FIRST RESULTS FROM GA.SP. EXPERIMENTS

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Introduction

Large arrays of high-efficiency γ–ray spectrometers are coming now into operation or are under construction. The key feature of such arrays is the power to identify weak cascades of γ–rays within the enormous γ–ray flux which is emitted in a nuclear reaction. Such instruments will give a great impetus in the study of high spin phenomena and of very exotic-weak channels. One such array has started operation recently at Legnaro and in this talk its main characteristics will be presented together with the first results obtained which are related to the decay out of the superdeformed band in the nucleus ^{133}Nd.

The γ–ray spectrometer Ga.Sp.

Ga.Sp. is a general purpose 4π detector for advanced γ–ray spectroscopy and, at the same time, a suitable system for reaction mechanism studies. The array consists of 40 Compton suppressed HPGe detectors and of a 4π calorimeter composed of 80 BGO crystals. The detector surrounds a reaction chamber of 34 cm diameter where a charged particle multiplicity filter composed of 40 Si detectors is going to be installed. Evaporation residues produced in the centre of Ga.Sp. can be injected into the recoil mass spectrometer in use at LNL, without the need to remove any of the γ detectors. The coupled operation of Ga.Sp., RMS and Si ball will give a unique instrument for identification and study of weak reaction channels.

The 4π γ–detection systems proposed in recent years try to maximize the photopeak efficiency by means of non-standard germanium designs and of shared Compton suppressors. In this respect Ga.Sp. is a detector system of the standard type as it uses individual Compton suppression shields. The increase of efficiency is obtained using big volume germanium crystals which became available in recent years. Our HPGe detectors are built out of n-type cylindrical crystals of 72 mm diameter and about 82 mm length. The mean relative photopeak efficiency of the 38 detectors delivered up to the time of this writing is (see Fig. 1) about 83% at 1332 keV. The average energy resolution of these detectors is 2.2 keV. Compton suppression is performed by symmetric BGO shields composed of eight 19.5 long optically isolated crystals. The dimensions and the cost of the BGO crystals have been optimized by means of extensive Montecarlo calculations exploiting the benefit of the higher intrinsic P/T ratio of the big volume germanium crystals.

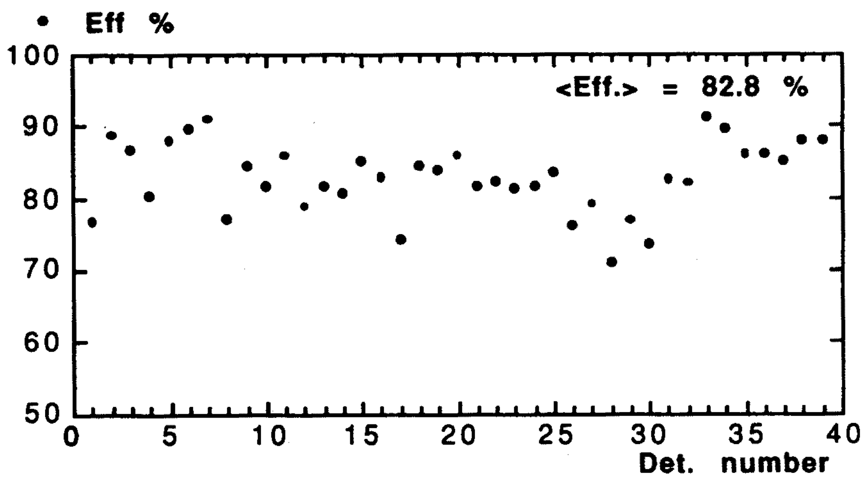

Figure 1. Relative photopeak efficiency at 1332 keV for the Ge–detectors of Ga.Sp.

When using the inner BGO ball, the germanium detectors are positioned at 27 cm from the target; the detectors of the inner ball act as partial collimator and the solid angle subtended by the germanium detector is 0.26%. In this situation the calculated absolute photopeak efficiency is 0.086% and the P/T is about 70% at 1 MeV. A measurement of the absolute photopeak efficiency at 1332 keV has given 0.074% which translates to about 3% for the complete system. Tests performed with the ^{60}Co source have given Compton suppressed spectra with P/T of 65%. This results confirm that, as planned, Ga.Sp. has the best response function among the arrays being built at present.

