SAMURAI Project at RIBF

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Abstract. SAMURAI project aims to open a new research field in nuclear physics by the use of a large acceptance spectrometer for kinematically complete measurements of multiple particles emitted in RI-beam induced reactions. The SAMURAI spectrometer consists of a large gap superconducting dipole magnet, heavy ion detectors, neutron detectors, and proton detectors. What is special about the SAMURAI system is that projectile-rapidity protons or neutrons are detected with large angular and momentum acceptance in coincidence with heavy projectile fragments. With an effective combination of these equipments, the SAMURAI system allows us to perform various experiments: electromagnetic dissociation, various direct reactions, polarized deuteron induced reactions, and EOS studies. SAMURAI project is currently underway at RIBF. The construction of the superconducting dipole magnet will start in autumn 2010 and finish in spring 2011. The detectors are also being constructed in parallel. The first commissioning run will be performed in early 2012.

1. Introduction

A new-generation radioactive isotope (RI) beam facility called the RI Beam Factory (RIBF) [1] at RIKEN Nishina Center became operational in March 2007. The high-intensity RI beams can be converted from primary heavy-ion beams accelerated by a cascade of cyclotrons via the projectile fragmentation of stable isotopes or the in-flight fission of uranium isotopes by a superconducting fragment separator BigRIPS [2, 3]. Many kinds of experiments can be performed by using a wide range of exotic nuclei, and one of the greatest results by using the BigRIPS is the identification of 45 new neutron-rich isotopes over a wide range of atomic numbers [4].

We are constructing a large-acceptance multi-particle spectrometer for RI beam experiment at RIBF. The name of this spectrometer is SAMURAI which stands for Superconducting Analyser for MUlti-particle from RAdio Isotope beam. The SAMURAI is designed for kinematically complete measurements by detecting multiple particles in coincidence. The SAMURAI will be located on the downstream end of straight beamline from the BigRIPS as shown in Fig. 1. Figure 2 shows the schematic view of the SAMURAI spectrometer. The SAMURAI spectrometer consists of a superconducting dipole magnet, heavy ion detectors, proton detectors, and neutron...
detectors with a large vacuum chamber on a rotational stage. The SAMURAI will be utilized in the invariant mass measurement as well as the missing mass measurement.

The physics goals to be achieved using the SAMURAI spectrometer are discussed in Sec. 2. The overview and current status of the SAMURAI detector system are described in Sec. 3. A summary is given in Sec. 4.

2. Physics Goals
The SAMURAI is designed to enable various types of measurements. In the following subsection, we describe the physics goals by using the SAMURAI system.

2.1. Coulomb dissociation of neutron-rich nuclei
In the invariant mass spectroscopy, we propose to study unbound states above the neutron decay threshold, which is of vital importance in the region of very neutron-rich nuclei. The
invariant mass spectroscopy by measuring the four momenta of the outgoing heavy fragment and few neutrons in coincidence can provide information on not only the collectivity at the very neutron-rich extremes such as giant resonance (soft dipole resonance, pigmy resonance) studied by the Coulomb and nuclear dissociation but also the unbound exotic states such as $^{10}$He, $^4n$ system, $^{25-28}$O, and so on. The invariant mass spectroscopy in neutron-rich nuclei also provides experimental tool to investigate the structures and the reactions of $r$-process nuclei.

2.2. Coulomb dissociation of proton-rich nuclei
For astrophysical interest, studies of proton unbound states at proton-rich nuclei are important, since the energy and width of such states influence radiative capture cross sections under astrophysical conditions. Electromagnetic excitation of proton-rich nuclei can be used to measure these cross sections utilizing the invariant mass method and the principle of detailed balance. The BigRIPS and the SAMURAI spectrometer allow us to measure the radiative capture cross sections for explosive nucleosynthesis in nova, supernova, X-ray bursts, and so on. From these measured cross sections, more-reliable network-calculations on the nucleosynthesis can be expected. Coulomb dissociation of proton-rich nuclei also provides experimental tool to study their nuclear structure, such as the occurrence of new magic numbers, near the proton drip line by observing the excited states.

