Conseil Scientifique et Technique du SPhN

RESEARCH PROPOSAL MUST2 @ RIBF

Title: MUST2 campaign at RIBF,

1st phase: Structure and spectroscopy of the neutron-drip nucleus ^{24}O via proton elastic and inelastic scattering (p,p') at RIKEN.

Experiment carried out at: **RIBF-RIKEN**

Spokesperson(s): A. GILLIBERT (SPhN), V. LAPOUX (SPhN), H. OTSU (RIKEN)

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List of DAPNIA divisions and number of people involved: SPhN (5) + one post-doc

List of the laboratories and/or universities in the collaboration and number of people involved:

Members of the MUST2 collaboration GANIL, IPN-Orsay

Japanese teams of the collaboration "MUST2 @ RIBF"

University

SCHEDULE *for the ^{24}O exp.* ***NP0802-RIBF57*** *[for the campaign (to be defined see txt)]*

Possible starting date of the project and preparation time [months]: 2009; 2 months

Total beam time requested: for experiment RIBF57: **14 days** [whole campaign~ 2months]

Expected data analysis duration [months]: 2 years (calibration in common; analysis in parallel)

REQUESTED BUDGET

Total investment costs for the collaboration: travels; stays during experiments: support from the RIKEN laboratory; Share of the total investment costs for SPhN: travels of the members of the collaboration taken in charge by each laboratory.

Investment/year for SPhN:

Total travel budget for SPhN: 17 k€; Travel budget/year for SPhN: 9k€ [2008] + 8k€ [2009].

If already evaluated by another Scientific Committee: RIBF NPAC Feb 18-19th 08

If approved Allocated beam time: **14 days** Possible starting date: **2009**

Abstract

In order to test the validity of the nuclear models and to improve their predictive power, the exotic properties of the unstable nuclei such as very diffuse nuclear surfaces, low-lying resonances or new magic shells are experimentally investigated using radioactive ion beams.

In the region of the neutron-rich nuclei around ^{24}O, the neutrons occupy the sd-fp shells and new effects have been found, indicated or predicted for the shell structure, compared to the shell occupation known for the stable nuclei.

We want to investigate these new structures, to explore the spectroscopy and to deduce the nuclear shell effects in very-neutron-rich nuclei, like the drip-line nucleus ^{24}O. Ideally one would like to carry out experiments like elastic and inelastic proton scattering with enough beam intensity, at least few 1000/s is needed to obtain the angular distributions for (p,p) and the (p,p') excitation spectrum. These observables allow us to extract the elastic potential and matter density features, and to deduce the low-lying spectroscopy, giving hints about the N=16 shell behavior in O isotopes.

This is one part of a whole program involving (p,p') in neutron-rich nuclei in the Ne and Mg regions, in order to study neutron excitation and shell effects.

In 2008, there is only one place in the world to prepare such studies: at the RIKEN laboratory, with the RIBF (Radioactive Ion Beam Factory) facility which should soon accelerate ^{48}Ca beam and be able to deliver the very neutron-rich O, Ne, Mg beams of interest, with unique intensities. The measurement of the elastic and inelastic proton (p,p') scattering of the neutron-rich nuclei will be possible in a reasonable beam time ~ 10 days.

Introduction

The data collected on the magic nuclei appear as crucial, due to the specific properties of these nuclei like larger first 2+ excitation energies and increased stability compared to the nuclei in their neighborhood. The properties of doubly magic nuclei were the key–stones for the modeling of the nuclear structure and the understanding of the nuclear properties.

The nuclear structure models were built using the magic numbers:

- The properties of the magic nuclei were the rules used by M. Goeppert-Mayer and J.H.D. Jensen to postulate their shell model. Within the shell model, the magic nuclei represent the building block of the effective core interaction [ChW92].

-The values of a few shell energy gaps between single-particle states and the charge root mean square (rms) radii for the doubly-magic nuclei (^{16}O,^{208}Pb) are key values to fix the parameters of the effective Nucleon-Nucleon (*NN)* interactions like Skyrme-type [Cha95] and Gogny-D1S type interactions [Dec80] used in the mean-field and beyond mean-field Hartree-Fock-Bogolyubov (HFB) calculations. The ground structure properties of ^{132}Sn were taken into account in the Skyrme parameterization, along with the ones of other doubly closed-shell nuclei [Cha97].

- Recently a new Relativistic Mean-Field (RMF) effective interaction with explicit density dependence of the meson-nucleon couplings was adjusted, taking into account properties of doubly-closed shell nuclei, among which ^{132}Sn [Lal05].

The isospin dependence of the effective *NN* force is also a key ingredient of the structure models. When going to the drip-lines, we explore nuclei in which the influence of the isospin-dependent term is emphasized. One may expect that along with other parameters of the effective force, such as the spin-orbit coupling or the pairing term, readjustment of the nuclear forces far from stability will be needed.

To have experimental data on the evolution of the nuclear properties with the isospin degree of freedom, and to constrain the new developments of the nuclear models, the structure of the unstable nuclei is explored intensively using the radioactive ion beams.
For the very unstable nuclei, new phenomena have been found for the last twenty-five years: such as very diffuse nuclear surface-*neutron-halos, neutron-skins-,* clustering, low-lying resonances or new magic shells. These "exotic" phenomena were not predicted by the models built or tested on the stable nuclei. In order to test the validity of the nuclear models, and to improve their predictive power, it is important to investigate the new properties of the exotic nuclei. ***With the facilities developed worldwide, it is possible to start the investigation on the effect of large variation of isospin along isotopic chains and to search for new properties close to the drip-lines. Direct reactions such as (p,p') scattering and one-nucleon transfer reactions are measured, using the particle spectroscopy technique, to extract the properties of these nuclei.***

At GANIL, with the SPIRAL beams at energies E~ 5 to 15 MeV/nucleon, we can measure the angular distributions of cross sections –of the order of mb/sr- for the transfer reactions of one [(d,p) (p,d)] or two neutrons, like (p,t) reaction. These data give access to the neutron-shell structure. The reactions of one proton removal from the incident nucleus [the proton pick-up (d,^{3}He) and the knock-out (p,2p)] are favored at higher incident energies (typically higher than 40-50 MeV/nucleon). These measurements give access to the proton-shell structure.
Benchmark nuclei could be the new doubly magic nuclei which are searched amongst the exotic nuclei. The known doubly-magic nuclei are very few: in the valley of stability, they are ^{4}He, ^{16}O, ^{40,48}Ca and ^{208}Pb. Other unstable doubly magic nuclei with numbers of protons and neutrons corresponding to the established magic numbers, like ^{78}Ni, ^{132}Sn are under study at various facilities (GSI, Oak Ridge). ^{48,56,78}Ni and ^{100}Sn unstable nuclei should also rank amongst the set of doubly-magic nuclei but hints should be given.
Other doubly-magic nuclei are also expected, but with magic numbers corresponding to new ones. It is theoretically expected that the harmonic oscillator number should be the relevant magic numbers. Vanishing of magic numbers established in the valley of stability (*N=8, N=20*) and appearance of magic number (*N=16*) associated to new shell gaps have been found experimentally by the nuclear community, by collecting data on exotic nuclei in the RIB facilities all around the world during the last 20 years.
With the appearance of the new magic numbers, the unstable nuclei like **^{24}O (*Z=8, N=16*)** could represent new doubly magic nuclei whose properties could be crucial to readjust the nuclear forces and test the validity of the nuclear models.
We rely on the intensities provided by the facilities, in order to push forward our studies close to the drip-lines. At present, there is only one place in the world where a beam of ^{24}O, with enough intensity to carry out the (p,p') studies, can be delivered: RIBF facility at RIKEN.

Outline

We explain the context and the motivations of the campaign below (*Section I*). The highlight experiment for the collaboration appears to be the spectroscopy of **^{24}O via (p,p') scattering,** due to the uniqueness of **the RIBF intense ^{24}O beam, combined to the use of the advanced MUST2 array.**
This will be the first experiment of the campaign. The experimental set-up and the conditions are detailed (***Section II***); ^{22}O(p,p') will also be measured to have a reference measurement (spectroscopy of ^{22}O is known) in order to check the experimental conditions.

The experiment was submitted to the 3rd Nuclear Physics program advisory committee (NP-PAC) for RIBF, held in Riken on Feb.18-19th 2008. The positive decision of the PAC was given on April, the 2nd (see ***II. E***).

The whole campaign will be presented during the next PAC meeting, which will be scheduled in October or in Nov 2008. The organization of the MUST2-RIBF collaboration and of the future campaign is given in ***Section III***, the overview of the preliminary schedule and of the important steps can be found in ***Section IV***.
Finally the requested budget will be exposed in ***Section V***.

I. Context of the MUST2 campaign

In May 2005 the experimental program foreseen by the group for the short, mid and long-term ranges was explained to the CSTS. One of the research axes was dealing with the structure and spectroscopy of near-drip-line nuclei. We discussed the possible explorations of the evolution of the neutron excitation and structure of neutron-rich nuclei towards the drip-line in the light of the development of the Radioactive Ion Beam facilities. The program of the group concerning these drip-line lines studies, as extracted from the 2005 report, is recalled in the ***Appendix A.I***; the main results obtained by the group are given in ***App A.II***.

Hereafter, we resume the main research axes presented in 2005, and discuss the recent evolutions.

The main research program foreseen in 2005 was the direct reaction studies at low-energy, using the present SPIRAL beams, and expecting new SPIRAL beams, and in the mid-future (~2013) the RIB delivered by the SPIRAL2 project.
For the program discussed in the CSTS of 2005, we presented the MUST2 array developed specifically by the DAPNIA, GANIL and IPNO teams for the direct reaction studies at GANIL. Since 2005, MUST2 was completed and used in experiments, in 2007 the MUST2 array was completed (4 then 5 modules) and it has been used extensively during 2 campaigns. 6 telescopes are now available for the experiments; the power of this array for the direct reactions was demonstrated. Characteristics of the detector and present status of the equipment can be found in ***Appendix B***.

For the long-term future we have highlighted the neutron-rich EURISOL beams to explore the change in the shell structure and the possible effects of halo or neutron-skin structure.
In particular we stressed that the spectroscopy of the drip-line ^{24}O nucleus was a key-experiment to be considered with the second generation RIB facility EURISOL. The $^{30\text{-}34}$Ne nuclei were also considered as interesting beams to look for the evolution of the neutron-skin structure and for possible super-deformed skin nucleus.

Since the CSTS held in 2005, the panorama of the RIB facilities –present and future- have deeply changed. The RIA project in the United States was quasi-buried, the SPIRAL2 obtained official green light and (part of) the funding, the official start of the future facility FAIR at GSI was also announced in 2007. In Japan, since 2007, a « factory » for the production of radioactive beams: RIBF is in operation on the site of the RIKEN accelerator. RIBF includes the new fragment separator BigRIPS, which provides the selection and the transmission of the beams. BigRIPS has delivered the first beams in May 2007. It is important to note that in **2007**, RIBF was the first next-generation facility operational and delivering RI beams. The new facility corresponds to an upgrade of RIKEN, and to new developments making it a world-class heavy-ion accelerator complex. It includes also new experimental area for the transmission of the beams, like BigRIPS. Complementary information about *RIBF, the beams and the expected intensities can be found in* ***Appendix C.***

In the meantime, at GANIL, the range of available beams has been suddenly reduced, since the SISSI fragmentation device at GANIL is not available for the moment: SISSI broke down in June 2007. It appears rapidly that the repair and re-operation of SISSI could not be possible before 2010, in the best case. Details about the SISSI failure and repair can be found in ***Appendix D.***

For our experimental program, we require exotic beams with enough intensity (>5 10^3/s); for the moment, with the beams delivered by the SPIRAL facility or produced by fragmentation with the production target at the LISE spectrometer, the possibilities are limited.
In March 2007, the structure group of SPhN carried out the first MUST2 experiment of the campaign. The ^{8}He SPIRAL beam was used to measure the low-lying spectroscopy of ^{6}He via the ^{8}He(p,t) transfer reaction. The data analysis is the subject of a PhD (X. Mougeot) in our group; it will be completed in mid-2008.
In March 2008 the MUST2 collaboration has still several accepted experiments not yet scheduled, for most of them the SISSI beams were needed. A part of these experiments have been reconsidered since the last 6 months, and they could be carried out using the fragmentation target in the LISE area. We have also one MUST2 experiment (E569S) which was accepted by the PAC in December 2007. It will be performed using the ^{14}O SPIRAL beam, probably in 2009. A future MUST2 campaign could take place in 2009 (details of this campaign can be found in ***Appendix E***). Schedule is not yet fixed at GANIL.

Since the possibilities to have neutron-rich exotic beams at GANIL were reduced, we have considered the beams offered by the other facilities in the world in order to pursue our experimental program for the direct reactions with the MUST2 device. In 2007, the information about the operation of the new RIBF facility sounded rapidly very promising: it appeared that beams of very neutron-rich nuclei should be available at RIKEN with unique intensities. On June 11th 2007, the RIKEN direction announced the discovery of a new isotope ^{125}Pd (*Z=46, N=79*), obtained with RIBF. Various systems of RIBF are still under upgrade and tuning and up to now, the intensity of the Uranium beam [$^{238}U^{88+}$] is only ~1.8 10^8 /s [0.03 pnA] which corresponds to a factor of 10^5 less than the final goal [6.25 10^{12}/s; 1pμA]. But with the discovery of ^{125}Pd, which was obtained with the equivalent of one-day data taking, the RIBF facility has demonstrated its potentiality even in the conditions of limited beam intensities.
It is clear that the RIBF facility could offer some of the beams of interest before the hypothetical advent of EURISOL in the years 2020. The RIBF accelerator has the potentiality to extend the range of the radioactive beams available with unreached intensities till now. The region of the neutron-rich nuclei, in particular, between *Z=6* and *Z=16* with the Oxygen, Neon, Magnesium and Silicium chains, could be investigated. New phenomena are expected in this region (shell changes, halo or neutron-skin structures). To understand the nuclear correlations which are underlying these structures, we will need to use direct reactions and in particular to measure elastic and inelastic scattering of exotic nuclei on proton target.
We will take advantage of the secondary beams which could be produced far from the valley of stability, using the primary beam of ^{48}Ca. In 2009 it is expected that the RIBF facility produces this beam at the maximum intensity of 200 pnA, at 350 MeV/nucleon.

In the light of the opportunities offered by RIBF, we have decided in 2007 to complement our experimental program in the region of neutron-rich nuclei between *Z=6* and *Z=16*.
To carry out the particle spectroscopy studies at the RIBF energies (of the order of 150 to 300 MeV/n for the secondary beams), the dynamical range and the performances of the MUST2 array turned out to be well-adapted.

For all these reasons –availability of the new exotic beams at RIBF, extension of the experimental programs close to the drip-lines, use of the dedicated device MUST2 for the particle spectroscopy at RIBF- an experimental program was established by the French and Japanese teams; the list of the physicists involved in this collaboration is given in ***Section VI****.*
Our program is first focused on the structure of neutron-rich nuclei produced by RIBF and studied using MUST2.

History of the MUST2@RIBF collaboration
To discuss the prospective of nuclear reaction studies using the MUST2 array at RIBF, we decided to build a team gathering a few members of the MUST2 collaboration and Japanese physicists belonging to the RIKEN Institute (teams of H. Sakurai and T. Motobayashi) and to the laboratories of the University of Tokyo and of RCNP-Osaka.
The detailed list of the MUST2@RIBF collaboration is given below (**Section VI**).

The first collaboration meeting was held during the DREB07 conference at RIKEN in May 2007 and the first workshop was organized at RIKEN in November 2007, to explain the characteristics and potentialities of the MUST2 device, to examine its implantation in RIKEN and to discuss the ideas of physics.
The nuclear structure group of CEA Saclay SPhN [DSM/IRFU] prepared a program of (p,p') experiments with the neutron-rich beams and the MUST2 array. The goals were to study the structure and spectroscopy of neutron-rich nuclei close to the drip-line.
It was decided that a first experiment should be submitted at the RIBF NPAC (Nuclear Physics Advisory Committee in order to express the interest for the acceleration of the intense ^{48}Ca beam to produce exotic beams at A~20-30.

Amongst these nuclei, we wanted to investigate first the structure and the spectroscopy of ^{24}***O since it appears to have key-properties: it is the last bound isotope of the O chain (with respect to the strong interaction); with N=16 neutrons, it is expected to be a new doubly-magic nucleus and to have exotic properties like large extension of the neutron densities with a neutron-skin. The experiment, "Structure and spectroscopy of neutron-rich nuclei via proton elastic and inelastic scattering:*** ^{22,24}***O(p,p')" was proposed by the nuclear structure group of SPhN during the collaboration meeting. It aims at measuring the elastic and inelastic scattering of*** ^{24}***O(p,p').*** ^{22}***O(p,p') will be used as a reference measurement, to check the set-up and analysis.***

The proposal of this experiment (***RIB08-NPAC57***) was sent in January 08 in the name of the MUST2@RIBF collaboration. It was defended during the PAC meeting in Feb 2008, 18th. Positive decision was given in April 2008. It is the first step for a series of proposals which will be presented by the collaboration during the next NPAC-RIBF in July 08. All these experiments could be scheduled in 2009, and be done as a campaign, to share preparation time and calibration runs (see ***Section IV*** for the next steps).

