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Current progress of nuclear astrophysics study and BRNBF at CIAE

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Abstract

A secondary beam line (GIRAFFE) at the Beijing tandem accelerator lab was constructed for yielding low energy secondary beams. The current progress on the study of nuclear astrophysics and nuclear structure is presented. Up to now, we have carried out measurement of $^{7}Be(d,n)^{8}B$, $^{11}C(d,n)^{12}N$, $^{8}Li(d,n)^{9}Be$ and $^{6}He(p,n)^{6}Li$ reactions. The proposed Beijing radioactive nuclear beam facility and its current R&D progress are briefly introduced. This facility is based on the exist HI-13 tandem accelerator. A proton cyclotron will be built to provide 100 MeV 200 μA proton beam, together with an isotope separator on line system and a super-conducting heavy ion LINAC. By this facility, intensity of order of 10^9 pps radioactive nuclear beams for mass up to $A = 120$ will be produced.

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Keywords: Secondary beam line; Nuclear astrophysical reaction; Radioactive nuclear beam facility

1. Description of secondary beam line GIRAFFE

The secondary beam line (GIRAFFE) for producing and for utilizing low energy beams of unstable nuclei has been constructed at the HI-13 tandem laboratory [1]. GIRAFFE was designed for studying reactions of astrophysical interest and the structure of unstable nuclei. The GIRAFFE beam line is shown in Fig. 1. It comprises a primary reaction chamber, a dipole–quadrupole doublet (D–Q–Q) beam transport system and a secondary reaction chamber (see Table 1). The primary beams such as ^{7}Li from the HI-13 tandem accelerator were used for producing unstable nuclei of interest via reactions such as $^{1}H(^{7}Li,^{7}Be)n$ (see Table 2). Because of the kinematic effect, the desired unstable nuclei are compressed into a forward cone. The radioactive nuclear beams (RNB) of interest were then magnetically separated from the scattered ^{7}Li beam and unwanted reaction products, and finally focused onto a secondary reaction target by using the D–Q–Q system.

1.1. Production of secondary beams

A gas cell was used as the primary target, and the RNB can be the time-of-flight (TOF) analyzed

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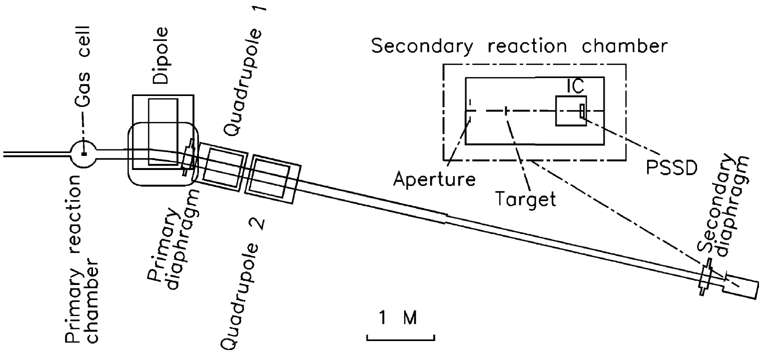

Fig. 1. Layout of GIRAFFE.

by a pair of microchancel detectors. The RNB were measured by using a ΔE–E counter telescope consisting of an ionization chamber or silicon detector backed by position-sensitive silicon detector. So far, the production of the ^{6}He, ^{8}Li, ^{7}Be, ^{11}C, ^{13}N and ^{17}F beams has been produced (see Table 3 and Fig. 2).

Table 1
The basic parameters of secondary beam line GIRAFFE

Maximum solid angle	$\Delta\Omega = 1.8$ mSr ($\Delta\theta = \pm 16.4$ mrad, $\Delta\phi = \pm 34.8$ mrad)
Maximum rigidity	$B\rho = 1.4$ Tm
Total length	$L = 9.8$ m
Focal plane dispersion	$\Delta X/(\Delta p/p) = 0.47$ cm/%
Acceptance angle	3°
Deflection angle	13°

2. Progress of astrophysical and nuclear physics reaction in GIRAFFE

2.1. Physical motivation

The astrophysical S-factor for the ^{7}Be(p, γ)^{8}B reaction at solar energies is a crucial nuclear physics input for the "solar neutrino problem". It was proposed that the S-factor can be indirectly determined through the asymptotic normalization constant (ANC) extracted from the proton pickup reactions of ^{7}Be, with an accuracy comparable to that from direct radiative capture or Coulomb dissociation reaction.