The target–germanium distance can be reduced to 20 cm if the inner ball is removed and if the increased Doppler broadening can be accepted. As in this way one can gain about a factor of two in detection efficiency, the supporting structure has been designed in order to allow for this option.

The inner ball is built out of 80 hexagonally shaped 6 cm thick BGO crystals of two slightly different shapes but with almost exactly the same efficiency. The ball covers a solid angle of 80% and, as a result of the tests with radioactive sources, it has an absolute efficiency of about 70% at 1 MeV and a resolution in multiplicity of 31% for a cascade of 30 transitions.

One of the most interesting characteristics of this project is the coupled operation of Ga.Sp. and RMS. As this is achieved without removing any γ detector we get an increased resolving power without sacrificing detection efficiency. The distance between the two spectrometers is about 4 meters and the coupling of the two instruments is achieved by means of a magnetic quadrupole doublet, positioned at 70 cm from the center of Ga.Sp., which focuses the recoils on the target position of RMS. Ray tracing calculations give an overall acceptance of the coupled system of about 5 msr (compared with $\approx$ 8 msr when the target is in the RMS chamber) with a mass resolution of 1/170 for a central mass A=100. This acceptance is sufficient to collect almost 100% of the residues from HI induced reactions with evaporation of only neutrons and protons.

First experiments: performances of the array

Installation of Ga.Sp. began in late fall 1991 and was completed in March 1992. Commissioning of the system (using 28 Ge+Ac systems and the BGO inner ball) was performed in May 1992. A test of coupled operation of Ga.Sp. and RMS has also been performed using the reaction ^{32}S + ^{58}Ni at 125 MeV. The achieved mass resolution was indeed 1/170 but the acceptance was significantly less than expected, so a detailed study of the matching of the two instruments using the beams from the Tandem is currently being performed. Experiments were started shortly after the commissioning runs. Test experiments performed during commissioning (e.g.

the $^{106}Pd + ^{32}S$ reaction at 160 MeV with a beam current of about 10 pnA such to have 10 kHz of singles in the germaniums) have shown that the system with 30 detectors can give about 6 kHz of triple coincidences. Various experiments have been carried out since then: a) search for the linking transitions from the superdeformed (SD) band in ^{143}Eu, b) two-proton particle transfer between high-spin states around the Coulomb barrier, c) a study of high spin states and possible SD states in the odd-odd nucleus ^{134}Pr, d) properties of nuclei toward ^{100}Sn and e) a study of the decay-out of the SD band in ^{133}Nd. I will present here the experimental details and the results of the ^{133}Nd experiment. The states in ^{133}Nd were populated by the reaction $^{105}Pd(^{32}S,2p2n)^{133}Nd$ at a beam energy of 155 MeV. The target consisted of 2-3 self supporting foils isotopically enriched to 94% in ^{105}Pd with a total thickness of 1 mg/cm^2. Data has been collected requiring coincidence of at least 3 suppressed Ge detectors with at least three BGO detectors of the inner ball. In this experiment the number of Ge-detectors was 31 and the triple rate between 5 and 6 kHz. To give an idea of the quality of the data Fig. 2 shows the total projection of the γ–γ matrix together with a single, double, triple gated spectrum(without background subtraction) with gates on the known transitions of the SD band in ^{133}Nd. As is evident from the figure, the peak to background ratio is improved by a factor ≈ 3 for each increase in the coincidence–fold. The use of the BGO inner ball is also of help in selecting, with proper gates on the multiplicity and on the sum-energy, the different nuclei produced in the reaction and this has been done for the analysis of the decay–out of the SD band in ^{133}Nd presented in the following paragraphs. Also a thick target experiment was performed for ^{133}Nd using the same reaction and energy. A target of 1 mg/cm^2 of ^{105}Pd on a 12 mg/cm^2 Au backing was used. This experiment proved to be crucial for finding an isomeric state on which all the previously known[1] excited states of the ^{133}Nd nucleus are built.