II. Experiment: ^{22,24}O(p,p') at RIBF

II. A. Motivations

With the few parameters adjusted on the properties of the doubly-closed shell nuclei, the nuclear forces were found to give a satisfactory description of the stable nuclei. But the validity of the present theories to describe the radioactive nuclei has been put under question.

The first-generation of RIBs beams around the world have opened a first window on the nuclear chart and provided data on the light unstable nuclei. The important learning was the modification of the usual shell structure established for the stable nuclei. Today, the location of the neutron drip line is known only up to the oxygen isotopes: in the search for the neutron drip line, ^{24}O (*N=16*) has been fixed to be the last bound oxygen isotope [Tar97,Sak99] in contrast with the predictions of the standard shell model, for which the doubly-magic nucleus ^{28}O (*N=20*) should be bound with respect to particle emission. Moreover ^{22}C and ^{23}N (*N=16*) have been found experimentally to be the last bound isotopes of their chain, and new magic numbers have been indicated experimentally, like *N=16* for C, N, O isotopes [Oza00].

This effect for the C, N and O isotopes was already predicted in [Bei75] within the density-functional method: far from the valley of stability, *N=16* turns out to be a good magic number, whereas at *N=20* the magicity is vanishing. This would correspond to a larger energy gap between *1s1/2* (*N=16*) and *0d3/2* than between *0d3/2* (*N=20*) and *0f7/2* shells, with the neutron drip line at ^{22}C, ^{23}N and ^{24}O.

New shell effects were found around N=16 for ^{26,27}Ne [Obe06] and the shell effects associated to the well-known magic numbers like N=20 were shown to vanish in the neutron-rich nuclei like the deformed ^{32}Mg nucleus [Mot95].

Theoretically, the new N=16 magic number was interpreted [Ots01,Ots03] as the effects of the proton-neutron tensor force, producing an enhancement of the neutron shell gap between the *s1/2* and the *d3/2* subshells, as compared to the situation of the *sd* shell in the stable nuclei.

Recently, T. Otsuka et al., have discussed the general rules for the evolution of the Effective Single Particle Energies (ESPE) [Ots05] and found that the movement of the ESPE (repulsive or attractive effects between orbitals) was driven by the proton-neutron tensor force. Along the isotonic or isotopic chains, moving towards the drip-lines, the spherical single-particle energies are shifted as protons or neutrons occupy certain orbits.

In the model beyond-mean field using Gogny forces, HFB calculations have exhibited shell modifications but the evolution of the shell gaps is less pronounced [Obe05]. Recently RMF calculations have explored the change of the spin-orbit term for neutron-rich nuclei [Tod04]. The spin-orbit potential may be strongly different from what was usually assumed for the stable nuclei.

Isovector force, pairing correlations, isospin-dependence of the interaction terms are not well determined in this procedure since the sample of nuclei in the valley of stability, offers a too narrow range for the variation of the isospin degree of freedom. This is one of the reasons why the present parameterizations are failing in reproducing the nuclear data collected up to now in the case of the exotic nuclei. Another cause for the observed discrepancy is attributed to the role played by the continuum correlations, which were found to be enhanced when the nuclei are getting more and more weakly-bound, which is the case, going to the drip-lines.

To determine the shell structure modifications and to test the features of the renewed nuclear models, we need to explore the change of the nuclear shell properties at higher isospin when going far from the valley of stability. At RIBF, we first want to focus our study on the N=16 problem. The experimental signature in favor of a new magic number N=16 for C,N,O came from the one-neutron separation energy S_n [Oza00] but still more information is necessary to establish the clear picture of the shell gap at N=16, especially we need data corresponding to the 2^+ state of these N=16 nuclei.

Scarce data is available on excited states of ^{24}O. In an experiment of gamma-ray spectroscopy [Sta04], no gamma-ray associated to the decay of ^{24}O was observed. This suggests that the expected excited states 2^+ and 3^- are unbound, above the neutron threshold S_n = 3.7 MeV.
The Figure **II.1** presents a simplified spectroscopy for the even-even Oxygen isotopes and a schematic shell picture for the oxygen isotopes, with a large *N=16* shell gap. In this picture, if the *d3/2* state has positive single particle energy, the neutrons are occupying the *d3/2* orbital.
The structure of ^{24}O has been reinvestigated with theories including continuum couplings. All these theories predict the 2^+ excitation energy above the neutron threshold. T. Otsuka, in the framework of the MCSM [Ots02], predicts this level 300 keV above the neutron threshold. In the QRPA calculations of [Col01], the couplings to 2^+ and 3^- states lead to a large energy gap between *2s1/2* and *1d3/2* states, in agreement with a new magic number at *N = 16*. In particular, the 3- vibrations are found to play a crucial role to push down the energy of the *2s1/2* state.

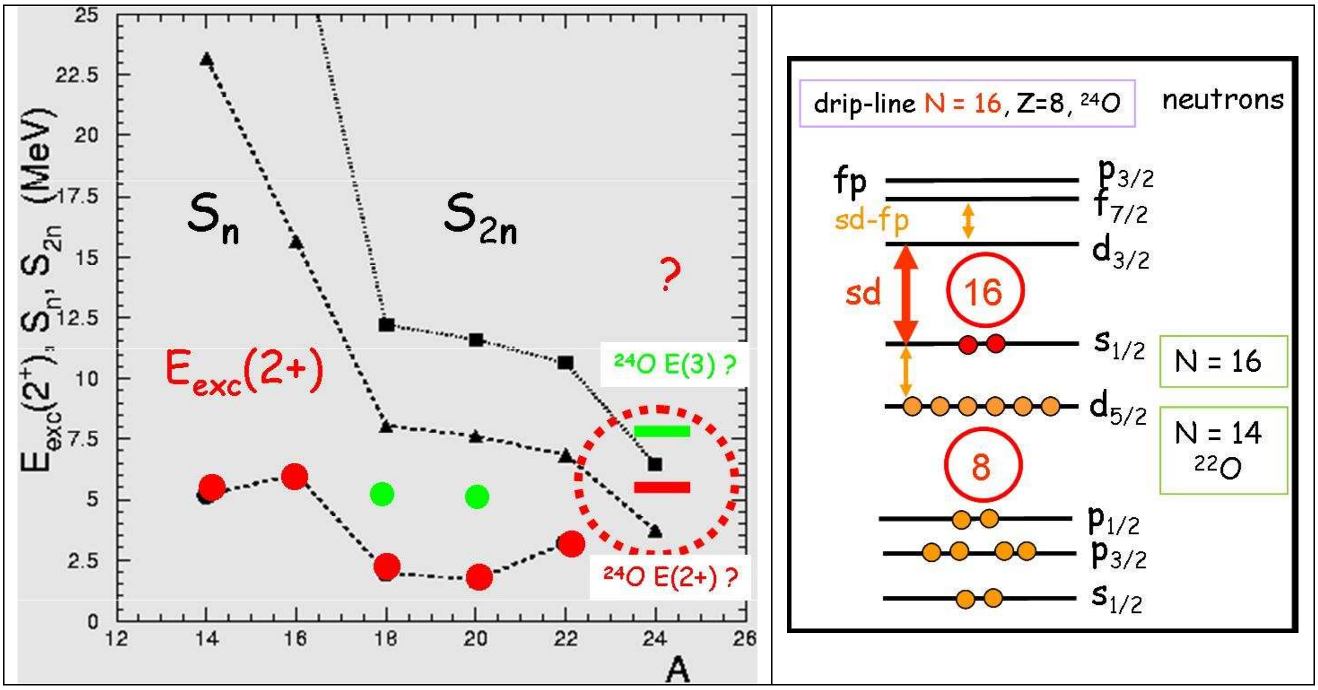


Fig II.1 (Left) Low-lying spectroscopy for the even-even Oxygen isotopes, including only the first 2+ state, and also the measured position for the first 3- states in $^{18,20}O$. The experimental one-neutron S_{1n} and 2-neutron S_{2n} separation energies are shown (values from [AMDC]*). Possible locations for the 2^+ and 3^- states in ^{24}O (circle) are indicated above the neutron threshold.*

(Right) Naïve shell model picture for the drip-line nucleus ^{24}O, showing the possible main occupation of the orbitals, with the large shell gap between s1/2 and d3/2 and the small gap d3/2 and fp.

A detailed discussion about the modification **of the sd-fp shell gaps in the region around ^{24}O** can be found in ***Appendix H***, it presents the interpretation of the recent data obtained in the neutron-rich region around *N=16*. We give below a summary and discuss the predictions of the shell gaps for the neutron-rich Oxygen isotopes.

sd-fp shell gap in the neutron-rich Oxygen isotopes

Theoretically the various models agree on the modification of the shell gaps –vanishing of *N=20*, apparition of *N=16*) in the Oxygen isotopes, but the evolution of this gap in the neutron-rich $^{20\text{-}24}$O isotopes and the value of the shell gap at *N=16* differ depending on the nuclear models and interactions chosen to calculate the single-particle energies. We discuss the shell gaps obtained by various models applied to calculate the spectroscopy of the neutron-rich Oxygen isotopes; the predicted values for the excitation energy of the 2+ and for the shell gap are displayed in ***Tab. II.1***. The order of the *fp* orbitals above the *d3/2* orbitals is also debated, the sequence of orbitals [low-lying *1p3/2* and above *0f7/2, p1/2*] depends on the models and interaction chosen for the description.

The first USD shell model (SM) calculations gave a size of 3.3 MeV for the *N = 16* shell gap [War92]. With this gap, the ^{26,28}O were predicted to be bound by a few hundred keV contrarily to the observation by Tarasov et al. [Tar97]. With the new version of USD05 [Bro06u], the gap corresponds to 4.0 MeV, which gives ^{26,28}O unbound.

From the calculations done by T. Otsuka et al in the Monte Carlo shell model (MCSM) framework using SDPF-M interaction [Uts01] the *N=20* shell closure disappears at *Z=8*. The effective *s1/2 –d3/2* shell gap in N=16 isotones is given as a function of *Z* for various SM Hamiltonians SDFP, USD and Kuo [Ots01]. The shell gap is indicated to be enhanced for neutron-rich nuclei at the drip-line, reaching 4 to possibly 6 MeV at N=16 [Ots01, Ots01a]. This large gap (***Fig.II.2****, left*) is the reason why the oxygen isotopes heavier than *A=24* are found unbound. T. Otsuka has attributed the enhanced gap to the effects due to the isospin change of the tensor term of the interaction.

The effects of the tensor terms were included recently in the Hartree-Fock (HF) calculations using new Skyrme-type interactions, *Skxta/b* forces including the ρ+π tensor in the fits to SPE, BE and radii [Bro06]. B.A. Brown et al. presented the HF SPE obtained for ^{24}O neutrons [Bro08] with the different parameterization of the Skyrme forces (***Fig. II.2*** *right*).

Depending on the force, *Skx*, or modified *Skxta* or *Skxtb*, the *f7/2* orbital could be above or below the *p1/2*, and the gap *s1/2-d3/2* changes, from 4 MeV (Skx) to ~3.8 or 4.3 MeV for *Skxta/b*. In ***Fig. II.2*** *(right)*, in the case of the HF calculations using *Skxtb* version, the *f7/2* is predicted below the *p1/2* orbital. It is also interesting to note that the SPE for *d3/2* is positive in the case of *Skxtb*: it means that when the neutrons occupy this orbital (as is the case for the excited states of ^{24}O) the corresponding states are predicted unbound. This is consistent with the observation.

If the situation of the *d3/2* is similar in the other Oxygen isotopes, with *N=17-20*, it means that the ground states of these nuclei can be found unbound in the framework of the *HF+Skxtb* calculations. This would be consistent with the experimental situation of the Oxygen drip-line.

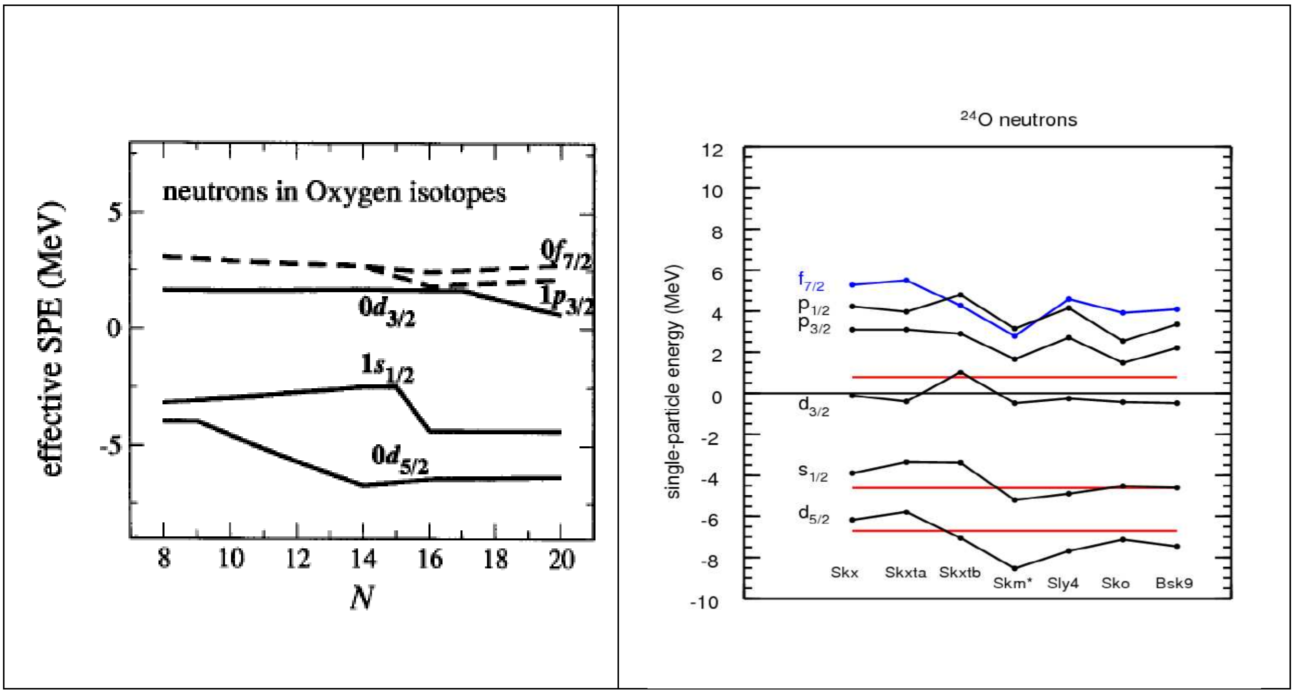


Figure II.2: *(left) Figure extracted from [Ots01a]: effective Single Particle Energies (SPE) for the neutron in Oxygen isotopes; calculated with the MCSM and sd-pf interaction.*
(right) Figure extracted from B. A Brown et al [Bro08], comparison of HF SPE with empirical values (straight red line).

Theories Interactions Ref.	SM USD [Bro06] [Ots01]	SM Kuo [Ots01]	MCSM SDPF [Ots01a]	HF+RPA Part-vib coupling [Col01]	Continuum QRPA Sly4 [Kha02]	HFB D1S [Obe05]	HF Skx [Bro06] [Bro08]	CSM [Vol06]
N=16 Effective shell gap Δε (1s1/2 - 0d3/2)	4.8	4.5	6	6.2	HF approx 5.1	4.0	4.0	HBUSD ~4.8-6
Eexc(2+)	4.2	4.	> 4.	HF:3.9 Continuum RPA: 3.48 (2+, 3- coupling)	4	RPA/4	4	4.85

Table II.1*: For the ^{24}O nucleus, values (in MeV) of the effective gap corresponding to N=16 and of the 2+ excitation energy, predicted by different theoretical frameworks and interactions.*

In the case of the beyond-mean field HFB calculations using the D1S Gogny force, the *N=16* shell gap between *s1/2* and *d3/2* is found to be 4 MeV for ^{24}O and ^{26}Ne isotopes [Obe05].
In the Continuum shell model (CSM) [Vol06] using the HBUSD interaction [Bro88] the shell gap can reach 6 MeV.

Energy shifts in single-particle energies were evaluated by a particle–vibration coupling model [Col01]; the authors underlined that "In the case of the ^{24}O core, the couplings to 3^- and 2^+ states lead to a large energy gap between *2s1/2* and *1d3/2* states, in agreement with a recent experimental evidence of a new magic number at N=16 near the neutron drip line. In particular, the 3- vibrations are found to play a crucial role to push down the energy of the *2s1/2* state."
The shell gap evaluated in this case was of the order of 6.2 MeV.
This study means that the determination of the position of the 3- state could turn out to be as important as the determination of the 2+ to conclude about the shell gap at *N=16* for Oxygen isotopes.
In our ^{24}O(p,p') experiment the shell gap information will be given for the occupancy of the particles corresponding to the single-particle excitation of the *N=16* Oxygen nucleus; it means that contrarily to what is done in the experiments on ^{23}O [Ele07] and on ^{25}O [Hof08] (see *App.H*) we do not extrapolate the values obtained in the neighbor nuclei to deduce the *N=16* shell gap. If we consider the picture of the shell gap for the Oxygen isotopes (*Fig II.1 left*) doing the (p,p') experiment we will fix the shell picture at *N=16*.

