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Large-Acceptance Multi-Particle Spectrometer

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(**S**uperconducting **A**nalyzer for **Mu**lti-particle from **Ra**dio **I**sotope Beams)

Abstract

We propose to construct large-acceptance multi-particle spectrometer for radioactive-beam experiments. The central part of the spectrometer system is a large-gap superconducting magnet with 7 Tm of bending power for momentum analysis of heavy projectile fragments and projectile-rapidity protons with large angular and momentum acceptance. The large gap also enables measurements of projectile-rapidity neutrons with large angular acceptance in coincidence with heavy projectile fragments.

This system is suitable for various radioactive-beam experiments such as electromagnetic dissociation including radiative-capture reactions, various direct reactions as well as polarized-deuteron-induced reactions and EOS studies.

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Ⅱ Physics subjects to be investigated and observables to be measured

The large-acceptance multi-particle spectrometer is primarily designed for kinematical complete measurements by detecting multiple particles in coincidence, such as the invariant-mass measurement. The large bending power and large gap also enable various types of measurements. Following table summarizes the physics subjects in terms of the reaction types.

Reaction types	Category	Physics subjects	Observables
Electromagnetic dissociation (photon target)	Soft dipole excitation Giant resonance Radiative capture reaction	Single-particle orbit Collective motion Nuclear astrophysics	Invariant mass
Proton and light target	Elastic/inelastic, (p,p), (p,p') Knockout, (p,pN)	Density distribution Single-particle orbit	Missing energy & decay tagging
Polarized d beam Induced reaction	(d,d) (d,p)	2-3 nucleon force Short range correlation	polarization
4π measurement		Equation Of State	pions

(2-1) Soft Dipole Excitation via Coulomb Dissociation

Electromagnetic excitation by low-energy virtual photons induces direct non-resonant type excitations to continuum for neutron-rich nuclei with loosely-bound neutrons. Low-energy E1 strength can be studied utilizing the invariant-mass spectroscopy by measuring four-momenta of outgoing heavy fragment and few neutrons in coincidence. Such strength provides useful information on the ground state properties such as characteristics of the single-particle orbit. Measurements performed for 1-n halo nuclei ^{11}Be[1] and ^{19}C[2] give valuable information on the extended s-wave component of the single-particle state in light-mass region. In the new facility, measurements can be extended to N=21 and N=51 nuclei, where the lowering of 2p and 3s states are expected. In addition to the nuclear structure problems, it might be possible to extract information on the 2n correlations for neutron-rich nuclei with two weakly-bound neutrons [3].

Electromagnetic excitation also provides experimental tool to observe soft dipole resonance (SDR) related to the thick neutron skin with collective nature. Although this type of resonance has never been observed in the light-mass region, measurement extended into the heavier-mass region might give information on the collective motion in a very asymmetric system.

(2-2) Radiative Capture Cross Sections via Coulomb Dissociation

Radiative capture cross sections, $\sigma(p,\gamma)$, at low energies are of crucial importance for studying nuclear astrophysics. Electromagnetic excitation of proton-rich nuclei can be used to measure the cross sections in the inverse reaction utilizing the invariant-mass method.

Several reactions for the p-p chain and CNO cycle have been studied using the Coulomb dissociation method, for example, the ^{13}N(p,γ)^{14}O reaction which is a key reaction of hot-CNO cycle [4]; ^{7}Be(p,γ)^{8}B reaction related to the solar neutrino problem [5]; ^{22}Mg(p,g)^{23}Al reaction relevant to break out of the NeNa cycle [6]; ^{8}B(p,γ)^{9}C, ^{11}C(p,γ)^{12}N and ^{12}N(p,γ)^{13}O reactions relevant to hot p-p chain [7]. Using the Big-RIPS and a large-acceptance spectrometer, the cross sections for radiative capture reactions for explosive nucleosynthesis (the rp-, r-, and s- processes) in nova, supernova, X-ray bursts, etc., are expected to be measured. 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 the nuclear structure, such as the occurrence of new magic numbers, ear the proton drip line by observing the excited states.

(2-3) Direct nuclear reactions on a proton target

Direct reactions on the proton target, such as the proton elasticand inelastic scattering, (p,p) and (p,p’), and nucleon knockout reactions, (p,2p) and (p,pn), provide information on the nuclear density distribution of the whole system, spatial distribution of bound nucleons via momentum-distribution measurement, and single-particle orbit. Although the main part of these measurements is missing-energy measurement by detecting recoil nucleon(s), tagging the projectile fragment by the spectrometer allows studying the decay mode of the residual nuclei at the same time.

