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# HIGHLIGTHS OF THE PHYSICS PROGRAM AT AGOR

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ABSTRACT :

The AGOR cyclotron has passed successfully the beam tests at the assembly site at Orsay during the first months of 1994. The final installation of the first european superconducting cyclotron is now being performed at Groningen. The beam guiding system, the location and equipments of the main experimental area are currently completed. The physics program is scheduled to start around the summer of 1995. A broad range of ions and energies (from 200 MeV protons, 100 MeV fully stripped ions down to 6 A. MeV lead beams) will become available. Specialized multidetectors systems are ready to be used in connection with the high acceptance spectrograph BBS in order to explore new modes in the nuclear continuum and the spin, spin-isospin response of nuclei using polarized proton and deuteron beams between 150 and 200 MeV.
The nucleon-nucleon Bremstrahlung (NN$\gamma$) reaction is also proposed to be studied in order to provide a much better understanding of the elementary NN$\gamma$ process. Of particular interest are the off-shell behaviour of the N-N interaction and hard photons production in nucleus-nucleus collisions at intermediate energies.

## I - INTRODUCTION

- On april 8, 1994 a first beam of 200 MeV $\alpha$-particles was successfully accelerated and extracted at Orsay from the AGOR cyclotron, and celebration to commemorate this important milestone was held at Orsay on May 27. In the meantime the cyclotron is being disassembled and we expect the machine to be commissioned in its final site, the KVI in Groningen (The Netherlands) before the summer of 1995.

- In the next section of this paper, the framework of the Franco-Dutch collaboration, AGOR (Accélérateur Groningen ORsay), to design, built, test and exploit the first european superconducting cyclotron will be briefly presented as well as the unique features of the machine and its performance. In section III, the facility at Groningen (beam guiding system, new equipments) will be described, along with the main directions of the physics program at AGOR.

- In section IV, a few selected examples of the physics which will be investigated with AGOR ranging from the decay of resonant single-particle states to isovector resonances will be discussed.

## II - THE AGOR CYCLOTRON

The AGOR cyclotron has been constructed and built in a close and very beneficial collaboration between the IPN-Orsay and the KVI Groningen laboratories with the support of the respective national funding agencies CNRS-IN2P3 (France) and FOM (The Netherlands). The agreement between the funding agencies foresees that once AGOR is installed in Groningen about 20 % of the beam time will be made available to the French partner.

AGOR is a second generation cyclotron with superconducting coils. Details of the design have been published elsewhere [1]. The unique feature of AGOR is that it can accelerate both protons and heavy ions. It is a compact, three-sector cyclotron with a pole diameter of 1.88 m equiped with three accelerating electrodes, located in the pole valleys (see Fig. 1).