2.3. Direct nuclear reactions on a light ion target
Direct nuclear reactions on a proton target, such as the elastic and inelastic scattering ($p$, $p'$) and the nucleon knockout reactions ($p$, $pN$), provide information on the nuclear density distribution of the whole system, spatial distribution of bound nucleons, and single particle orbitals. The various types of reactions, such as ($d$, $d'$), ($\alpha$, $\alpha'$), and ($^{3}$He, $t$), are powerful tools for investigating the transition matrix elements. In addition, direct reactions on the polarized proton target [5] allow us to assign the spin-parity of nuclear states, which is essential for the discussion of the change of the shell structure. Although the main part of these measurements is missing energy measurement by detecting recoil light ions, tagging the projectile fragment by the spectrometer allows studying the decay mode of the residual nuclei at the same time.

2.4. Polarized deuteron induced reactions
One of the main interests in nuclear physics is to clarify the nature of nuclear forces and to understand nuclear phenomena from the view point of fundamental Hamiltonian. Based on the intensive theoretical and experimental efforts, the realistic nucleon nucleon (NN) potentials have been obtained and have described the rich set of experimental NN data. The accuracies of these theoretical predictions are remarkable and they give $\chi^2$-value per degree of freedom very close to 1. However, they fail to reproduce the experimental binding energies of light nuclei for which exact solutions of the Schrödinger equation are obtainable. These discrepancies has been found to be reduced by including the three nucleon force (3NF). But the spin structure of the present-day 3NFs is not been clearly understood yet. In order to further study the 3NF effects, rich spectra of spin observables are to be measured in the $dp$ reactions at energies higher than 200 MeV/A where large 3NF effects have been predicted [6, 7]. We propose to perform the polarization measurements with polarized deuteron beams of $E_d \leq 440$ MeV/A at the SAMURAI spectrometer.

2.5. Asymmetry energy of nuclear matter
RI beams provide a great opportunity to explore experimental constraints on the density dependence of the asymmetry energy of the nuclear equation of state (EOS). Although symmetry energy of the EOS has been well investigated through compressional giant resonances and
collective flows observed in heavy ion collisions at intermediate and relativistic energies, the knowledge of asymmetric energy is still very limited. Suggested by the recent theoretical calculations [8], we propose to measure the isospin dependence of $\pi^+$ and $\pi^-$ production using a time projection chamber (TPC) installed in the large magnet gap for information on the density dependence of the asymmetry term at above normal densities.

3. Detector System

In order to realize these multiple purposes discussed in Sec. 2, we design the SAMURAI very flexible way as shown in Fig. 3. By using the rotational stage, the SAMURAI spectrometer can be rotated from 0 to 90 degrees. With an effective combination of several detectors, the SAMURAI system allows us to perform various experiments.

![Figure 3. Experimental setup for various configurations.](image_url)

In order to provide the particle identification (PID) for heavy fragments, at least three independent measurements are required, such as charge ($z$), magnetic rigidity ($R$, momentum), and velocity ($v$), or $z$, $R$, and total energy ($E$). In the case that five sigma of mass separation ($\sigma_A = 0.2$) is desired for $A = 100$, the error propagation, $\sigma_A^2 = \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_z}{z}\right)^2 + \left(\frac{2\sigma_\beta}{\beta}\right)^2$, requires a rigidity resolution of $\sigma_R/R \approx 1/700$ (rms) at $R \approx 7.3$ Tm ($p/z = 2.2$ GeV/c), and a velocity resolution of $\sigma_\beta/\beta \approx 9 \times 10^{-4}$ at $\beta = 0.62 \sim 0.66$. Obtaining a rigidity resolution of $1/1000$ requires a combination of high-field magnet and precise position-measuring detectors. In order to satisfy above conditions, we design and construct the superconducting dipole magnet and detectors for heavy fragments.

