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Nuclear Physics Programs for the Future RIBs Facility in Korea

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Abstract: We present nuclear physics programs based on the planned experiments using rare isotope beams (RIBs) for the future Korean Rare Isotope Beams Accelerator facility(KRIA). This ambitious facility has both an Isotope Separation On Line (ISOL) and fragmentation capability for producing RIBs and accelerating beams of wide range mass of nuclides with energies of a few to hundreds MeV per nucleon. Low energy RIBs at $E_{\rm lab}$ = 5 to 20 MeV per nucleon are for the study of nuclear structure and nuclear astrophysics toward and beyond the drip lines while higher energy RIBs produced by in-flight fragmentation with the reaccelerated ions from the ISOL enable to explore the neutron drip lines in intermediate mass regions. The planned programs have goals for investigating internal structures of the exotic nuclei toward and beyond the nucleon drip lines by addressing the following issues: how the shell structure evolves in areas of extreme proton to neutron imbalance; whether the isospin symmetry maintains in isobaric mirror nuclei at and beyond the drip lines; how two-proton radioactivity affects abundances of the elements; what the role of the continuum states including resonant states above proton-decay threshold in exotic nuclei is in astrophysical nuclear reaction processes, and how the nuclear reaction rates triggered by unbound proton-rich nuclei make an effect on rapid proton capture processes in a very hot stellar plasma.

Key words: Rare Isotope Beam; nucleosynthesis; mirror nuclei; In-Flight fragmentation; two proton radioactivity; transfer reaction; one and two nucleon removal (knockout) reaction

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1 Introduction

Atomic nuclei are complex quantum-mechanical many-body systems with a finite number of nucleons; protons, Z, and neutrons, N. As a result, shell structure of the nuclei changes discretely with Z and N numbers. The question of how shell structure develops in the finite quantum many-body systems has been a common problem among various disciplines; nuclear physics, atomic physics, condensed matter physics, molecular physics, and biophysics. The shell structure of the atomic nucleus is one of the cornerstones for a comprehensive understanding of the many-body quantum mesoscopic system. The new isotope beams offer an opportunity for approaching and mapping regions of the drip lines, and helps the study of nuclear many-body quantum stability toward the proton and neutron drip lines. The study of nuclear structure including nuclear astrophysics is going through a new era owing to the development of rare isotope beams (RIBs) accelerators and a new generation of sophisticated detector systems.

World-class accelerator facilities to produce RIBs being operated and planned in the world are: SPIRAL I and II(Système de Production d'Ions Radioactifs en Ligne) at GANIL(Grand Accélérateur National d'Ions Lourds) in France[1], RIBF (Radioactive Ion Beams Factory) at RIKEN in Japan[2], NSCL(National Super Conducting Cyclotron Laboratory) at Michigan State University (MSU) in USA[3], which will become the FRIB (Facility for RIBs) at MSU[4], FAIR at GSI (Gesellschaft fur Schwerionenforschung mbH) in Germany[5], ISAC I and II (Isotope Separator and ACelerator) at TRIUMF(Tri-University Meson Facility) in Canada[6], and REX and HIE-ISOLDE at CERN[7].

The future of nuclear physics depends to a large extent on the planning of the new facilities. In this respect, the Korean Rare Isotope Beams Accelerator facility (here after called KRIA) to be built stands on

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the heart of the future of nuclear physics in the world. We report on nuclear physics programs at the KRIA with a goal for exploring new areas of the nuclei and the extreme areas of astrophysical nuclear reaction processes.

2 An overview of the shell structure evolution

To observe the behavior related to a fundamental characteristic of nuclear structure, it is better to draw a systematic and detailed overview of the experimental manifestation of the shell structure change over the nuclear chart. Especially systematic studies of the long isotones and isotopes sequences of the nuclei across the major shell closures provide stringent tests of the nuclear shell model theory.

Fig. 1 describes the nuclear structure on the basis of two regimes, theory and experiment; (1) upper part shows the nuclear energy level sequences based on the

