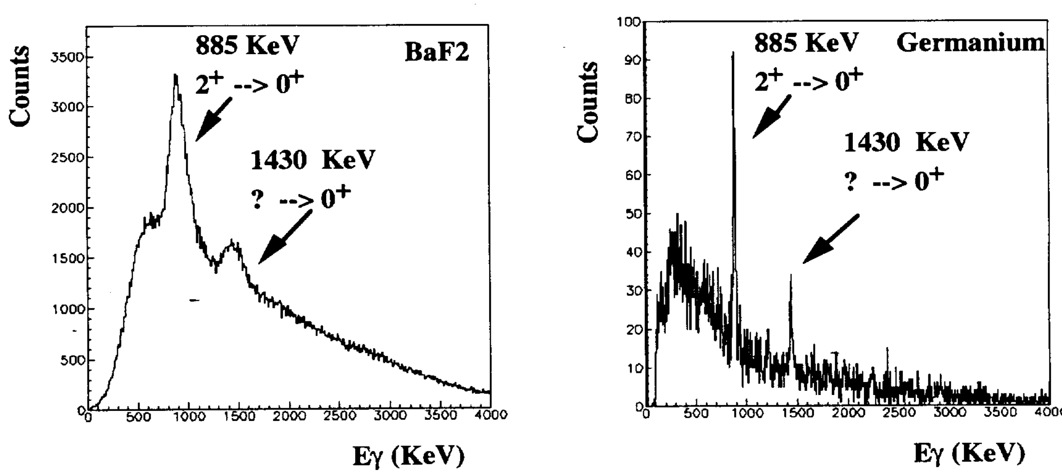

Fig. 4 : Gamma energy spectra of ^{32}Mg in the BaF_2 (left) and in the germanium (right).