Superdeformation in the A=130 region: the nucleus ^{133}Nd

Since the discovery, in ^{132}Ce[2], of a band characterized by a narrow (≈ 70 keV) and fairly regular energy spacing, many rotational bands with similar character (called superdeformed) have been reported in the A=130 region[3,4]. Such SD bands have the properties of deformed prolate rotors ($\beta = 0.35, 0.40$) and are associated with the

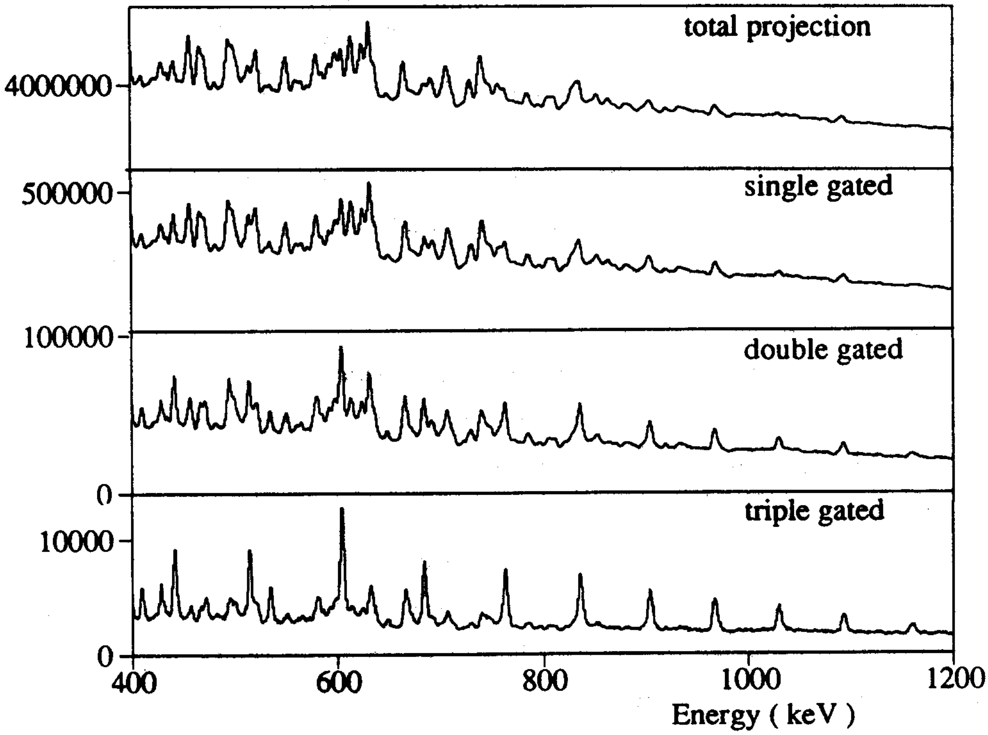

Figure 2. Coincidence spectra (without background subtraction) of the reaction ^{105}Pd+^{32}S at 155 MeV obtained from the analysis of doubles, triples and quadruples data with gates on the SD band of ^{133}Nd.

second minimum in the nuclear potential energy surface. This second minimum appear to originate, in this particular region, from highly deformation-driving intruder orbitals based on the $i_{13/2}$ orbital. In many cases lifetime measurements have also been performed[5)] which confirm the large deformations inferred from the SD band level spacings.

One of the major deficiencies in knowledge regarding the phenomenon of superdeformation at high spin, in all nuclear regions where it has been seen, is the fact that excitation energies and spins of the bands are not known. It has proven to be difficult to establish the decays out of the SD bands since such decays proceed through many weak parallel cascades which are difficult to detect. A link into the normal deformed (ND) states from the SD band was claimed in ^{135}Nd[6)], but this was not confirmed in a subsequent experiment[3)]. Highly deformed bands which $\Delta E_\gamma \approx 90$

keV (called "intruder bands") have been found in Sm and Gd isotopes and in two cases ^{137}Sm[7] and ^{135}Sm[8] their decay into the ND states has been identified. Only recently in ^{143}Eu[9] a method of analysis of triples data has been employed which apparently yields the excitation energy of the band but not a detailed knowledge of the decay out of the band. Of course, the precise measurement of the excitation energies and spins of known SD bands is essential for any further understanding of the nuclear superdeformation phenomenon and for more stringent tests to theoretical calculations.

The nucleus ^{133}Nd seemed to us the best case to examine for discrete linking transitions between the SD states and the normal deformed states, since the population of the band is reported to be the highest among the known SD bands ($\approx 20\%$). Lifetime measurements have been recently performed for the SD band of this nucleus[5] and the analysis of the data gives β values of 0.33 and 0.37 if the centroid shift or the line-shape fit analysis is adopted. These experimental β values are in agreement with theoretical Routhian surface calculations which give β values from 0.36 to 0.32 over a rotational frequency range from $\hbar\omega = 0.29$ to $\hbar\omega = 0.70$.

