TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 18

Title of proposed experiment:

Direct measurement of astrophysical $^{11}C(p,\gamma)^{12}N$ Reaction at DRAGON

Name of group: Nuclear Astrophysics

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Start of preparations: January 22, 2004	Beam time requested:
Date ready: Fall 2004	12-hr shifts: 60; Beam line/channel: ISAC-HE/DRAGON; Polarized primary beam?: No
Completion date: 2005	

Excitation function of the ^{11}C(p,γ)^{12}N at $E_{\mathrm{c.m.}}$=0.2-1.0 MeV will be measured in inverse kinematics with the secondary ^{11}C beam at DRAGON. The ^{11}C(p,γ)^{12}N is one of the key reactions in the hot pp chains, which are believed to be of importance for the evolution of very low-metallicity, massive stars. There are large discrepancies in the existing indirect measurements and theoretical calculations of this reaction for both direct and resonant captures. The present proposal aims at clarifying these discrepancies through the direct measurement of excitation function by using high precision DRAGON spectrometer. Based on the measured excitation function, we will be able to derive the energy dependence of astrophysical S-factors for direct capture into the ground state of ^{12}N and resonant captures into the first and second excited states of ^{12}N at 2^+ 0.960 MeV and 2^- 1.191 MeV, as well as the interference between the direct capture into the ground state and resonant capture into the second excited state. The temperature dependence of direct capture-, resonant capture- and total reaction rates will be given.

Experimental area

ISAC-HE, DRAGON

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

500 MeV $40\mu A$ unpolarized proton beam.

ISAC Zeolite production target.

Secondary channel none

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

DRAGON beams of unstable ^{11}C with energies of 0.2-1.0 MeV/u.

The beam fluxes must be on the order of 10^8 to 10^9 pps. The lowest possible contamination level of ^{14}N and ^{12}C is required.

TRIUMF SUPPORT:

- ISAC
- development of a ^{11}C on-line ion source
- technical support for operating the windowless gas target
- technical support for operating the DRAGON facility
- MIDAS data acquisition system

NON-TRIUMF SUPPORT

Most of collaborators are the residents at TRIUMF. There are several outside collaborators, for whom we would like to be able to provide partial travel support. Funds for this purpose will be requested from NSERC for the 2003/2004 fiscal year, and/or from Ministry of Science and Technology (MOST) of China.

The basic supply of man power should come from current DRAGON collaboration. The members from China Institute of Atomic Energy (CIAE) come to TRIUMF to take part in the experiment, and then perform the offline analysis at home.

The financial support come from TRIUMF that supplies the daily operation and maintaining of DRAGON, and from CIAE through the support from MOST that supply the travel and stay of Chinese members.

The safety concerns for this experiment are:

- radioactivity of the beam ^{11}C, of which most will be dumped within the DRAGON facility.
- use of hydrogen gas in the target.

Local shielding has to be arranged and proper local radiation monitors have to be installed. The gas target will run in a recirculating mode, so the pollution to the atmosphere is negligible.

1 Scientific Justification

1.1 Astrophysical Importance

The proton- and α-capture reactions on proton-rich unstable nuclei of A$\leq$13 involved in the hot pp chains are thought to be another alternative way to the 3α process for transforming material from the pp chains to the CNO nuclei in the peculiar astrophysical sites where the temperature and density are high enough so that the capture reaction becomes faster than the competing β decay [1–3]. These linking reactions between the nuclei in the pp chains and the CNO nuclei might be of immense importance for the evolution of massive stars with very low metallicities.

One of the key reactions in the hot pp chains is the ^{11}C(p,γ)^{12}N which is believed to play an important role in the evolution of Pop III stars. This reaction is also responsible in ^{11}B synthesis in novae.[3]. As a result of the low Q-value, its cross section at astrophysically relevant energies is likely dominated by the direct capture into the 1^+ ground state of ^{12}N, and the resonant captures into the first- and second excited states of ^{12}N at 2^+ 0.960 MeV and 2^- 1.191 MeV, respectively.

