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GANIL

FIRST RESULTS FROM GANIL

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FIRST RESULTS FROM GANIL

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The first beam from the GANIL accelerator was extracted in November 1982. In January 1983 the experiments started and have been steadily performed since then in runs of two or three weeks separated by maintenance periods of one week. The efficiency of the accelerator, defined as the ratio of the time with beam on target to the time devoted to experiments averaged 51% during 1983, and ranged between 75 and 85% for the last 4 months. Ions of oxygen, neon, argon, krypton and xenon were accelerated at various energies ranging between 25 and 95 MeV/u. The beam intensity on target is typically 5×10^{11} pps for Ar. It is higher for lighter ions and lower for heavier ones. The beam qualities are as good as anticipated (fig. 1).

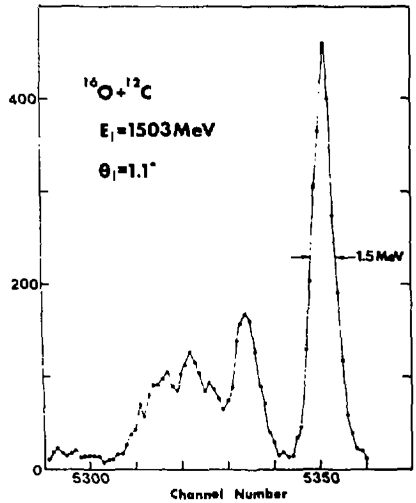


Fig. 1 : Energy spectrum of elascticalLy scattered ^{16}O ions of 94 MeV/u from a ^{12}C target[1]. The ability to obtain clean spectra at very forward angles, her 1.1° but sometimes 0.7° only, and the good energy resolution, with overall value of 10^{-3} in this ca were clearly demonstrated.

Figure 2 presents a schematic view of the machine and experimental areas. GANIL is a national facility which acts as guest to physicists from all French laboratories as well as from other countries. Without including the solid-state and atomic physicists who use about 10% of the beam time, some 300 nuclear physicists have participated so far in 40 experiments.

For years it was stressed that, between 10 and 100 MeV per nucleon, a transition should occur in heavy-ion reaction mechanism from dissipative phenomena to nucleon-nucleon interaction. There was little doubt indeed that when the energy per nucleon varies from less to more than the Fermi energy, major changes should occur. The reduced wave length which characterizes the motion of a nucleon of the projectile as compared to a nucleon of the target, $\pi\lambda_{NN}$, should decrease and become smaller than the average inter-nucleon distance. Correlatively, the very concept of mean field, which is so effective for describing the collision of nuclei up to, say, 10 MeV/u, is expected to become inadequate. Very often in physics, transition regions allow the observation of new phenomena and give insight into fundamental properties.