II. B. Goals and methods

Proton elastic and inelastic scattering (p,p') in inverse kinematics, using the particle spectroscopy technique, is particularly well suited for the study of weakly bound nuclei like ^{24}O with only unbound excited states. We proceeded similarly to investigate the halo features of ^{6}He [Lag01], the low-lying collective states in $^{20,22}O$ [Kha00, Bec06] and the structure of $^{10,11}C$ [Jou05] and ^{8}He [Ska05,Ska06,Lap07,Kee07]. Particle spectroscopy gives access to both bound and unbound excited states.
From the proton scattering, it is possible to have access to the matter properties of the nuclei, like the matter density, the transition densities or the rms matter radius. We want to apply the (p,p') method to the even oxygen isotopes ^{22}O and ^{24}O, and to explore the low-lying excited states 2+, 3- of ^{24}O. For the production of the very neutron-rich ^{24}O beam, we need a primary beam of ^{48}Ca as intense as possible- with intensity not smaller than 200pnA. ^{24}O(p,p') scattering is planned to be the first experiment of a campaign of (p,p') scattering at RIKEN, taking advantage of the high performances of the RIKEN accelerator and spectrometer facilities.

Nuclear structure from elastic and inelastic scattering

The elastic scattering is sensitive to the nuclear structure information (root mean square radius of the matter density distribution). It is possible to test the matter distribution given by i) electron scattering for *N=Z* stable nuclei assuming identical distribution for neutrons and protons, ii) theoretical densities.

The theoretical cross sections are calculated using several sets of density distributions and compared with the (p,p') data. Conclusions are drawn to confirm or infirm the validity of the structure calculations. The (p,p') data are used as a benchmark for the various structure models. In order to obtain the theoretical (p,p') cross sections, the appropriate reaction framework and relevant proton-nucleus potentials have to be defined and checked. The choices of the potentials and the approximation for the reaction mechanism depend on the energy domain we consider.

In the case of the $^{10,11}C$ nuclei [Jou05] the DWBA method was applied successfully using the optical microscopic proton-nucleus JLM potential (see Ref. in [Jou05]). This standard method is applied at Ganil energies (25-100 MeV/nucleon). In general, DWBA is only a limited framework which could turn out to be not valid in the case of the strong coupled channel reactions. Coupled reaction channel analysis should be applied in order to extract accurate nuclear structure information, as done for the study of the ^{8}He structure at low energy (15.6 MeV/n) using the (p,p') probe: strong coupling effects between the (p,p) and the (p,d) reactions were found [Ska05,Ska06,Lap07,Kee07].
Whatever the incident energy, the parameters of the nucleus-proton potential used to calculate the proton scattering must be checked. The assumptions of the optical model framework used for the description of the reactions must be also questioned. The effects of the coupled channels, of the correlations induced by the projectile should be examined carefully.

Optical potentials and optical model approaches

We will measure the angular distributions for the elastic proton scattering of ^{24}O and compare it to the various elastic calculations.
At high incident energies (few 100 MeV/n), the usual approach consists in calculating the (p,p') scattering with the Distorted Wave Impulse Approximation (*DWIA*). In the *DWIA* the effective *NN* interaction is taken to be the free *NN* t-matrix. Modified approach including the knock-on exchange term exactly were developed using the code *DWBA70* [DWB70]. This was applied for instance to the $^{90,92,94,96}Zr$(p,p') scattering at 200MeV in Ref [Cra82]. Other ingredients of these calculations are the optical potential describing the proton scattering from the nucleus and the amplitudes describing the transition from the ground state to the final state. In optical model calculations employing relativistic impulse approximations and a microscopic folding model using a non-relativistic *G* matrix, appropriate potentials taking into account the in-medium effects were developed in [Sak98] for the analysis of the ^{58}Ni(p,p) at E_p=192, 295 and 400 MeV.

Recently, calculations were carried out to investigate the role of the correlations in the ground state wave functions for doubly-closed shell nuclei (^{16}O, ^{40}Ca, ^{208}Pb) by M. Dupuis, E. Bauge and collaborators at DAM/SPN. They determined the optical potential using the microscopic Melbourne nucleus-nucleon interaction and they used the RPA wave functions to treat explicitly the correlations. They have showed [Dup06] the importance of introducing these correlations in order to account for the cross sections in the case of the proton scattering of ^{16}O, ^{40}Ca, ^{208}Pb. The ^{24}O(p,p') at Ep= 100 MeV was also calculated in this formalism [Dup06].
To extract the structure information and to probe its ground state structure, we plan to compare our elastic scattering data to these microscopic calculations which treat consistently the coupled-channel effects, with the deformation, the ground state correlations included from the beginning in the formalism. We will check the validity of the microscopic densities included in the calculated potentials.

Experimental constraints and detection

In the ^{24}O(p,p') experiment, we will measure the angular distribution of the scattered protons for the elastic scattering. Integrated inelastic scattering will be measured simultaneously with the same beam and the same experimental set-up.

The recoiling protons will be detected with the MUST2 array at angles close to 90 degrees in the laboratory frame. The beam will be produced at maximum intensity for incident energies around 300 MeV/u. Kinematics is very strong for the proton and its energy rapidly increases with smaller laboratory angles, as shown by the kinematical lines (solid lines) in ***Fig.II.2***. The MUST2 array is well adapted to measure protons from 0 to 100 MeV. Each detector will be composed of a 300µm thick double sided Si strip detector and a layer of a 16-fold segmented CsI scintillator, 4cm thick. The corresponding range is enough to stop protons up to 90 MeV.
At 300 MeV/u, the angular range of interest is limited to [70, 90] deg, corresponding to [0, 30] in the cm frame. The MUST2 threshold energy (~500 keV) is a limitation for the detection of protons at low and high energy. 500 keV protons are emitted at θ_{cm} = 2.3 degrees (see ***Tab.II.1***). On the high energy side, an energy loss of 500 keV in the 300µm thick stripped-Si corresponds to 75 MeV protons.
A simulation of the proposed experiment ^{24}O(p,p') at 300 MeV/n with a 1mg/cm^2 CH_2 target is shown in ***Fig.II.2***. The adopted set-up will consist in 4 MUST2 detectors located at 30cm with a geometrical configuration shown in ***Fig.II.3***. In the simulation we have included the reactions of the elastic scattering and the (p,p') to 3 excited states assumed at E* = 4, 5, and 6 MeV. The cross sections were considered with an intensity ratio of 1 for the elastic scattering (p,p) , 0.1 for the (p,p') to the 4 MeV state and 0.01 for the (p,p') to the 5 and 6 MeV states.

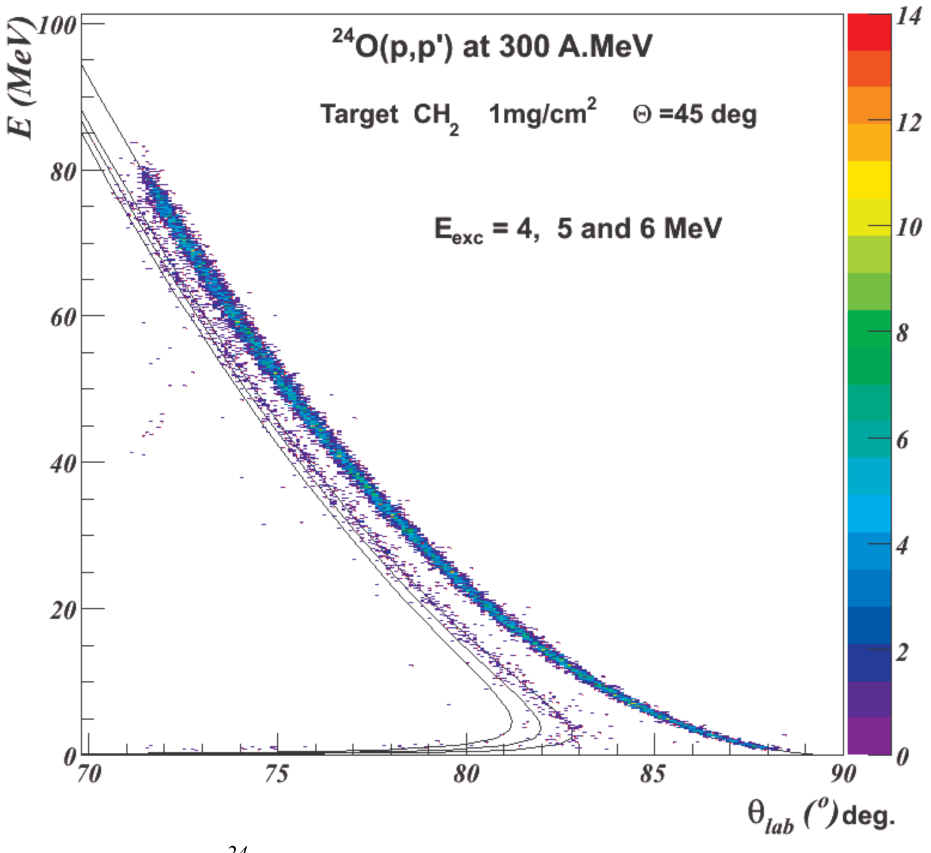


Fig.II.2: *Simulation of the ^{24}O(p,p') at 300 MeV/u with a CH_2 target: the spectrum presents the kinematics (energy versus angle in the lab frame) of the scattered protons measured with MUST2. Elastic and inelastic (3 states assumed at E* = 4, 5 and 6 MeV) scattering is shown.*

Due to the large expected energy gap, it may be seen that elastic scattering will be easily resolved in that angular domain. The lower value of the excitation energies of the first unbound excited state should also be given for the first time in this experiment.

θ_{cm}	0	2.3	10.1	20.6	26.0	31.4
$\theta_{p\ lab}$	90	88.5	83.5	76.8	73.4	70.0
E_p (MeV)	0	0.5 *threshold*	9.7	40.2	63.7	92.6
θ_{lab} (^{24}O)	0	0.09	0.4	0.8	1.0	1.2

Table II.1: *Kinematics of the proton and ^{24}O in the elastic scattering $^{24}O(p,p)$ at 300 MeV/u.*

II. C. Comments on the choice of the beam and of the probe, other possibilities?

In 2003 we propose to study the spectroscopy of the ^{24}O via the ^{23}O(d,p) reaction. Idea was to use the (d,p) to produce the ^{24}O and study its excited states. This experiment was submitted to the GANIL PAC and we require 34 UT (1UT=8 hours) to measure the excitation spectrum of ^{24}O. The estimation was based upon a ^{23}O beam intensity of ~500/s and a measurement of the excitation spectrum integrated between 15° and 35° in the c.m frame.
This experiment was rejected with the arguments that it could be difficult for the machine to insure a mean intensity of at least 500/s during the whole experiment and that if the ^{23}O beam was less intense than expected, a number of UT larger than 34 would be requested. Finally they found the number of beam time units too important compared to UT to share between all the users proposing experiments at that PAC.
At that time, we estimated the beam intensity of ^{23}O from the fragmentation of a ^{36}S at E=77.5 A.MeV and maximum power (1kW) using the SISSI device. This experiment was not proposed after 2004 – at that time SISSI was broken down (already !)- and other programs started using the SPIRAL beam of ^{8}He.
In another laboratories, intensities are too low or energies too high to carry out either the ^{23}O(d,p) or the ^{24}O(p,p') measurement. Note that due to angular momentum matching conditions (see for instance R. Satchler's text book [Sat83]) the (d,p) reaction should be done at energies below 50 MeV/n. This would favor the angular momentum window of L~2 to 4 and would optimize the population of the excited states with the lower momentum transfer, like the 2+, 3- below 10 MeV.
Due to kinematical conditions, the energy resolution in the measured (p,p') excitation spectrum is improved when the beam incident energy is lower. But the production of the fragmented beams is roughly optimized at the larger possible incident energies, of few 100 MeV/n. We have to determine the best compromise between the kinematical conditions ruled by the incident energy and the counting rates. When possible, and at the price of a lower intensity we prefer using beams at lower incident energy (typically <100 MeV/n) in order to improve the angular resolution, as we did for $^{10,11}C$(p,p') [Jou05].
In the present fragmentation facilities other than RIKEN, whatever the beam energy, the intensities of ^{24}O are too limited (< 500 /s) to perform (p,p') experiment with a reasonable beam time of the order of several days.
It means that if we want to investigate the ^{24}O spectroscopy we need to use the (p,p') probe, and to carry out the particle spectroscopy in the best conditions of intensity and dynamical range: namely at RIBF with a ^{24}O beam of 5000/s and at 300 MeV/n.

Note that today SISSI is no more available (see ***appendix D***) and that the production yields of the Oxygen isotopes produced by SPIRAL are too low (for the moment, the more neutron-rich produced Oxygen isotope is ^{20}O, with an intensity of ~5000/s; extrapolating this value, it means that the ^{23}O SPIRAL beam intensity should be of a few 10/s –at maximum 100/s).

II. D. Experimental set-up for $^{22,24}O$(p,p')

The set-up used for (p,p') experiments already done at GANIL (around 40-50 MeV/u) is the following [Jou05] :

- 2 beam tracking detectors (BTD) and reconstruction of the beam on the polypropylene target $(CH_2)_n$
- Detection of recoiling protons in the forward hemisphere with light charged particles array MUST.
- Detection of ejectiles scattered close to 0 degrees in the laboratory frame with a scintillator wall or a magnetic spectrometer, depending on the solid angle necessary for the maximum center of mass (c.m.) angle to be measured.

The same kind of experiment may be done at RIBF at higher incident energies. The experimental set-up at RIBF will include 2 PPAC detectors to track the beam; 4 modules of the MUST2 array for the recoil proton; in coincidence with the proton detection a detection system is needed for the identification of the heavy ejectile; this will be done using the zero-degree spectrometer of BigRIPS (see ***Appendix G***).

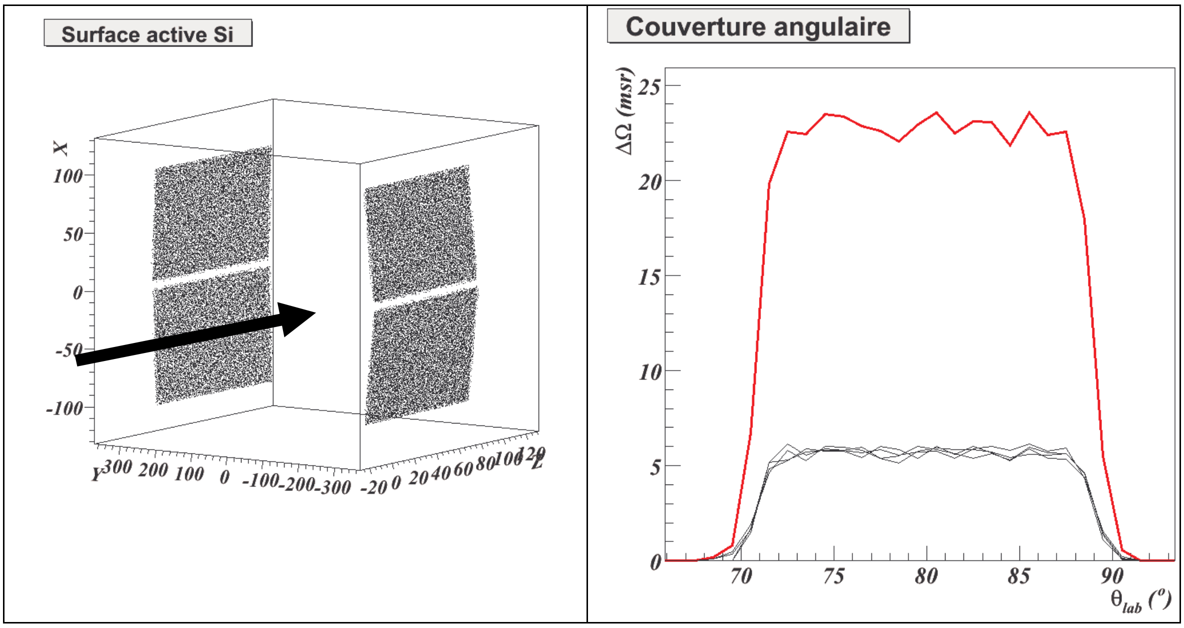


***Fig.II.3**: (Left) Geometrical configuration adopted for the simulation of the experiment using the MUST2 array. The distance between the target and each MUST2 module is 30 cm. The beam direction is indicated by the arrow. The target is at the central (0,0,0) position. The protons will be detected in the angular range [70, 90] degrees in the lab frame; (Right) angular coverage of each detector (black lines) and sum in red.*

The energy resolution for the excitation spectrum of ^{24}O strongly depends on the angular resolution and the high performances of the MUST2 array will be required. We have examined the geometrical configuration of the MUST2 array to optimize the angular, energy resolution of the set-up and angular coverage. The MUST2 array will be composed of two walls (4 detectors) to measure angles from 70 to 90 degrees in the laboratory frame (***Fig.II.3*** *left*). The

1mg/cm^2 thick CH_2 target in between will be tilted by 45 degrees relative to the beam axis. The distance between the target and each detector will be 30 cm.
The angular range in the *lab* frame is shown in ***Fig.II.3*** (*right)* with $d(\Delta\Omega) / d\theta = 23$ msr/deg and a total solid angle roughly equal to $\Delta\Omega = 4x\ (10)^2/(30)^2 = 444$msr.
In ***Appendix F,*** we discuss the constraints on the angular and energy resolutions and the ejectile identification in the spectrometer. The conditions for the beam production are detailed.