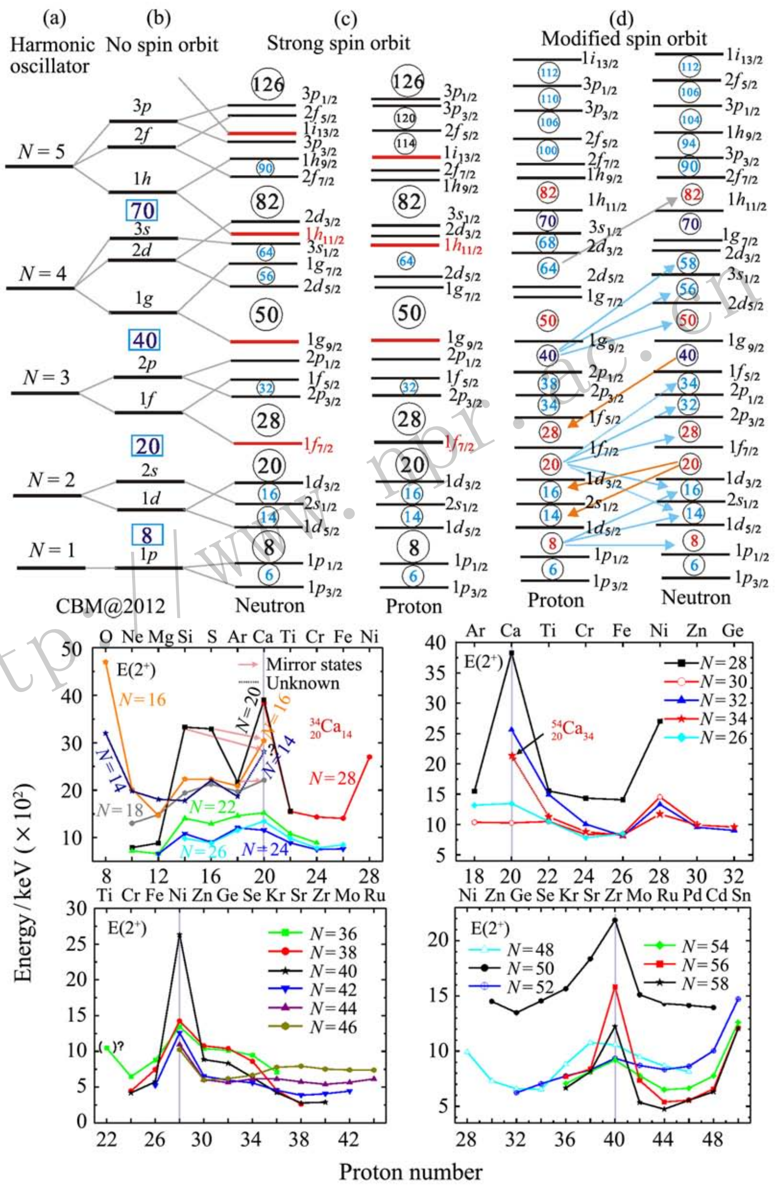

Fig. 1 (color online) (a) The single particle energies of a harmonic oscillator potential as a function of the oscillator quantum number N. (b) A schematic representation of the single-particle energies of a Woods-Saxon potential. (c) A schematic illustration of the level splitting due to the spin-orbit coupling term. The numbers at the energy gaps are the subtotals of the number of particles represented by $Nj=2j+1$ of identical particles that can occupy each state. Note that the levels are numbered serially by a given orbital quantum number. (d) Modified energy levels according to the existing experimental data for neutron-rich region. The level pattern given represents only qualitative features. The arrows represent possible combinations of the proton and neutron (sub) shell gap numbers for developing a semi-double shell closure. (Below) energy level systematics for the first excited 2^+ states in even-even nuclei as a function of proton numbers. Data are taken primarily from NNDC[8].

shell model theory and (2) lower part shows the systematics of the first excited 2^+ states experimentally observed in even-even nuclei as a function of proton numbers at a given neutron number[8]. At first, we notice that large energy gaps are observed at ^{40}Ca, ^{48}Ca, ^{56}Ni, ^{68}Ni, and ^{90}Zr, which as already mentioned are known as a doubly-magic nucleus. Dynamical structural changes along the lines of Z, $N = 20$, 28, and 40 isotones and isotopes have been main subjects of the studies in nuclear structure physics aiming to uncover the mechanisms driving these changes, experimentally and theoretically.

Excluding characteristics of the doubly magic nuclei, we notice the following features in the energy patterns for the first excited 2^+ states: First, shell gap at $N = 20$ is more pronounced at $Z = 14$ and 16 compared with that at $Z = 18$, and weakens below $Z = 14$ and above $Z = 20$. Second, the shell closure at $Z = 20$ (Ca isotopes) is more enhanced at $N = 16$ and 32. It is important to know that the shell gap at $Z = 8$ (O isotopes) has a semi-doubly shell closure at $N = 14$ and 16, respectively. According to the level sequences, $N = 14$ and 16 occupy sequentially $1d_{5/2}$ and $2s_{1/2}$, leading to a sub-shell gap. Similarly, $N = 32$ and 34 correspond to the sub-shell gap numbers that occupy $2p_{3/2}$ and $2p_{1/2}$ orbitals, respectively. If we follow this tendency for a shell gap, we expect that ^{34}Ca with $N = 14$ and ^{54}Ca with $N = 34$ would have a semi-doubly magic character. Considerable experimental and theoretical efforts are being made to answer the question of whether ^{54}Ca becomes a semi-doubly magic core[9]. The study of ^{34}Ca, known as a nucleus with two proton radioactivity, is one of the subjects for our plans[10]. Third, the shell gap at $N = 40$ is enhanced only at $Z = 28$. This implies that the nuclei with neutron number 40 favor collectivity rather than individuality in ground states. Fourth, proton number 40 (Zr isotopes) develops a semi-doubly magic character at $N = 56$ and at $N = 58$, which are also the sub-shell gap numbers.

By focusing on the harmonic oscillator shell closure numbers, namely 8, 20, 40, and 70, we find the following characteristic responses to sub-shell closures: $Z = 8$ responds to $N = 14$ and 16; $Z = 20$ does to $N = 32$ and 34 (not yet confirmed experimentally); and $Z = 40$ does to $N = 56$ and 58 for developing a semi-doubly shell closure. For $N = 40$, we address a question of why it does not respond to $Z = 32$ and 34 for developing a semi-doubly shell closure. This problem may be intimately connected with the concepts of shape coexistence in the corresponding ^{72}Ge ($Z = 32$) and ^{74}Se ($Z = 34$) nuclei. Meanwhile, both of $N = 70$ and $Z = 70$ shell numbers have no shell gap partners for developing a semi-doubly shell closure. For example, ^{120}Sn ($Z = 50$ and $N = 70$) shows no evidence for a semi-double shell closure, indicating that $1h_{11/2}$ orbital remains in a strong intruder state. In this regard, it is questionable that ^{110}Z ($Z = 40$ and $N = 70$) would reveal a semi-magic character.

3 An overview of nuclear experiments

The general experimental technique for nuclear physics includes mass measurements, stopped beam spectroscopy for radioactive decay, and nuclear reactions[11].

The mass measurements allow us to obtain fundamental information on nuclear structure, nuclear astrophysics, and fundamental interactions[11]. The nuclear masses are a direct reflection of the energies of the nuclei. In equilibrium, a system trends toward the lowest energy states and the transition to lower energy states releases energy, providing a source to power and to explode stars[12]. The stability of the nuclei against the various modes of radioactive decay can easily be understood in terms of the liquid drop model mass formula: $M(Z,A) = (A-Z)m_{\rm n} + Z(m_{\rm p}+m_{\rm e}) - a_1A + a_2A^{2/3} + a_3(A/2-Z)^2/A + a_4Z^2/A^{1/3} + a_5\delta(A)$, here a_1, a_2, a_3, a_4, and a_5 are coefficients due to volume, surface, asymmetric, Coulomb, and pairing energy terms, respectively. The pairing term $\delta(A)$ corresponds to $1/A^{3/4}$ for odd-odd nuclei, 0 for odd-even nuclei, and $-1/A^{3/4}$ for even-even nuclei[13].

The stopped beam $\beta-\gamma$ spectroscopy allows us to identify and to study electromagnetic decay of isomeric and excited nuclear states, and to measure gamma rays following beta-decay of excited states into the daughter nuclei. Besides, the stopped beam spectroscopy with sophisticated detector systems offers information on exotic decay modes such as β-delayed proton(s) or neutron(s) emission in the nuclei toward the drip lines[14]. Data on β-delayed neutron emission plays a key role in understanding the abundances of the elements as it affects the pathways of the s-process and the r-process. Both the detailed stopped beam and the in-beam spectroscopic techniques provide complementary data on the location and the ordering of single particle states for exotic nuclei of interest. They also enable us to deduce radiative neutron capture on the very neutron-rich nuclei impossible to access in direct measurements.

