GANIL-SPIRAL2 : a new era

S. Galès

GANIL-SPIRAL2: A NEW ERA

SYDNEY GALES

GANIL, DSM-CEA/IN2P3-CNRS, Bd. Henri Becquerel, F-14076 Caen cedex, France

GANIL presently offers unique opportunities in nuclear physics and many other fields that arise from not only the provision of low-energy stable beams, fragmentation beams and re-accelerated radioactive species, but also from the availability of a wide range of state-of-the-art spectrometers and instrumentation. An overview of the physics with secondary beams carried out at GANIL is presented. Selected examples of recent experiments using fragmentation of high energy intense stable heavy ions beams and re-accelerated SPIRAL1 "exotic" beams and the associated instruments are used to illustrate the ongoing physics program. With the construction of SPIRAL2 over the next few years, GANIL is in a good position to retain its world-leading capability. As selected by the ESFRI committee, the next generation of ISOL facility in Europe is represented by the SPIRAL2 project to be built at GANIL (Caen, France). The future prospects of the accelerator complex GANIL-SPIRAL1 and the path towards SPIRAL2 is also briefly introduced.

1. Introduction

In this paper, I would like to present the recent highlights of the physics of "exotic" nuclei and/or the main results obtained recently on nuclei far off stability at GANIL, a emerging field which we as, physicists we can compare to the exploration of a new territory. The perspectives offer by the SPIRAL2 project at GANIL will be shortly introduced in the last paragraph of this paper.

Since its beginning in 1983, GANIL [1] has been involved in active research in the field of exotic nuclei. At GANIL the available stable ions beams range from ^{12,13}C to Kr isotopes with intensities up to 2pμA for ^{13}C at 95MeV/n and 0.1pμA for Kr at 50 MeV/n (beam power between 3 to 6 KW on target). For heavier ions (Lead and Uranium) an energy range between 5-25 MeV/n with 10^{10}pps can be achieved. Light and medium mass ion beams raised to high energy are fragmented on a thin target, giving rise through the "fragmentation process" to light exotic nuclei.

The successful program of the physics of "exotic" nuclei produced by the so-called "in-flight " method was extended recently towards new possibilities offered by high-quality, low-energy Radioactive Ions Beams (RIB) at the SPIRAL facility [1] using the "ISOL" production method.

This SPIRAL facility, which became operational in September 2001, can be summarized as follows: the high energy, high power beams extracted beams from the three GANIL accelerators C01 (2)-CSS1-CSS2 is sent to a carbon target. The incident nuclei are fragmented by nuclear reactions in this target, generating a population of radioactive nuclei which diffuse out of this hot target (2 000°C). After ionization in an ion source, the particles are injected into the CIME cyclotron to be accelerated to energies of 1.7 to 25 MeV per nucleon. Since its start-up, various ions have been produced and accelerated in the SPIRAL facility, ranging from exotic nuclei as light as ^{8}He to heavier nuclei like ^{76}Kr. About 200 shifts per year are devoted to experiments with SPIRAL beams.

At GANIL, the rather unique capabilities, using both “In flight” and “ISOL” techniques, to produce a large variety of light and medium “exotic” species have boosted the scientific program.

2. Exotic nuclei at GANIL: recent physics highlights

As intensities of secondary Radioactive Ion Beams are usually four or five orders of magnitude lower than typical intensities of stable beams, physics with secondary RIB requires very specific detection devices. Reactions and Structure studies of “exotic” nuclei are carried out using intensively the high energies of the fragmented “in flight” RIB from GANIL, the post accelerated ISOL-SPIRAL1 RIB and low energy (5-10 MeV/n) intense Uranium beams. The beams are coupled to spectrometers like LISE, VAMOS and/or $4\pi-\gamma$ array called EXOGAM, charged particle detectors like MUST and TIARA. Those combinations are ideal tools for the studies of nuclear structure and reactions.

In the following we will present a few recent highlights of the physics results achieved in the last few years.

2.1. *Tunnelling of exotic systems*

A modern variation of the Rutherford experiment to probe the tunnelling of exotic nuclear matter from the measurement of the residues formed in the bombardment of ^{197}Au by extremely neutron-rich ^{8}He nuclei was carried out. Using a novel off-beam technique the most precise and accurate measurements of fusion and neutron transfer involving reaccelerated unstable beams are reported. The results show unusual behaviour of the tunnelling of ^{8}He compared to that for lighter helium isotopes, highlighting the role of the intrinsic structure of composite many-body quantum systems and pairing correlations [2].