II. E. Beam time request:

$$N_d / N_i \;=\; 1/Jac_{(lab \rightarrow c.m.)}\ (d\sigma/d\Omega)_{c.m.}\ N_{at/cm2}\ \ \Delta\Omega$$

We have estimated the angular cross sections for ^{24}O(p,p') using the global parameterizations of the nucleon-nucleus optical potentials "KD" given in [Kon93] and the coupled-channel ECIS code [Ray81]. The orders of magnitude we have obtained for the proton scattering are similar to the values measured in the same range of incident energies and range of mass numbers (see for instance [Kel91]).
From these estimations, we have considered a mean cross section $(d\sigma/d\Omega)_{c.m.} = 0.5$ mb/sr in the angular range of interest.
In (p,p') experiments, we are mainly concerned by the detection of low energy protons for small center of mass angles, whatever the incident beam energy may be. So the CH_2 target may not be much thicker at RIBF compared to GANIL.
For a 1mg/cm^2 thick CH_2 target, $N_{at/cm2} = 2\ (6\ 10^{23}\ 10^{-3}) / 14 = 8.6\ 10^{19}$ at/cm^2 ;
For the 4 MUST2 set-up at 30 cm, we have a mean value $\Delta\Omega = 0.44$sr.
We obtain $N_d / N_i = 0.5\ 10^{-27} \times 8.6\ 10^{19} \times 0.44 = 1.9\ 10^{-8}$.

From a ^{48}Ca 200pnA beam and the estimations given in ***Tab G.1*** (***appendix G***), for ^{24}O, we may assume $N_i = 5\ 10^3$ pps, taking into account the uncertainties of the beam calculation.
We obtain $N_d = 9.5\ 10^{-5}$ part/s or 8.2 part/day. In these conditions, a 10 day measurement will be necessary to observe the 2^+ state of ^{24}O, with one day more for the tuning of the ^{24}O beam.
Obviously, the primary beam intensity cannot be smaller than 200 pnA, and should be as close as possible to the nominal 1 pμA value.
First, to test the set-up, we plan to make the (p,p') measurement to the 2^+ state of ^{22}O. This state has already been observed at 3.2 MeV [Bel01, Bec06] and it will be used as a reference measurement. Since the ^{22}O beam intensity is estimated a factor 10 higher than the ^{24}O, 1 day will be necessary for the data taking, with 1 day more for the tuning of the ^{22}O beam.

RI Beams			Tuning of the beams	Beam-On-Target Time for DATA RUN	Total/beam
isotope	Energy(A.MeV)	Intensity(/s)		hours/days	
^{22}O BigRIPS	283	$7\ 10^5$	1day	1 day	2 days for ^{22}O
^{24}O BigRIPS	283	$9.6\ 10^3$	1day	10 days	11days for ^{24}O
TOTAL FOR THE EXOTIC BEAMS TOTAL including 1 day of ^{48}Ca for tuning			2 days → 3 days (72 h)	11 days/data runs [264 hours]	**13 days** **→ 14 days [336h]**

Table II.2*: Summary of the beam time request for the ^{22}O(p,p') and ^{24}O(p,p') at ~300 MeV/u.*

We need one day for the tuning of the set-up (detectors, electronics) using the ^{48}Ca primary beam. A total of 14 days is required for the experiment. The beam time requested for the tuning of the beam and the data taking is summarized in ***Tab. II.2.***

II. F. NPAC organization; decision

The 3rd call for proposals of nuclear-physics experiments at the RI Beam Factory (RIBF) of RIKEN Nishina Center for Accelerator-Based Science (RNC) was sent in Nov 07.
It was announced that to facilitate the exploration of the scientific opportunities, RNC and CNS (Center for Nuclear Study, University of Tokyo) decided to have a joint Program Advisory Committee. This PAC is international and will be held twice a year.
The PAC reviews all nuclear physics proposals, for RIBF facilities and CRIB, based on their scientific merits and feasibility. Then the PAC submits reviewed papers to the director of RNC, while those proposals for CRIB experiments (CRIB, Center for RIB, belongs to the Univ.of Tokyo) are submitted to the director of CNS.

Our experiment was approved by the PAC committee, and by the direction of RIKEN. We receive the letter with the decisions of the 3rd PAC on April 2nd, 2008; hereafter is an extract of this letter: **"The PAC recommends approval of 14 days as requested. In order to obtain a meaningful amount of events, the actual beam time should be assigned only after an intense ^{48}Ca beam, with intensities higher than 200 pn, is realized."**

III. Organization of the MUST2-RIBF collaboration; future campaign

The French-Japanese collaboration interested by the direct reactions induced by the radioactive beams of RIKEN participated to two meetings organized at RIKEN: one during the DREB07 conference [29th May -2nd June 2007] the other one was a collaboration workshop [17-18 November 07].
The experimental program foreseen at RIBF using MUST2 was discussed during these two meetings. Here are the main experiments discussed during the November workshop, and evoked for the first campaign:
- (p,p') studies of light neutron-rich nuclei : e.g. ^{24}O; shell effects in neutron-rich Ne, Mg via (p,p') proposed by the SPhN group.
- Missing-mass spectroscopy (e.g. ^{8}C, ^{34,36}Ca): H. Iwasaki (UT/U.Köln)
- d light ion induced reaction program: Y.Satou (TITECH); (d,d') reaction e.g. for ^{31}Mg.
- (d,2p) as the (n,p) reaction : p-rich or n-rich, H. Okamura (RCNP).
- Alpha-cluster correlation in unstable nuclei with alpha knock-out reaction (e.g. neutron-rich Carbon and Oxygen isotopes): T. Kawabata (CNS).
- Pygmee dipole resonance and Spin-flip reaction studies (^{3}He,t): D. Beaumel (IPNO).

The (p,p') studies were considered as a first step for the beginning of the campaign.
The proposition for the ^{24}O(p,p') measurement was submitted to the committee NPAC-RIBF in February 2008. Following this experiment which was accepted, other MUST2 proposals of the collaboration will be submitted by the IPNO and Riken physicists at the next RIKEN 4th NP-PAC meeting. This PAC will be held around October 2008. The 5th NP-PAC meeting will be scheduled in June, 2009.
The ^{24}O(p,p') will constitute the first phase of the MUST2 campaign at RIKEN, it will start in 2009 then BigRIPS will be available and when the intensity of the ^{48}Ca beam will reach at least

200pnA. The preparation of the experiments will last **1 month** and the data taking for the whole campaign should be approximately **2 months**.
Several physicists of RIKEN involved in this MUST2-RIBF collaboration have experience with the MUST2 array, they already participated to a few experiments using MUST2 detector at GANIL, during the first campaign in 2007; the spokesperson of one of these experiments was H. Iwasaki, when he was a scientific visitor during 8 months at IPN-Orsay.
A campaign of experiments proposed by the French partners (SPhN, GANIL, and IPNO) of the project and the Japanese physicists (CNS-Tokyo, RIKEN, RCNP Osaka) should be done in 2009-2010. To explore the spectroscopy of the exotic nuclei, the collaboration will use mainly two kind of probes, the direct reactions on proton target, to obtain the distributions of (p,p') scattering and the direct reactions using deuteron targets to obtain (d,d') and (d,2p).

After 2010, this program should be pursued during several years, following the possibilities opened at RIBF for the production of the very neutron-rich beams, in the region between Z=10 and 30. With the high intensities of the RIBF beams produced using the ^{48}Ca beam; the teams working at RIKEN will have the possibility to:
-map the neutron drip-line from F to Mg isotopic chains,
-investigate expected neutron *p-wave* halo in ^{31}Ne,
-explore manifestation of deformation at N=22, at N=28.
With the primary beam of ^{238}U, many new isotopes will probably be found between Z=20 and Z=60, and new phenomena of magicity, deformation should be discovered and investigated.

IV. Overview of the Schedule (preliminary); Important steps

- **Readiness**

The first two campaigns of experiments with an array of 5 MUST2 telescopes were successfully performed in March-April, and during autumn 2007 at GANIL. The MUST2 telescopes will be used for a new campaign in the second half of 2008. So the first experiment at RIBF could be considered for the second half of 2009.

- **Implantation in RIKEN area, preliminary tests**

The set-up of MUST2 in Japan has to be prepared; this includes the implantation of the device, of the cooling down system, the adaptation of cables, the power supply, and the organization for the Data Acquisition System outside from GANIL.
Preliminary tests, possibly during the autumn 2008, could be done during an experiment of elastic scattering carried out by the teams of the University of Tokyo and RIKEN at the HIMAC facility. One MUST2 module could be installed in the experimental set-up. The detailed schedule and organization are still under discussion. 3 physicists from SPhN would participate to these tests with the collaboration of one or 2 MUST2 collaborators from IPNO.
At the end of 2008, we also plan to organize at GANIL a workshop-meeting of the MUST2@RIBF collaboration in order to define the program for the next NPAC of RIBF and the MUST2 campaign at RIKEN for the years 2009-2010. Implantation of MUST2, tests and schedule of the campaign will be discussed.

- **Schedule for 2009**

These estimations are submitted to revisions, depending on the capabilities of the RIBF facility for the acceleration and intensities of the ^{48}Ca primary beam.
Second semester 09: preparation and realization of the ^{24}O(p,p') experiment (4 weeks for 4 physicists)

- Participation in the experiments of the campaign (3 weeks pour 4 persons).
Crucial parameters for the feasibility of the program are the intensities of the very neutron-rich beams which will be produced by the RIBF facility, using the ^{48}Ca primary beam.
The collaboration is waiting for the first machine tests using ^{48}Ca (in 2008) to define precisely the schedule of the MUST2 campaign.

V. Requested budget

The transport of the MUST2 equipment to RIKEN will insured by the technical coordinator of MUST2 at GANIL, using procedures for the exchange of detectors which are already well established between the two laboratories.
The mechanical integration of MUST2 in RIKEN areas will be taken in charge by the Japanese teams of the MUST2-RIBF collaboration. No budget is requested in this proposal for investment in R&D of additional devices. We present here (***Tab V.3***) our demand for the travel and stay expenses for the preliminary phase of the program, which will consist in testing MUST2 in Japan, either at HIMAC facility or in a dedicated area of RIBF. For one person the global budget estimated for travel and one week of stay is of 2 kEuros.
One important element to consider is that, once the experiment is accepted by the PAC committee, the stays of the foreign members of the teams are funded by the RIKEN facility during the preparation and realization of the experiments.

Period /Budget Travel 1k€ 1 week 1k€	Number of physicists and weeks	Number of travels	*Total number* weeks of stays	Budget
Fall08 Test Experiment 2008 budget	3 for 2 weeks	3	6 weeks	**Total 08:** 9k€
Fall 2009 Experiment ^{24}O(p,p')	4 for 4 weeks	4	16 weeks	Only travels : 4k€ Stays: RIKEN
2009 Campaign	4 for 3 weeks	4	12 weeks	Only travels : 4k€ Stays: RIKEN
2009 budget		8	28	**Total 09: 8k€**

Table V.3. *Budget requested for 2008 and 2009.*

Request for a Post-doctoral position/visitor:
We would like to welcome a Japanese physicist in our group. We think that Hironori Iwasaki would be a good candidate for a fellowship position: he worked at RIKEN and during his stay at IPNO in 2007, he worked within the MUST2 collaboration and proposed an experiment with this device. He is working at present at Koln University and his Humboldt fellowship contract was prolonged till end of May 2009.
The period covered by the grant should be May 2009 till end of 2010, which will correspond to the organization of the MUST2 campaign at RIKEN. The first experiments using the RIBF beams could start in 2009 and the post-doctorate will contribute to the preparation of the MUST2 campaign, data taking and analysis. ***We would like to propose him a budget for a one-year contract starting in June 2009 till June 2010.***

VI. Collaboration (April 2008)

Teams involved in the experimental program MUST2@RIBF and in the $^{22,24}O(p,p')$ experiment [* co-spokespersons]:

CEA-SACLAY SPhN [DSM/IRFU/SPhN]:
N. Alamanos, A. Gillibert*, V. Lapoux*, L. Nalpas, A.Obertelli, E. Pollacco.
RIKEN-RIBF: H. Otsu*, T. Motobayashi, H. Sakurai, H. Baba, H. Okamura.
Contact person for RIBF/ BigRIPS: T. Kubo; **Univ of Koln:** H. Iwasaki.
University of Tokyo: D. Suzuki.
RCNP-Osaka University: H. Okamura, M.Takechi.
IPN-Orsay: D. Beaumel, Y. Blumenfeld, F Hammache, F. Maréchal, A. Matta, N de Séréville, J-A. Scarpaci.
GANIL: P. Roussel-Chomaz, R. Raabe, J. Gibelin.
GANIL technical support for MUST2**:** JF Libin, P Gangnant.

VII. Theoretical support for structure and (p,p') calculations.

The spectroscopy of ^{24}O offers the possibility to check the validity of the several theoretical frameworks which were examined in this proposal (see ***Section II.A motivations and discussion on the shell gaps***). We have examined the various calculations on the subject, and we are in contact with the theory groups proposing at present the most advanced developments on the shell gap studies. We have already started to present our future experimental campaign and to explain the goals to these theory groups.
We also benefit from the theoretical environment provided by the virtual theory laboratory on structure, called ESNT "Espace de Structure Nucléaire Théorique" [ESNT]: the new developments for structure and reactions are the subjects of the various workshops organized at CEA-Saclay in this virtual laboratory ESNT.

We are in contact with theorists to discuss the following topics:

- Evolution of the shell gaps at large isospin;
- Effect of the effective interactions on the calculated shell gaps and on the excited levels, effect of the tensor term of the interaction (N. Pillet, S. Peru et al , CEA-DAM/SPN; T. Duguet SPhN/ESNT; comparison to T. Otsuka's findings about the shell gaps);
- Effect of the continuum coupling on the low-lying spectroscopy of the neutron-rich Oxygen isotopes (N. Michel et al. ESNT) ;
- Calculations of the $^{24}O(p,p')$ at RIKEN energies (~300 MeV/n) including accurately the ground state correlations: E. Bauge, M Dupuis, DAM/SPN [Dup06]. We will compare the experimental elastic cross sections to the theoretical ones to deduce the characteristics of the matter ground state density of ^{24}O. In the PhD work done by M. Dupuis [Dup06] the $^{24}O(p,p')$ was calculated at Ep=100 MeV. Such calculation should be extended at the appropriate energies for RIBF experiments. Discussions are in progress with the theory group of BIII.

Recently we had discussions with the SPhN theory group (T. Duguet) about the effects of the tensor force on the single-particle neutron and proton shell structure expected for ^{24}O*, and* *with the DAM-SPN group (S. Peru and N. Pillet) about the effects of the continuum on the excited state and on the shell gap at N=16. We discussed the expected resulting spectroscopy for the neutron-rich O nuclei.*

The SPN group will be involved in the calculations of the (p,p') induced by the RIBF beams. Theory groups from SPN, ESNT will be involved in the future discussions about the extraction of the structure and of the shell gap information, from the data collected during the 2009 campaign. The structure calculations provided by the SPN theorists will be compared to the predictions given by other theory groups, T. Otsuka's team, working in the MCSM framework H. Sagawa et al. (HF and correlations framework) [Hag05] G. Coló, E. Khan et al (HF+QRPA) [Col02,Kha00], A. Volya et al (CSM) [Vol05].

Theoretical support for structure: expected development

Works are in progress to extend the predictive power of the nuclear theories throughout the nuclear chart, to reduce the phenomenological inputs and to establish the foundations of the models on a fully-microscopic basis. From the new developments of the Density functional Theory (DFT) and of its applications within the HFB framework, it is expected that a theory with improved predictive power for the calculations of structure, spectroscopy, and excitations modes will be available for the studies of the intermediate-mass and heavy nuclei.

The theory will include the restoration of broken symmetries, long-range correlations, large amplitude vibrational modes, density-dependent pairing terms deduced from bare *NN* interactions [Dug04]. Such developments are undertaken for instance by T. Duguet and collaborators. In this respect, the data collected on the neutron-rich exotic nuclei could be used as benchmark to test the prescriptions of the new theory.