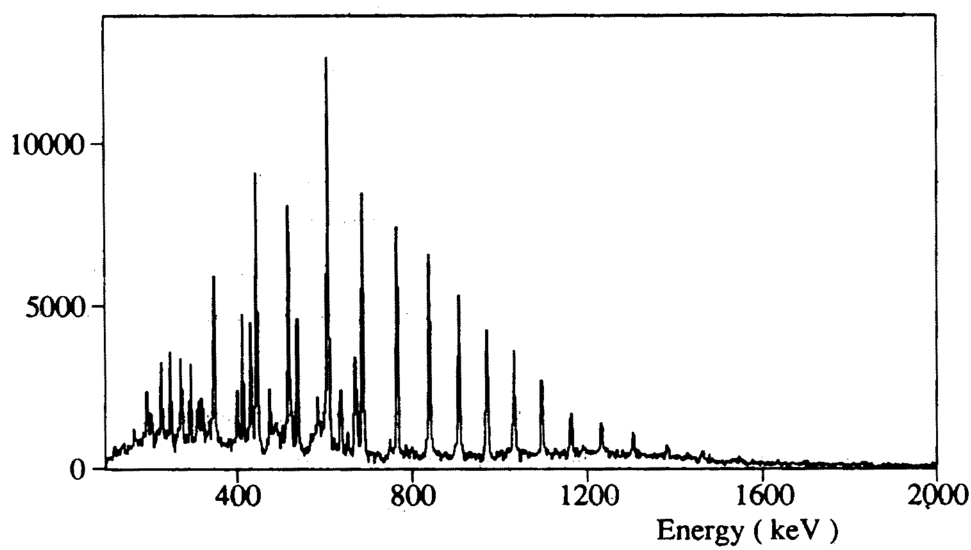

Figure 3. Triple gated spectrum with gates on all lines of the ^{133}Nd SD band.

The superdeformed band in ^{133}Nd and its decay–out

We have observed the SD band of ^{133}Nd up to a transition energy of 1631 keV which has an intensity of 0.7 per cent of the total population of ^{133}Nd corresponding to $2 \cdot 10^{-4}$ of the total fusion cross section of the ^{105}Pd + ^{32}S reaction. We could extend the band by only three transition since its population is decreasing very rapidly with spin. Fig. 3 shows a triple gated spectrum with gates on the transitions of the SD band. In the energy region from 100 to 800 keV a number of lines are evident which, due to the high selectivity of the quadruples data, can be firmly assigned to the decay of the SD band or to low lying states in ^{133}Nd. The only knowledge from literature of excited states in ^{133}Nd, apart from the SD states, comes from ref. 1) which reports a quite strong negative parity band based on a $9/2^-$ state. From the systematics of this region (see e.g. ^{131}Ce[10]) one expects also a positive parity band based on the $g_{7/2}$ orbital to lie low in energy. By looking at the data taken with the thick target, it was immediately recognized that the negative parity band is built on an isomeric state with $T_{1/2} \approx 100$ ns which decays through a 177 keV transition. An analogous isomer is observed in the isotone ^{131}Ce where the $9/2^-$ state (on which the negative parity band is built) has an half–life of 80 ns and decays through an 162 keV transition to the $7/2^+$ ground state. From this comparison we fix also in ^{133}Nd the relative energy of the negative and positive parity states. In order to build the level scheme above the $7/2^+$ state we have performed an excitation function measurement from 145 to 170 MeV in the reaction ^{105}Pd + ^{32}S and found a family of γ–rays in coincidence with a strong 245 keV transition which follow the same trend with increasing bombarding energy as the known negative parity transitions. Furthermore, in the data taken in main run at 155 MeV, gates placed on many different lines of the γ–ray spectrum showed that the 245 keV transition and the transitions from the SD band and the negative parity band all display the same distributions in multiplicity and sum energy, but different from any other nucleus populated in the reaction. We should note here that all lines of the 245 keV family are in coincidence with the SD band (see Fig. 3) which was assigned to this nucleus[11] just because of the coincidence with the 245 keV line which in turn was assigned to ^{133}Nd from γ–recoil coincidences.

