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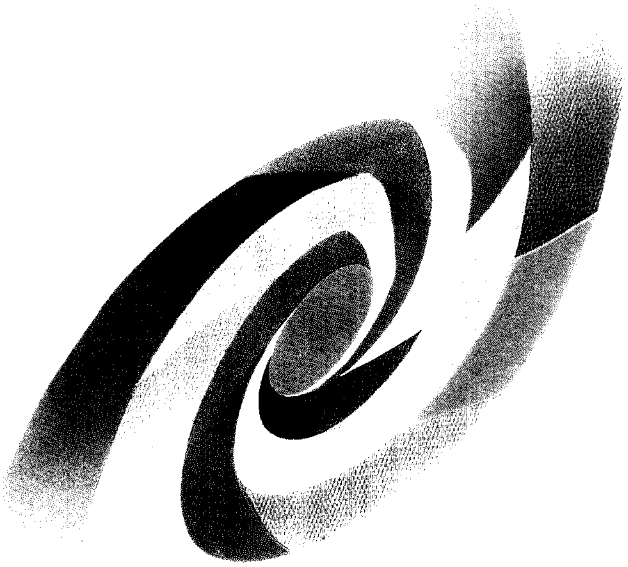

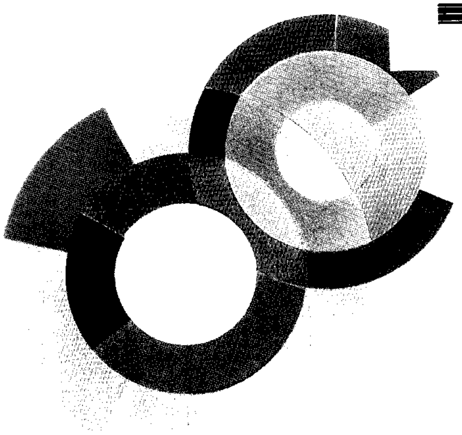

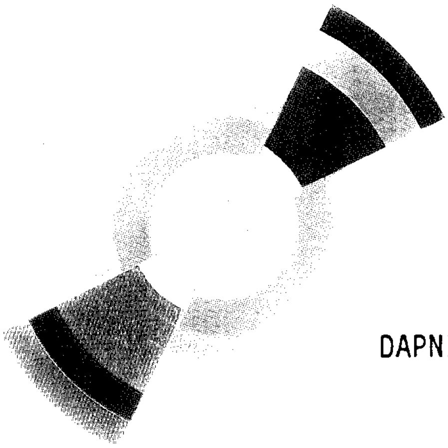

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Direct measurement of sub-Coulomb fusion for exotic nuclei*

V. Fekou-Youmbi[1], J.L. Sida[1], N. Alamanos[1], F. Auger [1], D. Bazin[2], C. Borcea[3], C. Cabot[4], A. Cunsolo[5], A. Foti[5], A. Gillibert[1], A. Lépine[2,6], M. Lewitowicz[2], N. Lecesne[2], R. Liguori-Neto[6], F. Marie[1], W. Mittig[2], E.C. Pollacco[1], A. Ostrowski[2], S. Ottini[1], P. Roussel-Chomaz[2], C. Volant[1], Y. Yong Feng[7]

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Abstract : *Radioactive nuclear beams provide a perfect probe to understand the correlations between all reactions near the Coulomb barrier. A new detection technique was proposed to challenge this problem. An experimental program on sub-barrier fusion for the systems* $^{7,9,10,11}Be+^{238}U$ *is underway at GANIL. A first data set with* ^{9}Be *and* ^{11}Be *was obtained using the F.U.S.ION detector. Preliminary relative fission cross sections are given.*

1. Introduction

Fusion phenomena at low energy are related to the possibility of two colliding nuclei to overcome the repulsive Coulomb interaction which exists between them. This reaction which can only be quantum mechanically understood, is, in a sense, the inverse problem of the α-decay of heavy nuclei. While α-decay was satisfactorily explained by a one-dimensional barrier penetration calculation, sub-Coulomb fusion of ions far exceeds the predictions of this model [1–3]. As clearly shown by Stokstadt *et al* [4] for the Samarium isotopes, the enhancement of sub-barrier fusion cross section is extremely sensitive to the structure of the nuclei. A global understanding of fusion was proposed in the framework of coupled channel calculations which allow a consistent understanding of elastic, inelastic and fusion reactions.