The ^{11}C(p, γ)^{12}N reaction is one of the key processes in hot pp chain. This reaction may be responsible for the production of ^{12}C in astrophysical scenarios where temperature T_9 (in unit of 10^9 K), greater than 0.1, such as X-ray burst star. The

Table 2
Summary of production reactions for the secondary beams and the characteristics of resulted beams

RNB	Production reaction	E_{beam} (MeV)	$d\sigma/d\Omega$ (mb/Sr)	E_{RNB} (MeV)	$\Delta B\rho/B\rho$ (%)	Intensity[a] (pps)
^{6}He	^{2}H(^{7}Li,^{6}He)^{3}He	42.0	160+	34.0 ± 1.0	17.3	2.2×10^5
^{7}Be	^{1}H(^{7}Li,^{7}Be)n	35.0	5000+	33.0 ± 0.5	−3.1	1.4×10^7
^{8}Li	^{2}H(^{7}Li,^{8}Li)^{1}H	42.0	900+	40.0 ± 0.5	5.2	1.2×10^6
^{11}C	^{1}H(^{11}B,^{11}C)n	78.1	6700−	57.0 ± 1.0	−17.5	4.5×10^6
^{12}B	^{2}H(^{11}B,^{12}B)^{1}H	66.0	1100+	65.0 ± 1.0	6.3	1.5×10^6
^{13}N	^{2}H(^{12}C,^{13}N)n	70.8	3000+	70.0 ± 1.0	−9.7	2.1×10^6
^{15}O	^{2}H(^{14}N,^{15}O)n	84.0	8300+	82.0 ± 1.0	−12.7	3.7×10^6
^{17}F	^{2}H(^{16}O,^{17}F)n	88.0	28 000+	85.0 ± 0.3	−10.8	1.3×10^7

The marks + and − refer to the forward and backward center-of-mass angular group selected, respectively.
[a] Values calculated by assuming a primary beam intensity of 1.0 pμA, gas cell pressure of 1 atm and differential cross sections at their optimum angles.

Table 3
Summary of the produced RNB at GIRAFFE

RNB	Reaction	Energy (MeV)	FWHM (MeV)	Purity (%)	Beam intensity (pps)[a]
^{6}He	^{2}H(^{7}Li,^{6}He)^{3}He	35.3	0.5	90	500
^{7}Be	^{1}H(^{7}Li,^{7}Be)n	23.0	1.3	92	1000
^{8}Li	^{2}H(^{7}Li,^{7}Be)^{1}H	39.0	0.8	90	500
^{11}C	^{1}H(^{11}B,^{11}C)n	38.2	2.7	85	1000
^{13}N	^{2}H(^{12}C,^{13}N)n	65.7	2.3	6	500
^{17}F	^{2}H(^{16}O,^{17}F)n	74.9	4.8	24	2000

[a] With 2 mm diameter collimator and primary beam intensity 10–100 enA.