3.1. Superconducting dipole magnet

The superconducting dipole magnet is the most important component of the SAMURAI spectrometer. The magnet is a H-type dipole, having cylindrical poles of 2 m diameter and circular superconducting coils. The upper and lower superconducting coils are installed in their respective cryostat, and cooled separately by liquid helium bath based cooling system. The maximum magnetomotive force is 1.9 MA/cm, which generates a magnetic field of about 3 T at
the center of the poles in the median plane. The magnet is designed to have a maximum bending power (BL integral) of 7 Tm. For high-resolution measurement, the last superconducting triplet quadrupole magnet in the beamline is used with the superconducting dipole magnet in the Q3D mode, providing the momentum resolution of 1/3000. Large momentum bite of $R_{\text{max}}/R_{\text{min}} = 2 \sim 3$ allows us the detection of heavy fragment and projectile-rapidity proton in coincidence. The opening in the magnet, i.e., the horizontal distance between the side return yokes, is 3.4 m and the effective pole-gap width is 0.8 m. This geometry allows us a large angular acceptance for projectile-rapidity neutrons: vertically $\pm 5^\circ$ and horizontally $\pm 10^\circ$.

The assembling and installation of the main part of the SAMURAI spectrometer, the superconducting dipole magnet and the rotational stage, will start at the RIBF site in autumn 2010 and finish in spring 2011.

3.2. Detector system for heavy fragments
In order to measure the beam phase space, two beam drift chambers (BDC1, BDC2) are placed in front of the target. Each of the BDCs consists of eight anode planes of $xx'yy'xx'yy'$, having an effective area of $80 \text{ mm} \times 80 \text{ mm}$. They have been used for tracking high-intensity beams between $0.5 \sim 2.0 \text{ MHz}$ combined with new ASD (amplifier-shaper-discriminator) and multi-hit TDC (time-to-digital converter). The position resolution is $\sigma \sim 120 \text{ pm}$ for a proton at 1 MHz. In order to measure the charge of beams, an ion chamber for beam (ICB) is placed following the BDCs. The ICB consists of multi-layers of 10 anodes and 11 cathodes, having an effective volume of $140 \text{ mm} \times 140 \text{ mm} \times 420 \text{ mm}$. The ICB has been tested using primary and secondary beams from $^{84}\text{Kr}$ at 400 MeV/A. The charge resolution is $\sigma_z = 0.17$ for $z = 36$.

In order to measure the scattering angle of fragments, a forward drift chamber (FDC1) is placed after the target. The FDC1 consists of 14 anode planes of $xx'uu'vv'xx'uu'vv'xx'$ with shield planes, having an effective circular area of $\phi 315 \text{ mm}$. In order to measure the position and angle of fragments throughout the superconducting dipole magnet, a forward drift chamber (FDC2) is placed behind the magnet. The FDC2 consists of 14 anode planes of $xx'uu'vv'xx'uu'vv'xx'$, having an effective volume of $2.23 \text{ m} \times 0.81 \text{ m} \times 0.79 \text{ m}$. Both of FDCs are under construction and will be finished in 2010. In order to measure the charge of fragments, an ion chamber for fragment (ICF) is placed following the FDC2. The ICF consists of multi-layers of 12 anodes and 13 cathodes, having an effective volume of $750 \text{ mm} \times 400 \text{ mm} \times 480 \text{ mm}$. The ICF has already been constructed and will be tested using RI beams in 2010. In order to measure the time of flight (TOF) of fragments, scintillator hodoscope for fragment (HODF) is placed following the ICF. The HODF is composed of 16 modules of plastic scintillators, having an effective area of $1.6 \text{ m} \times 1.2 \text{ m}$. The HODF is under construction.