1.2 Current Status

The ^{11}C(p,γ)^{12}N reaction has increasingly attracted the theoretical and experimental studies. However, it is very difficult to directly measure this reaction at energies of astrophysical interest because of the vanishing small cross section and low intensity of the available ^{11}C beam at present. Wiescher *et al.* derived the gamma widths of the 2^+- and 2^- states in ^{12}N equal to 2.59- and 2.0 meV from the life time of the first excited state in ^{12}B and the systematic rule of E1 matrix elements in light nuclei respectively, under the assumption of a 100% branching ratio to the ground state in ^{12}N [1]. Subsequently, Descouvement and Baraffe performed a microscopic cluster model calculation which gave Γ_γ = 140 meV for the 2^- state [2], and the repeated calculation yielded an updated value of 68 meV [3]. The Coulomb-dissociation experiment of ^{12}N by Lefebvre *et al.* derived Γ_γ = $6.0^{+7}_{-3.5}$ meV for the 2^- state and an estimate of astrophysical S-factor for the direct capture [4], whereas a similar measurement by Minemura *et al.* yielded $\Gamma_\gamma = 13\pm0.5$ meV [5]. Recently, Timofeyuk and Igamov have performed a theoretical calculation of the direct capture contribution to the ^{11}C(p,γ)^{12}N reaction, derived S-factor at zero energy S(0) equal to 0.149- and $0.111^{+0.025}_{-0.020}$ keV b based on two different methods, respectively [6]. Most recently, Tang *et al.* have indirectly studied the direct capture reaction ^{11}C(p,γ)^{12}N by measuring the angular distribution of the ^{14}N(^{11}C,^{12}N)^{13}C peripheral transfer reaction and using the asymptotic normalization coefficient (ANC) approach [7], with S(0) equal to 0.093$\pm$0.013 keV b. This result was supported by an independent indirect experiment by using d(^{11}C,^{12}N)n reaction [8], S(0) equal to 0.157$\pm$0.050 keV b . Both experiments reveal the importance of the direct capture process(DC) in the astrophysical temperature of T_9 from 0.1 to 0.3, that is considered to be negligible in previous calculations [2].

The implication of the difference of currently available ^{11}C(p,γ)^{12}N reaction rates to CNO cycle can be seen in Fig. 3. This figure shows the resulted difference for ^{3}He to CNO transforming rates. The higher the reaction rate, the faster the transforming speed from ^{3}He to CNO material.

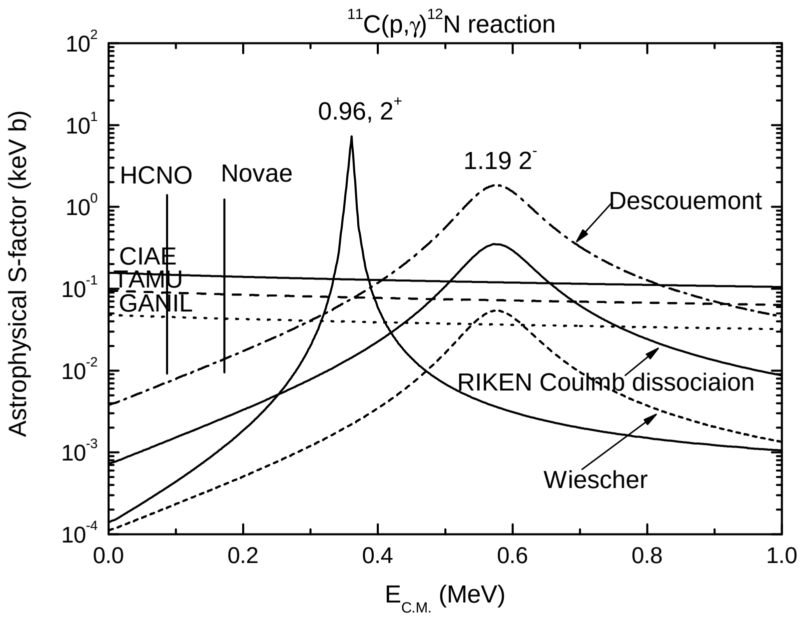

Fig. 1 The deviation of ^{11}C(p,γ)^{12}N s-factor for direct capture and resonances.

E_x (MeV)	E_R (MeV)	J^π	Γ_p (keV)	Γ_γ(The.) (meV)	Γ_γ(Exp.) (meV)
0.960	0.359	2^+	5.5 [4]	2.59	
1.190	0.589	2^-	118±14 [2]	2 [11],68,140[12]	6[4],13±0.5[5]

Table 1 The current status of ^{12}N level property.

In summary, there are large discrepancies for both DC and resonant capture contributions in the ^{11}C(p,γ)^{12}N reaction, as illustrated in Fig. 1 and summarized in Table 1 and 2. Thus the more reliable direct measurement is necessary.

The level scheme of ^{12}N is shown in Fig. 2. The basic properties of the levels in ^{12}N, including excitation energy, center of mass energy, measured and calculated gamma widths are listed in Table 1. The currently available DC S-factors are given in Table 2.

Result	Method	Reference
157±50 eVb	ANC	CIAE[8]
93±13 eVb	ANC	TAMU[7]
47 eVb	Coulomb	GANIL[4]
149 eVb	Microscopic	Timofeyuk[6]

Table 2 The current status of direct capture contribution for ^{11}C(p,γ)^{12}N S(0)-factor.