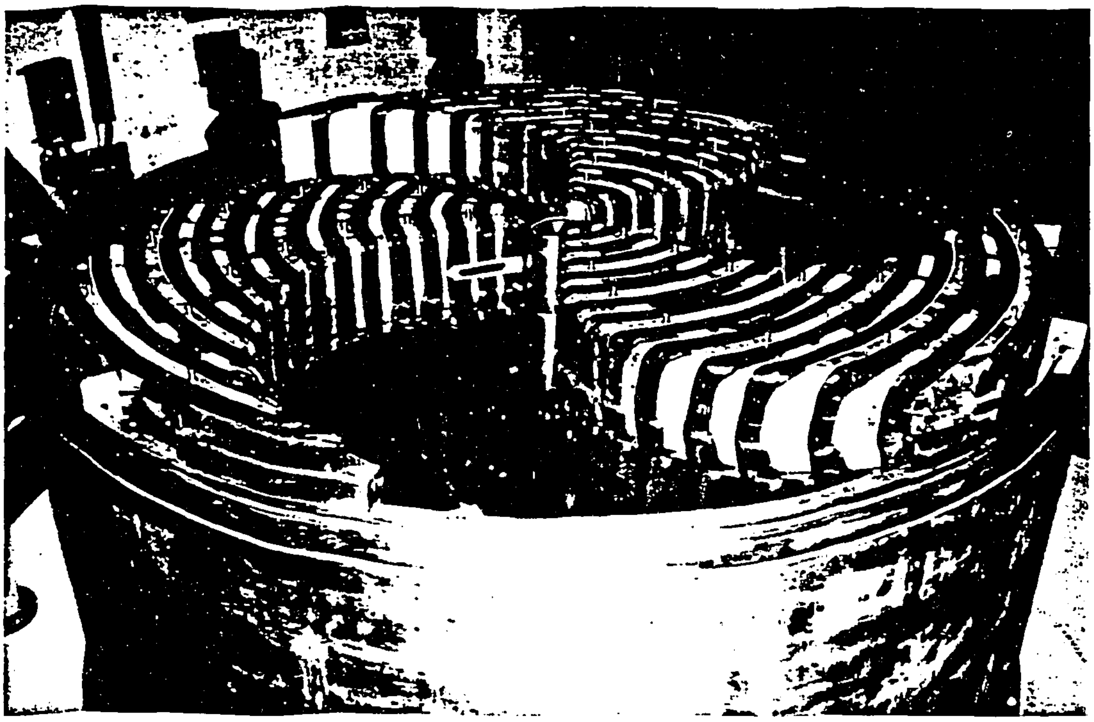


***Figure 1*** *: View of the pole with the three fold symetry. The spiral flutter pole is covered by the winding of the 15 correction coils.*

The maximum magnetic field is 4 T, therefore the bending limit is K = 600 MeV.

For protons however, the spiraled pole sector determine the focusing limit of 220 MeV. The maximum energies for the heavy ions depend on their charge to mass ratio Z/A. For fully stripped ions (q/A = 0.5) the maximum energy is 95 A.MeV. The range of beams that can be accelerated is illustrated in figure 2 showing a diagram of available beam energies (E/A in A.MeV) as a function of q/A.

A large energy range is achieved due to a special design of the RF system allowing acceleration in three different harmonic modes (h = 2,3,4). The ions are produced in external ions sources and injected along the axis of the lower pole. Much of the ultimate performances of AGOR will depend on the quality of the external ion sources. Three external ion sources will be connected to the axial injection line, a multicup source, producing hydrogen and helium ions, an ECR source for highly-ionized heavy ions, and a source for polarized protons and deuterons.

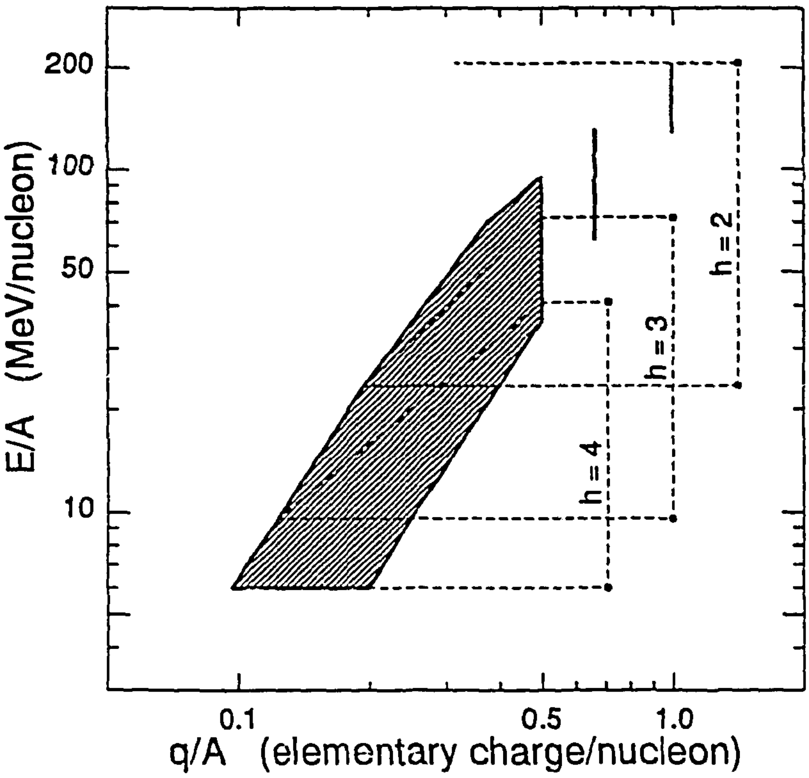



*Figure 2 : The operating diagram of AGOR. The thick lines and the hatched areas indicate available beams. Also indicated are the harmonic modes 2, 3 and 4.*

## III - THE FACILITY AT GRONINGEN

The uniqueness of the polarized protons and deuterons beams at incident energies around 200 MeV, the so-called "spin window", will allow to develop a strong physics program devoted to spin excitations in nuclei and to nuclear dynamics through nucleon-nucleon Bremstrahlung.