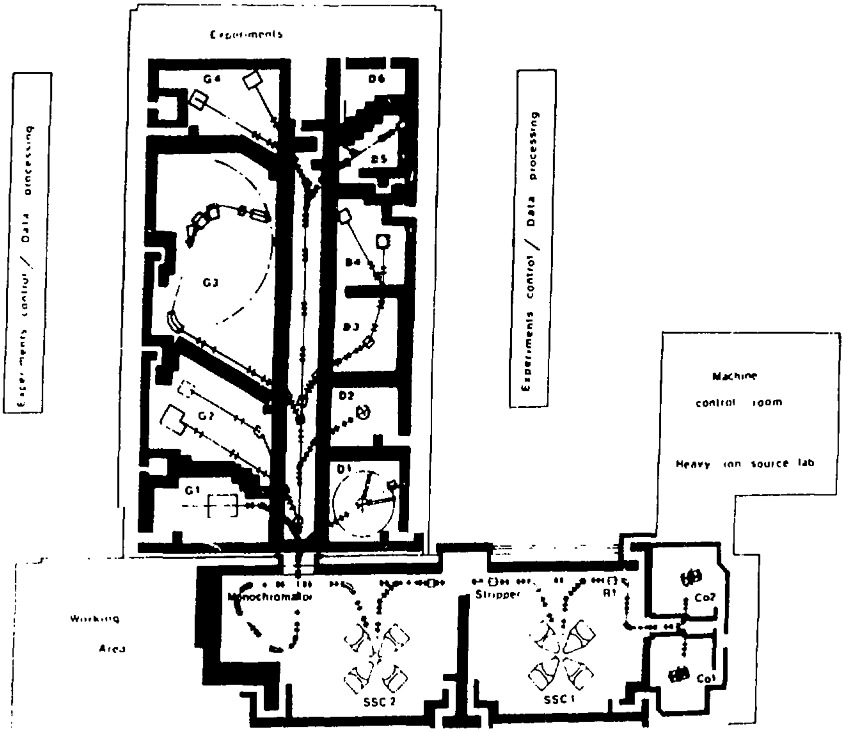


Fig. 2 : Schematic view of the machine building and of the experimental areas. The second injector cyclotron, Co2, will be operational before the end of 84 and will be equiped with an axial injection and an ECR source during 1985. The various experiment rooms are equiped with a time-of-flight scattering chamber (D1), a 35 m3 walk-in scattering chamber (G1), a correlation table and a spin-multiplicity filter for γ-ray studies (G2), a high precision scattering chamber (D2), a double magnetic analizing system (LISE) for the study of H-or He-like ions and the observation and study of rare exotic nuclides (D3-D4), and a He- jet system, an on line mass spectrometer and a refrigerated irradiation facility for solid-state studies (D5). A magnetic spectrometer with on-line high qualities for solid angle and energy resolution is being completed in G3 and will be operational at the beginning of 1985.

That such could be the case in the range of energies between 10 and 100 MeV/u opened by GANIL is the major challenge faced by the physicists concerned. It first requires that significant data be collected. But it already appears that neither dissipative phenomena nor fragmentation processes alone can account for the first results.

1. Reaction mechanisms at GANIL energies

The parameter which is known to vary in the shortest time scale in dissipative phenomena is the N/Z ratio. It was then natural to examine the variation of this ratio for projectile-like fragments when the incident energy increases. Such was the aim of the first experiment performed at GANIL in January 1983. The result (fig. 3) at first sight suggests an unambiguous answer. There seems to be no equalization of N/Z at 44 MeV/u between target and projectile, and one should then conclude that Ar projectiles are fragmented in the same way as at much higher energy.

This apparent simplicity is in sharp contrast with the results of fig. 4 where the fragments observed cannot be so simply assigned to Ar fragmentation.

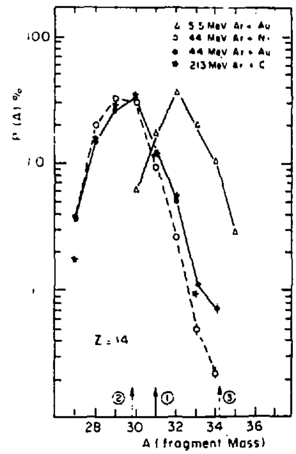


Fig. 3 : Comparison of the production of silicon isotopes from 5,5 MeV/u Ar + Au [ref[2]], 44 MeV/u Ar + Ni and Au [ref.[3]]; and 213 MeV/u Ar + C [ref[4]]. Lines are drawn to guide the eye. The arrows labelled 1,2,3 indicate the N/Z ratio for the projectile, the (Ar + Ni) and (Ar + Au) composite systems, respectively.

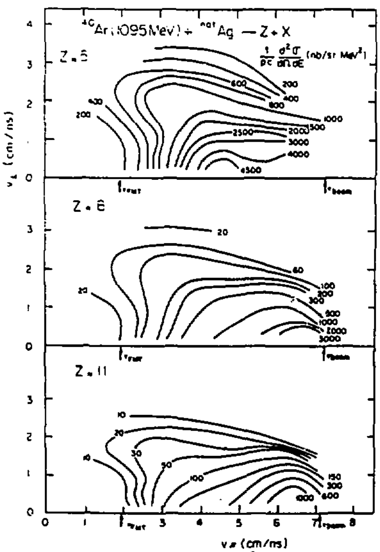


Fig. 4 : Contour plots of invariant cross sections for fragments of different Z as a function of parallel and transverse velocities from 27.5 MeV/u Ar + Ag collisions [ref[5]].