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* Experiment performed at GANIL

The two remaining major problems were pointed out by M.A. Nacarajan in his concluding remarks of the *Heavy Ion Fusion Conference* held in Padova (May 1994). **Is there a correlation between transfer cross section and fusion enhancement ? Does break-up inhibit fusion or not ?** Studies with exotic beams could be the way to obtain some answers, especially when the other direct reactions are measured simultaneously. Furthermore, some exotic nuclei present structure anomalies, like neutron halos [5] or anomalous changes in the B(E2)-values, for instance in the N=20 shell [6], which may precisely test our ability to calculate the interaction potential with various densities and couplings to inelastic states.

Such a program is underway at GANIL since 1991. The Fusion Utility for Secondary IONs (FUSION) allows to distinguish the fusion-fission from transfer-fission and then provides fusion cross-section and global transfer cross-section for actinide targets. A first experiment [7] was performed in July 1993 for ^{9,11}Be+^{238}U with secondary beams selected in LISE [8]. A second measurement, in November 1994 by using decelerated beams from SISSI is expected to provide data on ^{10,11}Be+^{238}U.

We plan to use the INDRA [9] multi-detector to measure fusion and transfer reactions with SPIRAL. A first measurement will be done during next year at GANIL with stable projectiles to test the feasibility of this program with radioactive beams at SPIRAL. $^{6,\,7}$Li projectiles will be used. These nuclei are puzzling, especially ^{6}Li for which the folded potential for heavy ion scattering must be reduced in strength by a factor of about two [10].

Two other groups have taken up the challenge. A group from Dubna investigates fusion reactions of ^{6}He on bismuth [11] by measuring fission fragments. A Japanese-italo group which has taken data at RIKEN for the system ^{11}Be+Pb determines α-emitters of the residual nuclei [12]. Another experiment of this latter group is devoted to study fusion-fission reactions for $^{27-33}$Al+^{197}Au.

2. Motivation to study fusion with exotic nuclei

2.1. *Transfer influence*

There have been several attempts to correlate the sub-barrier fusion enhancement with large transfer cross-sections. A review of the main results was proposed by L. Corradi [13]. A seducing interpretation of elastic scattering and fusion cross-section taking into account inelastic (2^+ and 3^- states) and transfer (1n and 2n) channels for ^{58}Ni on ^{64}Ni was proposed by A.M. Stefanini *et al* [14]. They involve a strong coupling to the one neutron transfer to reproduce elastic scattering at laboratory energies around 190 MeV whereas the two neutron transfer seems to be responsible for the enhancement in fusion cross section around 175 MeV.

In several cases where transfer channels were supposed to play a major role, other interpretations were suggested. For example, a recent calculation taking into account high order coupling effects in inelastic channels or multi-phonon excitations succeeds in reproducing the data [15] for ^{58,64}Ni+ ^{92,100}Mo. This calculation leads to a poor influence of transfer channels.

To obtain an unambiguous interpretation, it seems necessary to measure cross sections for the elastic scattering, the fusion and the inelastic/transfer channels involved in the calculation (like in ^{12}C+ ^{48}Ti [16] or in ^{16}O+ ^{208}Pb studies [17]).

Positive Q-values are expected to explain how the transfer channel will play a role in fusion. In that way, nuclei far from the stability line seem a good probe to test the transfer influence on fusion since one could reach really high Q-values (up to 20 MeV in ^{7}Be+^{238}U). More generally, exotic nuclei have many possible transfer reactions and could then test our understanding of their influence on the fusion reaction.

2.2. Break-up influence

The role of break-up effect on elastic scattering has been known for some time for weakly bound projectiles, mainly ^{6,7}Li [10, 18]. It was shown that the real part of the nuclear folded potential has to be multiplied by a factor around 0.6 to reproduce the data. If this factor is also valid for barrier energies, the weaker attractive nuclear interaction may result in an enhancement of the barrier so an hindrance of the sub-Coulomb fusion cross-sections.

This effect is expected to be dominant in the case of radioactive nuclei where dissociation is one of the most important reaction channels like for neutron halo nuclei [19]. This problem strongly stimulates theoreticians. M. Hussein *et al* [20] and N. Takigawa *et al* [21] argue that dissociation in ^{11}Li+Pb (or U) would inhibit fusion by almost two orders of magnitude at the barrier. C. Dasso and A. Vitturi [22] propose in contrast an extra-enhancement in the framework of coupled channel calculations.