It is difficult and/or impossible to directly measure the thermal nuclear reaction rates based on (p, γ), (p, α), and (α, p) with RIBs such as ^{14}O, ^{15}O, ^{17}F, ^{18}Ne, ^{22}Mg, ^{23}Mg, ^{26}Al, ^{25}Si, ^{44}Ti, *etc.*, because secondary beams are limited to both intensity and production from ISOL. Instead, indirect measurements based on elastic resonance scatterings, transfer reactions, and Coulomb excitations provide information on the reaction rates for a given reaction system. The cross sections for the capture reactions can be determined by Coulomb dissociation based on the inverse photo-dissociation reactions[15]. The elastic scattering reactions are needed to study resonant states at higher excitation energies and provide information on the Coulomb amplitude and the nuclear amplitude[11,16]. The inelastic scatterings offer the properties of states in a compound nucleus where decay by particle emission to an excited state is possible. Among direct nuclear reactions, the single-nucleon removal (knockout or breakup) reactions with heavy projectile ions at intermediate energies (100 $\sim$ 300 MeV per nucleon) have become a specific and quantitative tool for studying single-particle occupancies and correlation effects in the nuclear shell model. Charge exchange reactions are another method to measure Gamow-Teller strength compared to the usual β–decay study. While the measurements of the β–decay are limited with Q values, the charge exchange reactions do not have such a limit. The charge exchange reactions will play another important role in studying the properties of exotic nuclei.

For nuclear astrophysics, the proposed experiments are mainly focused on the rapid proton capture reactions (rp-process) in a very hot stellar plasma. The rp-process has been known to be considerably complex due to the interplay of proton captures, decays, possibly photo-disintegrations, and particle induced reactions[17]. The important factors that influence the rp-process nuclear reaction networks above $Z \geqslant 32$ include the proton-capture reaction rates and their inverse photo-disintegration rates, and the β-decay and electron-capture rates[17]. We should remember that nuclear deformations significantly affect the rp-process reactions.

4 The characteristics of the KRIA facility

To produce radioactive ion beams, there are two main approaches; ISOL production[16,18] and In-Flight production[19]. The KRIA facility has both an ISOL and fragmentation capability. Our efforts to create, separate, and study radioactive nuclides are being undertaken for the coming decade. This is an ambitious project to build a multi-beam facility capable of producing and accelerating beams of a wide mass range of nuclides with energies of a few to hundreds MeV per nucleon. See Fig. 2. The KOBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus) and the IFFS (In-Flight Fragmentation Separator) facilities will provide the selection and identification of the beam-like particles as well as target-like ones, and with the combination of a γ-ray detectors array offer spectroscopic information on internal structures of the nuclei to be investigated.

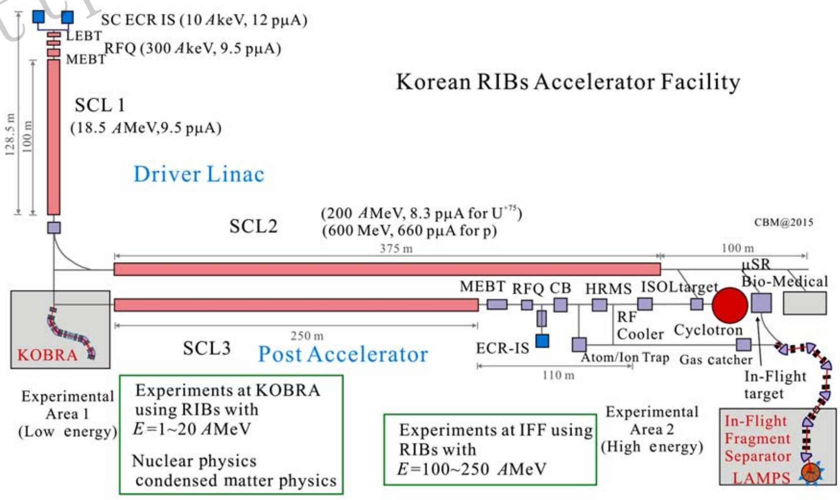

Fig. 2 (color online) Layout of the KRIA facility
Note that AMeV means MeV per nucleon.

The KOBRA facility is divided into two stages by consisting of a series of magnetic dipoles, quadrupoles, and Wien filters as shown in Fig. 3[20]. The stage 1 is utilized to produce the low energy RIBs via multi-nucleon transfer reactions at about 20 MeV per nucleon or via direct one or two nucleon transfer reactions at a few MeV per nucleon[21]. It is worthwhile knowing that it is designed to reject the primary beams for the studies of thermonuclear, namely direct capture reactions under high temperature plasma conditions in hot stars. The stage 2 placed at down-stream of the stage 1 is employed to separate the fragments following the reactions of RIBs on a reaction target, or to reject the primary beam in the same manner as for the stage 1.

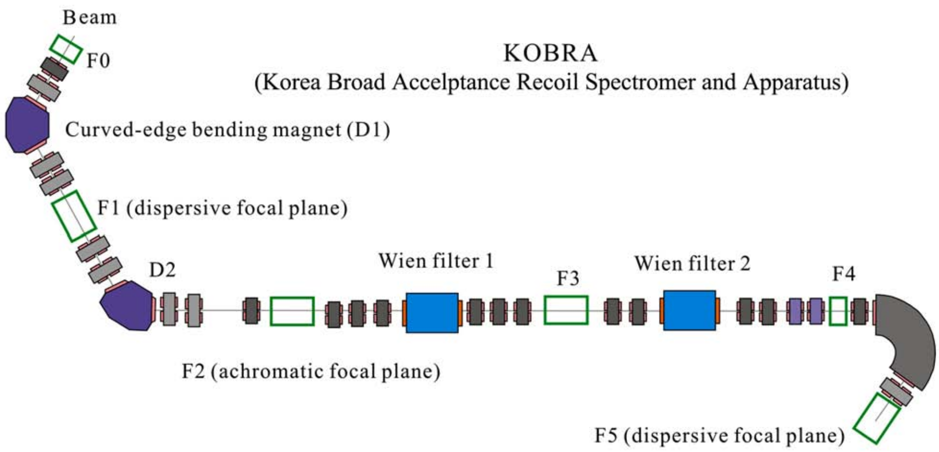

Fig. 3 (color online) Layout of KOBRA. This facility is divided into a stage 1 (F0 ~ F3) and a stage 2 (F3 ~ F5). Curved-edge shape bending magnets are utilized to minimize the high order aberration[20].