2.2. *Another major research area at GANIL is the quest for shell structure changes far off stability*

Experiments on shell structure evolution around magic number 8, 20 and 28 have been recently investigated using both “in flight” and ISOL RIB via knock out or transfer reactions associated to gamma spectroscopy.

For the N=14 shell, measurements were performed using 10.5 MeV/n ^{24}Ne beam (10^5 pps) on a 1 mg cm^{-2} CD_2 target .The charged particle array TIARA was used to detect protons, in combination with four segmented clover detectors of the EXOGAM array placed at 90° around the target. The heavy transfer residues ^{25}Ne were detected and identified in the focal plane of VAMOS. The high efficiency of the whole system allowed three-fold coincidences data (g +proton+ ^{25}Ne) to be acquired. Excitations energies, l transfer and spectroscopic factors were measured for states up to 4.0 MeV. The salient features of this work can be summarized as follows [3]:

The N=14 gap is large in ^{25}Ne, the N=20 gap formed between the $d_{3/2}$ and fp intruder states seems to be small and the N=28 gap has greatly increased in the Ne isotopes. This lead to an inversion between the $f_{7/2}$ and $p_{3/2}$ orbit, as inferred from the energies of the 3/3- and 7/2- states.

For the N=28 neutron shell, the energies of the excited states in very neutron-rich ^{42}Si and $^{41-43}$P have been measured using in-beam γ-ray spectroscopy from the fragmentation of secondary beams of $^{42-44}$S at 39 MeV/n. The low 2^+ energy of ^{42}Si, 770(19) keV, together with the level schemes of $^{41-43}$P provide evidence for the disappearance of the Z=14 and N=28 spherical shell closures, which is ascribed mainly to the action of proton-neutron tensor forces [4]. Recently the evolution of the structure of N=28 nuclei from the doubly-magic ^{48}Ca nuclei to the strongly deformed ^{42}Si has been investigated at GANIL. Of particular interest is the low lying level scheme of nuclei with Z<20 and N=28 like for example ^{44}S. In the neighbouring nuclei N=29, the spectroscopy study of ^{43}S have led to the discovery of a low lying 7/2- isomeric state, very weakly connected to the deformed 3/2- ground state demonstrating a shape coexistence at low excitation energy in ^{43}S [5]. The N=28 isotone ^{44}S have been recently investigated at GANIL.

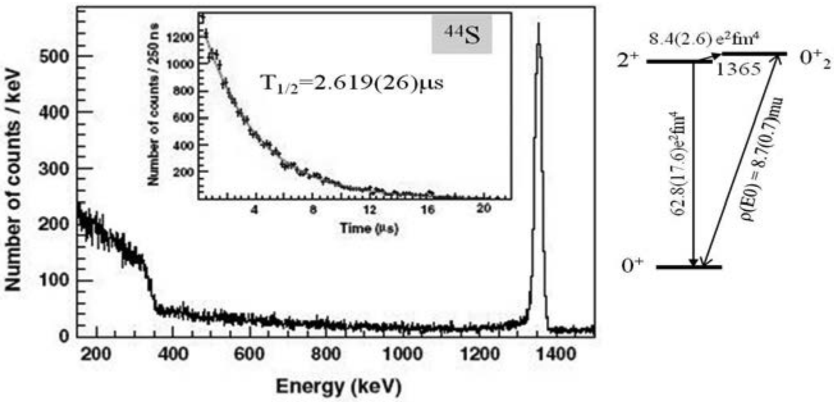

Figure 1. Electron Energy Spectrum showing the 0^+_2—0^+_1 E0 transition in ^{44}S Left the low excitation energy spectrum of ^{44}S [6]

A low-lying second 0^+_2 isomer has been clearly identified in ^{44}S through the measurement of the 0^+_2 –0^+_1 transition as shown in figure.1 and its lifetime measured (2,62 μs). From the measured B (E2) reduced transition probability and the extracted Monopole strength ρ^2, it has been shown [6] that the two 0^+ state are rather pure, in agreement with the conclusion that ^{44}S a spherical prolate shape transition is evidenced. The spectroscopy of $^{43,44}S$ support the previous finding, namely a shell erosion of the N=28 gap in that region of mass.