Other theoretical problems occur when going to the neutron drip-line, along an isotopic chain: the modification of the nuclear forces (spin-orbit, spin-isospin terms) results in a nuclear system which is less and less bound. On the theoretical point of view, the question is not only on the evolution of the nuclear forces with the isospin degree of freedom but also to work in the appropriate framework for the weakly-bound nuclei.

The coupling between bound and continuum states for nuclei close to the drip-line was introduced in HFB calculations [Dob94, Naz94], and several important effects were predicted: increase of pair correlations, of surface diffuseness [Dob95]. Shell gaps are reduced and shell structure is deeply modified by the continuum coupling effects in contrast with the near-stability regions.

Theoretically the description of the exotic nuclei requires the development of the models including the coupling to the continuum and treating explicitly the continuum couplings of bound and scattering states. Such attempts are in progress in the self-consistent mean field model in the HFB approach [Dob96], and also in the shell model framework [Ben99], with the Gamow Shell Model (GSM) [Mic02] and in the Continuum Shell Model (CSM) [Vol05].

For instance in [Mic03], the neutron-rich He isotopes are found bound by the Continuum-continuum correlations and the low-lying spectroscopy of the neutron-rich Oxygen isotopes is modified by the continuum coupling (excited states are found at lower energies when the coupling is included).

Appendix A: **Experimental program of the group [I. CSTS in May 2005 ; II. Recent results and publications]**

A. Extracts of the report status for the scientific committee CSTS May 2005 for the structure group (the references given in the 2005 report have been actualized and are labelled as in the rest of this proposal; they can be found at the end of the document).

CSTS05- NUCLEAR STRUCTURE TOWARDS THE DRIP-LINES Contact: V. Lapoux

Our objectives are to explore the shell structure and the shell gaps as far as possible from the valley of stability, at large isospin and at the limits of nuclear binding, in order to confront the most advanced microscopic predictions to our experimental results and analysis. We will study the evolution of the neutron excitation along isotopic chains, and also inspect the behaviour of the neutrons in the vicinity of the expected neutron shell gaps. We want to explore the shell gaps:

i) at N=16,20 in the neutron-rich O, Ne, and Mg isotopes,
ii) at N=40,50 in the Ni chain,
iii) in the vicinity of expected doubly-magic neutron-rich radioactive nuclei (^{78}Ni, ^{132}Sn, and the possible new doubly-magic nucleus ^{110}Zr)

Detailed information on the structure of light exotic nuclei and a complete picture of the spectroscopy can be deduced from direct reactions such as elastic and inelastic proton scattering (p,p') and transfer reactions:

- Excitation modes of the nucleus and the couplings to the low-lying states, to the continuum, and to other reaction channels, are probed by the inelastic scattering, e.g. (p,p') or (d,d').
- The single-particle shell structure and the overlap of the wave-functions are studied via nucleon transfer reactions like (p,d), (p,t), and (d,p).

The shell structure and shell gaps will be explored via a joint program of Coulomb excitation and (p,p') reactions. Coulomb excitation provides the proton contribution to the excitation, expressed as the electromagnetic transition strength, B(EL). The (p,p') reaction is sensitive to the neutron and proton contributions to the excitation. The combined information from the (p,p') and the Coulomb excitation measurements will disentangle the proton and neutron contributions, namely the transition matrix elements M_p (for a L=2 transition B(E2) = $|M_p|^2$) and M_n. Measurements along isotopic chains allow to compare the evolution of the M_p and M_n values to the microscopic calculations, and to deduce the underlying shell structure. Nuclei, as neutron–rich as possible, will be studied in the next few years, using beams delivered by the present GANIL and SPIRAL facilities, and in the mid-term by SPIRAL2.

The experiments are performed in inverse kinematics where the beam of interest impinges on a target containing the light probe (p, d, or t) and the light recoil is identified in a position-sensitive particle detector such as the telescope device MUST2 in coincidence with the heavy ejectile detected in a spectrometer, like SPEG or VAMOS.

CSTS05 - I. Results and near-future perspectives

I.1 ***Reaching the drip-line in the He chain*** […]

I.2 ***Shell structure exploration far from stability***

Today, the location of the neutron drip line is known only up to the oxygen isotopes; the last bound nucleus being ^{24}O (N=16) and not the expected doubly-magic nucleus ^{28}O (N=20). Recently, the MUST collaboration has studied the ^{20}O and ^{22}O(p,p') scattering reactions in order to determine the evolution of neutron excitations in the neutron-rich oxygen isotopes. The data strongly support the existence of an N=14 sub-shell closure [Bec06]. A study of the low-lying states in ^{24}O would be of great interest, since it is expected to be a doubly-magic nucleus with a new shell closure at N=16. However, the present facilities cannot deliver beams of ^{24}O with sufficient intensity to perform a (p,p') measurement in a reasonable time of a few weeks.
In the same context, we have investigated the N=16 shell gap around the Ne isotopes. [In 2004], in collaboration with physicists from GANIL and Ioannina, we have measured the low-lying bound states of ^{27}Ne with the one-neutron transfer reaction $^{26}Ne(d,p)^{27}Ne$, induced by the SPIRAL beam of ^{26}Ne [Obe05TH]. To compensate the low beam intensity (2000 pps) we used a 1mm-thick cryogenic target of solid deuterium. The bound states of ^{27}Ne were studied by measuring gamma rays with the EXOGAM array in coincidence with ^{27}Ne nuclei detected at the focal plane of the VAMOS spectrometer. Two excited states at 885(5) and 765(5) keV were observed; the preliminary analysis gives new indication for low-lying negative-parity states in this neutron-rich region. Quantitative results on the evolution of the shell structure and deformation effects in the vicinity of neutron-rich N=16 nuclei can be derived [Obe06].
For a complete spectroscopy, it would be desirable to couple VAMOS and EXOGAM to a Si-strip telescope array like MUST or MUST2. Information on unbound states is only given by the additional proton detection. However, such a measurement can only be performed with a thin target, and higher beam intensities are required. Such a complete experimental set-up is well suited to study the evolution of neutron excitations in neutron-rich Ne, Ar, and Kr isotopes by measuring the cross sections of (p,p'), (p,d), and (d,p) reactions with beams produced by the SPIRAL facility, with an intensity of at least few 10^4 pps.
The experimental program will benefit from the new MUST2 array, developed in a DAPNIA-IN2P3-GANIL collaboration. It improves the angular coverage for the particle detection, as compared to the MUST device. MUST2 will be the perfect tool to achieve the new goals described above using both SPIRAL1 and 2 beams. The experimental analysis is based upon the complete reconstruction of the reaction kinematics. The small centre-of-mass angles are obtained from the identification and precise measurement of the light recoils at energies below 5 MeV. This requires a low energy threshold in order to correlate energy and time of flight, which is achieved with MUST2.

CSTS 05- II. Mid and long-term perspectives

II. 1 Exploration of the shell structure far from stability

Also for medium-mass nuclei far away from stability the shell gaps at Z=28; N, Z=50, and N=82 are predicted to be weakened, and new gaps are expected to appear at N, Z=40, 70 when approaching the neutron drip line. Transfer reactions provide direct access to the single-particle shell structure of nuclei. SPIRAL2 will provide beams to study one and two-nucleon transfer reactions in the vicinity of the expected double-magic nuclei ^{78}Ni and ^{132}Sn, and FAIR will provide access to the possible new doubly-magic nucleus ^{110}Zr. […]

II.2 Shell structure exploration at the drip line using high-intensity EURISOL beams

With the EURISOL beams we will be able to reach the drip-line nuclei for the isotopic chains which are beyond the scope of the present studies and the present accelerators. For instance, a milestone experiment like the ^{24}O(p,p') measurement, becomes feasible only with EURISOL. With the next-generation beams, we will be able to pursue the study of the S and Ar isotopes, which was started in the past, up to the N=28 isotones ^{44}S and ^{46}Ar, in order to investigate the evolution of the neutron excitations. It will become possible to explore the shell structure and shell gaps around the expected new doubly-magic neutron-rich nuclei (like ^{78}Ni). According to microscopic models, which were successful for the light neutron-rich nuclei, halo, neutron-skin, and alpha-cluster phenomena are also expected in heavier neutron-rich nuclei near the drip line. As an example, the very neutron rich (and perhaps unbound) isotope ^{38}Ne, is predicted to develop a neutron skin, to be studied via the (p,p') probe.

CSTS 05- III. Conclusions and summary, request for technical developments.

Recent experiments of direct reactions with the GANIL beams either produced by projectile fragmentation or by SPIRAL were carried out using the most advanced detection available. The program covered a wide range of nuclei close to or at the drip-lines, and a large set of data was collected and physics results published (see list of recent publications and ref. therein). The next step will be the exploration of the shell structure and neutron and proton density profiles in the neutron-rich Ne, Ar, and Kr isotopes. Direct reactions induced by beams of these isotopes will be measured using the MUST2 array coupled to the EXOGAM and VAMOS detectors.

Future accelerators will produce high-intensity beams of rare nuclei with the objective to push the exploration of the nuclear chart towards unknown regions of large isospin. However, even with the most advanced RIB facilities, the most exotic beams will be weak and beam time limited, so that the reaction products need to be collected very efficiently. Much progress was made in detector development to improve the angular coverage and efficiency compared to the previous generation. […]

In the mid- and long-term future, we want to study the evolution of the proton and neutron excitations as a function of the isospin degree of freedom, going as far as possible from the valley of stability. This will give further constraints for the nuclear structure models, and refine the isospin-dependent term of the effective NN interaction used to predict the shell structure. A complementary program of Coulomb excitation and direct reactions of the neutron-rich nuclei is prepared by improving the experimental set-up, and by building new detectors.

B Years 2001-07: previous works and main results using particle spectroscopy at GANIL

This technique has been applied using detectors like MUST. With the next-generation device MUST2, the MUST2 collaboration, gathering physicists from CEA-Saclay, GANIL and IPN-Orsay, has developed a program of direct reactions induced by radioactive beams to determine their structure and spectroscopy, and to check the evolution of the proton and neutron excitations and of the shell gaps. The experiments are performed in inverse kinematics where the beam impinges on a target containing the light probe (p, d, or t) and the light recoil is identified in a position-sensitive particle detector such as MUST [MUST] or MUST2 [MUST2] in coincidence with the heavy ejectile detected at forward angles in a plastic scintillator or in a spectrometer, like SPEG or VAMOS. The incident trajectories of the beam particles are reconstructed using the event by event positions measured by beam tracking detectors [Cats99].

The following list gives an overview of the recent results obtained by the collaboration on the structure of the light exotic nuclei and on the shell structure exploration far from stability (the SPhN group was in charge of the experiment (spokesperson) and of the analysis for the topics 1, 2 and 4):

1. Investigation of the nuclear matter distributions of the weakly-bound neutron-rich isotopes ^{6,8}He. The analysis of ^{6}He(p,p') reaction at 40 MeV/n was in favor with the halo of ^{6}He [Lag01]; from the direct reactions of the ^{8}He SPIRAL beam at 15.7A.MeV on a proton-rich target, the neutron-skin structure of ^{8}He [Ska04TH,Ska05,Ska06] was discussed;
2. The neutron excitation in the ^{10}C compared to its mirror nucleus ^{10}Be [Jou05];
3. The evolution of the neutron excitation in the O chain, up to ^{22}O in favor of an N=14 sub-shell closure [Bec06];
4. The evolution of the shell gap at N=16 via the ^{26}Ne(d,p)^{27}Ne reaction using the SPIRAL ^{26}Ne beam (these results are discussed in the main ***section I***.) ;
5. The evolution of the shell gap at N=28 via the ^{44,46}Ar(d,p)^{45,47}Ar reaction using the Ar SPIRAL beam [Gau06], the analyses indicates a reduction of the spin-orbit splitting at the N=28 shell closure.

We would like to underline that the direct reactions of the ^{8}He SPIRAL beam on a proton target was fruitful to develop our understanding, not only on the drip-line nucleus ^{8}He itself, but simultaneously of the reaction tools, namely the analysis of the reactions within the coupled reaction channel framework. The interplay between structure and reactions was explained in the case of ^{8}He and the tools and information needed to disentangle structure from reaction aspects were discussed in [Ska05, Kee07].
The ^{8}He(p,p') scattering to the first 2^+ state were measured at E_{lab} =15.7A.MeV, using the ^{8}He beam produced by the SPIRAL facility at GANIL. Other direct reactions ^{8}He(p,d)^{7}He$_{gs}$ [Ska05, Ska06] and (p,t) [Kee07] were measured simultaneously at the same energy. The excitation spectra for the ^{8}He and the unbound ^{7}He [Ska06] were extracted. The interpretation of all these results, using coupled reaction model [Kee04], was explained. For the (p,p'), the entrance channel potential and transition form factor from ground to 2^+ state were calculated within the framework of the microscopic complex JLM [JLM77] nucleon-nucleus potential using the microscopic ^{8}He gs and transition densities, generated by the no-core shell model [Nav98]. It was shown that the ^{8}He(p,d)^{7}He$_{gs}$ reaction has a strong effect on the ^{8}He(p,p'), this coupling changes deeply the features of the entrance potential and strongly affects the extraction of the structure information [Ska05]. This has to be taken into account for all our future structure studies of weakly-bound nuclei via direct reactions at low energies. From the (p,p') analysis within coupled reaction framework, we have extracted the features of the density profiles for the ground state and transition densities of ^{8}He, and compared it to the structure models [Lap07]. All this analysis was full of learning, in the light of our future program of direct reactions. Both the theoretical framework and the experimental technique can be used as guidelines to develop the future experimental program.

At GANIL, the main physics cases, neutron-skin structure, search and study of new shell structure, will be pursued during the following years, using the promising probes and techniques developed for the direct reactions and the SPIRAL beams. These studies will be extended, in the same spirit, to investigate the structure of heavier neutron-rich nuclei produced with the SPIRAL2 facility.
The Saclay team working on direct reactions has elaborated a proposal to present the future program for the exploration of the *unbound states of the neutron-rich isotopes* produced by SPIRAL2. This was the subject of a letter of intent (LOI-16) submitted to the SPIRAL2 scientific Council by the SPhN group with an international collaboration in October 2006 (see the web site for the proposal:
http://www.ganil.fr/research/developments/spiral2/files/LoIs_SP2_final/LoI_SP2_16_Lapoux.pdf).

Appendix B: **Overview of the MUST2 array**

For the measurement of the direct reactions with the radioactive beams delivered by the GANIL accelerator, a collaboration of CEA-Saclay IRFU (ex-DAPNIA) and the laboratories of IPNO and GANIL has developed a novel ensemble of telescopes to detect the light charged particles produced in the reactions on light targets (p,d,t): MUST2 - Murs de STrips, 2 : of 2^{nd} generation. ***Fig. B1*** presents a possible configuration of this modular device, for the direct reactions measured at forward angles, for instance in the case of the one and 2 neutron transfer reactions on a proton target, in inverse kinematics.

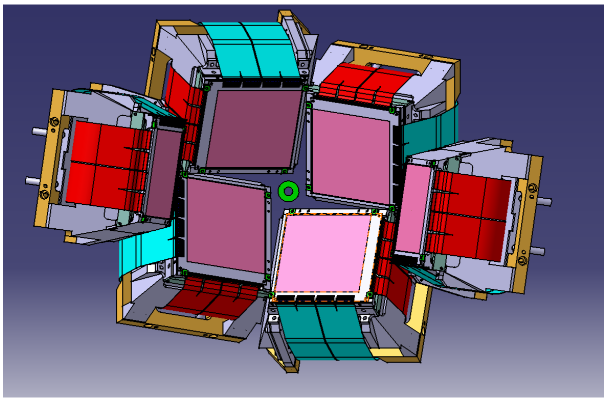


Figure B1. *A view of six MUST2 telescopes placed at forward angles to cover a large fraction of the reaction products in one and two-nucleon transfer reactions like (p,d) and (p,t).*

The MUST2 array is a large-area (1000cm²), position-sensitive DSSD telescope with excellent energy and time resolution, respectively 40 keV and 700 ps. It represents a major development for the detection of light ions in direct reaction studies. The front-end electronics is based on ASICs (applied specific integrated Circuits) and has enhanced performance compared to the original MUST array and higher compactness.
DAPNIA/SEDI (IRFU/SEDI) was responsible for the design, construction, and testing of the ASIC electronics.