Obviously a complex reaction mechanism is taking place. Fragments close to the projectile, such as Z = 11, roughly behave as expected if created in a fragmentation process. Yet their velocity diagram is certainly not the circular one which would result if these fragments were emitted from a source moving along the beam axis with about the beam velocity. The diagrams of Z=8 and even more so Z=5 fragments strongly differ from the pattern corresponding to fragmentation. The Z=5 diagram for instance qualitatively suggests that three emitting sources must contribute, a high-velocity projectile-like one, an intermediate one with about 4cm/ns velocity, and one with very low energy probably corresponding to an evaporation process.

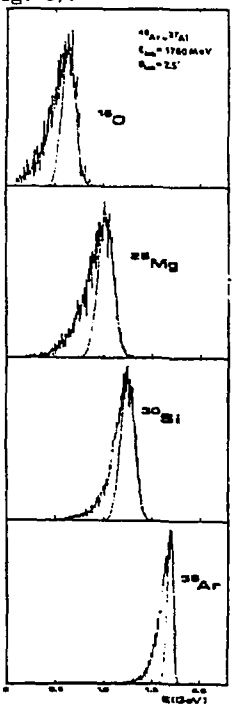
Some important practical conclusions can be drawn from the apparently conflicting evidences brought by fig.3 and fig.4. First, one experiment alone might lead to misleading generalizations. Second, as expected in a transition region, various processes are at work and systematic experiments with a wide scope are necessary to properly assess their importance.

The result of fig.3, even if it should not be oversimplified nor unduly generalized, yet points to the fact that contrary to what is observed at lower energy, a process reminiscent of high energy fragmentation accounts for a major share of the total cross section at 44 MeV/u.

This process must be examined in detail . At least five aspects of the properties of the observed fragments show the limits of a fragmentation description of the actual reaction process.

1.1 Energy spectra of the fragments :

In case of a fragmentation process, the fragments are emitted with the velocity of the beam, once corrected for energy conservation. Their spectrum is broadened by the Fermi motion. Yet, the theoretical shape calculated under such assumptions clearly fails to account for the experimental results (fig. 5).



The parameter $\sigma_{//}$ which is extracted however (see fig. 5) is itself related to the parameter σ_0 characteristic of the momentum distribution in the nucleus. This procedure obviously carries serious difficulties since the experimental spectrum which is not symmetrical (fig.5) by itself shows the inadequacy of the model.

Fig. 5 : Fits to the 2.°5 energy spectra from 44 MeV/u Ar + Al reactions [ref.[6]]. The asymmetry of the energy peak makes the fits inadequate. In order to extract the parameter $\sigma_{//}$, the variance of the momentum distribution in the direction parallel to the beam, the right hand side only of the peak was fitted with the theoretical formula.

Hence the overall consistency apparent in fig. 6 cannot be taken as proof that fragmentation is an adequate description of the actual reaction process. First, the theoretical formula is a very simplified one, and if one treats the emitted fragment as a Fermi gas in the same way than the projectile[7]) the predicted values of $\sigma_{//}$ are reduced by a factor of about 2 and their variation with A is altered[8]). Thus the nice agreement of fig.6 disappears. Further, various analysis of results obtained at GANIL (see e.g. ref.[9]) lead to different values of σ_0.