(2-4) Two- and Three-nucleon interactions

One of the primary goals of nuclear many-body physics is to understand nuclear structure starting from the fundamental nucleon-nucleon (NN) interactions. The state-of-the-art NN interaction models, such as CD-Bonn, Nijmegen-I, AV18, can reproduce deuteron static properties and several thousands of NN scattering data almost perfectly. However, when the interactions are applied to nuclear structure calculations, it is revealed that the interactions alone can not give the correct values of binding energies. Apparently, it is necessary to refine our understanding of the NN interactions to achieve the primary goal.

The purpose of this project is to improve our understandings of the nuclear interaction through polarization measurements with a primary beam of polarized deuterons with an energy of $E_d < 880$ MeV. The proposed investigations are:

- Three nucleon force effects in the d+p scatterings [8,9], putting special focus on spin-dependences and relativistic effects.
- Short-range part of the NN tensor interactions probed by the polarization correlation measurements for the ^{3}He(d,p)^{4}He reaction.

(2-5) Asymmetry Energy of Nuclear Matter

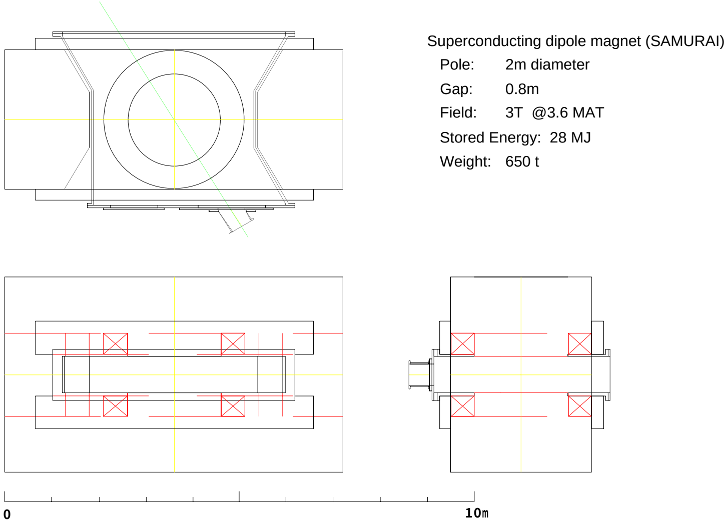
RI beams provide a great opportunity to explore experimental constraints on the density dependence of the asymmetry energy of the nuclear equation of state (EOS). Though symmetry energy of the EOS has been well investigated through compress ional giant resonance's and collective flows observed in heavy ion collisions at intermediate and relativistic energies, the knowledge of asymmetric energy is still very limited.

Suggested by the recent theoretical calculations[10], we propose to measure the isospin dependence of π^+ and π^- production using a time projection chamber (TPC) installed in large the magnet gap for information on the density dependence of the asymmetry term at above normal densities.

Ⅲ Experimental Devices

(3-1) Superconducting dipole magnet

Large-gap superconducting dipole magnet is a central part of the detection system. Out of various designs, H-type superconducting magnet with a round pole was selected as shown in Fig.1. The main parameters of the magnet are: (1) Field integral of 7 Tm, providing rigidity resolution of 1/600 (rms) at 2.3 GeV/c for particle identification upto A=80; (2) Vertical gap of 80 cm, providing vertical angular acceptance of ±80mrad for projectile-rapidity neutrons; (3) Rotatable base from 0 to 90 degrees for various configurations; (4) Field cramps to minimize the fringing field; (5) Built-in vacuum chamber with flanges; (6) Hole in the return yoke for detecting projectile-rapidity protons and heavy fragment in coincidence.



Superconducting dipole magnet (SAMURAI)

Pole: 2m diameter
Gap: 0.8m
Field: 3T @3.6 MAT
Stored Energy: 28 MJ
Weight: 650 t

Fig. 1 : Superconducting dipole magnet

(3-2) Q3D option for high-resolution measurement

Last triplet Q magnet in the beam line is used with the dipole magnet in the Q3D mode, providing momentum resolution of 1/3000 and solid angle of 9 msr. This mode is for high-resolution measurement using primary deuteron beams.