The experimental determination of the fusion cross section with weakly bound nuclei such as ^{11}Li or ^{11}Be may go forward a clarification of this issue. Our first proposal with INDRA is also an attempt to an exhaustive study (elastic scattering, dissociation, transfer and fusion) of the weakly bound projectiles ^{6,7}Li .

2.3. High diffusivity (halo) influence

Halo nuclei present a special interest due to their anomalous structure. Two effects have to be taken into account : the diffuse density of these nuclei will change the real interaction potential and the weakly bound particle(s) generate low lying levels [23] which could couple to fusion. Several predictions, taking also into account a break-up effect or not, have been proposed [24–26, 20, 21].

3. Our experiment

The first strong experimental limitation in this field is the availability of radioactive beams at energies near the Coulomb barrier. The main technique actually available is projectile fragmentation and lowering of the energy with an appropriate degrader [8]. Some transfer reactions could also be used. The advent of SPIRAL at Caen (FRANCE) will be an important progress in the beam intensity and quality.

In order to discuss our experimental choices, the different particles involved in transfer and fusion reactions are presented. A transfer reaction, generally of few nucleons, leads to a target-like nucleus which could be excited and a projectile-like nucleus. When fusion occurs, there is formation of a compound nucleus. The prompt de-excitation of the compound or target-like nucleus could produce neutrons, charged particles, statistical and discrete γ-rays or it could fission. Some characteristic radiations emitted by the eventual radioactive residual nucleus along its path back to the stability line could also be measured, α-rays, converted electrons, γ-rays or X-rays.

Right now, the most important effort has been made to identify the residues from the recoil compound nucleus. In case of very asymmetric target and projectile, it is very difficult to distinguish between a fusion residual nucleus and a transfer residual nucleus. Thus the data interpretation becomes extremely dependant of evaporation models. We propose a completely different philosophy to solve this problem. The basic idea is to build a 100% efficiency detection for the residual projectile and to define **fusion** as ***the process without projectile-like nucleus***. Furthermore, the identification of this nucleus informs on the reaction (transfer channels, elastic or inelastic scattering). The advantage is that projectile-like nucleus has broad angular distribution with small contribution at low angles. The high efficiency needed by this logic allows measurements with weak beams like radioactive nuclear beams. The main difficulty is to control the efficiency for the different possible particles at the different energies. There is also a strong constraint on the usable projectiles since identification is easier for light nuclei which have larger ranges than the heavy ones.

3.1. The FUSION detector

The first experiment made with this philosophy was the study of ^{9,11}Be+^{238}U. Fusion leads to a Cm isotope with more than 30 MeV of excitation energy which fissions. A first stage of detectors detects fission fragments in coincidence. It is composed of 10 PPAC surrounding the target. They measure time (resolution less than 1 ns), position in two plans (5 mm) and charge. They cover more than 70% of all space. The measurements of fission cross-section also includes non-fusion events (some transfer or inelastic reactions). The second shell is devoted to the detection of the residual projectile. This is realized by plastic scintillators surrounding the shell of PPAC.