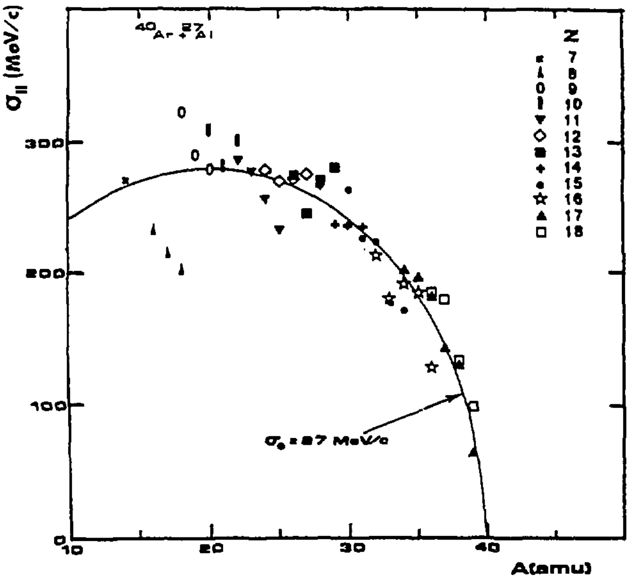


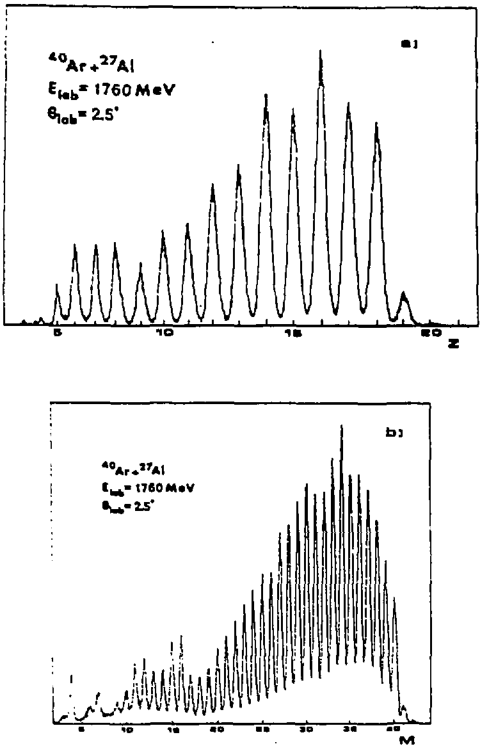
Fig. 6 : Longitudinal momentum variances as a function of the mass of the observed fragments from the 44 MeV/u Ar + Al reactions [ref[6])]. They are compared with the simple theoretical model of fragmentation. A good overall agreement is obtained for the value σ_0 =87 MeV/c of the parameter characteristic of momentum distribution in the projectile.

1.2 Observation of transfer reactions

Most studies of fragments have observed that nuclei with Z or N larger than those of the projectile are emitted with high energy at forward angles. Such was not the case in the clean-cut fragmentation process studied at higher energy. A typical example[6]) of this result is given in fig. 7. The energy spectra of such transfer reaction products appear to be well described[11]) in the framework of a direct one-step process by the double folding of level density formulae with the diffractional model DWBA cross section[12]).

1.3 Dependence of the projectile-like fragment on the target

The main effect apparent in fig 3 is that the average neutron member $\bar{N}$ for a fragment of given Z, at GANIL energies is close to the $\bar{N}$ value measured at high energy from a fragmentation process, and differs markedly from the $\bar{N}$ value which results from a dissipative phenomenon. Yet a closer look at the results shows that the $\bar{N}/Z$ ratio of the projectile-like fragment which, at higher energy, is independent of the target is systematically affected by it at GANIL energies. Fig. 8 shows some of the experimental results. The heavier the target, the more neutron-rich the fragment is. The complexity of the situation is clearly apparent here. This target dependence is obviously incompatible with a fragmentation process. Yet the overall variation of $\bar{N}/Z$ with Z is reasonably accounted for [10]) by the abrasion-ablation model. This model can even describe the minimum at Z = 8 and the increase for lower Z values if the effect of fragment excitation is included.



It is also certainly worth noting[8]) that the target dependence increases, with the neutron number N. The ratio of the yields of a (Z,N) fragment with Au and Ni targets[10]) is close to 1 for fragments near stability, i.e. with N/Z around 1, as expected for a fragmentation process. However this ratio increases up to 2 or 3 when N/Z increases from 1 to 1.5 for all the projectile-like fragments in the case of the 44 MeV/u Ar beam of ref[10]). A possible explanation might be provided by the simple microscopic model of Harvey[14]) which uses the effective nucleon-nucleon cross sections, very different for np collisions and for nn and pp ones, and includes a neutron-rich surface for heavier targets.