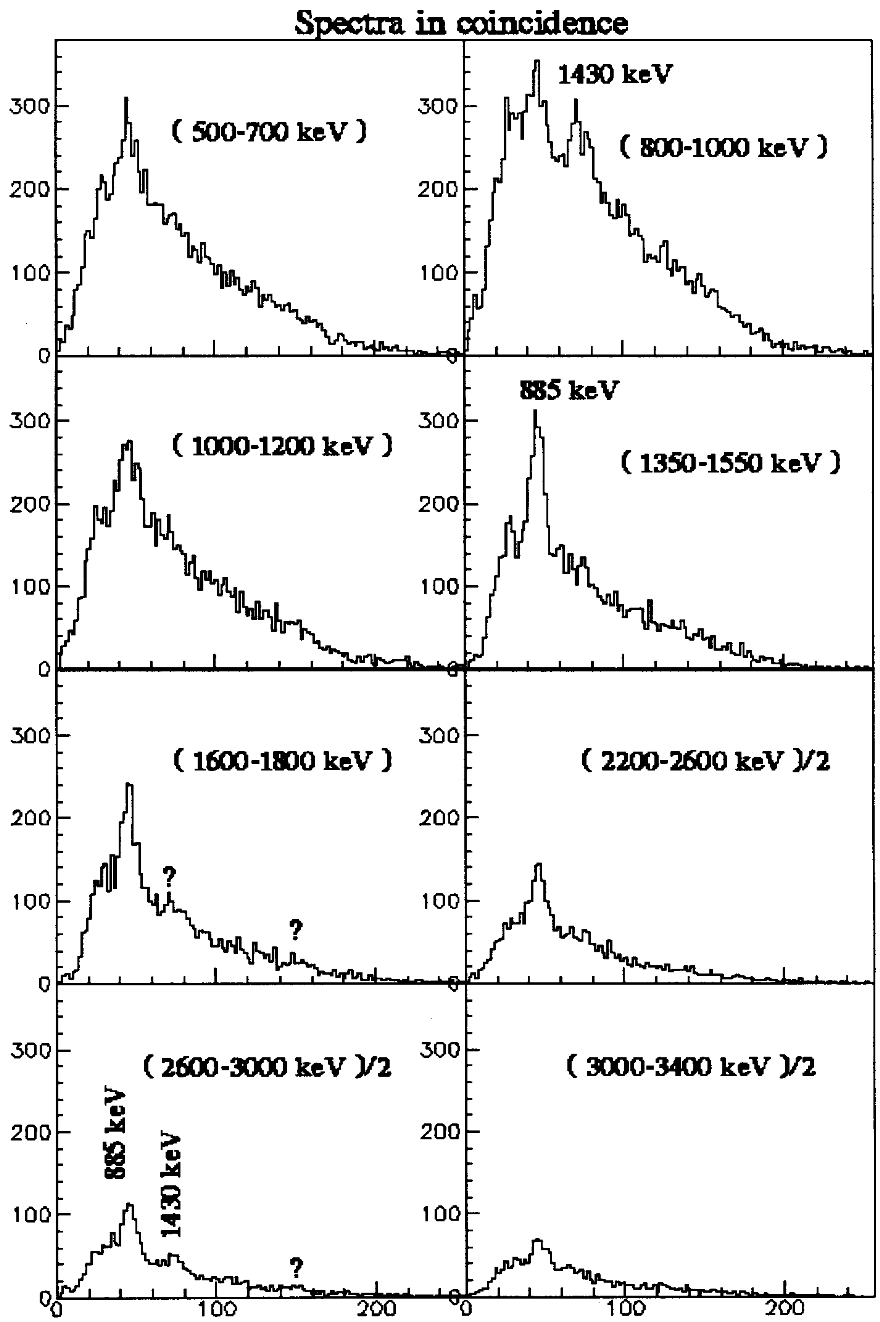

Fig. 5 : ^{32}Mg coincident_γ-γ spectra corresponding to different energy gates : The gates (800-1000) and (1350-1550) corresponds to the 885 keV and 1430 keV lines. Two other gates (2600-3000) and (1600-1800) seem to be in coincidence with the 1430 keV. The other gates correspond to γ-background.

For ^{26}Ne and ^{28}Ne, strong lines respectively around 2.010MeV and 1.320 MeV are observed. The 2^+ excitation energy of ^{26}Ne has been already measured in a β-decay experiment at GANIL [Re98]. Being the most intense, these lines are very likely to be the 2_1^+ to 0^+ transition in ^{26}Ne and ^{28}Ne. Their energies show that, approaching N=20 the 2^+ energies in the Ne isotopes decrease from around 2 MeV in ^{24}Ne and ^{26}Ne to 1.3 MeV in ^{28}Ne (see figure 6). This is presumably a sign of shell structure change for neutron rich Ne isotopes similar to the one observed in the Mg isotopes. No result has been obtained yet on the gamma angular distribution and correlation for the angular momentum assignment.

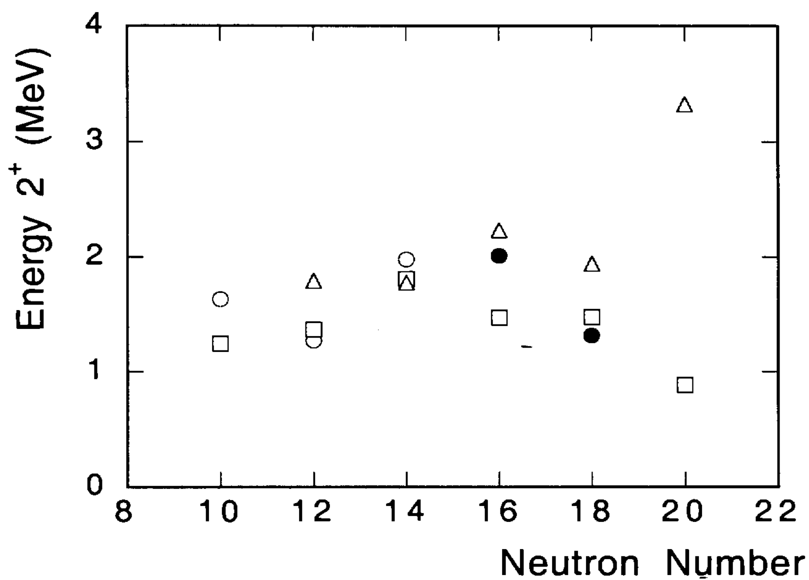

Fig. 6 : Gamma energy in MeV of the first 2^+ levels in isotopic chains : circle = Neon, square = Magnesium and triangle = Silicon. The black points are preliminary new results of this work.

Conclusion :

Even though the analysis of this data is still in progress, the preliminary results obtained up to now prove the feasibility of such in beam γ-spectroscopy experiment using projectile fragmentation. The gamma detection system from the point of view of efficiency, resolution and Doppler broadening reduction can be improved by the use of the soon available EXOGAM [Az97] detectors. The high selectivity and the large acceptance SPEG spectrometer turned out to be experimentally crucial to the success of such an experiment. It gives us an indication of the powerful association of a spectrometer and an highly efficient gamma array for nuclear structure studies.

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