Fig. 4 shows a partial level scheme of ^{133}Nd extracted from the analysis of triple and quadruple data. All the known states in the SD band are shown together with the transition connecting the SD band with the positive parity states built on the $7/2^+$ state and with part of the decay of the band to the ground state. Decisive in determining the excitation energy of the SD band has been the observation of the two linking transitions of 307 and 633 keV which connect the state at 3326 keV to two levels of the band based on the $g_{7/2}$ orbital. Furthermore a 553 keV line connecting the $29/2^+$ level of the $g_{7/2}$ band to the $25/2^+$ level of the SD band has been found, thus fixing unambiguously the crossing between the two bands at spin $29/2^+$. The spin assignment shown in the figure is based on an angular correlation analysis of the triples data which gives, in particular, $\Delta I = 2$ for the 633 transition and $\Delta I = 1$ for the composite, 307 keV transition, thus fixing the spin for the 3326 keV level at $29/2^+$.

Only about 20% of the SD intensity feeds out at the 3326 keV level, whereas the rest of the intensity divides into two paths with almost equal intensity at spin $21/2^+$ and it divides into more paths below until it reaches the ground state. Some of the γ–ray cascades through which the SD band decay to the ground state could be determined and are shown in Fig. 4. It is worth noting that in a recent β–decay study[12)] of the nucleus ^{133}Pm, which populates states in ^{133}Nd, lines of 245, 291, 225, 270, 191 have been reported which we also observe at the bottom of our level scheme. This fact confirm that the main part of the decay of the SD band is reaching the ground state of ^{133}Nd.

Other highly deformed bands in ^{133}Nd at high-spins.

Taking advantage of the high quality data produced with Ga.Sp. we could also extend the positive parity band based on the $g_{7/2}$ orbital up to spin 67/2. Fig. 5 shows a sum of gates on the low lying transitions of the two signature partners of the band. The most striking feature to note is the spacing between transitions in the two cascades which is similar to those of the SD band (see Fig 2). A plot of the moment of inertia $\Im_1$ which, knowing the spin, can be calculated also for the SD band, is shown in Fig. 6. The moment of inertia of the SD band is 53 $MeV^{-1}/\hbar^2$ to be compared with the value of 56 $MeV^{-1}/\hbar^2$ expected for a rigid rotor with $\beta = 0.35$. From the figure it's evident that a deformation similar to that of the SD band is reached by the positive parity band after the alignment, which in this region is due