The large energy range and variety of light-heavy ions (100-30 A.MeV) with the help of appropriate instruments, will be used to investigate new high-lying single-particle or collectives modes in the nuclear continuum. To obtain clear signatures and sometimes decisive information on the microscopic structure of such states, two arm experiments will be carried out using a magnetic spectrometer in coincidence with large and efficient array of neutron, $\gamma$-rays, particles or e+, e- detectors.

For the first experiments planned at AGOR and centered around the main themes summarized above (spin physics, nuclear dynamics, nuclear structure in the continuum), the floor plan of the cyclotron vault and the experimental area are shown in figure 3.

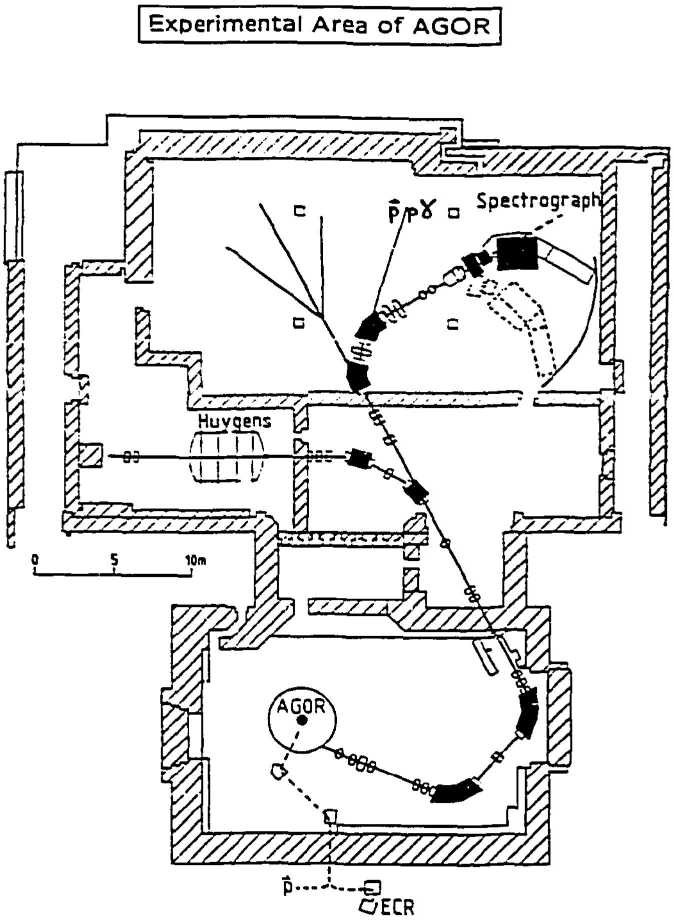



*Figure 3 : Floor plan of cyclotron vault and experimental areas.*

Four ion-optical sections with different functions can be distinguished. In the first section (cyclotron to first bending magnet), the beam emittance will be matched to the acceptance of the beam guiding system. In the second section (bending magnets) an achromatic beam will be produced at the exit of the second bending magnet. In the third section (straight line), the transport will be achromatic. The beam will be analyzed in section 4 to produce a non-dispersed or dispersed matched beams on the target of the QQD "Big-Bite - Spectrometer" (BBS). In addition to the line leading to the spectrograph there will be a beam line for the ppγ set up next to the spectrometer.

## III.1 – Experimental equipment : the Big-Bite Spectrometer

A major piece of equipment is the new Big-Bite Spectrometer (BBS). The BBS has a large solid angle ($\Delta p/p = 2.10^{-4}$). It consists of 2 quadrupoles magnets followed by one 60° dipole magnet as shown in figure 4.