(3-3) Large-area neutron detector

Projectile-rapidity neutrons around 250 MeV are detected by large-area neutron detector for invariant-mass measurement, with large acceptance (±10° horizontal and ±5° vertical), high efficiency (>70% for single neutron), good velocity resolution (0.6%), and good angular resolution (5mrad).

(3-4) Tracking detectors

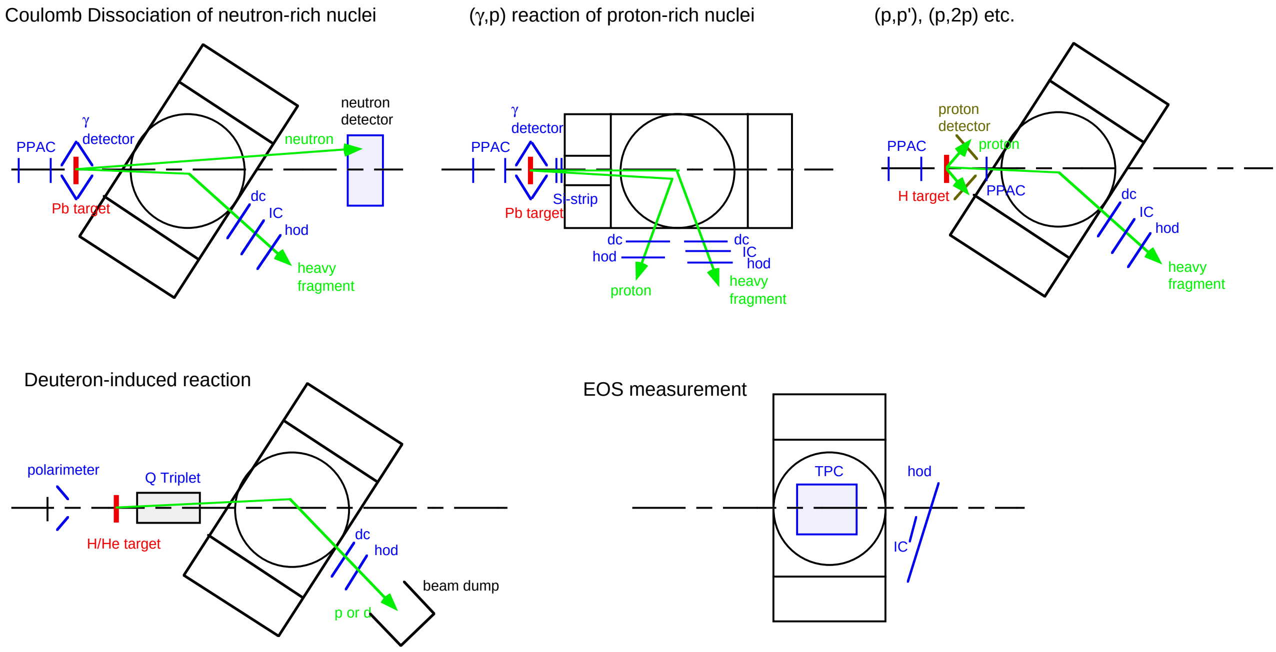
Momentum of beam is tagged with 1/1000 precision by PPAC's in the tagging section of the beam line. Angle and position of the incident beam on the target are measured by two beam-line PPAC's. Position of particles from the target is measured by PPAC or Si-strip in vacuumupstream of the dipole. Angle and position of the particle downstream of the dipole are measured by drift chambers in the air. Two separate drift chambers are used to detect heavy fragments and protons.

(3-5) Charge-measuring device

Charge of the heavy fragment is measured by a combination of ion chamber and plastic scintillaor hodoscope. Detailed design of the ion chamber is not finalized yet.

(3-6) Velocity-measuring device

Conventional plastic scintillator hodoscope is used for velocity measurement of the heavy projectile fragments. For mass separation of A=100, usage of TOF hodoscope is marginal, since the required velocity resolution is about 1/1000 at 250 MeV/A. R&D is necessary for velocity detector with better resolution.


Coulomb Dissociation of neutron-rich nuclei

(γ,p) reaction of proton-rich nuclei

(p,p'), (p,2p) etc.

Deuteron-induced reaction

EOS measurement

Fig. 2 : Schematic experimental configurations

(3-7) Beam dump

For experiments using primary deuteron beam, beam dump with concrete shield is installed.

(3-8) TPC

Time Projection Chamber (TPC) will be similar to the HISS TPC [11] for EOS studies. The TPC is installed in the dipole gap for maximum acceptance.