At the KOBRA facility the lower energy re-accelerated ISOL rare isotope beams with energies 5 to 15 MeV per nucleon can be separated and identified. Such low energy reaccelerated RIBs are suitable for producing the nuclear reactions such as Coulomb excitations, nuclear fusion-evaporation reactions, elastic resonance scatterings, inelastic scatterings, one or two nucleon transfer reactions, and direct capture reactions. The higher energy RIBs with energies of 100 up to 250 MeV per nucleon will be produced by nuclear fragmentation at the IFFS. High quality and intense RIBs combined with re-accelerated ISOL beams including high efficient detector systems will provide unique experimental possibilities to study the very neutron-rich and proton-rich nuclei toward and beyond the drip lines.

The KOBRA and the IFFS have two complex detector systems: one is located at the target position for detection of reaction products including light-charged particles and γ rays; and the second one is positioned at focal plane for detection and identification of heavy recoiled nuclei as well as for spectroscopic study of delayed activity. Conjunction of detector systems with a polarized spin target (or polarized beam) is desirable for studying spin-orbit interactions.

5 The planned experiments

In the following we describe briefly, as for examples, the proposed experiments aiming at the KRIA. More detailed descriptions are found in Ref. [10].

5.1 Study on two proton capture reactions

The proton drip line imposes a constraint on the reaction path of the rp-process. As shown in Fig. 4, many proton-rich nuclides near the $Z=N$ line are unbound to proton decay. If we assume an immediate proton-decay for these proton unbound nuclei, we expect that no further proton-capture proceeds. Thus further processing depends on the β-decay of the last proton stable isotone. This bottleneck is called a waiting point. However, if the lifetime of a proton unstable nucleus is appreciably long due to a high Coulomb barrier, 2p-capture reactions on the last proton bound isotone would be possible[14]. The 2p-capture reactions allow to bridge the single proton unstable nucleus to a proton bound nucleus. This plan aims at measuring the 2p capture reaction rates combined with the proton resonance scatterings for the associated unbound nuclei. The 2p-capture reactions to be studied are summarized in Table 1.

We introduce, as an example in this field, a proposal for investigating the unbound states of ^{73}Rb. This proposal aims to measure the unbound states of the proton radioactive ^{73}Rb through the proton elastic resonance scatterings with ^{72}Kr on a hydrogen thick target. ^{72}Kr is a waiting point where the proton capture is followed by the instantaneous emission of a proton by the proton unbound ^{73}Rb nucleus. This waiting point, however, as already pointed out, can be bypassed by a two-proton radiative capture reaction if the nucleus ^{74}Sr is bound. Such alternative paths can be estimated by the calculations using the properties

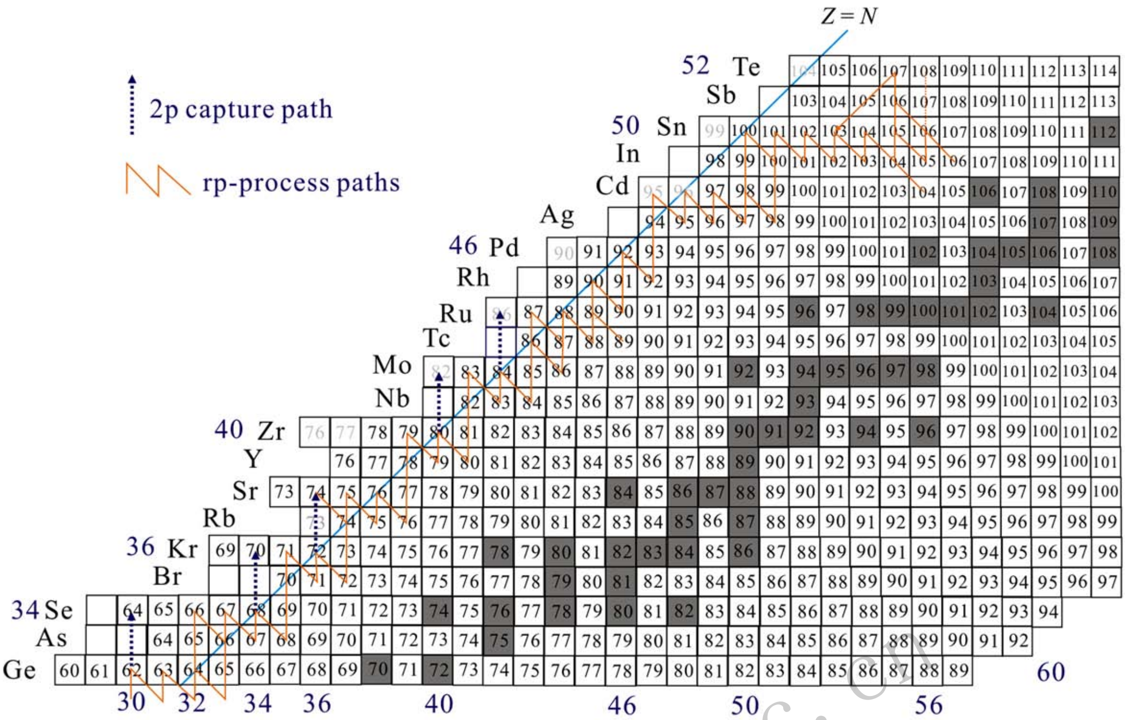

Fig. 4 (color online) The chart of nuclides in the mass region of Ge to Te.

Table 1 Candidates for the two-proton capture reactions and their intermediate proton-unbound nuclei.