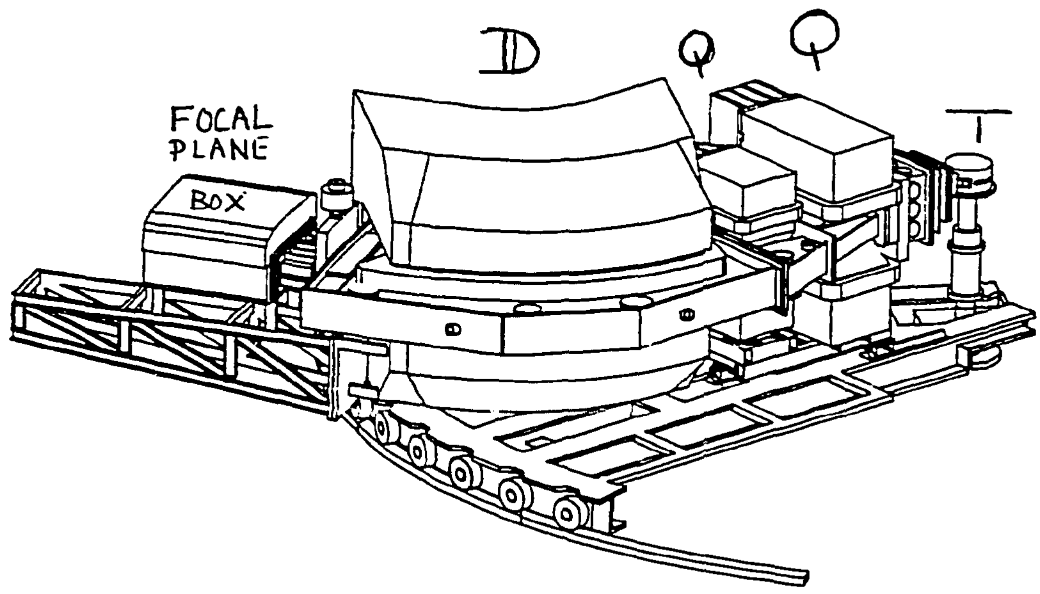



*Figure 4 : Artists impression of the Big-Bite Spectrometer*

The spectrometer is specifically designed to measure scattering and reactions induced by high-energy beams at very small angles including 0°. A large free space around the target (1-1.5 m) is available to operate the spectrograph in coincidence with other specified detectors (see next section). The spectrograph is presently being installed and it is expected to be operational during the fall of 1995.
The range of ions and ions energies that will be available for the AGOR cyclotron calls for the design and the construction of different detection systems. For the detection of unpolarized ions with mass number A < 20, a set of multi-wire proportionnal chambers are presently under construction at the IPN Orsay. In addition the same institute will build a detection system for heavy ions (A > 20), foreseen as an upgrated version of the wire-chambers located at the focal plane of the SPEG spectrometer of GANIL. For the measurement of polarization transfers in experiments with polarized proton and deuteron beams a dedicated vertical drift chamber will be built in a European collaboration.

### III.2 – SPECIALIZED DETECTION SYSTEMS

Three specialized detection systems, TAPS, EDEN and PEPSI will be available at AGOR at least for part of time. The Two-Arms Photon Spectrometer (TAPS), a collaboration between GANIL, Giessen, Groningen, GSI and Valencia, consists of 6 blocks of 64 BaF2 detectors each, equipped with plastic veto detectors in front of each module. TAPS is specifically designed for the detection of hard photons and neutral mesons, the latter via the reconstruction of their invariant mass from their two-photon decays. TAPS will be moved in the beginning of 1996 to Groningen where it will stay most of the year.
In collaboration with the IPN Orsay a neutron time of flight spectrometer, EDEN, has been developed. It consists of 48 NE213 liquid scintillators cells with a diameter of 20 cm and a depth of 5 cm. At 1 MeV the detector efficency and resolution are respectively 40 % and 50 keV