Fig. 7 : Z-and M-distributions of projectile-like fragments emitted at 2.5° from the 44 MeV/u Ar + Al reaction. Note that nuclei with Z=19 and 20, and M=41 and 42 are clearly observed[6]).

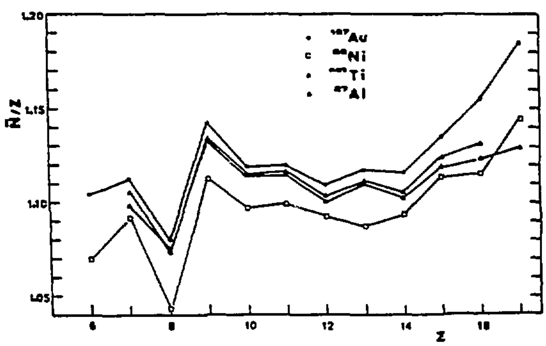


Fig. 8 : Variation of $\bar{N}/Z$ for the projectile-like fragments emitted from 44 MeV/u Ar collisions with targets of Al and Ti [ref[3])] and Ni and Au [ref[3])]

1.4 Evidence for large energy dissipation

Fig.4 shows the obvious departure at 27.5 MeV/u from the circular velocity pattern characteristic of a pure fragmentation process. The broad range of the measurements represented in that figure allows to clearly observe the complexity of the mechanism. At 44 MeV/u there is also evidence for dissipation effects in the velocity diagram of the projectile-like fragments (fig. 9). For decreasing Z of the fragment, this diagram shows increasing evidence for large energy dissipation. With an incident beam of 35 MeV/u Kr, few products are even found with velocities close to the incident one and their Z distribution peaks between 20 and 28 with energies lower than 1 GeV. Thus the character of the reaction mechanism appears to be much less reminiscent of fragmentation than in the case of 44 MeV/u Ar [ref[13])].

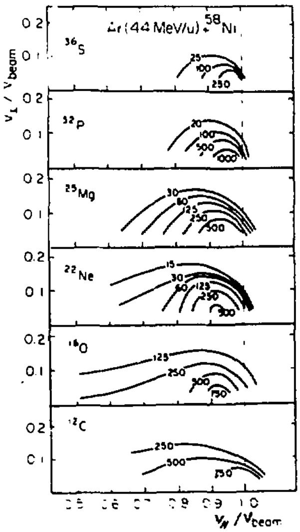


Fig. 9 : Contour plots of invariant cross sections for different ejectiles as a function of parallel and transverse velocities for 44 MeV/u Ar+Ni collisions. The $d^3\sigma$ / dv^3 cross sections are in units of (10^5 mb/MeV sr) (MeV/C)$^{-1}$ [ref[10])].

1.5. Variation with E_{CM} of the Z distribution of the fragment yields

The shape of the Z distribution of the fragments varies strongly when different targets are used (fig. 10). This illustrates the effect of the energy dependence of the reaction mechanism since very different E_{CM} values result from the bombardment by a 44 MeV/u Ar beam of targets ranging from C to Au. With a C target, the broad maximum around Z = 14 is well accounted for by an evaporation model (dashed curve), while the steady increase in the case of heavier targets, hence higher E_{CM}, is correctedly reproduced (dashed curve) by a calculation[14]) based on the abrasion-ablation model, and resembles closely the shape of the Z distribution measured at even higher energy, i.e. 213 MeV/u [ref[4])].

Some conclusions can be drawn from the above survey of experimental data. The gross feature of the results is that the major part of the total reaction cross section gives rise to the emission of projectile-like fragments at forward angles with a velocity close to the beam velocity. This is qualitatively reminiscent of the fragmentation process observed at higher energies.

This alone opens fruitfull possibilities of studying exotic nuclei (see section 2.4).