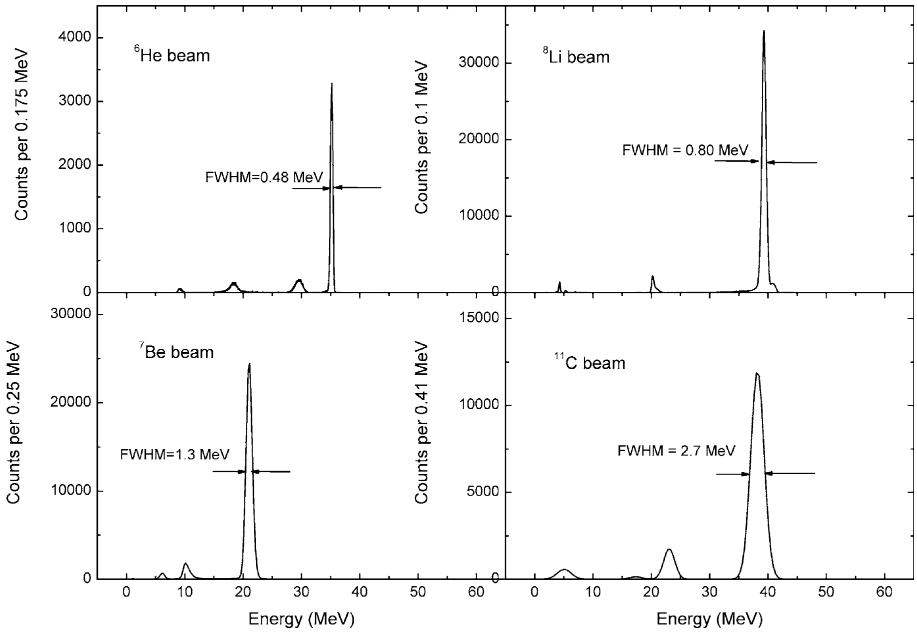

Fig. 2. Typical secondary beams produced in GIRAFFE.

reaction rate results from the contributions of the tails of 0.95 2^{+} and 1.19 MeV 2^{-} resonance in ^{12}N and the direct capture (DC). The DC component can be measured via (d,n) reaction using ANC method.

Since some neutrons are weakly bound in the excited states of stable nuclei, it seems natural that they exhibit spatially extended halo structure as drip line nuclei. This would be the case for the 0^{+} 3.563 MeV excited state of ^{6}Li and can be explored by (p,n) reaction.

2.2. Experimental setup and data analysis

The inverse kinematics of the (d,n) and (p,n) reaction restricted the emerging angle that can be covered by a single detector. For ^{11}C experiment, the TOF parameter was applied to select the ^{11}C-induced event off-line, and thus suppressed background from beam contaminants. For the ^{8}Li(d,n)^{9}Be reaction, the energy and particle identification was accomplished by using a ring silicon detector, a central ΔE–E silicon detector. This ensures particle detection in forward angle; the reliable angular assignment, and the elimination of pulse pile-up in the ring detector.

The distorted-wave Born approximation (DWBA) codes adopted in the analysis of all the (d,n) data. The optical potential parameters for the deuteron and neutron are carefully chosen from the nearby nuclei at the closest energies or from

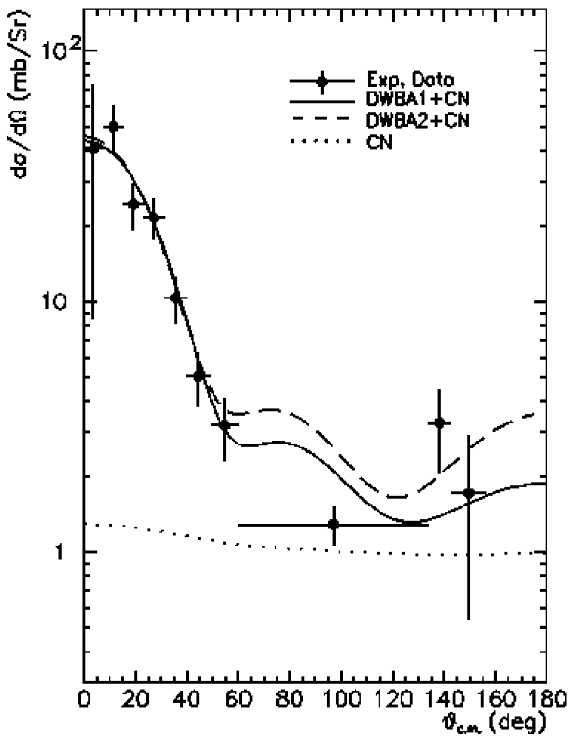

Fig. 3. The ^{7}Be(d,n)^{8}B angular distribution in $E_{\mathrm{c.m.}} = 5.8$ MeV with DWBA analysis.