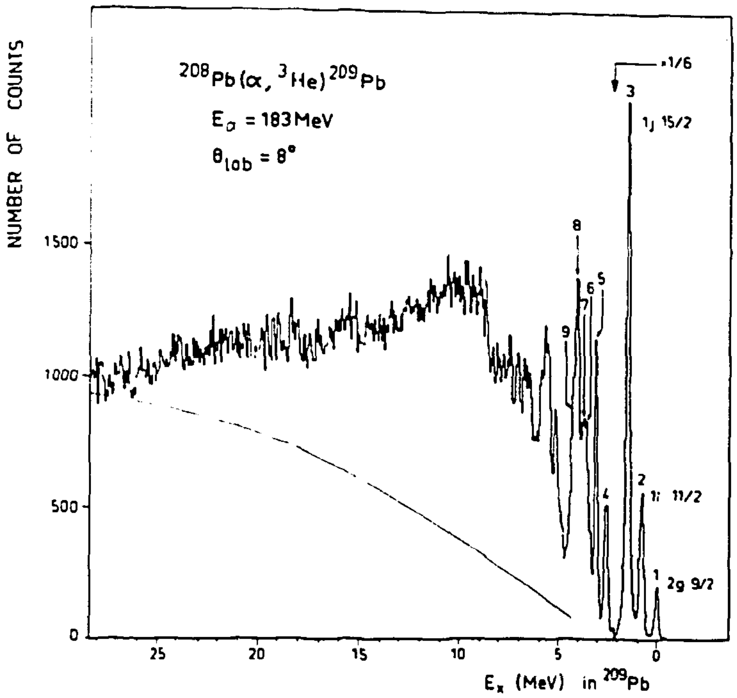
whereas at 6 MeV the values are 20 % and 300 keV. At a flight distance of 2 m the array covers a total solid angle 0.4 sr (see ref. [2]). For the detection of high-energy (E > 10 MeV) electron-positron pair, a multi detector system PEPSI has been built and successfully tested. It is composed of a 4π-mini-orange like magnetic filter and of 32 plastic scintillators (12 for $e^+$ and 20 for $e^-$). The maximum coincidence efficiency for this instrument for pair detection is in the order of several percent.

## IV - SELECTED PHYSICS PROJECT

### IV.1 - TRANSFER REACTIONS TO CONTINUUM STATES

A large body of data has been already collected on the gross properties (excitation energy, width, strength) of resonant single-particle states [3]. These simple modes are observed as "giant" states embedded in a substantial continuum in one nucleon transfer reaction. Decisive progress in the understanding of the damping process of highly excited states can be made by studying their decay properties.

A typical example of the onset of neutron single-particle strengths in the nuclear continuum is shown in figure 5 where is displayed the $^3$He energy spectrum for the reaction $^{208}$Pb(α, $^3$He)$^{209}$Pb at 183 MeV. At low excitation energies, the spectrum is dominated by transfers to the available high-spin valence orbitals, e.g. $1i_{11/2}$ and mostly $1j_{15/2}$ (see Fig. 5) whereas around 10 MeV in $^{209}$Pb, broad structures are strongly populated and arise from the population of high-spin outer subshells namely $1k_{17/2}$ and $1l_{19/2}$ [5]. To investigate the decay properties the reaction $^{208}$Pb(α, $^3$He, n) has been studied using the α-particle beam of 122 MeV delivered by the KVI-AVF cyclotron. The outgoing $^3$He were detected at the focal plane of the Q-MG/Z spectrograph.




← *Figure 5 :*
*$^3$He residual energy spectrum from the reaction $^{208}$Pb (α, $^3$He) $^{209}$Pb a 183 MeV. The solid line indicates the yield from elastic break up α-particles [4].*

The resulting $^3$He single spectrum is quite simular to the one shown in figure 5. To measure in coincidence with the $^3$He ejectile, detected around 0°, the neutron emission from unbound $^{209}$Pb highly excited states (from 4 to 20 MeV), the neutron time of flight spectrometer EDEN has been employed. The cells were located at 1.75 m from the target covering the angular range 68° to 168° and 190° to 210°. Two dimensional $[E_{3He} - E_n]$ spectrum for each EDEN neutron cell were further transformed into $[E_{xi} - E_{xf}]$ spectrum, where $E_{xi}$ is the excitation energy in $^{209}$Pb and $E_{xf}$ is defined $E_{xi}$ - $E_n$(c.m) - $S_n$ or apparent excitation energy in $^{208}$Pb.