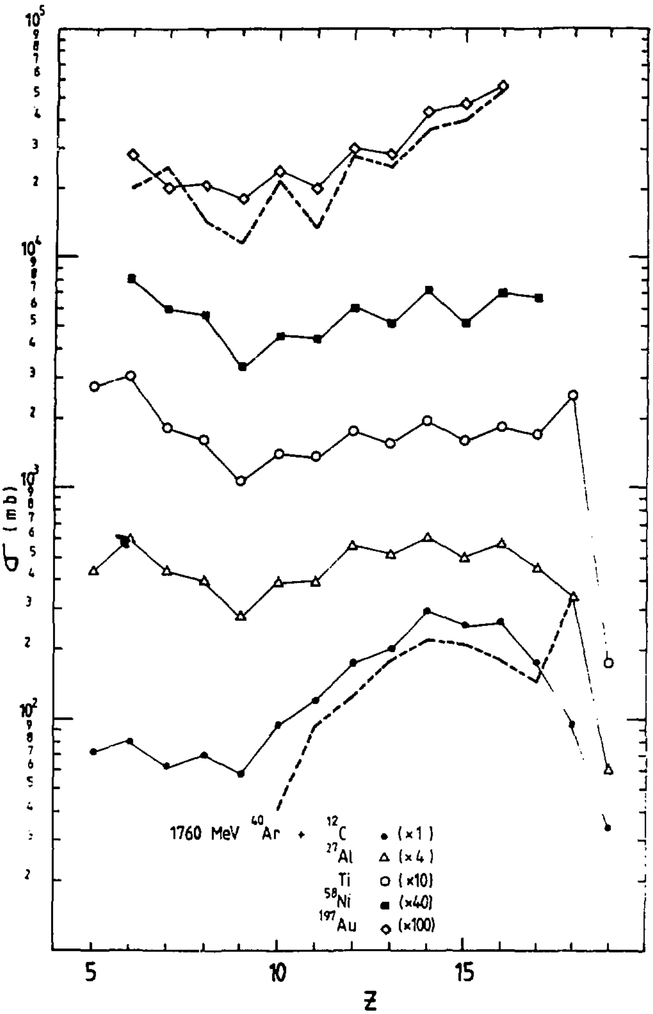


Fig. 10 : Z-distribution of fragment production cross section from 44 MeV/u Ar incident on various targets : ^{12}C[ref[15])], ^{27}Al and Ti [ref[6])], ^{58}Ni and ^{197}Au [ref[3])]. Dashed curves are theoretical calculations (see text).

Yet a closer look shows, as discussed at length above, that many aspects of the results deviate from what would be expected from a fragmentation reaction. It is in the apparent complexity of the reaction process, illustrated for instance by fig. 4, that we must look for new unifying ideas, and concepts which would not be just extrapolations from earlier studies but which could shed a new light on the properties of nuclear matter when the mean field reaches the limits of its validity. In the recent history of nuclear physics, one can find at least one example of experimental results apparently helplessly complex which can be accounted for by a simple model with few parameters. That is the intricate patterns of angular distributions of direct reactions, varying abruptly from one state to the other, and slowly with energy. DWBA calculations, undoubtedly based on simple concepts, and spectrocopic factors were effective enough to even make nuclear structure a quantitative science.

In the same way the apparent complexity of the first experimental results on reaction mechanisms should not be taken as a sort of final situation where one can only observe that several known mechanisms are at work, but as a challenge to elucidate, behind this complexity, the possible new phenomena. Among the suggested new ideas is the liquid-gas phase transition which is also examined with GANIL beams[21]). Up to now, experimental evidence appears to be scanty, to say the least. But a study can be undertaken with beams of several tens of MeV/u. It could bring unambiguous results as long as i) it is systematic ; ii) one lesson from fig. 4 is learnt, that is the need to observe the entire velocity diagram to avoid biased data.

As a last point, it must be emphasized that the reaction mechanisms were discussed in this section under the light of the known properties of fragmentation or dissipative phenomena. Other leading threads may be followed. One is the analysis of how much momentum is transferred. It is not presented here since it is discussed by Harar[16]) at this conference.