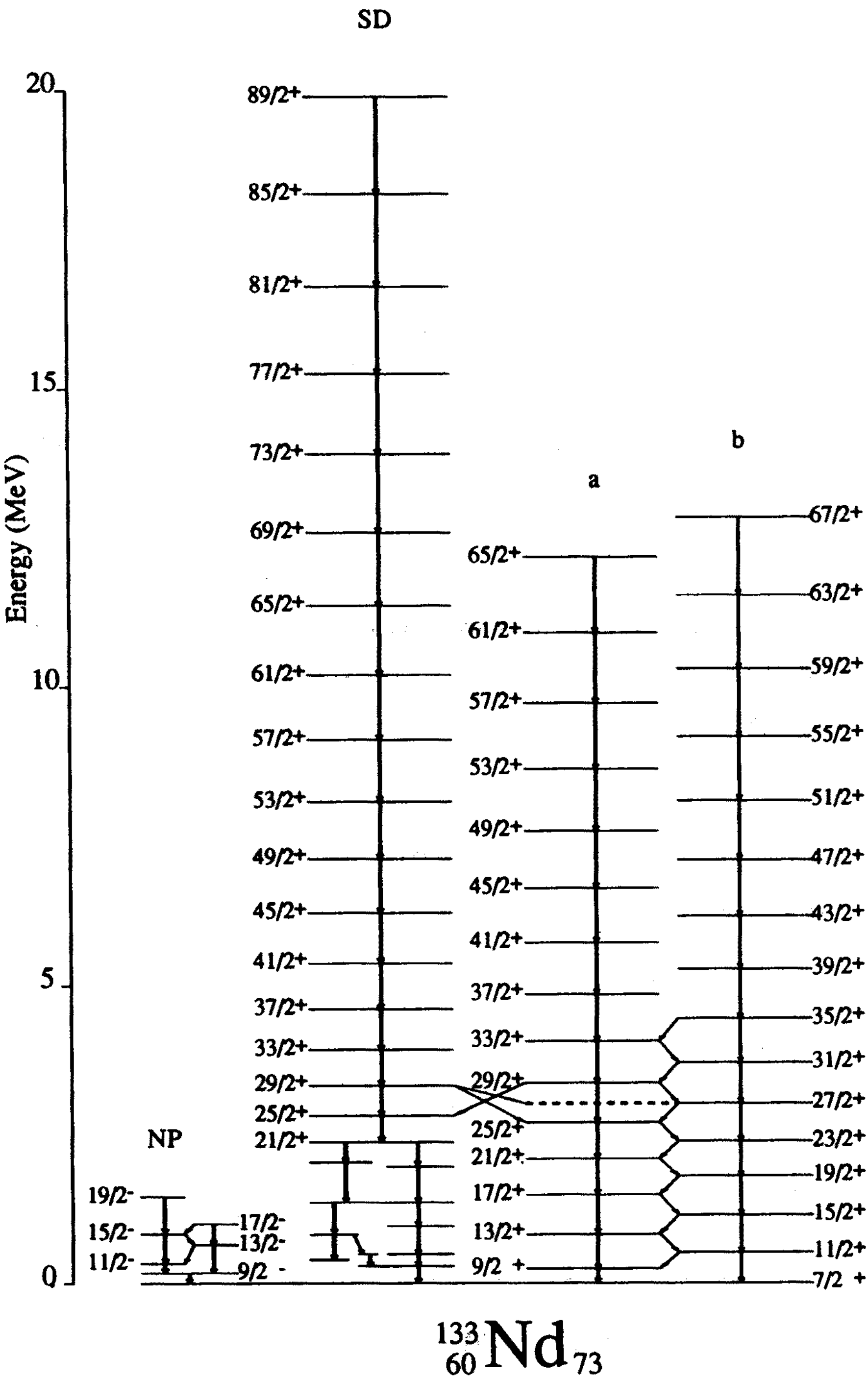

Figure 4. Partial level scheme of ^{133}Nd deduced from the present work. Only the low lying states of the negative parity (NP) band are drawn.

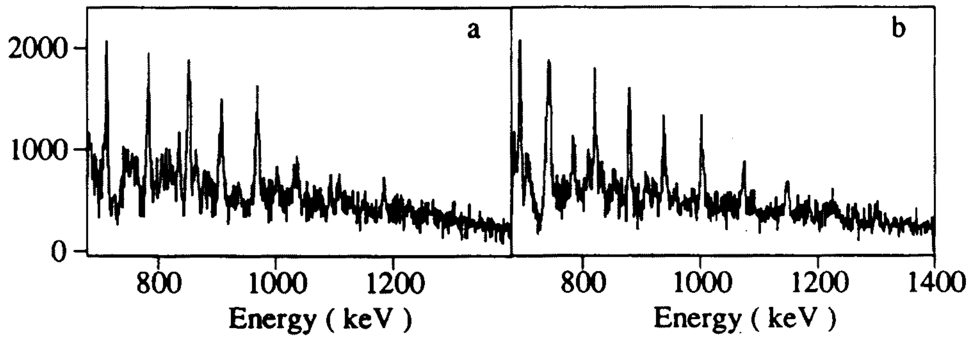

Figure 5. Double gated spectrum with gates on the low lying transitions of the two signature partners of the $g_{7/2}$ band.

to the $h_{11/2}$ protons. This result should not be surprising since the normal states of this region, unlike the A=150 and 190 regions, have already a deformation $\beta = 0.2$ and the alignment of two protons could stabilize the nuclear shape at a value close to that induced by the neutron $i_{13/2}$ intruder orbital.

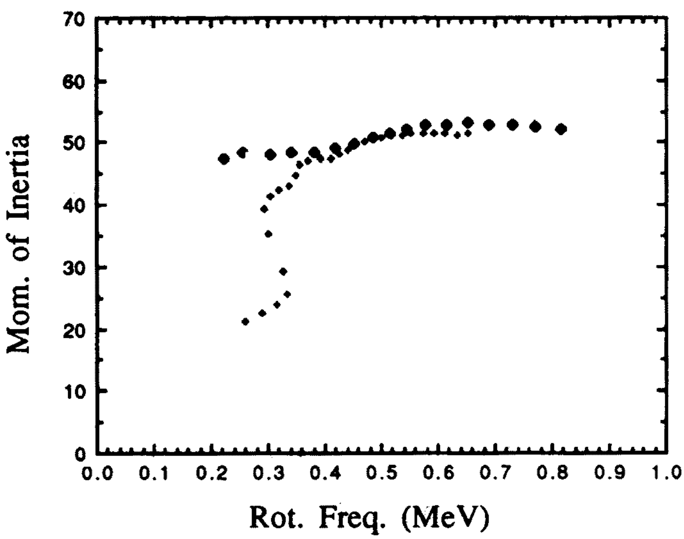

Figure 6. Moment of inertia $\Im_1$ in units of $MeV^{-1}/\hbar^2$ for the SD (diamonds) and ND (crosses) positive parity states of ^{133}Nd.