Figure 6 displays the $E_{xf}$ spectra of neutron in coincidence with $^3$He particles corresponding to six energy regions in $^{209}$Pb. At rather low $E_{xi}$, neutron decay to ground and low-lying collective $3^-$, $5^-$ states in $^{208}$Pb is favoured. Above 13-16 MeV, the neutron spectra do not display any sharp peak but have rather typical statistical patterns (see lower part of Fig. 6). Statistical calculations (code CASCADE) were compared, for each energy bins, with the experimental data of figure 6. Direct decays to the GS and excited states ($3^-$, $5^-$) account for 3-6 % of the observed total neutron spectra in the region of the 10 MeV bump. Above 16 MeV excitation energy in $^{209}$Pb, the decay of continuum single-particle states in $^{209}$Pb is mostly statistical [6].
Similar studies were carried out for high-lying excitations in $^{49}$Ca, $^{59}$Ni, $^{91}$Zr and $^{121}$Sn nuclei.

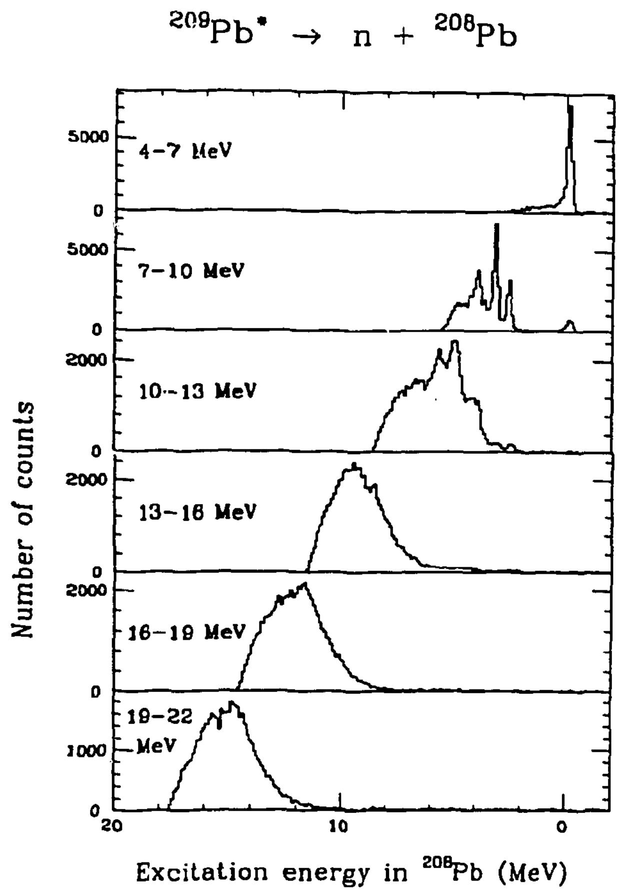



*Figure 6 : Final states population of $^{208}$Pb from the neutron decay of $^{208}$Pb excited states (4 - 22 MeV). Well-resolved $^{208}$Pb final states are populated up to 13-16 MeV.*

## IV.2 - SEARCH FOR THE ISOVECTOR GIANT MONOPOLE RESONANCE IN HEAVY NUCLEI

Knowledge of the properties of giant resonances has improved during the past fifteen years partly because of the possibility of exciting these resonances with heavy ion beams at intermediate energy. The large choice of beams available permits the study of many of these collective modes under very good conditions, i.e. in reactions where they are excited selectively and are observed with very good peak to background ratios [6,7]. This is particularly true for the isoscalar electric modes ($\Delta T = 0$, $\Delta S = 0$) and the isovector magnetic modes ($\Delta T = 1$, $\Delta S = 1$). However, some modes are difficult to excite selectively. An example is the electric Isovector Monopole Resonance ($L = 0$, $\Delta T = 1$, $\Delta S = 0$). This mode is particularly interesting because its properties provide a measure of the compressibility of the nuclear fluids of protons and neutrons. It can also gives information about the isospin purity. Unfortunately this state has not yet been observed unambiguously.