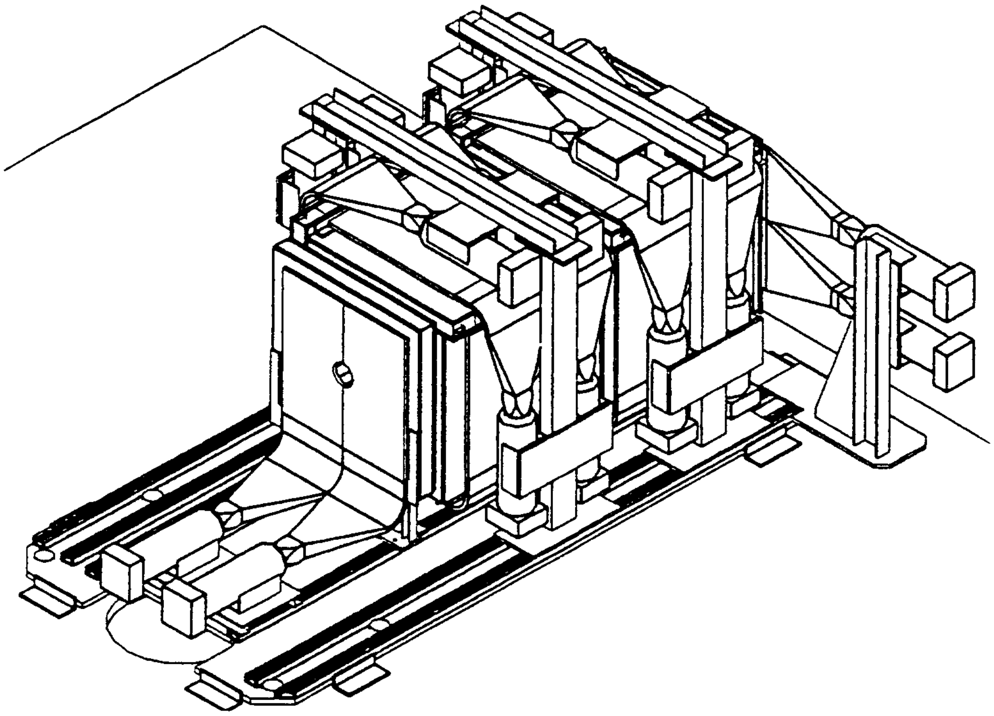

Fig. 1. *View of the F.U.S.I.O.N detector.*

A global realistic view is presented in fig.1. A more explicit schematic view was previously presented [7]. The inner shell of PPAC could not be clearly seen. Photo-multiplier tubes, light guides, scintillators and their mechanic compose the outer shell. The beam passes through the detector. The hole at the exit can be seen in the back scintillator. The size of this set of 10 PPAC and 20 plastics is 60x60x120 cm^3. The geometrical efficiency is defined by the mechanics of PPAC so exactly checked with a californium source. On fig. 2, we have reconstructed the Θ-Φ (usual spherical coordinates) distribution for fission fragments based on position measurements. There is clearly designed the shadow of the mechanic. The geometrical efficiency is then controlled with high precision. On this figure, a typical problem of intrinsic efficiency for a couple of PPAC can be seen : the statistic is lower and edges are undefined. Such problem which is created here by a low high tension could be rapidly seen and solved by this control.

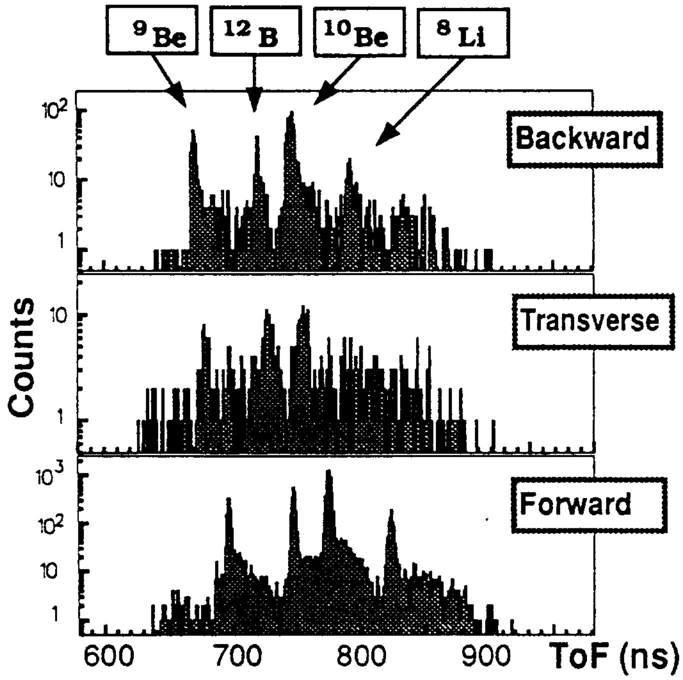

Fig. 3 *Absolute time of flight measurement for scattering particles from a non-purified beam at Bρ= .8470 Tm which allow a precise calibration of plastic scintillators. A secondary emission detector is used as a start detector.*