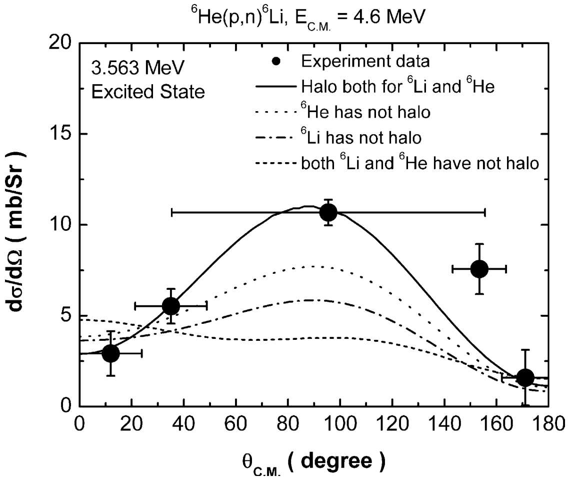

Fig. 4. The experimental deduced ^{11}C(p, γ)^{12}N astrophysical S-factors.

the systematic evaluations [2,3]. The experimental ^{7}Be(d,n)^{8}B angular distribution with DWBA analysis is shown in Fig. 3. Because of the position distortion due to the radiation damage, the integrated ^{11}C(d,n)^{12}N reaction cross section was used to deduce ANC. The ^{11}C(p, γ)^{12}N cross section was calculated by microscopic code. The results shows that the DC contribution is dominant in the interested astrophysical sites, as shown in Fig. 4. The ^{8}Li(d,n)^{9}Be was directly used to deduce the primordial reaction S-factor. All measured astrophysical reactions and their deduced parameters are summarized in Table 4.

A DWBA analysis was also used to analyze ^{6}He(p,n)^{6}Li data to explore the valence nucleon distribution. Results show that both the ground state of ^{6}He and the second excited state of ^{6}Li(0^{+}) have "halo" structures [4], as shown in Fig. 5.

3. Proposed BRNBF project

3.1. Introduction

The isotope separator on line (ISOL) type RNB facility is an indispensable selection, as proposed and constructed in nuclear laboratories worldwide. The user community in China strongly suggest such facility. The Beijing radioactive nuclear beam facility (BRNBF) was proposed accordingly [5]. With the support of multi-financial sources, we

Table 4
The summary of astrophysics experiment results

Reaction	$E_{\mathrm{c.m.}}$ (MeV)	σ_{tot} (mb)	ANC	Deduced	S-factor
^{7}Be(d,n)^{8}B	5.8	58 ± 8	0.711 ± 0.09	(p, γ)	27 ± 4 eV b
^{7}Be(d,n)^{8}B	8.3	28 ± 3	0.62 ± 0.12	(p, γ)	24 ± 5 eV b
^{11}C(d,n)^{12}N	5.0	47 ± 23	3.5 ± 1.5	(p, γ)	190 ± 80 eV b
^{8}Li(d,n)^{9}Be	7.9	6.2 ± 3.3	–	(d, n)	180 ± 90 keV b

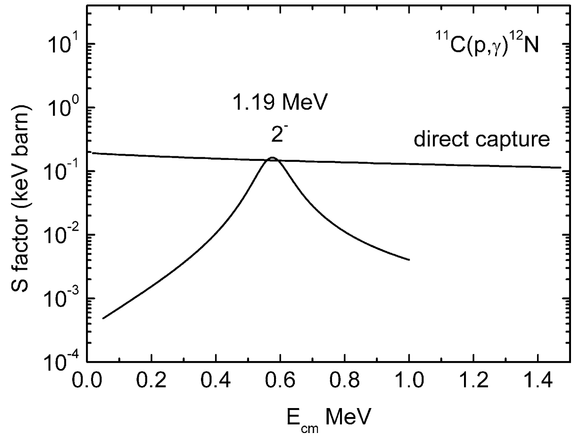

Fig. 5. The experimental angular distribution of $^6He(p,n)^6Li^*$ compared with DWBA calculations with different nucleon density distributions.

have carried out the R&D study, concerning the key technology related with BRNBF.