Elastic resonance scatterings	Intermediate proton-unbound nuclei	Two proton capture reactions	Spin-parity and half-life for the final nucleus
^{15}O+p	^{16}F	^{15}O (2p, γ)^{17}Ne	1/2$^-$; 109 ms
^{18}Ne+p	^{19}Na	^{18}Ne (2p, γ)^{20}Mg	0$^+$; 90.8 ms
^{20}Mg+p	^{21}Al	^{20}Mg (2p, γ)^{22}Si	0$^+$; 9 ms
^{29}S+p	^{30}Cl	^{29}S (2p, γ)^{31}Ar	5/2$^+$; 14.4 ms
^{37}Ca+p	^{38}Sc	^{37}Ca (2p, γ)^{39}Ti	(3/2$^+$); 31(+6/-4) ms
^{38}Ca+p	^{39}Sc	^{38}Ca (2p, γ)^{40}Ti	0$^+$; 52.4 ms
^{41}Ti+p	^{42}V	^{41}Ti (2p, γ)^{43}Cr	(3/2$^+$); 20.6 ms
^{58}Zn+p	^{59}Ga	^{58}Zn (2p, γ)^{60}Ge	0$^+$; $>$110 ns
^{62}Ge+p	^{63}As	^{62}Ge (2p, γ)^{64}Se	0$^+$; $>$180 ns
^{68}Se+p	^{69}Br	^{68}Se (2p, γ)^{70}Kr	0$^+$; $>$0.05 s
^{72}Kr+p	^{73}Rb	^{72}Kr (2p, γ)^{74}Sr	0$^+$, $>$1.2 μs

of the intermediate unbound nucleus, ^{73}Rb. Therefore, investigation for the unbound states of ^{73}Rb nucleus is very important in this context.

As for nuclear structure studies, we investigate the shape coexistence in the proton-rich Kr nuclei with $Z \leqslant N$. For this purpose, the proposed experiments using ^{70,72}Kr RIBs employ Coulomb excitation measurements which provide information on the nuclear shape built on the ground state as well as built on the first excited 0^+ state. It is known that the ground state of ^{72}Kr would be of oblate in shape while ^{74}Kr and ^{76}Kr are known to be prolate in their ground states[22−24]. The proposed experimental methods that would require conversion electron spectroscopy are shown in Fig. 5.

In addition, we propose invariant mass measurements for the proton unbound nuclei, such as ^{82}Mo, ^{86}Ru, and ^{90}Pd. This is because they can provide information on isospin symmetry, as well as rp-processes beyond the proton drip lines.

5.2 Study on shell structure evolution along a chain of $N = 19$, 20, 21 isotones with $Z = 22$ and 24; ^{41}Ti, ^{44}Cr, and ^{45}Cr

The proposed experiment aims at measuring the internal structures of proton-rich ^{41}Ti, ^{44}Cr, and ^{45}Cr nuclei to test the symmetry of mirror states in isobaric $A = 41$, 44 and 45 by comparing with the structures of ^{41}K, ^{44}Ca, and ^{45}Sc. The nuclei of interest are produced through a one (or two) neutron knockout reaction of secondary beams on a thick ^{9}Be target. The secondary beams are produced by the fragmentations of a 250 MeV per nucleon ^{78}Kr primary beam on a thin ^{9}Be production target. The proposed reactions are as follows: ^{9}Be(^{42}Ti, ^{41}Ti+n)X for ^{41}Ti, ^{9}Be (^{46}Cr, ^{44}Cr+2n)X for ^{44}Cr, and ^{9}Be(^{46}Cr, ^{45}Cr+n)X for ^{45}Cr. The γ-ray spectroscopy employs to measure the internal electromagnetic transitions in the nuclei of interest.

The goals of the proposal are: (1) Identification of

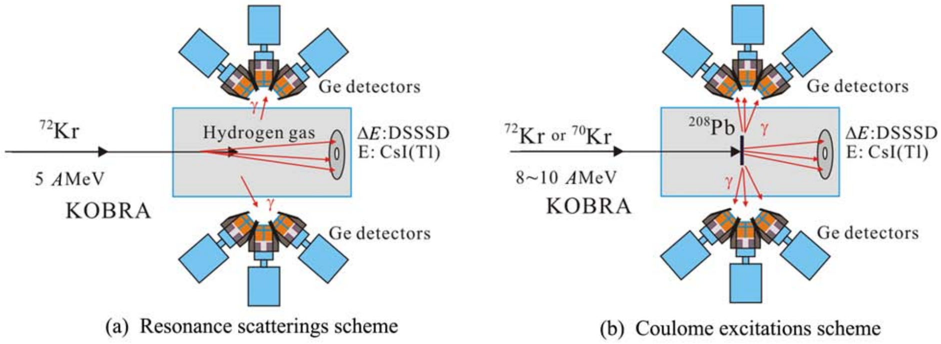

Fig. 5 (color online) Experimental set-up schemes for measurements of (a) unbound states in ^{73}Rb and (b) excited states of ^{72}Kr and ^{70}Kr.

E(2^+) and E(4^+) in even-even ^{44}Cr for investigating the magic N = 20 shell evolution like an emergence of collectivity; (2) measurements for the low-lying excited states in odd-Z ^{41}Ti and ^{45}Cr for testing charge symmetry between mirror nuclei, Z, N = 19 and 21 with A = 41 and 45; and (3) search for isomers in the nuclei of interest to study the single-particle and collective features based on isomerism.

Fig. 6 illustrates the partial single-particle energy level diagram and the energy level systematics for the