Characteristics of the MUST2 array
Each MUST2 is a telescope composed of 3 detectors: the first stage is a 300µm-thick Si-strips of area 10 by 10 cm^2 (built by MICRON) a second one is a 4.5 mm –thick SiLi and a 4 cm –thick CsI detector of 16 pads. Such module can stop protons for energies ranging up to105 MeV. An exploded view indicating the energy dynamics for the proton and the alpha particles is given in ***Fig. B2.***

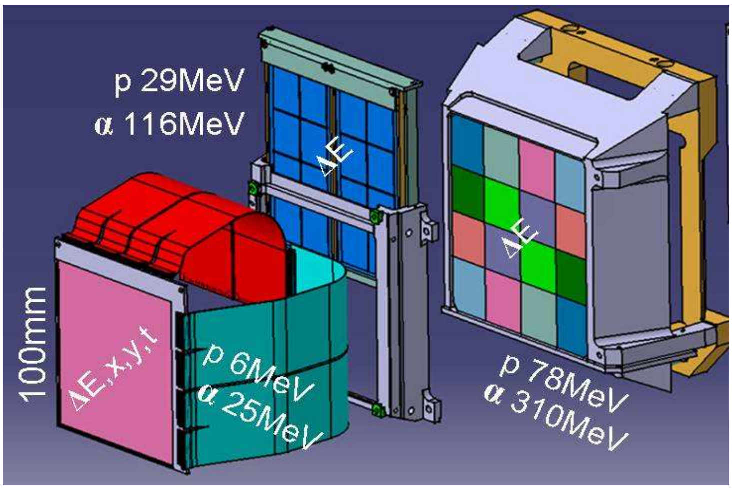


Figure B2. *An exploded view of a MUST2 module showing the three-stage telescope: the first stage on the left is the 300 µm--thick Si-strip detector of 10cm² active area ; the second one is the 4.5mm thick SiLi detector composed of 2 segmented pads (2*8), and third one is the 4 cm-thick CsI with the 4*4 pads. Energies of the proton or alpha stopped in each stage are indicated for each stage.*

One MUST2 module and its electronics can be seen in the photographs (***Fig.B3***). The compact electronics and the acquisition system were conceived to be easily implanted in another environment outside from GANIL. At present, 6 MUST2 modules are available for the experiments of the collaboration.

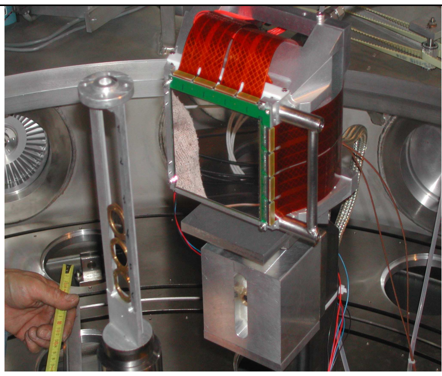
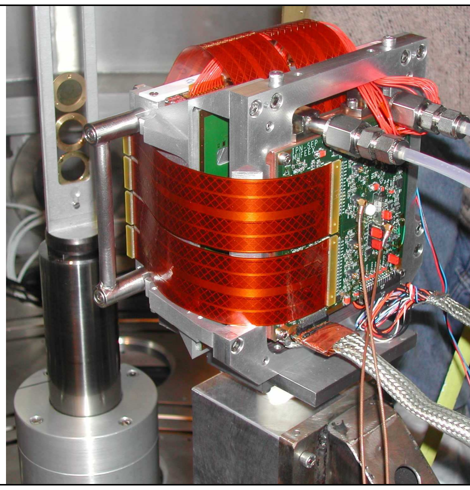


Figure B3. *Front-side view of a MUST2 module and back-side of the telescope, with the compact electronics ASICs* →



Requested specifications given in the MUST2 project have been reached. Six telescopes are available since 2007. With the modularity of the telescopes it is possible to optimize the geometrical arrangements of the MUST2 telescopes around the target and to obtain a very large angular coverage. Due to its very compact design it is well adapted for use in combination with the VAMOS spectrometer and EXOGAM gamma-ray detector, where space is limited.

Two MUST2 campaigns were done in 2007, with several configurations of the MUST2 telescopes (see ***Appendix E*** for details on the experiments):
- In the reaction chamber of the SPEG area, for the experiments E525S, E5473S and E537, a mechanics of 4 telescopes in a square was used, and a fifth MUST2 detector was located at zero degrees, behind the block of 4 modules ; the mechanics of the 4 MUST2 was placed at forward angles for the one (p,d) and 2 (p,t) neutron-transfer measurement, and at backward angles for the (d,p) transfer reaction;
- In the VAMOS area, 4 MUST2 modules were placed in a square compact geometry at forward angle in the TIARA reaction chamber; they were used for additional measurement of the direct reactions (d,t) and (d,^{3}He) in combination with the TIARA Si-strip array used at backward angles for the (d,p) reaction and the EXOGAM array for the gamma-ray emitted by the product nuclei.

During all the campaigns of 2007 the MUST2 telescopes were composed by two stages, DSSD and CsI stages, without SiLi.

The status and information on the array, pictures of the set-up during the experiments done at GANIL in 2007 can be found in the site:
http://www-dapnia.cea.fr/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=446).

A view of the experimental set-up used at GANIL for the measurement of the reaction products at forward angles (see ***Appendix E***) is presented in ***Fig. B4***.

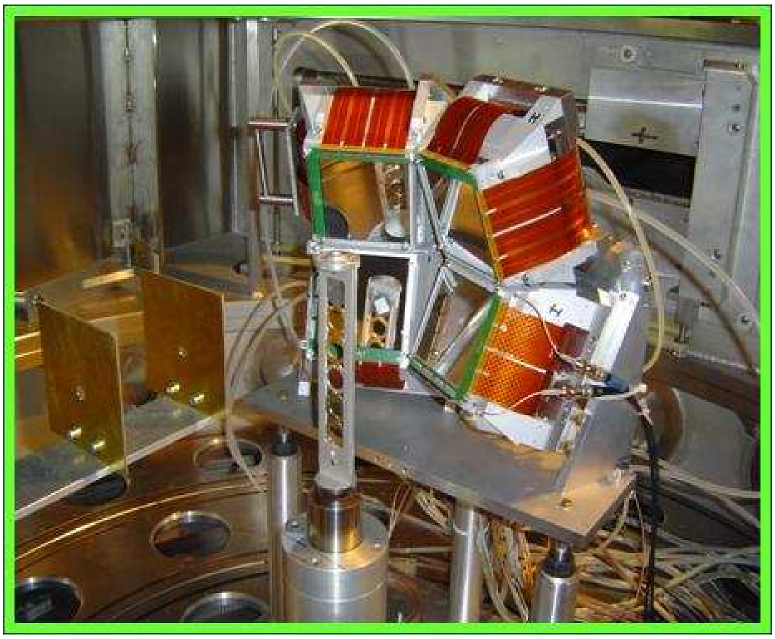


Figure B4. Experimental set-up in the reaction chamber of the SPEG area at GANIL
4 MUST2 telescopes are located in a wall at forward angles; a target-holder is located in the center of this photograph.

An example of the E-DE correlation plots obtained during the 2007 experiments can be seen in ***Fig. B5.***

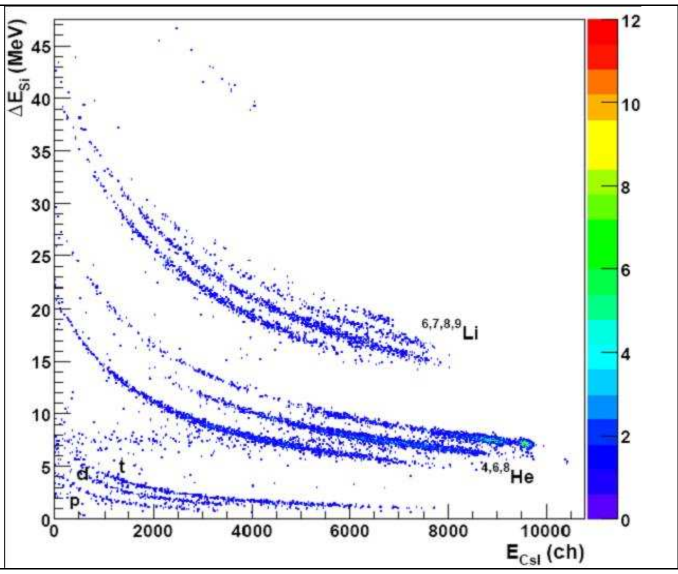


Figure B5. *Correlation spectrum of the energy loss in the Si-strips detector with respect to the energy deposited in the CsI telescope. Identification of the light charged particles p, d, t, ^{4,6,8}He and ^{6,7,8,9}Li. The events were obtained in the MUST2 telescope located at forward angles during the E525S experiment with the SPIRAL ^{8}He beam at 15.4 A.MeV. The particles in this plot correspond to the reaction products of the ^{8}He on the proton target.*
(The MUST2 telescope had the two stages, DSSD and CsI, without SiLi).

Appendix C: **RI Beam Factory (RIBF) facility**

The existing facility at RIKEN has the world-class heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) and a couple of different types of the injectors: a variable-frequency heavy-ion linac (RILAC) and a K70-MeV AVF cyclotron (AVF). Moreover, its projectile-fragment separator (RIPS) provides the world's most intense light-atomic-mass (less than nearly 60) RI beams.
Till 2007 the RI Beam Factory (RIBF) has been the upgrading project of RIKEN Accelerator Research Facility (RARF) (***Fig. C1***). Now RIBF is no more ***a project*** of a new facility - it is facility ***under operation***.

The RIBF add new dimensions to the existing facility's present capabilities: it consists of three new cyclotrons, one of which is the world's largest superconducting cyclotron, SRC, and a new fragment separator, BigRIPS.
The new high-power heavy-ion booster system of three ring cyclotrons with K=570 MeV (fixed frequency, fRC), 980 MeV (intermediate stage, IRC) and 2500 MeV (superconducting, SRC), respectively, will boost energies of the output beams from the RRC up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. An 880 MeV polarized deuteron beam will also be available. The goal of the available intensity is set to be 1 pμA, which is limited due to presently planned radiation shielding power around a primary-beam dump.
These energetic heavy-ion beams can be converted into intense RI beams via the projectile fragmentation of stable ions or the in-flight fission of uranium ions by the superconducting isotope separator, BigRIPS, a new development of the experimental area.

In **2006**, RIKEN has completed the construction of RIBF.
The first beam from the new accelerator complex was successfully delivered in December 2006. After a half-year of commissioning, RIBF started the RI-beam delivery from BigRIPS for experiments in **May 2007**.

In the following years, it is expected that the RIBF accelerators will provide a lot of users with the world's most intense RI beams at energies of several hundreds MeV/nucleon over the whole range of atomic masses. The combination of the SRC and the BigRIPS should expand the nuclear world on the nuclear chart into presently unreachable region.
Such expansion has already started, even during the phase preparation: a new isotope of Pd (^{126}Pd) was found even with the reduced intensities of the primary beam.

Now, the RIBF consists of the new facilities which started operation from 2007, and of the existing facilities, GARIS and RIPS.
Physics program and proposals to the PAC are considered for RIBF and for CRIB, which belongs to the Center for Nuclear Study (CNS), University of Tokyo. Approved nuclear-physics experiments at the existing facilities, such as GARIS, RIPS and CRIB, have also been scheduled from April 2007.

Complete information about the RIBF facility is available on the Web site of RIKEN
http://www.rarf.riken.jp/Eng/facilities/RIBF.html

and on the web site for Riken Nuclear Center (RNC) Users:

http://www.nishina.riken.jp/UsersGuide/Nuclear/index.html (*last access, March 08).*

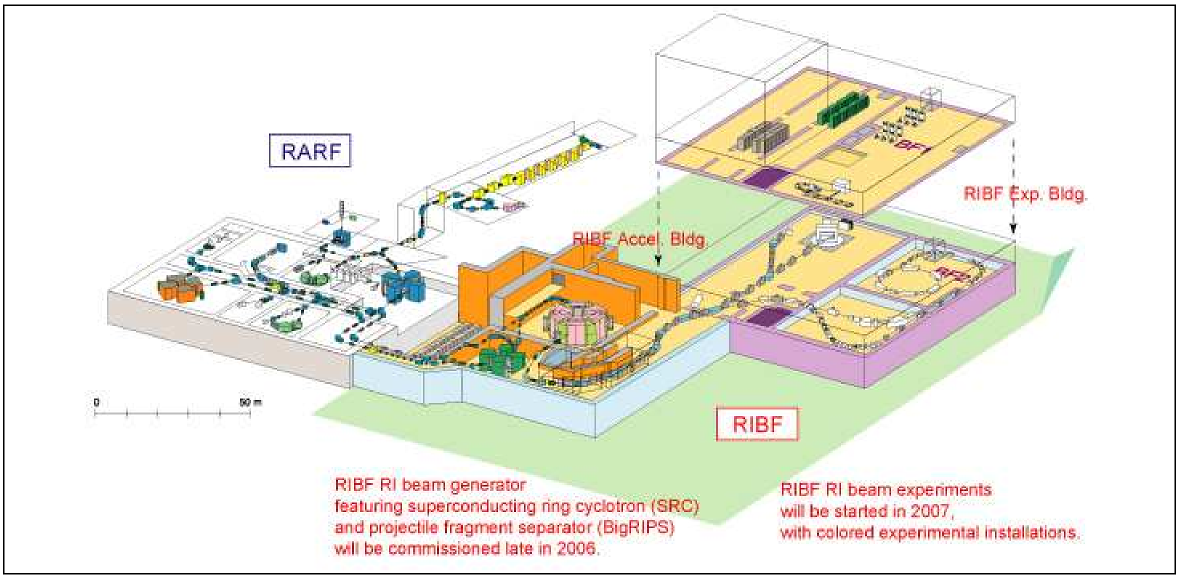


***Figure C1**: upgrading project of the RARF facility presented in 2006, RIBF extension scheme.*

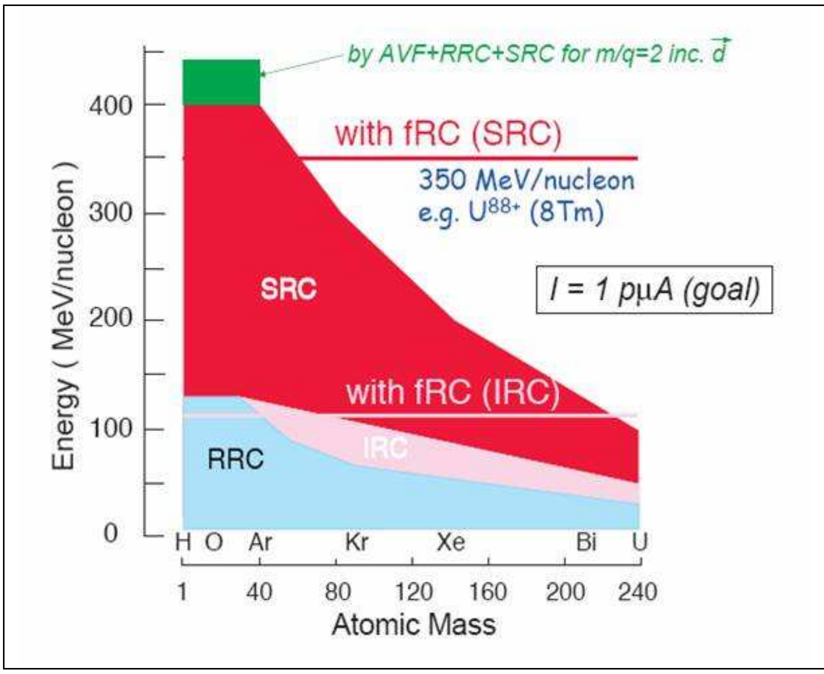


***Figure C2**: performances of the accelerator systems of RIBF with the three ring cyclotrons fRC (fixed frequency), IRC (intermediate stage) and SRC (superconducting) they will boost energies of the output beams from the RRC up to 440 MeV/n for light ions and 350 MeV/n for very heavy ions.*

BigRIPS

In order to take full advantages of high-energy, high-intensity heavy ion beams including Uranium available at the coming RIBF, a fragment separator with a large angular and momentum acceptance was constructed. This is BigRIPS (***Figs. C3 and C4***). It provides a reasonable transmission even for fission fragments produced by U-fission in-flight.
The BigRIPS SC (with Superconducting quadrupole magnets) has a tandem configuration consisting of two stages, as shown in the figure above. The 1st stage is for the radioactive ion (RI) production and separation, and the 2nd stage for the RI tagging.
In addition, in parallel to the superconducting BigRIPS, another fragment separator was constructed, having reduced angular and momentum acceptance with the normal conducting magnets. The beam switching system, with a switching magnet installed in the upstream of the two BigRIPS enables two independent users to perform their experiments utilizing independent isotope beams (produced with the same primary beam).