3.2. The research opportunity of BRNBF

Nuclei at extreme condition of spin and isospin is one of the frontiers of nuclear physics. With proton-rich and neutron-rich beams from BRNBF, a great extension of our existing research in these fields will become possible. Using fusion evaporation reaction, the isospin of the reaction products is related to the beam isospin. With proton-rich beam of BRANF, we can study the structure of $N = Z$ nuclei and to search for new proton-rich isotopes and to discover their exotic decay properties.

In the field of nuclear astrophysics, the explosive nuclear process intend to the region of proton- and neutron-rich area far from β-stability line. Those processes can be measured directly and indirectly the reactions induced by unstable beam and the decay properties of unstable nuclei. With BRNBF, we are capable to perform many measurements in the field such as nuclear reactions involved in the primordial nuclear synthesis, hot pp-chain, hot CNO cycle, reactions in the NeNa–MaAl cycle and p-process.

In the high-spin study of rare earth nuclei, many new findings such as back banding, band termination, disappearance of pair effect and super-deformation have been discovered. With the existing tandem, we can only using light beam such as ^{16}O and ^{19}F to reach this area. By using the energy booster capability of BRNBF, the heavier beam such as P, S and Cl stable and unstable beams will allow us to explore even higher spin states and new phenomenon.

The higher heavy ion beam energy will greatly enhance the research field of atomic physics, with high purity, high charge state and high excitation. The data measured will be used in the fields such as fusion reactor, X-ray laser, astrophysics, etc.

RNBs separated and extracted from ISOL can be widely used solid state physics and semiconductor material study. It will use many novel methods such as tracer expansion, channeling effect, PAC, etc. Such a study will provide a unique probe to detect the structural defect, contaminant expansion and position of crystal in the semiconductor.

3.3. Project description

BRNBF will be based on the existing 13 MV tandem accelerator (now undergoing upgrading to 15 MV). A compact cyclotron, with proton beam energy of 100 MeV and intensity of 200 μA will be built upstream tandem. An ISOL with mass resolution of 20 000 will be constructed in between to convert intense proton beam into RNB that suitable for tandem injection. After the tandem, a super-conducting LINAC sector will be installed to further boost the beam energy by 2 MeV/q (see Figs. 6 and 7).

In general, the production efficiency of primary H^+ beam to exotic nuclei is about 0.1%. The ionization efficiency of exotic atoms to ions in the ion source is about 30%. The conversion efficiency of positive ions to negative ions passing through charge exchange device is about 30%. The transmission of RNB in the on-line isotope separation system is about 40%. The transmission of RNB through the HI-13 tandem accelerator and the booster is about 30%. According to above estimation, RNB intensity of more than 10^9 pps will be produced by BRNBF. It will produce up to 40 proton-rich and 80 neutron-rich RNB species as shown in Fig. 8.