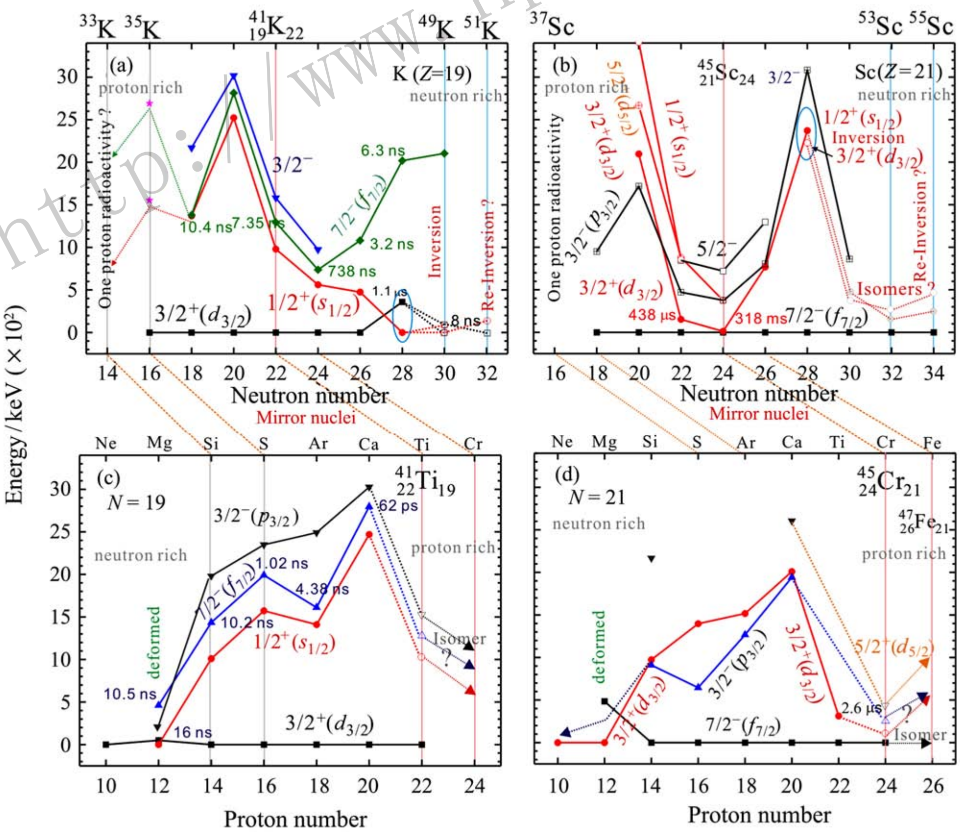

Fig. 6 (color online) Systematics of the ground and some low-lying excited states in Z = 19, 21 (upper) as a function of neutron numbers and in N = 19, 21 (lower) as proton numbers. Data are taken from NNDC[8]. For discussion, the associated level sequences are included as designating their relations by the arrows with the corresponding shell structure evolution.

ground and low-lying single-particle excited states in $Z = 19$ and 21 nuclei as a function neutron numbers and in $N = 19$ and 21 as a function of proton numbers. This proposal is focused on the proton rich side. The neutron-rich side will be investigated with plan C. In the region of Z, $N = 19$ and 21, the $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, and $2p_{3/2}$ orbitlas play a critical role in the strength of the shell gaps as shown in Fig. 6. We find the following distinctive features: First, for $Z = 19$ isotopes, the $1/2^+$ level due to $2s_{1/2}$ subshell decreases rapidly with increasing neutron numbers from $N = 20$ and finally becomes the ground state at $N = 28$. For $N = 19$ isotones the subshell also decreases toward ground level with decreasing proton numbers from $Z = 20$ and finally becomes the ground state at $Z = 12$. We notice that the nuclei at and below $Z = 12$ turned out to be deformed in their ground states at magic neutron number 20[16]. Second, for Z or $N = 19$, the $7/2^-$ level due to the $1f_{7/2}$ subshell forms isomers with half-lives of a few nanoseconds across the 20 magic gap region as an intruder state. Third, for Z and $N = 21$, the $3/2^+$ level due to $1d_{3/2}$ subshell changes dramatically with neutron and proton numbers and forms isomers near the ground states at $N = 22$, 24 and $Z = 22$. This proposal aims at proving the charge symmetries by observing low-lying states in isobars with Z, $N = 19$ and 21 toward $Z > 20$ and $N < 18$. Besides, we are interested in searching for isomers in ^{41}Ti and ^{45}Cr as denoted in Fig. 6.

5.3 Study on shell structure evolution based on the proton single-particle orbital changes in the vicinity of ^{54}Ca

This plan aims at exploring single-particle shell migrations in the vicinity of ^{52}Ca and ^{54}Ca. The experiments are based on the nucleon removal (knockout) reactions using the IFFS to be installed in the high energy experimental area. The proposed one-proton removal reactions are as follows: ^{9}Be(^{50}Ca, ^{49}K+p)X, ^{9}Be(^{52}Ca, ^{51}K+p)X, ^{9}Be(^{54}Ti, ^{53}Sc+p)X, and ^{9}Be(^{56}Ti, ^{55}Sc+p)X. This proposal has a goal for studying the internal structure of very neutron rich nuclei with $Z = 19$ and 21 and $N \geqslant 30$; ^{49}K, ^{51}K, ^{53}Sc, and ^{55}Sc. The measurements involve the thick reaction target ^{9}Be and the γ-ray spectroscopy of the projectile-like residual nuclei for the final state resolution. The residual nuclei are produced through the one-proton knockout reactions on a ^{9}Be target by the secondary rare isotopes beams produced from the fragmentation between a ^{86}Kr primary beam with 250 MeV per nucleon and a ^{9}Be production target.

As shown in Fig. 6, the $2s_{1/2}$, $1d_{3/2}$ and $1f_{7/2}$ subshells contribute dominantly to shell structure evolution in proton-single levels. In contrast, neutrons begin to occupy the $2p_{3/2}$, $2p_{1/2}$ and/or $1f_{5/2}$ orbitals cross over the $1f_{7/2}$ orbital, which separates the $N = 20$ gap and the $N = 28$ gap.

As was already discussed, for $Z = 19$ isotopes the $1/2^+$ level due to $2s_{1/2}$ subshell decreases remarkably with increasing neutron numbers and finally becomes ground state at and beyond $N = 28$. For $Z = 21$ isotopes, the $3/2^+$ level due to $1d_{3/2}$ subshell changes dramatically as it goes down to near the ground state at $N = 24$. It is interesting to notice that the levels of $3/2^+$ and $1/2^+$ are inverted at $N = 28$ in $Z = 19$ (^{47}K) and $Z = 21$ (^{49}Sc).

The inversion of the $3/2^+$ and $1/2^+$ levels, however, is uncertain in ^{49}K and unknown in ^{53}Sc and ^{55}Sc above $N = 28$. It is worthwhile to remind that $N = 32$ and 34 develop the semi-double shell gaps with $Z = 20$. We address how the distinctive quasiparticle levels, such as $2s_{1/2}$, $1d_{3/2}$, and $1f_{7/2}$ migrate and make an impact on the formation of the semi-double shell closure of ^{54}Ca. The migration of the proton $2s_{1/2}$, $1d_{3/2}$, $1f_{5/2}$ levels as well as the neutron $2p_{1/2}$, $1f_{5/2}$ levels with respect to neutron numbers may indicate an underlying physics not well accounted for in the present shell model interactions. In this regard, the present proposal is an important step toward extremely neutron-rich region where more exotic phenomena including halos or skins are expected.

5.4 Shell structure evolution and shape transitions in the vicinity of proton magic number, $Z = 82$

This region is a section of the nuclear chart that is not easy to access under current experimental condition. In particular, both the north-eastern area and the south area of the $Z = 82$ and $N = 126$ point remain mostly unexplored.