Recent experiments have attempted to study this elusive mode using the two charge exchange reactions ($\pi^-,\pi^0$) [8] and ($^{13}C,^{13}N$) [9] on targets of $^{208}Pb$, $^{120}Sn$ ,$^{90}Zr$, and $^{60}Ni$. Various structures were observed in these reactions which were interpreted as the excitation of the Isovector Giant Monopole Resonance (IVGMR), but no unambiguous signature of a monopole excitation was obtained. However, the work of Berat et al. shows clearly that the charge exchange reaction ($^{13}C,^{13}N$), as well as selecting $\Delta T = 1$, also provides good selectivity for the $\Delta S = 0$ mode if the reaction is carried out at energies near 50 MeV/A.

Thus, the neutron decay of the peak near 16.5 MeV in $^{208}Tl$ excited by the charge exchange reaction ($^{13}C,^{13}N$) on $^{208}Pb$ has been measured. The direct part of the decay of a giant resonance is related to the microscopic structure of the mode. Therefore a monopole mode can be clearly identified by measuring an isotropic angular distribution of the direct neutrons emitted by the recoil nucleus in the region of the observed peak. The ($^{13}C,^{13}N$) reaction was first performed on a target of $^{12}C$, in order to check the efficiency of the multidetector by measuring the branching ratio of the Giant Dipole Resonance for which the expected value is 1. This allowed us to obtain a first measurement of the final states population from the decay of the GDR in $^{12}B$.

This experiment was carried out with the SPEG Spectrometer, used in coincidence with the neutron multidector array EDEN [2]. The SPEG Spectrometer was set at an angle of 0.8 degree and could detect ejectiles at angles between -1.2 and +2.8 degrees. The vertical acceptance was [-2,+2] degrees. The direct beam was stopped in a block located between the two dipoles of SPEG. The detection was placed near the focal plane of the spectrometer, after the second dipole and consisted of two drift chambers, an ion chamber and a plastic scintillator. The energy resolution was about 500 keV full with at half maximum and the angular resolution was estimated to be about 0.2 degrees.

Excitation energy spectra for $^{208}Tl$ at different forward angles are shown in figure 7. Two strong peaks are seen above the background at an excitation energy of 5.8 and 16.5 MeV (3.5 MeV wide), in agreement with the earlier results of Berat et al. [9]. This result is in strong disagreement with the results from the ($\pi^-,\pi^0$) experiment of Erell et al. [8]. The angular distribution for the peak at 16.5 MeV is strongly forward peaked and is difficult to extract from the background at angles greater than about 1.6 degrees.

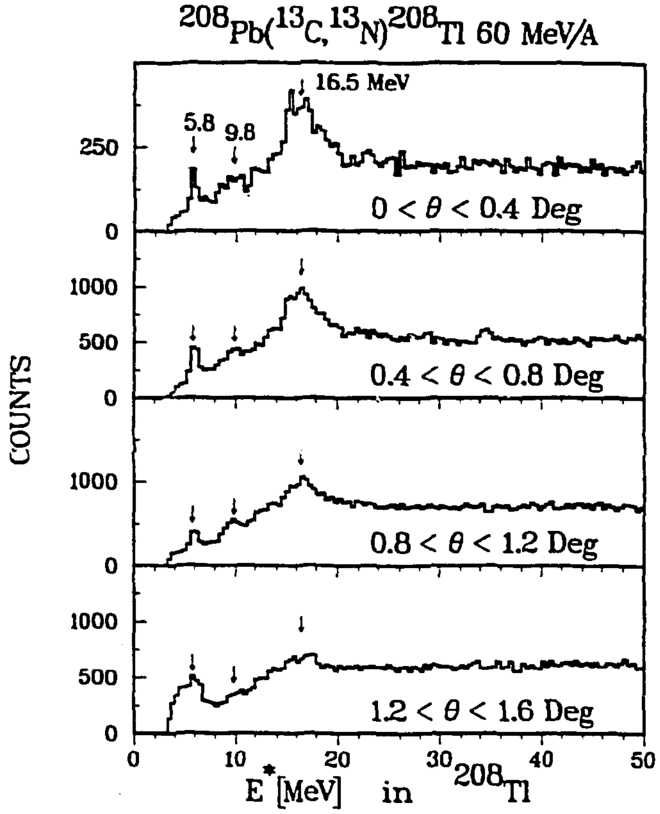



*Figure 7 :*
*Excitation energy spectrum of $^{208}Tl$ for the reaction $^{208}Pb(^{13}C,^{13}N)\,^{208}Tl$ at 60 MeV/A, for 4 angular selections.*

However the angular distribution does not show the strong diffraction structures predicted by DWBA calculations for $\ell = 0,1$ or $\ell = 2$ transfer. It could be fitted by a sum of $\ell = 0$ and $\ell = 2$ for angles lower than 0.8 degree, but the shape of the cross section beyond this angle cannot be reproduced.