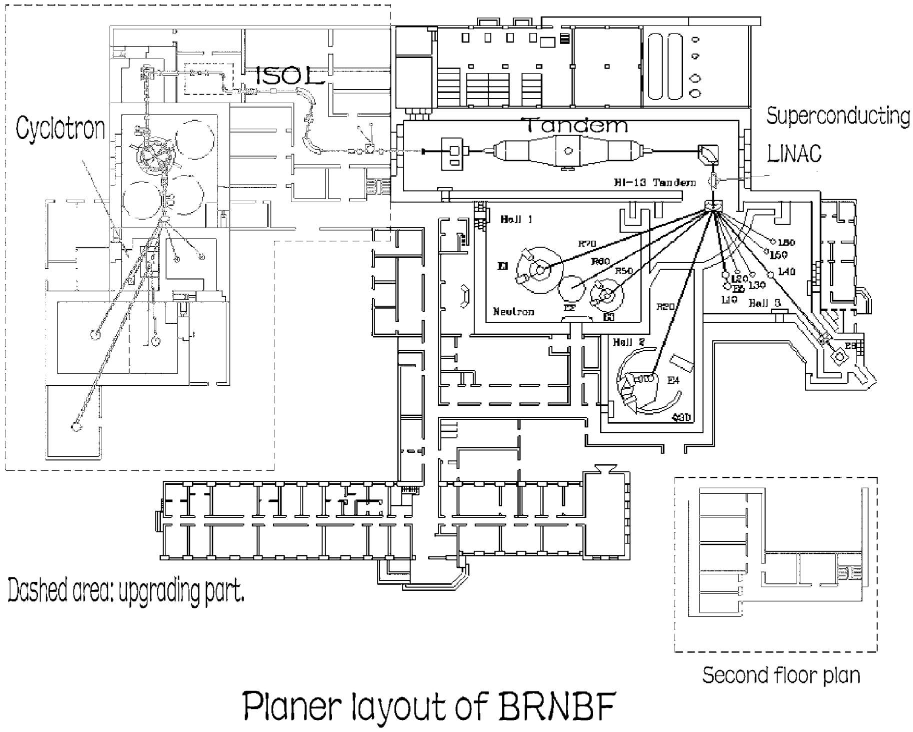

Fig. 6. General layout of BRNBF.

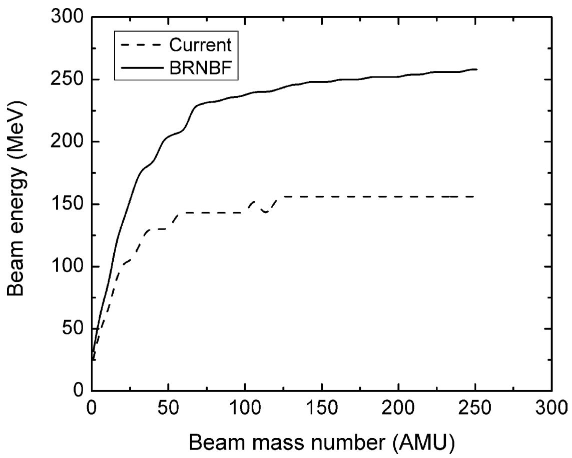

Fig. 7. Beam energy of BRNBF.

3.4. The cyclotron

3.4.1. General description

The driving accelerator, 100 MeV H^- cyclotron will provides 75–100 MeV continuous proton beam. Its beam intensity is 200–500 μA. For a beam energy of less than 100 MeV and beam intensity of less than 1 mA, a cyclotron with compact magnet and a H^- acceleration with stripping extraction design is a good choice in the sense of compactness and economy (see Fig. 9 and Table 5). The construction experiences from building the 30 MeV cyclotron in CIAE dedicated for medical use can be used for the new machine development. The machine will have the following features:

- The compact magnet with deep valley will provide high enough flutter and lower first harmonic though the harmonic coils will be absent.
- The H^- acceleration will allow us to extract the beam by stripping instead of by electrostatic deflector, which will increase the extraction efficiency up to almost 100%.
- The external source not only provides higher beam intensity, but also gives us a convenient way to maintain the ion source and keep a better vacuum in the main chamber. It is also

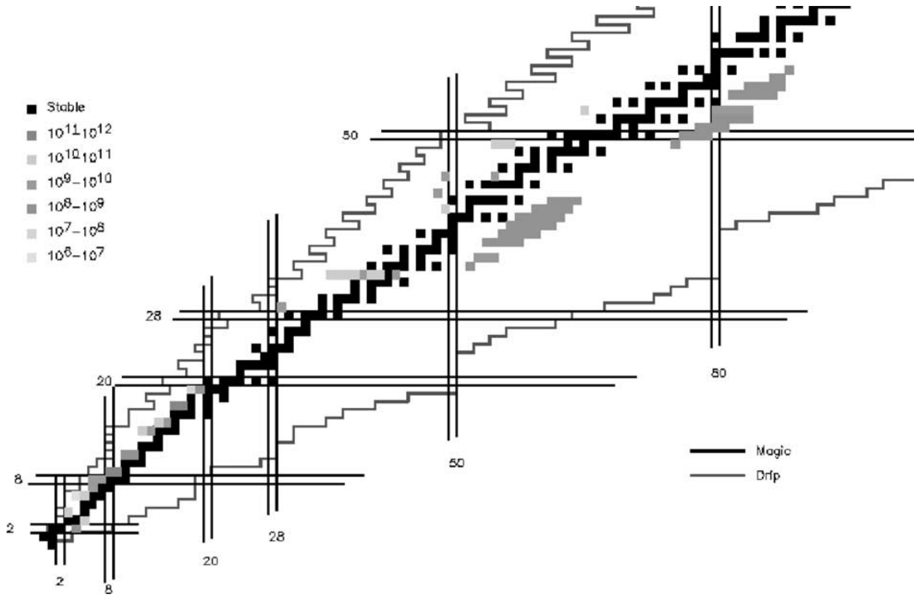

Fig. 8. RNBs produced by BRNBF.