As a starting point to study shell structure evolution based on the single particle configurations over $Z = 82$ and $N = 126$, we focus on investigating the level structures of Tl ($Z = 81$) and Bi ($Z = 83$) because the intruder states and the associated isomers in odd Z nuclei with ± 1 outside doubly magic core provide critical information on the shell structure evolution. Fig. 7 demonstrates the single-particle energy level systematics based on the low-lying excited states for odd-Z nuclei just around ^{208}Pb.

By considering the currently known nuclei, we will focus on the following nuclei: ^{175}Tl$_{96}$, ^{177}Tl$_{96}$, ^{179}Tl$_{98}$, ^{211}Tl$_{130}$, ^{213}Tl$_{132}$, ^{183}Bi$_{100}$, ^{185}Bi$_{102}$, ^{217}Bi$_{134}$, ^{219}Bi$_{136}$, ^{191}At$_{106}$, ^{193}At$_{108}$, ^{219}At$_{134}$, and ^{221}At$_{136}$. An interesting feature is that the levels at $J^{\pi} = 1/2^+$, $7/2^-$, as well as $13/2^+$ decrease down to the ground level as the neutron numbers decrease in Bi and At nuclei. It is also interesting to know whether the $7/2^-$ level would reach the ground state beyond $N = 132$ in the above nuclei. The shell migration of these orbitals is closely connected to the concepts of the triplet shape coexistence in the region of neutron deficient Pt, Os, Hg, and Pb.

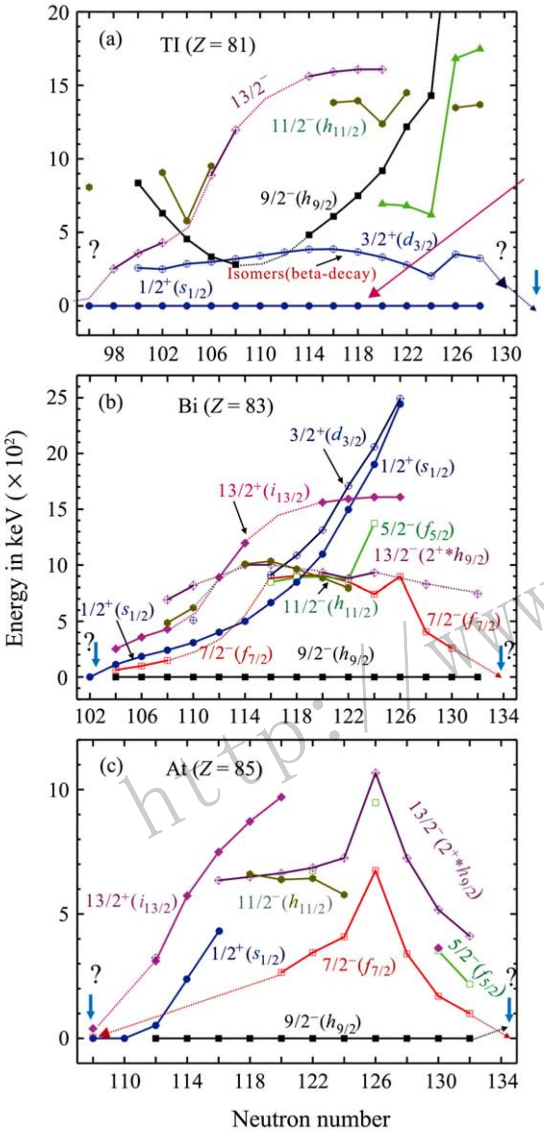

Fig. 7　(color online) Systematics of ground and low-lying states for the odd-mass nuclei; (a) Thallium, (b) Bismuth, and (c) Astatine as a function of neutron numbers. The expected level crossings on the basis of the systematic trends are denoted by the arrows. Data are from NNDC[8].

The nuclei of interest can be investigated by the multi-transfer reactions at $E \sim 10$ MeV per nucleon. For example the reaction of ^{136}Xe + ^{208}Pb at $E_{\rm cm} =$ 526 MeV is estimated to be 0.2 μb for the production of ^{219}At and 3 μb for the ^{217}Bi, respectively. However, the role of transfer channels is less clear due to the difficulty of making qualitative calculations for both the multi-nucleon transfer and the sub-barrier fusion simultaneously. The very neutron-rich RIBs, for example ^{144}Xe, with the high intensity and high quality with a few MeV per nucleon are essential for producing exotic nuclei far from the $Z = 82$ and $N = 126$ point, such as ^{196}Yb and ^{220}Pt. It is noteworthy to mention that the measurements of half-lives of the nuclei with $Z < 82$ and $N = 126$ provide decisive information on the r-process paths along waiting points with $N = 126$, while the β-delayed neutron emission schemes in these neutron rich-nuclei play an important role in determining abundances of Au and Pt elements.

6　Summary and outlook

We have introduced and discussed the planned experiments using RIBs for KRIA. This facility is one of the world-class multi-beam facilities capable of producing and accelerating beams of wide range mass of nuclides with energies of a few to hundreds MeV per nucleon. The low energy RIBs at $E_{\rm lab} = 5$ to 20 MeV per nucleon are used for the study of nuclear structures and nuclear astrophysics toward and beyond the drip lines while the higher energy RIBs produced by the in-flight fragmentation with the reaccelerated ions from the ISOL enable us to explore the neutron drip lines in intermediate mass regions. Beam specifications for the KOBRA and ones for the IFFS spectrometers are complementary, which allow scientists to extent the investigations toward the very neutron-rich and proton-rich nuclei.

The experiments are planned to investigate the internal structures of exotic nuclei toward and beyond the nucleon drip lines by addressing the following questions: how the shell structure evolves in areas of extreme proton to neutron imbalance; whether the isospin symmetry maintains in isobaric mirror nuclei at and beyond the drip lines; how two-proton or two-neutron radioactivity affects abundances of the elements; what the role of the continuum states including resonant states above particle-decay threshold in exotic nuclei is in astrophysical nuclear reaction processes, and how the nuclear reaction rates triggered by unbound proton-rich nuclei make an effect on rapid proton capture processes in a very hot stellar plasma.