Figure 8 shows the final energy spectra in $^{207}$Tl, for three different excitation energy regions in $^{208}$Tl (full line). These spectra are compared to the statistical calculation given by the code CASCADE (dashed lines).

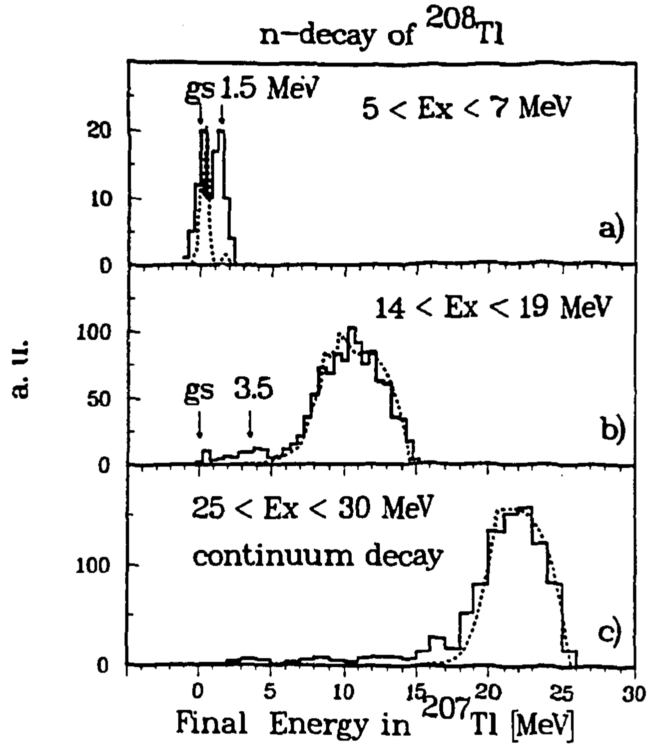



*Figure 8 :*
*Final energy spectrum in $^{207}Tl$ for 3 excitation engergy bins in decaying $^{208}Tl$. The dash lines shows the result of the statistical calculation (CASCADE).*

The part of the experimental spectrum that is not reproduced by the calculation is considered to correspond to direct decay to low lying states in $^{207}$Tl. For example, if a gate is placed around a 5 MeV wide slice centered at 27.5 MeV of excitation energy in $^{208}$Tl, the neutron spectrum is quite well fitted by a pure statistical calculation (Fig. 8c). In contrast, the low lying state at 5.8 MeV in $^{208}$Tl, decays primarily to the ground state and a state near 1.5 MeV in $^{207}$Tl. The decay to this latter state is not predicted by CASCADE (Fig. 8a). Then the analysis of the angular distribution of the neutron corresponding to this state could give information on the spin of the decaying level.

The state centered at 16.5 MeV shows a predominantly statistical decay (Fig. 8b). However, about 10 % of direct decay is obtained. To get insight for the nature of this direct branch, the neutron spectra have been gated by events measured at very forward angles (≤ 0.8 degree) where the peak to background ratio is maximum. It appears that the neutron decay branch of the 16.5 MeV structure feeds mainly the 3.5 MeV group of levels in $^{207}$Tl which could correspond to the well known 1g7/2 proton hole state. To learn more about this state it would have been necessary to analyze the angular distribution of neutrons, but the amount of direct decay was too small to obtain statistically significant data. A much larger statistical accuracy will be required to establish or not the isotropy of the measured direct branch.

## V - CONCLUSION

A new accelerator system with dedicated instruments will come into operation in the course of this year. A strong european collaboration is being implemented around the experimental equipments and the associated physics themes.
Heavy ions reactions studies need to be reinforced to make full use of the potential of the new facility. If so, AGOR will find its "niche" in a well organized network of european nuclear physics facilities.

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