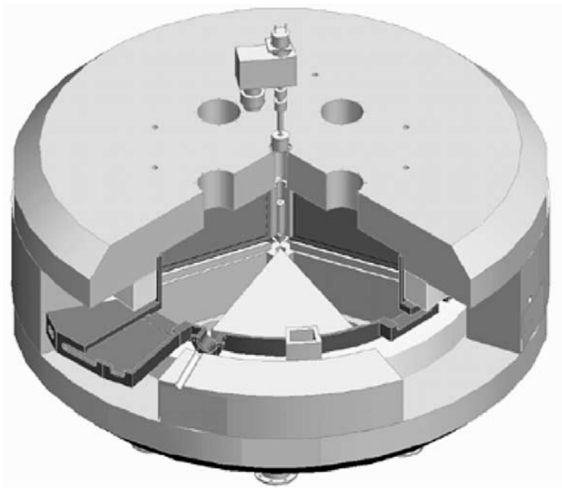

Fig. 9. Structure of 100 MeV proton cyclotron.

shows possible to provide pulsed proton beam by the cyclotron.

3.4.2. R&D study for basic components of cyclotron

For the magnet study, four simple sectors structure is selected for the main magnet firstly. The isochronous field can be achieved by some adjustment of the shimming bar attached at both sides of the sectors. The spiral sectors will be tried to get a stronger axial focus. The field distribution

Table 5
Cyclotron specification

Proton beam	Energy	75–10 MeV
	Intensity	200–500 μA
Ion source and injection	Type	Multi-cusp
	Current	>5 mA
	Injection energy	~30 kV
Four sector magnet	Sector angle	52°
	Field in hill	1.4 T
	Radius of the pole	1920 mm
	Gap between the hills	40 mm
	Total weight of iron	470 t
Main coils/power supply	Ampere-turn number	60 kA T
	Current density of coil	0.55 A/mm^2
	DC power	20 kW
	Stability	1.0×10^{-5}
Two Dee RF system	Dee voltage	50–60 kV
	Dee angle	34°
	Harmonic mode	4
	Frequency	49.6 MHz

based on spiral sector magnet is calculated recently.

For the RF cavity study, two half-wave cavities are installed in the valley of the main magnet. The cavity can be equivalent to an axial symmetrical structure so as to calculate the resonance frequency by a 2D code, such as SUPERFISH. Various dimension of the cavity are tested and the results are compared and optimum parameters are selected.

3.5. The ISOL system

3.5.1. Test bench of target/source

The test bench of target/source system has being developed. It consists of the primary beam line, the target–ion source, the Einzel lens, the magnetic analyzer, the device for measuring RNB and target chamber. The design and manufacture of this system have been completed. It has be assembled and tested on the beam line of the HI-13 tandem accelerator in 2002.

3.5.2. Conception design of ISOL system

The conception design of ISOL system for BRNBF has been completed. It is composed of two 300 kV accelerating tubes, an ion/source, the Einzel lens, three magnetic doublet quadruple lenses, the charge exchange device, two pre-magnetic analyzers, the electrostatic triplet quadruple lenses, two isobar separators, see Fig. 10.

3.5.3. Target/source

The EBPIS type of ion source is first selection for production of RNB because it is of high ionization efficiency, low ion beam emittance and big ability for production of more ion species. The cathode of the ion source is made from Ta and electron emission power is 2 KW. The wall of ionization chamber is coated by Re or Ir for reducing time which radioactive nuclides detain on surface of the ionization chamber. Power supplies of the ion source are as follows: cathode 6 V/500 A; anode 400 V/1 A; magnet foil 20 V/50 A; extraction 30 kV/10 MA.