Overview of BigRIPS: summary of the information given on the Web site

http://www.nishina.riken.jp/UsersGuide/Nuclear/BigRIPS/overview.html (*last access, March 08)*

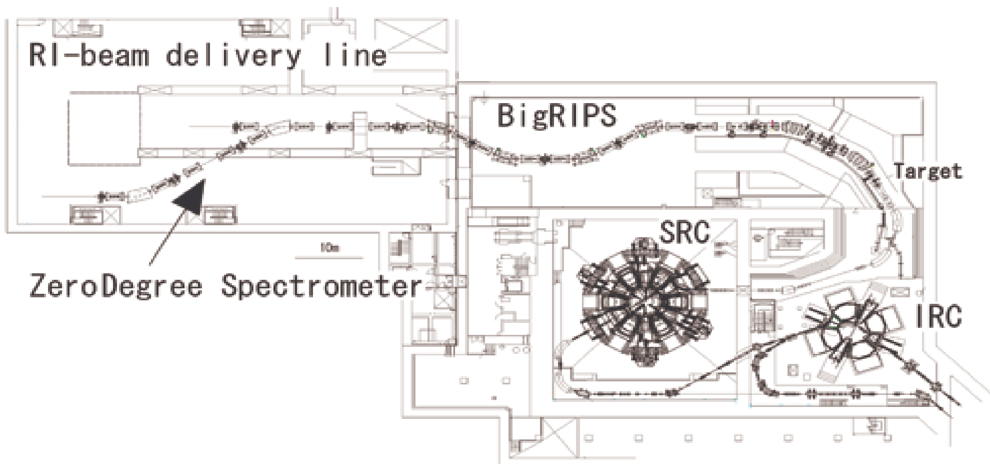


Figure C3: *View of the transmission lines for RIBF and of the fragment separator BigRIPS.*

Design Goal of the BigRIPS (Superconducting & normal conducting versions)
The design values of the BigRIPS separators are given in ***Tab. C1***.

	DP/p (%)	Dtheta (mrad)	Dphi (mrad)	Brho(max) (Tm)	D (cm/%)
BigRIPS (Super)	+-3	+-40	+-50	9	-2.3
BigRIPS (Normal)	+-1.5	+-10	+-15	9	-2.1

Table C1*: design values of BigRIPS for the two configurations (SC, superconducting and normal one)*

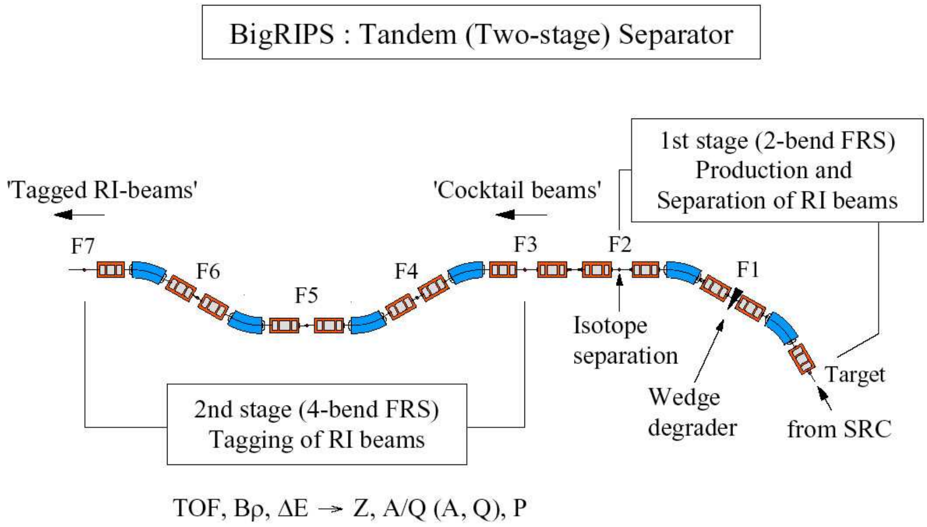


Figure C4: *Stages of the fragment separator BigRIPS.*

Achievements during the fiscal year FY2007 (starting in April in Japan – April 2007 March 08) and present status of the RIBF.

Nearly one year has passed since the RIBF teams successfully accelerated the U-beam and made commissioning of both the new accelerators and the BigRIPS. These achievements, including a discovery of new isotope, ^{125}Pd, were announced at INPC2007 (http://www.inpc2007.jp) as a flash report from RIBF.
Since then, continuous efforts have been made to improve the accelerator performances. Primary beam intensities achieved so far, and expected beam intensities as results of the improvement can be found in the user Group RIBF web site:
http://www.nishina.riken.jp/UsersGuide/Nuclear/accelerator/tecinfo.html.
The constructions of experimental installations were done in parallel (The Zero Degree Spectrometer, ZDS; BigRIPS and the SHARAQ spectrometer).

Status of ZeroDegree/BigRIPS Spectrometers in January 2008:
- Construction of BigRIPS and ZDS was completed in 2007.
- BigRIPS commissioning started from March 2007.
- The maintenance of BigRIPS cryogenic plant is on-going. The test operation of this plant is planned for this month. The final adjustment for the rotating target system of BigRIPS is now on-going. Beam dump system, control system, detector, and read-out system are working well. The analysis of commissioning data is in progress.
- ZDS: Construction and maintenance of magnets and control system have been finished. Preparation of beam-line detectors and read-out system is in progress. The construction of radiation shield in RIBF experimental hall started in Jan. 08 and continued for about a month.

Last update from the Quarterly News of RIBF-User in April 08 (available on the Web site: *http://www.nishina.riken.jp/UsersGuide/index.html*); Operation Schedule planned for the activities at the new facilities during the current fiscal year FY2008.

1. U-beam development: mid-April- the beginning of May;
2. The ZeroDegree commissioning and a BigRIPS experiment will be done in June;
3. Ca or Kr beam commissioning and experiments will be scheduled in October and November
4. The construction of the SHARAQ spectrometer and its beam line designed to achieve dispersion matching is on schedule, and its commissioning is scheduled at the end of March 09.

One of the other important on-going efforts is the construction of a superconducting 28-GHz ECR ion source (prototype), which is expected to provide much intense U beam. It will be installed in this fiscal year, and be in operation in the FY2009.
Long-term shutdown is scheduled this summer from July to September as usual. In addition, three-month shutdown is scheduled in the winter period, from December to February, to construct the new beam line for the SHARAQ spectrometer.

RIBF accelerator teams already called for the beam-time requests for the experiments ready to run in the first half of the FY2008, (April - September), and the beam time schedule has been fixed. Except for the BigRIPS experiments, all the experiments, whose beam-time requests have been submitted, are scheduled in the coming half year. The schedule is available in the web page, http://www.rarf.riken.go.jp/rarfmt/pc.html.
The beam-time requests for the second half of this FY year, October-March, will be called in June. The 3rd Nuclear Physics (NP) PAC meeting was held in Feb. 18 and 19, during which 18 proposals have been reviewed.

Budgetary situation
The budgetary situation was quite severe in FY2007. Fortunately, the situation, especially budget for the RIBF operation, is slightly improved for this year. The construction budget for the beam line to the SHARAQ spectrometer is approved. The operational schedule mentioned above reflects these. In addition, the construction of the SAMURAI spectrometer has been approved by the government. After a four-year construction, the SAMURAI spectrometer will be in operation.

Up-to-date primary beam intensities achieved so far:
For the U beam: 0.02pnA (June 2007) and for the Kr beam: 30pnA (Nov. 2007).
An overview of accelerators was given by A. Goto during the PAC meeting at RIKEN in Feb 08**;** he presented the expected intensities of 345 MeV/nucleon beams from SRC (***Tab. C2***).

Stable 1^{ary} beams	**^{48}Ca**	Kr	Xe	^{238}U
Intensity (pnA) April -Nov08	**30-50**	30-50	5 ~10	0.3- 0.5
Intensity (pnA) 2009	**200**	100	10	5 (final goal: 1pμA, 6 10^{12} pps)

Table C2*: Expected intensities for the primary beams of RIBF.*

Appendix D: **SISSI device at GANIL**

This part is a summary of information given by the GANIL direction to all Ganil Users on September 28th, 2007.

Status of equipment and programming for 2007

SISSI out of action for at least the first part of 2008

After consultation with GANIL's technical staff, we have to inform you that **SISSI** (*source d'ions secondaires supraconductrice intense*) – our in-flight target – will be out of action for at least the first part of 2008. The problem is a open-circuit in one of the two superconducting high-field solenoid coils. There are several options open to us which are now under evaluation:
(i) removal of the damaged solenoid coil, and replacing it with a quadrupole doublet;
(ii) by-passing the broken turns in the solenoid;
(iii) replacing the damaged solenoid with a completely new one.
The first option probably requires us to design and order a suitably large-aperture, high-field quadrupole doublet, with an inevitable delay before delivery and installation can take place.
The second option will require some careful work to bypass the broken part of the coil, and will result in a coil with some 70% of the original field strength. Using this degraded coil to focus the incident beam may limit the degradation of the SISSI capability.
The third option would be expensive, and would require the manufacture, supply and installation of a completely new coil, which would also take a significant time.
We are presently investigating these options as a matter of urgency. As a consequence, we cannot guarantee that SISSI will be repaired before summer of 2008 at the earliest, and hence no beam time using SISSI will be planned before this period.
Users with approved experiments which requested SISSI should therefore consult with the physicists and technical staff at GANIL to see whether another option such as LISE can be chosen.

CLIM a new target system for LISE
On a more positive note, the new rotating target and robotic target-changer CLIM is now installed on the LISE beam line and is scheduled to be fully in operation before the end of 2007. This will permit more experiments to run on LISE without our having to wait for the previous target(s) to cool down between experiments before changing targets.
Moreover, permission to increase the limitation on beam-loss in the target from the present 80 watts to some 800 watts is now being discussed with the safety authorities. We expect to be able to get this authorization by mid-2008 allowing a potentially strong increase of the exotic beam production on LISE.

CICS: Longer runs with SPIRAL
In addition, we have just received authorisation to permit much longer runs with the SPIRAL target/ion-source assembly. Starting now we can at least double the available beam time using the SPIRAL facility.

Appendix E: **past and future MUST2 campaigns at GANIL**

The analysis of the experiments carried out in 2007 will be achieved this year; presentations will be given during workshops, conferences (EURORIB08, June 2008) this year and publications prepared during 2008 and 2009.

MUST2 Outcome till April 2008:

- 4 PhD are in progress (CEA-Saclay/ SPhN: X. Mougeot; GANIL: T Kalanee; IPN-Orsay: A. Ramus, University of Tokyo-IPNO: D. Suzuki)
- 8 MUST2 experiments were accepted during the last PACs of GANIL. Four of them using SPIRAL beams (E525S, E473S, E522S, E569S), the rest asking for SISSI beams; now these experiments are reconsidered to use the fragmented beams in the LISE area.

The MUST2 device was presented at various Nuclear Physics conferences; one article summarizing the MUST2 array is:
A new generation array for nuclear reactions studies, E.C Pollacco et al., (collaboration MUST2), Eur. Phys. J A **25**, 287 (2005).

First MUST2 campaign in the SPEG area at GANIL- Spring 2007

E525S *Low-lying states of ^{6}He via 2 neutron-transfer of ^{8}He on proton*
SPIRAL beam of ^{8}He (@15.6 A.MeV) carried out during March-April 07;
Spokesperson: SPhN (V. Lapoux);
Analysis: PhD thesis, Xavier Mougeot, SPhN.

E473S *Spectroscopy of ^{9}He via ^{8}He(d,p)*
SPIRAL beam of ^{8}He (@15.6 A.MeV) carried out in April 07 ;
Spokespersons: GANIL and SPhN (P. Roussel-Chomaz, V. Lapoux);
Analysis: PhD thesis, Tareq Kalanee, GANIL.

E537 *Low-lying structure in ^{12}O and shell quenching at Z=8 studied by the (p,t) reaction with MUST2 (^{14}O(p,t) ^{12}O)*
This experiment begun in May 2007 with the secondary beam of ^{14}O (@ 50 A.MeV) produced by fragmentation with the SISSI device; it stopped due to persisting problems with the quenching of the SISSI device. Due to the SISSI failure (see ***appendix E***) it was postponed. It is expected that it should be re-scheduled during the autumn 2008, and the ^{14}O beam will be delivered using the production target located on the LISE area.
This experiment uses a thick H_2 cryogenic target to maximize the production rates of ^{12}O nuclei.
Spokespersons: RIKEN and IPN-Orsay (H. Iwasaki, scientific visitor at IPN);
Analysis: PhD thesis, Daisuke Suzuki, Univ. de Tokyo, IPNO.

Second MUST2 campaign in the VAMOS area- Autumn 2007

E522S -*Single-particle energies in neutron-rich Oxygen isotopes*
Spectroscopy of ^{20}O via ^{20}O(d,p) with the SPIRAL beam of ^{20}O at 10.9 A.MeV.

Spokespersons: University of Liverpool, Laboratory of Daresbury (B. Fernandez, R.Lemmon)
The experimental set-up included two sets of light charged particle detectors, TIARA (si-strip detector of the English collaboration) and MUST2 [for the detection at forward angles of the reactions (d,t) and (d,^{3}He)], the beam detectors CATS, the VAMOS spectrometer to identify the heavy ejectile of the reaction, emitted at forward angles, in coincidence with the photons detected by the gamma-ray spectrometer EXOGAM.
Tests and calibrations of the detectors, electronics and coupling between the 4 data acquisition systems of the various detectors [VAMOS, MUST2, TIARA and EXOGAM were done during September and October 07. Data taking was done during the first weeks of November.

Part of the analysis of E522S [for the transfer reactions at forward angles, (d,t) and (d,^{3}He)] is carried our by Alexis Ramus, for his PhD thesis at IPN-Orsay.

Tests were done in December 07, with a low-energy beam of ^{36}S at 24 MeV/nucleon to prepare the experiment **E546** (see below the program for 2009).

Experiments to be scheduled in 2008-2009:

Experiments which were previously foreseen using **SISSI** fragmented secondary beams now should be done **on the LISE Area.**
Available reaction chamber are the M2C chamber (cylindrical, H=1m, Ø=1m) and the TIARA vessel (for use on VAMOS area in conjunction with the EXOGAM array).
Three series of MUST2 experiments have to be scheduled:

**** MUST2 at forward angles and no EXOGAM detection***

E537: re-programmed experiment. (See above) *Spectroscopy of ^{12}O via ^{14}O(p,t)*
It will use the reaction chamber M2C, 5 MUST2 telescopes, a set of RIKEN particle detectors at forward angles, beam tracking detectors (BTDs) and the cryogenic target. The cryogenic target represents the main constraint in the planning of this measurement. If resources can be made available at GANIL, the measurement could take place **in the beginning of *Sept.08***.

E569S – *Study of the spectroscopic-factor reduction from deeply-bound nucleon transfer reactions*; Spectroscopic factors of ^{14}O.
Tool: reaction ^{14}O(d,t) and (d,^{3}He)
Spokespersons: CEA-Saclay SPhN- (L. Nalpas, A. Obertelli).
Set-up: the reaction chamber M2C, 6 MUST2 telescopes, VAMOS spectrometer
This experiment using the SPIRAL beam of ^{14}O should be scheduled in 2009.

**** Proton detection at backward angles, MUST2 + annular detection; 4 EXOGAM clovers surrounding the target, on LISE***

These experiments have a similar setup for the measurement of the (d,p) channel, using 4 MUST2 telescopes in the TIARA chamber ; there will be no TIARA detector; an annular detector will be placed at backward angles and the gamma-rays will be measured by EXOGAM in coincidence with the particles. For the charge identification of the beam-like particles an E-ΔE system will be used, composed of an ionization chamber and a plastic scintillator.

E536 –Spectroscopy of ^{35}Si, shell structure [^{34}Si(d,p), (d,^{3}He) reaction]
Spokespersons: GANIL, DAPNIA (O. Sorlin, A. Gillibert).
Initial devices: SISSI-VAMOS; MUST2 for the forward angles, TIARA: backward and EXOGAM.
Now it is scheduled that an annular detector is used at forward angles and the MUST2 detectors detect the backward angles.

E530 [25UT, Pac December 05] - Study of the direct capture component of the astrophysical reaction $^{60}Fe(n,\gamma)$ ^{61}Fe by transfer reaction.
Tool: Spectroscopy of ^{61}Fe via ^{60}Fe(d,p) reaction]
Spokespersons: IPNO (F. Hammache, N. De Séréville).
Initial devices: SISSI-VAMOS; MUST2+Annular detector for the backward angles; EXOGAM.

E507 [24UT, Pac December 05] - Search for the $2d_{5/2}$ strength in ^{69}Ni, interpretation of the spherical-to-deformed transition towards the neutron-rich Fe and Cr nuclei and predictions around ^{78}Ni.
Tool: Spectroscopy and shell structure of ^{69}Ni via ^{68}Ni(d,p) reaction
Initial Devices: SISSI-G1 VAMOS-MUST2 +EXOGAM
Spokespersons: IPNO-IPHC IReS (D.Beaumel, G. Duchêne).

This campaign of 3 measurements should take place after the winter shutdown in the first semester of 2009.