2. Nuclear structure studies

The relative velocities of projectile and target at GANIL energies encompass the Fermi velocity. This offers the opportunity to study highly selective transitions to discrete states. Of course a high energy resolution is required, which the SPEG spectrometer (see fig. 2) will provide. But already a few experiments which use the high energy and high intensity of the beam bring results dealing with nuclear structure.

2.1 Sub-threshold pion production

Pions can be created in a collision between a nucleon from the target and one from the projectile even if their relative energy is below the threshold if some extra momentum is provided by the remainder of the nuclei involved. This might come either from intra-nuclear Fermi motion or from the cooperative action of several nucleons. When the energy decreases, Pauli blocking more and more hinders pion production from the scattering of two nucleons. The cooperative process is thus expected to become sole responsible for π creation. Energy spectra and angular distributions should carry information on this process. The first results[17]) of π^0 production with 44 MeV/u Ar projectiles indicate that such a collective process is apparent in the angular distributions. More π-production studies are planned for the coming year.

2.2 Elastic scattering

Since most of the relevant information is to be obtained at very forward angles, the geometrical qualities of the beam were put to a difficult test in elastic scattering measurements. Actually, in the scattering chamber of room D2 (fig. 2), an angular precision of .02° and an angular resolution of .05° were obtained, which insured for instance the reproductibility of a very narrow minimum with 0.1° width in the angular distribution of the $^{16}O + {}^{12}C$ scattering[18]). Fig. 11 shows the results[19]) obtained in the scattering of ^{40}Ar on ^{60}Ni, ^{120}Sn and ^{208}Pb at 44 MeV/u. Optical model analysis shows that, near the grazing angle, the angular distributions are dominated by the Coulomb rainbow. The radius r_V found for the potential is smaller than at lower energy. It thus appears that the intricate interplay between the effects due to the reduction of Pauli blocking and the decrease of the nucleon-nucleon cross section σ_{NN} results in a smaller strong-absorption radius for the colliding nuclei. It thus seems that the latter effect dominates. Yet it is possible that a geometrical effect could participate to the reduction of r_V. When energy increases, the geometrical pattern of diffracted heavy ion trajectories favours forward scattering which might reduce the effect of nucleon-nucleon reactions[20]).

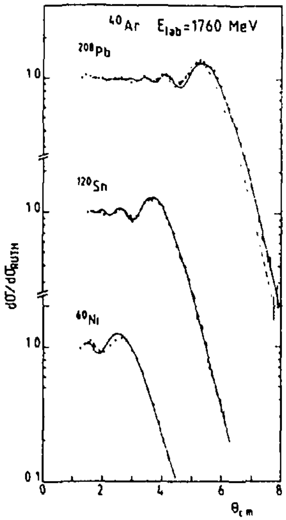


Fig. 11 :
Elastic angular distributions for ^{40}Ar scattering from three target nuclei at 44 MeV/u energy[19]. The solid lines are the optical model fits obtained in ref[19] while the dashed line corresponds to the fit obtained with a potential determined at lower energy (see ref[19]).

2.3. Structures at high excitation energies

Already observed at lower energies[22], such structures are even more clearly seen with incident beams of several tens of MeV/u[23] (fig.12). The fact that they are the signatures of excited configurations of the target nuclei appears now firmly established. It is suggested that they are due to multiphonon excitation[24]. If such is the case, GANIL energies will allow the detailed study of such vibrational states based on low-energy giant resonances. The properties of these states directly bear on the equation of state of nuclei.

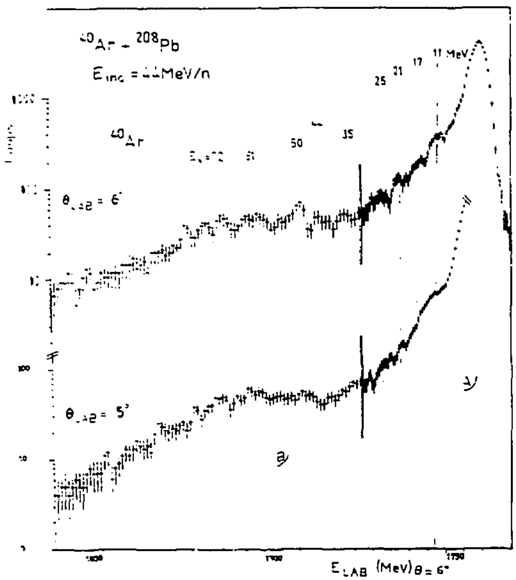


Fig. 12 : Energy spectra of 44 MeV/u ^{40}Ar nuclei scattered at 5° and 6° from ^{208}Pb. The excitation energies of the structures which appear in the continuum region are indicated.