The PID of heavy fragments requires velocity measurement or total-energy measurement in addition to the rigidity and the charge measurement. A Cherenkov detector operated at the total internal reflection (TIRC) for high-precision velocity measurement and a total energy detector using pure CsI (TED) for high-precision total-energy measurement are under development. The TIRC is composed of 10 modules of TADF30 glass, having an effective area of $700 \text{ mm} \times 200 \text{ mm}$. The TED is composed of 32 modules of pure CsI crystal, having an effective area of $800 \text{ mm} \times 400 \text{ mm}$. The TIRC and the TED have been tested using RI beams of Kr beam between $200 \sim 400 \text{ MeV/A}$. The PID around $A = 80$ are achieved by using the TIRC or the TED.

3.3. Detector system for neutrons
In order to determine the momentum vectors of neutron(s) emitted in the breakup reaction of unstable nuclei, we construct the neutron detector arrays NEBULA (NEutron-detection system for Breakup of Unstable-nuclei with LArge A cceptance). The NEBULA is composed of 240 modules of plastic scintillators which has a dimension of $120 \text{ mm} \times 120 \text{ mm} \times 1800 \text{ mm}$, coupled to photomultiplier tubes at both vertical ends. The NEBULA consists of 4 sets of
stuck each of which composed of two layers of plastic scintillators and one layer of thin plastic scintillator as veto detector.

In the breakup reaction of projectile for invariant mass spectroscopy, the acceptance for neutrons is much more critical than for the charged fragment emitted simultaneously. The effective area of 3.6 m × 1.8 m can cover the large acceptance of vertically ±5° and horizontally ±10°. For single neutrons, the NEBULA covers 100 % for relative energy less than 3 MeV and 40 % even at around 10 MeV. Another important feature of the NEBULA is its ability to unambiguously detect 4 neutrons in coincidence. Each stuck is separated by about 1 m to detect 4 neutrons in coincidence.

Half the volume of the NEBULA has already been constructed and tested using cosmic ray. Unfortunately, other half has not been funded. The present NEBULA, however, can unambiguously detect 2 neutrons in coincidence without reducing the acceptance for neutrons. In order to study the 4 neutron core system ³He, ¹⁹B as well as unbound 4n, ³He in detail, 4 neutron measurement is necessary. We need to make an effort to get the funds for construction of the full NEBULA.

3.4. Detector system for protons
In order to obtain the relative energy resolution of 0.1 MeV at $E_{rel} = 1$ MeV for two body breakup reaction, the opening angle resolution of 2 mrad and the momentum resolution of $\sigma_p/p = 1/200$ are required. The superconducting dipole magnet is designed to have rigidity resolution of $\sigma_R/R \simeq 1/700$, which satisfies the momentum resolution for above condition. In order to achieve the opening angle resolution of 2 mrad, silicon microstrip detectors are placed between the target and magnet to measure scattering angles of protons and heavy fragments. A preamplifier circuit for the silicon microstrip detector is required to have the broad dynamic range, because both proton and heavy fragment hit the detectors simultaneously. They are under development in collaboration with Texas A&M and Washington University.

In order to measure the position and angle of protons throughout the superconducting dipole magnet, two proton drift chambers (PDC1, PDC2) are placed behind the magnet. Each of the PDCs consists of two anode planes of U and V, sandwiched between cathode planes of U, V, and X. The effective area of 1.7 m × 0.8 m covers defocused protons in both the horizontal and vertical directions. In order to measure the TOF of protons, scintillator hodoscope for proton (HODP) is placed following the PDCs. The HODP is composed of 16 modules of plastic scintillators, having an effective area of 1.6 m × 1.2 m. The PDCs and HODP are under construction.

4. Summary
SAMURAI project is currently underway at RIBF. The construction of superconducting dipole magnet including the rotational stage will start in autumn 2010 and finish in spring 2011. The detectors for heavy ion, neutron, and proton are currently under development in parallel. We hope all these efforts will bear fruit in the commissioning run scheduled in early 2012 and in the following physics runs.

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