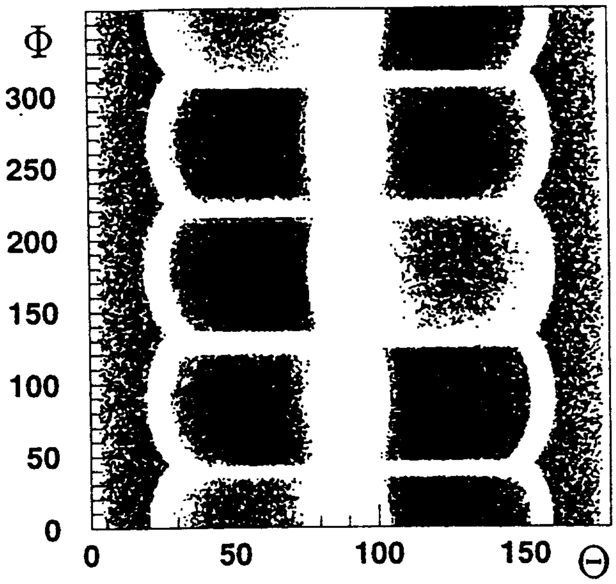

Fig. 2. *Positions where the PPAC are fired by fission fragments presented in spherical coordinates (Θ,Φ). At Θ around 90° the PPAC and target mechanics forbid the detection.*

A crucial point in this experiment was to detect quasi-projectile. This is the role of plastics which measure charge and time (resolution of 1ns). In our first experiment, the time of flight has only been measured with radio frequency. For low energy beams at GANIL, this is insufficient to recognize the different particles from the beam. Furthermore the charge information is not sufficient to clarify the identification. In consequence, the fusion was not separated from other reactions leading to fission.

In the second experiment, a secondary emission detector was used as a start and an absolute time of flight was measured. The efficiency of this detector was close to 100% for

Be-isotopes at energies close to the Coulomb barrier.

An example of measurement is presented on fig. 3 for a non-purified beam with a magnetic rigidity of 0.8470 Tm. A clear separation and identification is obtained in the case of elastic scattering on the front, back and lateral plastics. This crucial information will be a severe condition to disentangle fusion-fission from other channels leading to fission. The data are still under analysis.

2. Preliminary results

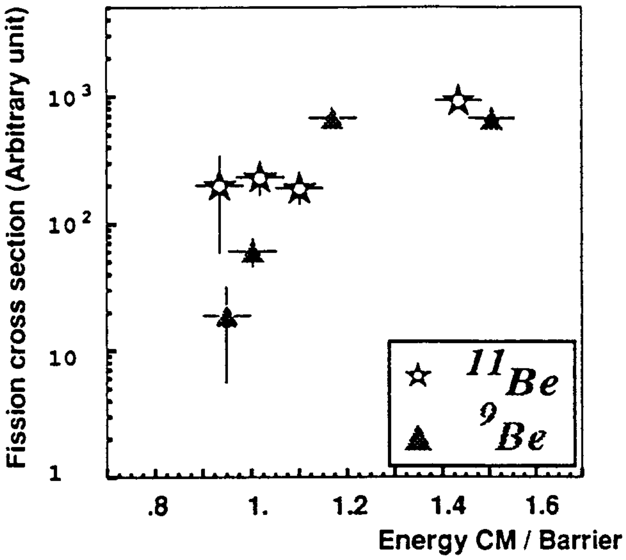

Fig. 4. *Fission cross section in arbitrary unit for 9Be (triangles) and 11Be (star) on 238U as function of the ratio (center of mass energy/ Coulomb barrier).*

Fission cross section for ^{9,11}Be+^{238}U has been extracted, fig. 4. Due to the high inhomogeneity of the U target, absolute fission cross section has not been obtained. The relative values are correct since the inhomogeneity does not affect the entrance channel but only the exit of the fission fragments. The error bars plotted on the figure are only due to statistics. The fission cross-section for the ^{11}Be isotope is higher by 30% at an energy $E_{cm}/V_b=1.5$ with V_b taken equal to 43.2 MeV for ^{9}Be and 42.7 MeV for ^{11}Be. Below the barrier, fission cross section is also higher for ^{11}Be. However the behavior of the data points near $E_{cm}/V_b=1.-1.2$ is puzzling. In this region the fusion with ^{11}Be projectiles seems to be reduced as compared to ^{9}Be. Obviously this first measurements suffer from a lack of statistics (only 10 events at $E_{cm}/V_b=1$). Furthermore, we have to determine the uncertainty due to background events before to conclude.

4. Conclusion

We have demonstrated the feasability of measuring sub-barrier fusion with very weak beams at GANIL and presented original results. An important effort of reflection and preparation has to be made to prepare high quality measurements with radioactive beams with SPIRAL. The goal must be the complete measurement of reactions (elastic, inelastic, break-up, transfer and fusion cross sections). A first step on this direction is to test the ability of INDRA to do these measurements. A more general set-up has to be prepared to investigate one of the most important field in nuclear physics.

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