2.3. *MUST2 Campaign at RIKEN*

Under the framework of the International Associate Laboratory (LIA), the MUST2 collaboration (GANIL, IPN Orsay and SPhN/IRFU/Saclay) and the RIKEN Nishina Center physics group have formed a new collaboration.

MUST2@RNC collaboration [7] prepared an experimental campaign using the unique opportunities offered by the "in flight" intense light "exotic" beams produced by the new facility RIKEN-RIBF and the Big-Rips fragment separator. Two direct reactions studies have been investigated using the reactions ^{11}Li (d, ^{3}He) ^{10}He and ^{24}O (p, p'). The light particles were detected by the charged particles array MUST2 consisting of a set of Si strips detectors placed around the gas target.

This campaign illustrates the power of coupling of state of the art detectors array, new and intense exotic beams to investigate the structure of nuclei even beyond the stability line.

2.4. *A new spin aligned pairing phase in 92Pd*

In nuclei with equal neutron and proton numbers (N=Z), enhanced correlations arise between neutrons and protons that occupy orbitals with the same quantum numbers. Such correlations have been predicted to favour an unusual type of nuclear super fluidity, termed isoscalar neutron–proton pairing, in addition to normal isovector pairing. Despite many experimental efforts, these predictions have not been confirmed.

An international collaboration have achieved an experimental observation of excited states in the N=Z=46 nucleus ^{92}Pd. Gamma-rays emitted following the ^{58}Ni (^{36}Ar, 2n) ^{92}Pd fusion–evaporation reaction were identified using a combination of state-of-the-art high-resolution γ-rays, charged-particle and neutron detector systems (EXOGAM,DIAMANT,NEDA). The results reveal evidence for a spin-aligned, isoscalar neutron–proton coupling scheme, different from the previous prediction (see Ref [8] and figure. 2). The authors suggest that this coupling scheme replaces normal super fluidity (characterized by seniority coupling) in the ground and low-lying excited states of the heaviest N=Z nuclei. Such strong, isoscalar neutron–proton correlations would have a considerable impact on the nuclear level structure and possibly influence the dynamics of rapid proton capture in stellar nucleosynthesis.

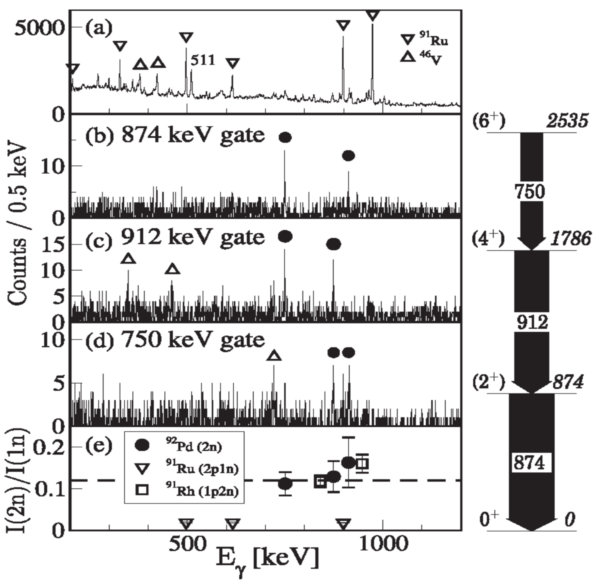

Figure 2. Gamma rays spectrum of the N=Z nuclei 92Pd at the basis for the evidence of a new np coupling scheme [8].

2.5. *Fission Time Measurements as New Probe for testing Super heavy Element Stability.*