2.4 Exotic nuclei

As stated in the conclusion of section 1, a large part of the reaction cross section gives rise to the production of projectile-like fragments with a narrow dispersion in energy and angle around 0°. Although this dispersion is larger than the one used at higher energies to observe exotic nuclei[25]), the intensities available at GANIL, which are in the vicinity of 10^{12} pps for light ions and a few 10^{10} pps for Kr, obviously make this accelerator the ideal tool for producing exotic nuclei through projectile fragmentation, at least among the presently available accelerators. The separation and identification of the fragments is accomplished by the triple-focussing magnetic analyser LISE[26]) (see fig. 2). Up to now only one experiment was performed[27]). Although the fragmentation of ^{40}Ar is hardly an optimized source of neutron-rich isotopes, three new nuclides, ^{23}N, ^{29}Ne and ^{30}Ne were observed. The particle instability of ^{19}B, ^{21}C and ^{25}O was also established. Fig. 13 shows some examples of the data. The yield of nuclei observed in a short run (9 hours) with moderate beam intensity (1.5×10^{11} pps), as well as the signal-to-noise ratio of the mass spectra, show that the field accessible to the LISE experiments is considerable. Other runs with improved conditions are already planned. Furthermore, the possibility of pulsing the GANIL beam with time constants in the range of 100ms will allow the study of radioactive properties of such exotic nuclei.

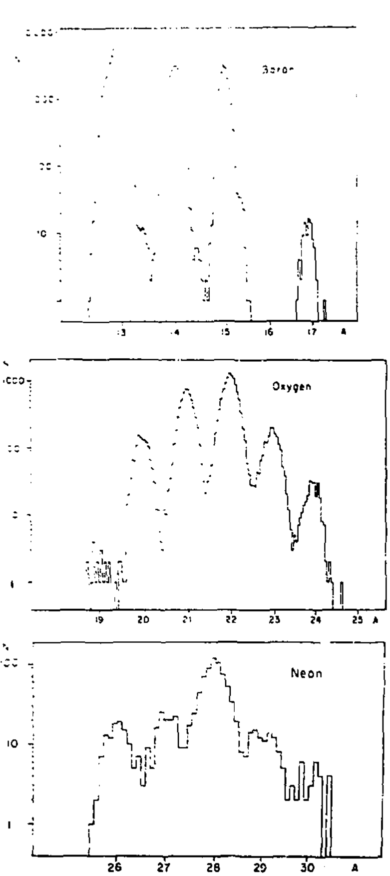


Fig. 13 : Examples of results from ref[27]. The mass histograms of boron, oxygen and neon (note the log scale) obtained while the tuning of the magnetic LISE spectrometer was optimal for masses 15 and 16, and 28 to 30, respectively. These isotopes are emitted at 0° under bombardment of a Tantalum target by 44 MeV/u Ar ions. The solid angle is 1msr and the acceptance of the magnetic analyser $\Delta B\rho/B\rho$ is 5%. Evidence for the non-occurrence of ^{16}B and ^{25}C, and for the existence of ^{29}Ne and ^{30}Ne was obtained from the spectra.

This review, even completed by what is said about momentum transfer measurements elsewhere in this conference[16]), does not cover the whole field of experiments initiated at GANIL since January 1983. The author apologizes for the papers which are not referred to here. This paper deals more with open questions than with definite and solid answers. That such should be the situation eighteen months after the experiments started does not come as a surprise. At least, it is hoped that the breadth of the field opened, and the fundamental character of the questions raised appear through this review of the current experiments.

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