(3-9) γ detector

In most invariant-mass measurements in the high-mass region, γ detector around the target is necessary to make sure that γ rays are not emitted from the projectile fragment. The operation in the veto mode requires 4π γ detector with high detection efficiency, but without position sensitivity.

These detector components are arranged depending on the experiment, as shown schematically in Fig.2.

Ⅳ Drawing of the System

Experimental Setup for Coulomb dissociation of neutron-rich nuclei, as an example, is shown in Fig.3A and Fig.3B.

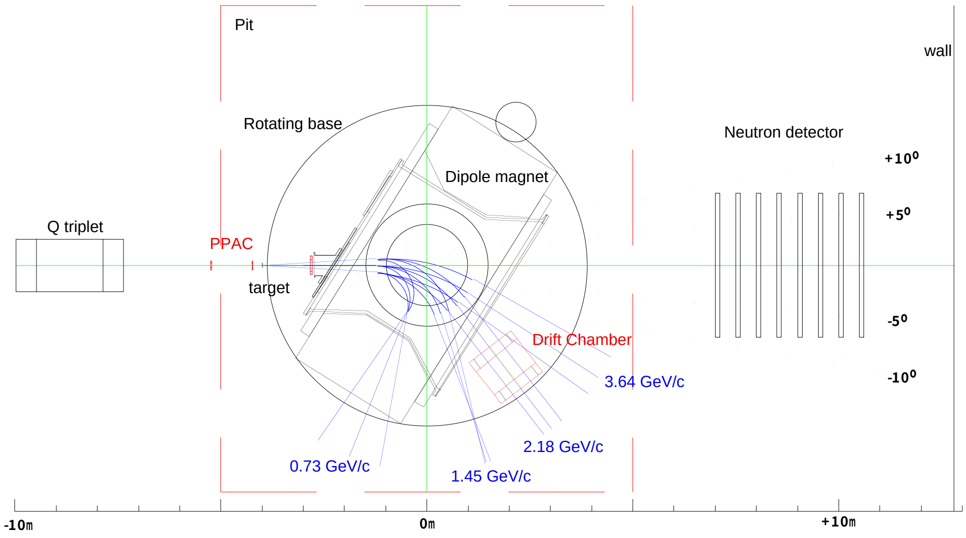


Fig.3A: Experimental Setup (top view)

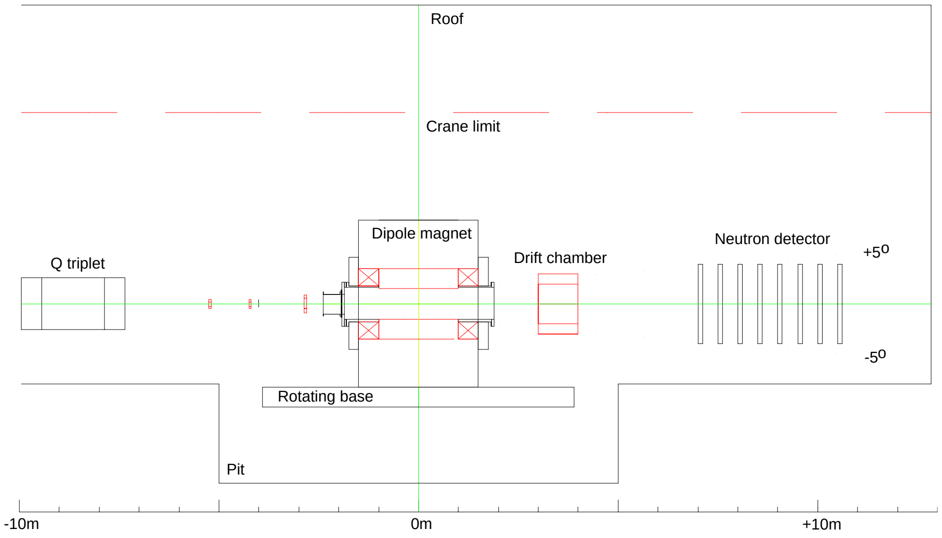


Fig. 3B: Experimental Setup (side view)

Ⅴ Specifications

Measurements will be performed using RI beams below A=100, mainly limited by the availability of fully-stripped beams, and around 250 MeV/A. The expected performance of the spectrometer system is as follows.