3.5.4. First stage analyzer and isobar separator

The technical specifications of the first stage magnetic analyzers are as follows: mass–energy production 12 MeV A; mass resolution 1000; radius of ion central obit 0.6 m; deflection angle 90°; gap 40 mm; width of magnetic pole 200 mm; maximum field 0.8 T. The technical specifications of the isobar separator are as follows: mass resolution 20 000; radius of ion central obit 2.5 m; deflection angle 100°; gap 50 mm; pole width 300 mm; maximum field 1.2 T.

3.6. The super-conducting LINAC

In order to extend the region of stable and the radioactive ion species with energy higher than relative Coulomb barrier, a booster following the

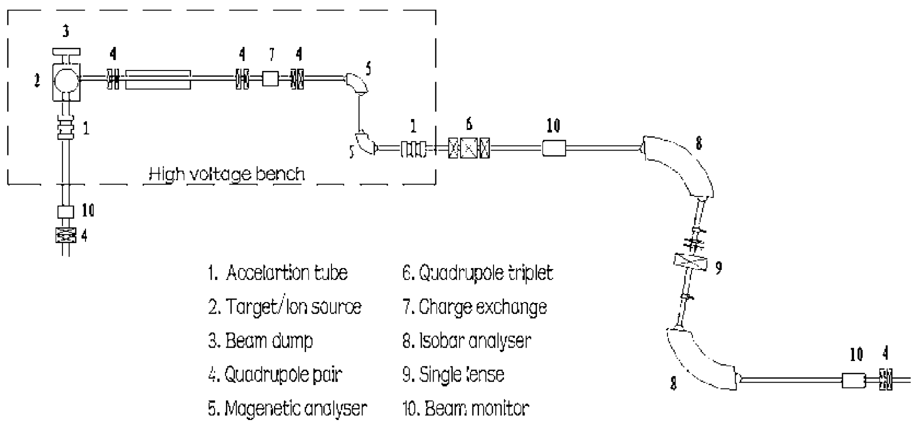

Fig. 10. The general layout of ISOL facility.

tandem accelerator has to be planned to build, that is a super-conducting booster.

The design goal of our LINAC booster is to have an energy gain of 2 MeV/q. A new post-stripper accepts the high-energy beam coming from the tandem accelerator, in order to increase the ions charge state. The 90° bending magnet can select desired charge state into the LINAC.

Our super-conducting booster is composed of four QWR cavities, which are located into one cryostat, which has a diameter of 1.1 m. We choose the cavities of the optimum $\beta = 0.07$ for frequency of 108 MHz.

The R&D of the mechanical and electrochemical preparation of the substrate of the cavity, the technology of the niobium-sputtered copper quarter wave resonators have been testing in Peking University.

3.7. Summary

A secondary beam line GIRAFFE was built for yielding low energy secondary beams. Up to now, ^{6}He, ^{7}Be, ^{8}Li, ^{11}C was used for nuclear astrophysics and nuclear structure studies. Such a simple electromagnetic device is proved to be an indispensable tool for studying low energy RNB reactions.

For the GIRAFFE development, a beam swinger may be installed for altering the incident angle of the primary beam on target, so that one can select the optimal acceptance angle for each RNB. Velocity filter may be installed to enhance the secondary beam selection. A more flexible detector chamber will be set up, which will cover larger angular range than current setup. In addition, the use of a MUSIC detector is planned by using the gas of the MUSIC both for detection and as a secondary target. And the fabrication of secondary gas target with windows was also considered.

The ^{7}Be(d,n)^{8}B, ^{11}C(d,n)^{12}N, ^{8}Li(d,n)^{9}Be and ^{6}He(p,n)^{6}Li reaction has been measured, from which the astrophysical *S*-factor for the (p,γ) reactions and/or nuclear radii were derived. The ANC method is proved to be of importance where the direct (p,γ) measurement is not possible.

The proposed BRNBF will provide new opportunities in Beijing tandem accelerator lab. With a proton cyclotron, an ISOL system and a super-conducting LINAC, up to 80 neutron- and 40 proton-rich RNBs with intensity of order of 10^9 pps will be produced.

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