The crossing between SD states and the normal deformed states.

As pointed out before, a peculiarity of the A=130 region, compared to the A=150 and A=190 regions where superdeformation has been experimentally observed is that here the low–lying states of the nuclei are not spherical but have a sizable deformation. Secondly here the shape in the second minimum has a value of $\beta = 0.35 \div 0.40$ to be compared with 0.6 or 0.5 of the other regions. In principle the two (normal deformed and superdeformed) structures should "talk" easier. Fig. 7 shows the plot of excitation energy vs spin for the normal deformed and SD states in ^{133}Nd. The two structures cross at spin 29/2 where the decay of the SD band into the positive parity band is observed just when, for the first time, the band is no longer yrast. The two $29/2^+$ states of the SD band and of the $g_{7/2}$ band lie very close in energy ($\Delta E = 40$ keV) and their wavefunctions mix so that from both levels a branching is observed to the other band. The three transitions of 307, 633 and 553 keV connect directly the two structures just at the point where also the normal deformed structure becomes highly deformed after the $h_{11/2}$ proton alignment.

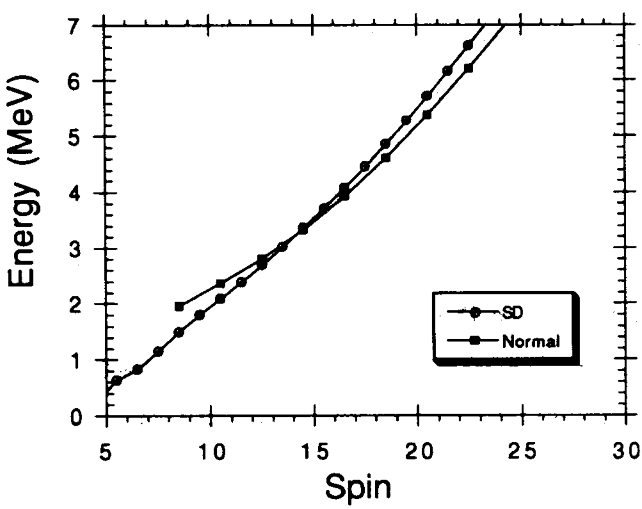

Figure 7. Excitation energy as a function of spin for the SD and ND positive parity states of ^{133}Nd. Only the low energy part is shown where the crossing between the two bands occurs.

Conclusions

The spectrometer Ga.Sp. is currently running for experiments and is producing the first exciting results. The data on the ^{133}Nd superdeformed band gave for the first time the precise excitation energy and spin of a SD band together with a big amount of data on neighbouring nuclei whose analysis is still in progress. These first results confirm that the new arrays, which just now are beginning to take data, are opening a new frontier in the field of high spin phenomena in nuclei.

References

1) Y. Choquer et al., Le Journal de Physique **38** (1977) L157

2) P. J. Nolan et al., J. Phys. **G11** (1985) 217

3) R. Wadsworth et al., J. Phys. **G13** (1987) L207

4) E. M. Beck et al., Phys. Lett. **B195** (1987) 531

5) S. M. Mullins et al., Phys.Rev. **C45** (1992) 2683

6) E. M. Beck et al., Phys. Rev. Lett. **58** (1987) 2182

7) E. S. Paul et al., Phys. Rev. Lett. **61** (1988) 42

8) S. M. Mullins et al., J. Phys. **G13** (1987) L201

9) A. Atac et al., preprint Risø1992

10) M. Palacz et al., Z. Phys. **A338** (1991) 467

11) S. M. Mullins, D. Phil. Thesis, University of York, UK 1989

12) J. Breitenbach et al., 6th. Int. Conference on nuclei far from stability, July 1992, Bernkastel–Kues, Abstracts, E15.