- Rigidity measurement: resolution of 1/600 (rms) for R= 2.2 GeV/C (A/Z=3 at 250 MeV/A) assuming an overall angular resolution of 1 mrad. This requires low-mass drift chambers with good position resolution. Combined with the charge and velocity measurement, expected mass resolution at A=100 will be 1/500. When the system is operated in Q3D mode, the momentum resolution is improved to 1/3000.
- Invariant-mass measurement for heavy fragment and neutrons: Angular acceptance for neutrons is ±5° vertically limited by the dipole gap, ±10° horizontally limited by the detector size. Detection efficiency for single neutron is about 70%. Relative-energy resolution is 0.5 MeV at 3-MeV decay energy.
- Invariant-mass measurement for heavy fragment and protons: When dipole magnet is rotated by 90 degrees, the setup allows momentum acceptance of over 300% covering from heavy fragment down to protons.

Ⅵ Costs

Rough cost estimate of the magnetic spectrometer is as follows.

Superconducting dipole magnet, including rotatable base, vacuum chamber, cooling system, and power supply:	1,000 Myen
Upstream detectors (PPAC x3):	5 Myen
Downstream drift chambers including positioning base and electronics, two sets for heavy fragment and protons:	100 Myen
Plastic scintillator hodoscope including electronics, two sets for heavy fragment and protons:	30 Myen
Downstream ion chamber:	5 Myen
High-resolution velocity detector:	(not clear at the moment)
Beam dump for primary deuteron beam:	50 Myen
Sub total	1200 Myen

In addition, rough cost estimate for additional detectors is

Neutron detector including electronics:	200 Myen
Si strip detector for upstream beam tracking:	13 Myen
TPC including electronics:	350 Myen
Sub total:	940 Myen

Ⅶ Uniqueness

The spectrometer system allows the detection of multiple particles in the projectile rapidity with large angular and momentum acceptance, moderate momentum resolution, and particle-identification capability. Operation of the spectrometer in Q3D mode allows the high-resolution measurement around 1/3000 for deuteron beam.

As far as the low-energy part of the E1 strength is concerned, measurement at 250 MeV/A is more favorable compared with the similar measurement at GSI at higher energies, due to the larger number of virtual photons in the region of interest and higher intensity of the RI beam from cyclotron-based facility. Situation is nearly the same for radiative proton capture experiment.

Compared with other facilities, high-energy polarized deuteron beam at RIBF is very unique, since the polarization direction can be controlled in any direction.

Ⅷ Experimental examples

- Coulomb dissociation of neutron-rich nuclei:

  We propose Coulomb dissociation of N=51 nuclei, ^{79}Ni, ^{81}Zn, ^{83}Ge. Since N=51 nucleus may be loosely-bound and its E1 strength is interesting in terms of the relation to the ground state, which may have a lower l configuration. This study is important in order to see the change of the shell structure in the very neutron rich nuclei around N=50, and to locate the r-process path in this region.

  We are also planning to observe the collective giant dipole resonances by changing N/Z ratio, for example for neutron rich calcium isotopes and nickel isotopes.

- Coulomb dissociation of proton-rich nuclei:

  We would like to measure Coulomb dissociation of proton-rich nuclei up to Z=50. Typical examples of the experiments are

  1) Coulomb dissociation of ^{31}Cl into ^{30}S+p which is a path in the rp process , and
  2) Coulomb dissociation of ^{22}Si into ^{20}Mg+2p related to a question if the newly proposed magic number 14 in the oxygen isotopes also appear for protons in the proton-rich region.

  Using predictions [12], the expected cross sections are 0.3 and 11 mb respectively, more than 100 events are expected to be measured within 10 days using beam intensity of 10^3, a 200mg/cm^2-thick lead target, and 50-66% efficiency.

- Polarized deuteron-induced reaction
  - Polarization correlation measurement for the ^{3}He(d,p)^{4}He reaction
  - Analyzing power and polarization transfer measurement for the d+p elastic scattering and breakup reaction.

- EOS of asymmetric nuclear matter

  It is essential to use good combination of beam and target nuclei for scanning a nuclear system with a wide range of N/Z ratio. Therefore, we would like to measure π^+ and π^- production ratios in ^{112}Sn+^{112}Sn, ^{124}Sn+^{124}Sn, and ^{124}Sn+^{132}Sn reactions at around 300 MeV/nucleon. The central collision events are selected using a charged particle multiplicity in the TPC. Beam intensity of 10^5 particle/sec would be sufficient to perform experiment in a several days machine time.

Ⅷ References

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