**** MUST2 at forward angles; TIARA at backward angles with EXOGAM around the target:***

These measurements require detection of light particles at forward angles. Initially the beams were secondary beams produced by SISSI and the experimental set-up included MUST2, CATS, TIARA, VAMOS, and 4 clovers of EXOGAM.
The feasibility, using the beam production target and the detection of LISE should be further investigated *[when the Z-identification of the beam-like particle is limited].*

E500 [31UT, Pac December 05]- *Study of n-p pairing through two-nucleon transfer reactions – not examined for the 2009 campaign.*
Tools: study of reactions (p,^{3}He) (d,^{4}He) with the secondary beams of ^{48}Cr and ^{56}Ni.
Initial set-up: SISSI, MUST2 at forward angles, TIARA at backward angles, BTD, VAMOS and 4 clovers of EXOGAM.
Initially this experiment has to be done using SISSI secondary beams; it appears not feasible for the moment on the LISE area.
Spokespersons: IPNO, DAPNIA, Daresbury (Y.Blumenfeld, E.C. Pollacco, R. Lemmon).

Study of proton-shell structure via transfer reactions – ^{72}Zn(d,^{3}He) and (d,p);

Initial set-up: SISSI, MUST2 at forward angles, TIARA at backward angles, BTD, VAMOS and 4 clovers of EXOGAM.
Spokespersons: IPNO (S. Franchoo).

Appendix F: **Laboratory International agreement (LIA) between French and Japanese laboratories**

On January 30th , 2008 , a meeting was held at the head quarter of CNRS to sign an agreement for the establishment of a virtual laboratory called “French-Japanese International Associated Laboratory for Nuclear Structure Problems”, “**FJNSP LIA**”. It was attended by the following Japanese representatives: Dr. Y. Yano, Director of RIKEN Nishina Center, Prof. T. Motobayashi, Division Director of User Liaison and Support Division, RIKEN Nishina Center, and Prof. M. Fujiwara from RCNP, Osaka University. The agreement was signed by Director of RIKEN Nishina Center (Japan) and Directors of IN_2P_3, GANIL and Division of material science Division, CEA (France).
Based on this agreement, these institutes in France will be able to send researchers to Japan using the budget for the promotion of collaborative research with nuclear physics society of Japan.

In particular it is expected that the collaboration of the teams of GANIL, CEA-Saclay SPhN and IN_2P_3 - IPNO institutes form one side, and of the RIBF laboratory from the other side should be facilitated as well as the exchange of physicists.

The scientific leaders are T. Motobayashi (RIBF) and P. Roussel-Chomaz (GANIL), the Japanese Steering Committee is formed by H. Sakurai (RNC), T. Otsuka (CNS), Kishimoto (RCNP)
Local board will be created. Programs for 2009 are being prepared.

Appendix G: **Complements about the experimental conditions of the (p,p') MUST2 experiment at RIKEN**

Discussion of the angular and energy resolution

To improve the angular resolution, not only the light charged particle detectors are concerned, but also the beam-tracking detectors, and the same level of performance is required for both devices. The quality of the beam reconstruction on the target is an issue we would like to address for that kind of physics. We illustrate this showing the excitation energy resolution which can be attained combining the performances of MUST2 with the good reconstruction of the incident trajectories.
Position sensitive detectors will be placed along the BigRIPS beam line. For the discussion, we consider 2 beam tracking detectors 1 meter far away from each other with $\delta x = \delta y = 0.7$ mm.
For the charged particle MUST2 array, the spatial resolution is $\delta x = \delta y = 0.7$ mm, that is $\delta\theta = 0.13$ degree at 30 cm for the measurement of the angle θ in the horizontal plane.
We obtain an angular resolution of 0.155 degree.

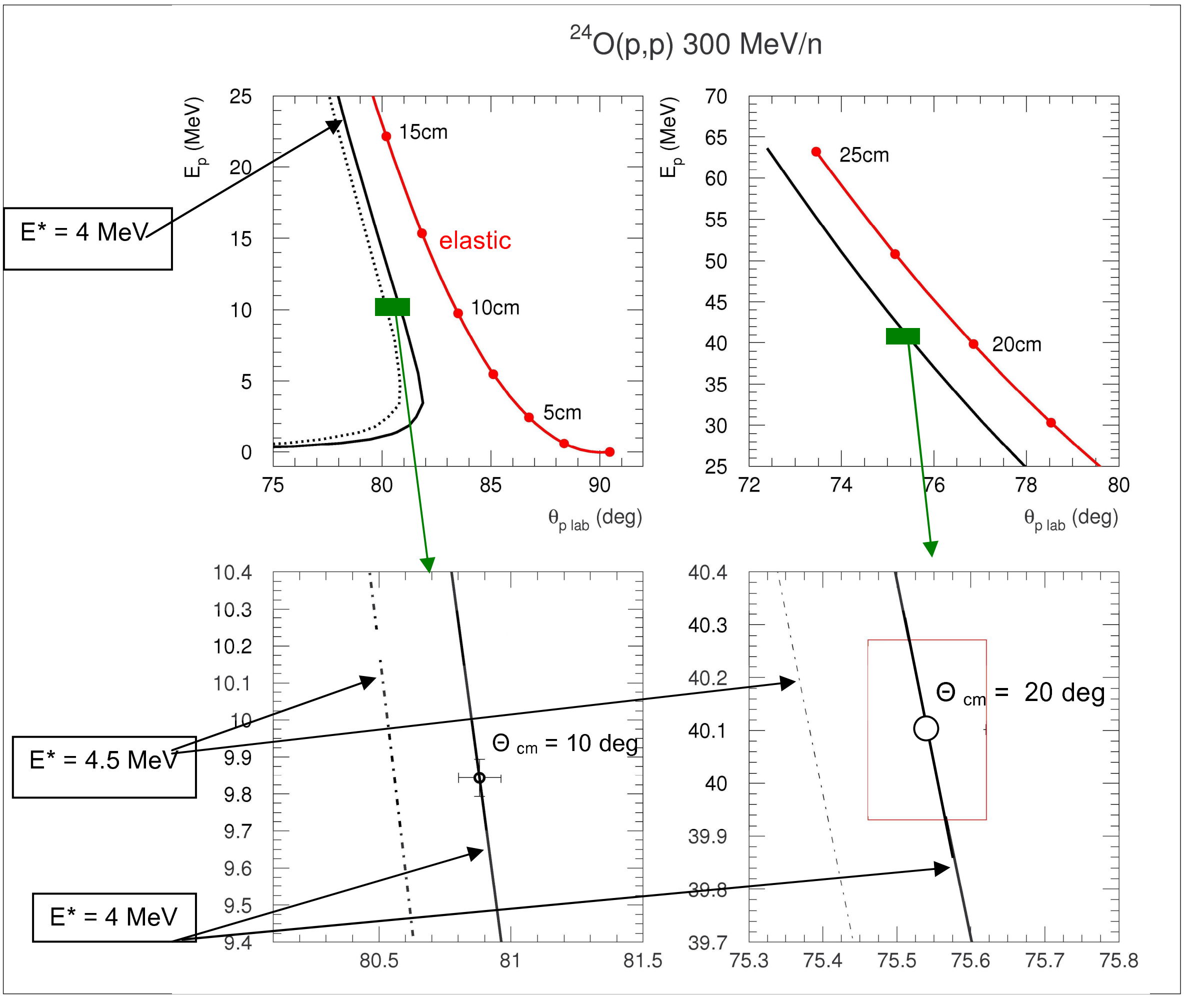


Fig.G1: *Estimation of the resolution in excitation energy* at 300 MeV/u.*(see text).*

The resolution in the excitation energy measured with MUST2 depends on the proton energy. To visualize this effect, two examples are shown in ***Fig.G1*** at E_p= 10 and 40 MeV, considering the kinematics of a ^{24}O beam at 300 MeV/n. The final resolution depends on the angular resolution, the proton energy resolution and the kinematics. It will be better for smaller center of mass angles. At Ep = 40 MeV and θ_p = 20deg$_{c.m.}$ (right part of ***Fig.G1***) the red rectangle stands for the experimental estimated resolutions superimposed on the curves corresponding to inelastic scattering to a states at E* = 4.0 (full line) and 4.5 MeV (dashed line). We deduce that in that part of the kinematics the excitation energy resolution is around **δE* = 600 keV**, corresponding to the extreme corners of the red box.

In these (p,p') experiments using the $(CH_2)_n$ solid target we have to take into account the uncertainties related to the target energy loss effects: since the vertex of the scattering is not reconstructed in the Si-particle spectroscopy technique, there is an uncertainty on the initial energy of the recoiling protons, due to the energy loss ΔE of the protons inside the target. This effect is maximum for low energy protons (small center of mass angles). For that reason, different target thicknesses are used for small and large cm angles. For the smallest cm angles, we will use a 1 mg/cm^2 thick target.

Beam production

Kinematically the conditions of the ^{24}O at 206 MeV/n would be more favorable for the measurement of the proton scattering in MUST2 in coincidence with the spectrometer.
But the lowering of the beam energy is at the price of a loss of intensity, which could be possible only if the primary beam intensity of ^{48}Ca is close to 1pμA.
For the first experiments at RIBF, the beam intensity of ^{48}Ca should be close to 200 pnA, we took this value and we examined two cases for the production of the ^{24}O beam:

- The production at high energy (~300 MeV/n) with the maximum energy of the ^{48}Ca beam;
- The production of ^{24}O at a lower energy, ~200 MeV/n.

The conditions for the production and transmission of the $^{22,24}O$ beams are given in ***Tab. G1***. they were calculated using the LISE++ version of the LISE code [LISE] and the configuration files for BigRIPS available on the web page of RIBF [***http://www.nishina.riken.jp/UsersGuide/Nuclear/BigRIPS/intensity.html***]

	Be Target Thickness (mg/cm2)	Bρ1 D1 (T.m)	C Wedge Thickness (mm)	Bρ2 D6 (T.m)	Slit F2 opening (mm)	Rate (pps)	Main Contaminants
^{22}O 283MeV/u	3207.2	7.4564	10	7.1537	-3, +5	7.0 10^5 (53.8%)	^{23}F(41.5%)
^{24}O 283MeV/u	3124.5	8.1038	10	7.8000	-5, +5	9.6 10^3 (17%)	^{25}F(36%), ^{23}O(39%)
^{24}O 206MeV/u	2264.6	6.9455	10	6.5447	-10, +10	6.2 10^3 (11%)	^{25}F(31.4%), ^{26}F(13.3%), ^{23}O(39.6%)

Table G1*: Conditions of the production of the secondary beams with BigRIPS, calculated using the LISE code.*

The beam intensity of ^{24}O at the conditions of a maximum production rate (283 MeV/n; predicted value of 9.3 10^3 /s) will be measured when the ^{48}Ca at 200 pnA is available. If the measured intensities are in agreement with the LISE calculations

With the LISE code and a ^{48}Ca beam at 350 MeV/u, the best tuning for ^{24}O is obtained for Bρ = 8.1038 T.m at D1 without wedge, corresponding to 283 MeV/u at D6. Adding a 10mm thick C wedge, it is possible to eliminate many contaminants with the slits F2. These slits are still selective if the wedge thickness is not too large. With the choice of parameters in ***Tab. G1***, there is still some major contamination due to ^{25}F and ^{23}O. To improve the purity of the secondary beam, it is necessary to increase the wedge thickness, which would also decrease the ^{24}O rate. As long as the intensity of the total secondary beam is not too high for the beam tracking detectors, we prefer to keep these contaminants in the beam. They will be studied as by-products as well. With the same tuning, it is also possible to re-introduce ^{22}O as a significant contaminant in the secondary beam when opening the negative slit F2 up to -10 mm.

For a final ^{24}O beam at 206 MeV/u, we should start from a primary beam at 270 MeV/u rather than using a thicker Be target to keep the momentum distributions not too wide. The ^{24}O rate is reduced as expected.

In all cases, $(B\rho)_1$ is smaller than the maximum bending power 9 T.m.

We will use the Zero Degree Spectrometer to detect and identify the ejectiles. The large acceptance mode is convenient for angular acceptance (90 mrad) and momentum acceptance (6%) but the maximum rigidity is only 7.3 T.m, too low for ^{24}O beam at 280 MeV/u. The dispersive spectrometer mode is more adapted with a maximum rigidity of 9 T.m, and also larger momentum dispersion necessary for a mass determination. However the angular acceptance is restricted to 40 mrad and the momentum acceptance to 4%.

As shown in ***Table II.1***, the angle of the scattered ^{24}O is smaller than 1 degree, so that the 40 mrad acceptance should be convenient.

We want to simultaneously detect elastic and inelastic scattering to unbound states which decay by neutron emission to the A-1 daughter nucleus. For ^{24}O at neutron threshold (excitation energy at 3.8 MeV), ^{23}O is emitted at about the same velocity $V(^{23}O) = V(^{4}O)$ and so a momentum difference Δp = 4% due to the mass change. The momentum dispersion due to the neutron emission angle is negligible. For all unbound states near this threshold, the same momentum shift of 4% will be observed.

Appendix H: **Discussions about the sd and fp shell gaps in the region around ^{24}O**

Vanishing of the N=20 shell gap in the neutron-rich region, example of Ne isotopes

Recently two low-lying states were found in ^{27}Ne by gamma-spectroscopy; one of them, at least, was consistent with a negative parity state. For this *N=17* nucleus, it was interpreted as an excitation from the gs 3/2+ to an excited state corresponding to a neutron in a *f7/2* or *p3/2* state. In the *N=17* isotones, when going far from the valley of stability, from ^{31}Si to ^{27}Ne – the closer to the neutron- drip-line- the excitation energies of the negative parity states are getting smaller and smaller. From these observations, it is expected that the single-particle energies for the *f7/2* or *p3/2* states are closer to the *d3/2* than was postulated in the standard shell model with the *N=20* shell closure and shell gap associated to *sd* and *fp* shells. The ^{27}Ne spectroscopy is interpreted in terms of the decreasing of *N=20* shell gap between *2s1/2* and *1f3/2* states and the apparition of a *N=16* new magic number associated to the enhanced shell gap between the orbitals *s1/2* and d3/2.
Afterwards, the indication of the narrower shell gap *N=20* between *d3/2* and *f7/2* orbitals was confirmed in other studies done at MSU [Ter06], from the knockout of a single neutron from the ground state of ^{28}Ne and at RIKEN [Dom06], from the study of excited states in $^{27,28}Ne$.

Summary of the recent data collected on the neutron-rich Oxygen isotopes

The spectroscopy of the near-dripline nucleus ^{23}O was studied via the neutron transfer reaction $^{22}O(d,p)^{23}O^*$, at RIKEN [Ele07]; the decay of $^{23}O^*$ in ^{22}O+n was measured, two resonant states were obtained; deduced energies were found to be 4.00(2) MeV and 5.30(4) MeV. Through comparison with Shell Model calculations, the first resonant state was assigned to the *d3/2* single particle state. It is considered in [Ele07] that the measured 4.0 MeV energy difference between the *s1/2* and *d3/2* states gives the size of the *N=16* shell gap; they found it in agreement with the recent USD05 ("universal" *sd* from 2005) shell model calculation.
The authors of [Ele07] claimed that the 5.3 MeV resonance could be assigned to be a state out of the sd shell model space and that its energy corresponds to a ~1.3 MeV sized *N=20* shell gap, this corresponds to a vanishing *N=20* shell gap in agreement with the MCSM model in [Uts01].

A recent study was done at MSU to observe the ground state of the unbound ^{25}O nucleus [Hof08]. It was produced in a proton knockout reaction from a ^{26}F beam.
They obtained a single resonance corresponding to a neutron decay energy of $770\,^{+20}_{-10}$ keV with a total width of 172 (30) keV. They deduced the N=16 shell gap by the energy difference between the *n1s1/2* and *n0d3/2* orbitals and they established it to be 4.86(13) MeV. They note that: "*The neutron separation energies for ^{25}O agree with the calculations of the USD shell model interaction. This interaction incorrectly predicts an ^{26}O ground state that is bound to two-neutron decay by 1 MeV, leading to a discrepancy between the theoretical calculations and experiment as to the particle stability of ^{26}O. The observed decay width was found to be on the order of a factor of two larger than the calculated single-particle width using a Woods-Saxon potential*".

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LIST OF ACRONYMS

ASIC: Applied Specific Integrated Circuits
BTDs: beam tracking detectors
CNS: Center for Nuclear Studies; University of Tokyo
CSM: Continuum Shell Model
CRIB: CNS- Radio Isotope Beam separator
GARIS: GAs-filled Recoil Ion Separator
ESNT: Espace de Structure Nucléaire Théorique
ESPE: Effective Single Particle Energies
GSM: Gamow Shell Model
LIA-FJNSP French-Japanese International Associated Laboratory (LIA) for Nuclear Structure Problems.
MCSM: Monte-Carlo Shell Model
MUST2: Murs à Strips 2, (*2:* telescope of second generation)
RARF: RIKEN Accelerator Research Facility
RCNP: Research Center for Nuclear Physics (Osaka)
RIBF: Radioactive Ion Beam Facility
RIPS: RIKEN fragment separator; BigRIPS: RIBF fragment separator
RMF: Relativistic Mean-Field
RNC: Riken Nishina Center
SAMURAI: Superconducting Analyzer for MUlti-particles with RAdio-Isotope beams
SHARAQ: Spectroscopy with High-resolution Analyzer and Radio-Active Quantum beams
SRC: superconducting ring cyclotron
ZDS: ZeroDegree Spectrometer