To summarize, we show a set of the planned experiments with the associated nuclei to be investigated over the nuclear mass chart in Fig. 8. We hope that the proposed experiments will play an important role in developing a concrete nuclear physics program for the rare isotope beams accelerator facilities, as well as

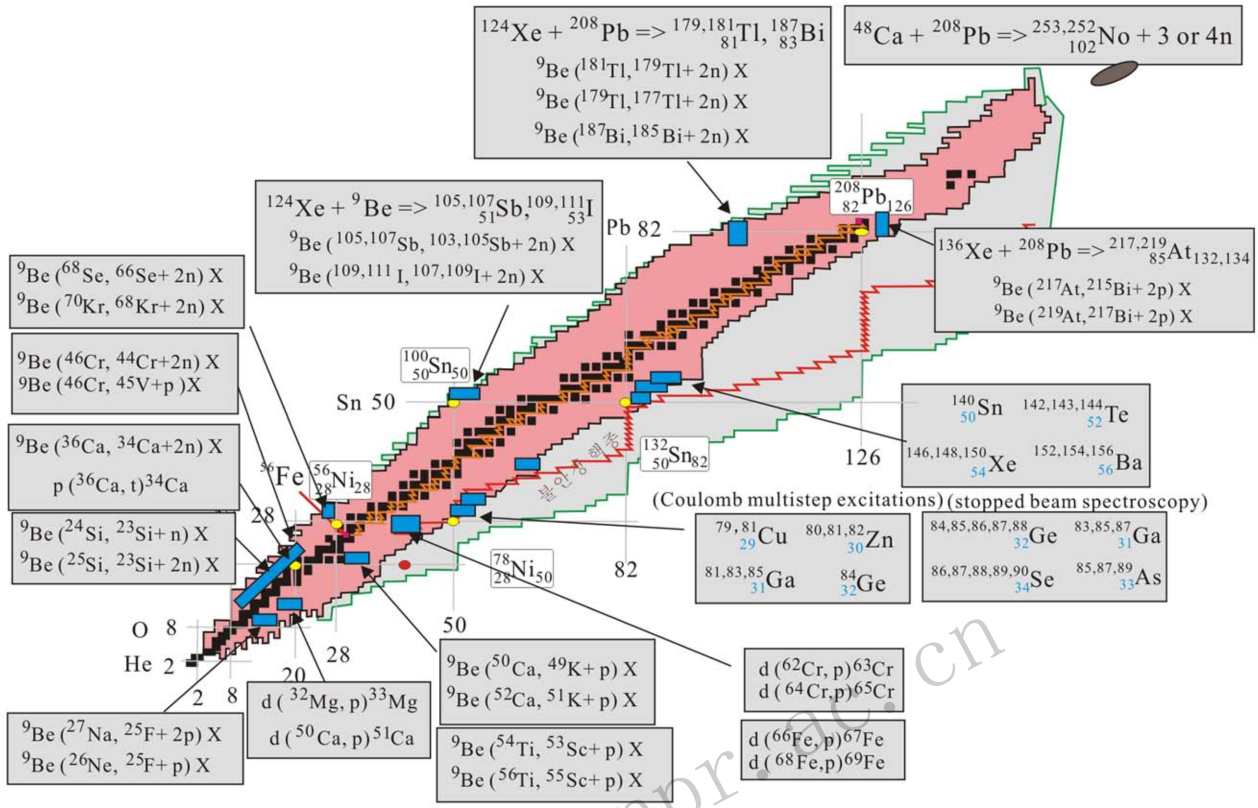

Fig. 8 (color online) The proposed experiments for studying exotic nuclei aiming at the rare isotope beams accelerator facilities.

in promoting the creation of next generation of nuclear scientists in the world.

Note The Rare Isotope Beams Accelerator Facility to be built in Korea has been named officially as 'RAON' which is said to mean 'joyful, delightful' in ***old*** Korean language.

References:

[1] http://www.ganil-spiral2.eu/.

[2] http://www.rarf.riken.go.jp/.

[3] http://nscl.msu.edu/.

[4] http://frib.msu.edu/.

[5] http://www.gsi.de/.

[6] http://www.triumf.ca/.

[7] http://isolde.web.cern.ch/ISOLDE/.

[8] National Nuclear Data Center, Brookhaven National Laboratory, http:// www.nndc.bnl.gov/.

[9] HAGEN G, HJORTH-JENSEN M, JANSEN G R, *et al.* Phys Rev Lett, 2012, **109**: 032502.

[10] MOON CHANG-BUM. AIP Advances, 2014, **4**: 041001.

[11] RIISAGER K, BUTLER P, HUYSE M, *et al.* HIE-ISOLDE: the scientific opportunities, CERN-2007-008.

[12] ARNETT D. Supernovae and Nucleosynthesis, Princeton University Press: Princeton, 1996.

[13] HEYDE H. Basic Ideas and Concepts in Nuclear Physics, IOP Publishing, Bristol and Philadelphia, 1999.

[14] PFUTZNER M, KARNY M, GRIGORENKO L V, *et al.* Rev Mod Phys, 2012, **84**: 567.

[15] BERTULANI C. 9*th* Symposium on Nuclei in the Cosmos (NIC IX), Proceedings of Science(PoS), 2006: 040.

[16] ORR N. J Phys G: Nucl Part Phys, 2011, **38**: 020301.

[17] SCHATZ H, APRAHAMIAN A, GÖRRES J, *et al.* Phys Rep, 1998, **294**: 167.

[18] RAVN H L, ALLARDYCE B W. Treatise Heavy Ion Science, Vol. 8, ed. BROMLEY D A. New York and London : Plenum Press, 1989: 363.

[19] TANIHATA I. Treatise Heavy Ion Science, Vol. 8, Ed. D. A. Bromley New York and London: Plenum Press, 1989: 443.

[20] Progress report for the RAON recoil spectrometer KOBRA, 2015.

[21] TSOO T, CHAE H, PARK J, *et al.* Proceedings of EMIS2015 (17^{th} International Conference on Electromagnetic Isotope Separators and Related Topics), to be published in Nuclear Instruments and Methods.

[22] BOUCHEZ E, MATEA I, KORTENET W, *et al.* Phys Rev Lett, 2003, **90** : 082502.

[23] POIRIER E, MARECHAL F, DESSAGNE P, *et al.* Phys Rev C, 2004, **69** : 034307.

[24] CLÉMENT E, GÖRGEN A, KORTEN W, *et al.* Phys Rev C, 2007, **75** : 054313.