The so-called "super heavy" elements (comprising more than 110 protons) are generally formed by fusion reactions between two lighter nuclei. One of the main difficulties of these attempts to synthesize Super Heavy Elements (SHE) resides in the excitation which is unavoidably generated within these nuclei, in the form of temperature and deformation, when they are formed by fusion. Fission events with times greater than 10^{-18} s (a billionth of a billionth of a second) were observed for nuclei with 120 and 124 protons. These compound systems were formed by bombarding nickel and germanium targets with uranium ions accelerated at the GANIL. They were identified by means of INDRA, a large array charged particle detector, which covers almost the entire space surrounding the targets. Using blocking techniques in the crystal-like targets of Ni and Ge and by comparing the yields of the cross-sections for quasi-elastic and fusion-fission events, very long half-life times were observed for these very large Z compound systems (~10^{-18}s). Although this 10^{-18} s time is clearly very short, on the scale of nuclear lifetimes, it is long enough to sign unambiguously the formation of elements having 120 and 124 protons, and to characterize them as being highly stable with respect to fission, when they are not excited [9,10]. More recently, the same compound Z=120 system was investigated by means of Ni+U reaction. During the collision and the formation of the compound system, electronic rearrangement of the system leads to X-ray emissions which are characteristics of the formed system. By detecting with INDRA the fission fragments in coincidence with X-rays, a clear evidence of an X-ray energy corresponding at Z=120 was observed [11]. The analysis is in progress. These results open up new perspectives in the race for super heavy elements, and the quest for the "island of stability".

2.6. *Prompt gamma spectroscopy of fully identified fission fragments with VAMOS*

Last but not least, thanks to the high intensity and low energy ^{238}U beams coupled to the VAMOS spectrometer and the gamma array EXOGAM, it has been possible for the first time to carry out a *prompt gamma spectroscopy of fully identified* fission *fragments.*

The reaction ^{238}U+ C at 6.1 MeV/n was carried out. Fission of U or Pu isotopes was induced in the collision. The fission fragments were detected and identified at the VAMOS focal plane by means of an ionization chamber (Z), time of flight, magnetic rigidity (M/Q) and total kinetic energy (M).

The focal plan detection of the VAMOS spectrometer was upgraded to achieve Z and A resolution for fission fragments both in A and Z as shown in figure 3.

The target was surrounded by a set of Si detectors to identify light inelastic or transfer fragments (SPIDER array) and a set of high efficiency Ge detectors from EXOGAM to achieve prompt spectroscopy of identified fission fragments.

Measurements of prompt Doppler-corrected de-excitation γ-rays from uniquely identified fragments formed in fusion-fission reactions of the type ^{12}C (^{238}U, ^{134}Xe) Ru were achieved [12].

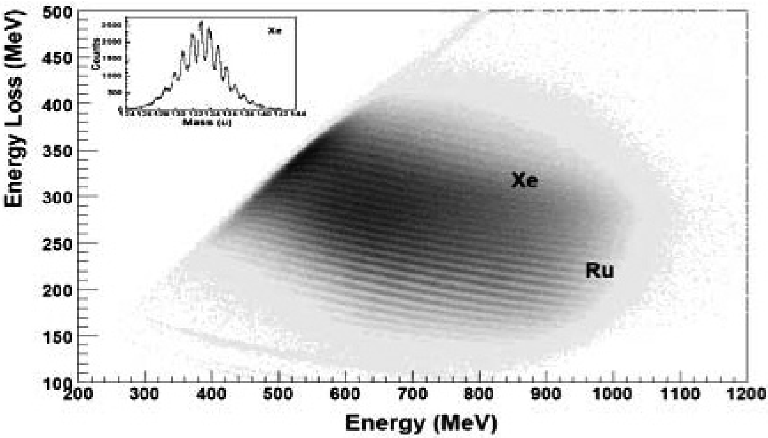

Figure 3 : Two dimensional spectrum of ΔE vs. E_{total} in the $^{238}U+^{12}C$ system at an incident beam energy of 1.45 GeV. The inset shows the associated mass spectrum for the Xe isotopes.

3. The future of GANIL – SPIRAL: SPIRAL2

Since the beginning of the SPIRAL project it was proposed to enlarge the range of RIB produced through the fission of uranium target and the delivery of high intensity neutron–rich fission fragments. This idea is now being concretized in the SPIRAL2 project [13].

The construction of SPIRAL 2 started in the middle of 2005 and is supported by the EU FP7 through the Preparatory Phase contract since 2008. The first beams are expected in the year 2013. As an added bonus, the facility will also produce over 10^{15} neutrons/s, making it the world's most powerful source of fast neutrons for several years.

A rather complete presentation of the current status of the project and of scientific case of SPIRAL2 facility will be presented in this meeting by M. Lewitowicz [13]).

Acknowledgments

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