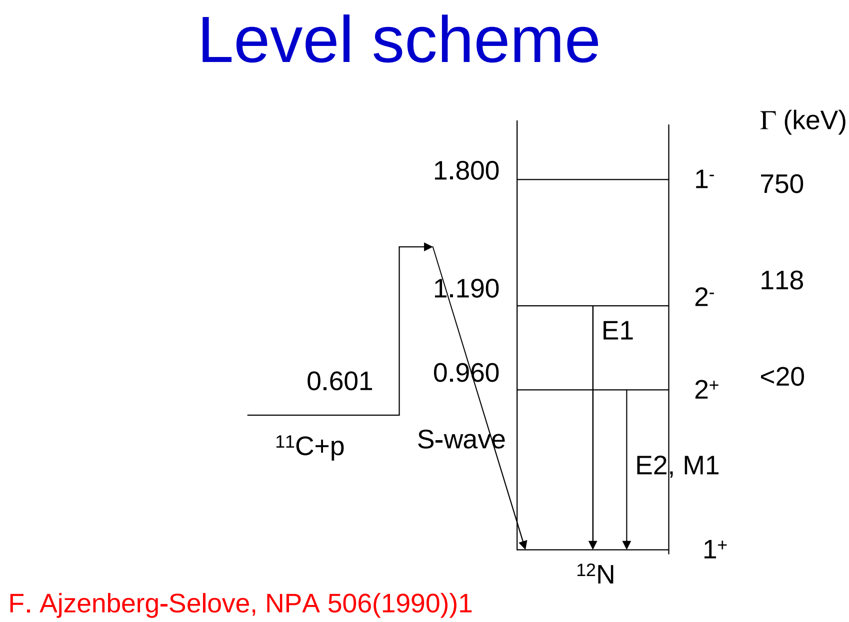

Fig. 2 The level scheme of ^{12}N and corresponding transitions.

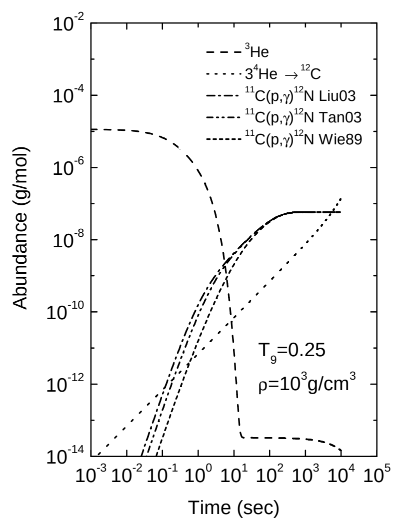

Fig. 3 Material flow of metal-poor massive star. The isotope ^{3}He transfer to CNO material via ^{3}He(α,γ)^{7}Be(α,γ)^{11}C(p,γ)^{12}N. The figure shows the consumption of ^{3}He, as well as reaction flow of other reaction.

1.3 Present Proposal

In this proposal, we will measure the excitation function of the ^{11}C(p,γ)^{12}N reaction and directly determine the direct capture S-factor and the rate for the ^{11}C(p,γ)^{12}N reaction at astrophysical energies. In addition, we will also extract the contributions of the resonant captures into the first- and second excited states of ^{12}N and the interference between direct capture into the ground state and resonant capture into the second excited state.

The experimental cross section will be converted to astrophysical S-factor via:

$$\sigma(E) = 1/E \exp(-2\pi\eta) S_{DC}(E)$$

Where,

$$\eta = Z_1 Z_2 \alpha (\frac{\mu C^2}{2E})^{1/2}$$

is Sommerfeld parameter.

The excitation curve in resonant part is related to the gamma-width via:

$$S_{RES}(E) = \pi \frac{(\hbar c)^2}{2\mu C^2} \frac{2J_r+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_{in}(E)\Gamma_{out}(E)}{(E-E_r)^2+(\Gamma_{tot}/2)^2} \exp(2\pi\eta)$$

The total S-factor and the interference term is expressed by:

$$S_{tot} = S_{DC}(E) + S_{Res}(E) \pm 2\sqrt{S_{DC}(E) S_{Res}(E)} \cos(\delta_{Res}(E))$$

where

$$\delta_{Res}(E) = \tan^{-1}(\frac{\Gamma_{in}(E)}{2(E-E_r)})$$

The sign of interference should be determined by this experiment.

The direct measurement for the ^{11}C(p,γ)^{12}N reaction is conducive to clarify some discrepancies for both the direct- and resonant captures and this is the goal of present proposal.

1.4 Competitive Measurements

As stated previously, nuclear astrophysics is a subject of research which is now being recognized as of prime interest at all of the radioactive nuclear beam factories. TRIUMF has a chance to be the first of the laboratories to directly measure this important reaction, if this proposal is approved with sufficiently high priority. At the moment, there is no strong competition because the only proposal for the direct measurement is with relative poor experimental feasibility. The situation, however, could change within a couple of years.

Laboratory	Beam energy	Beam intensity
LBL	60-130 MeV	10^7 pps
Louvain-la-Neuve	6.2-10 MeV	10^7 pps [28]
Beijing(CIAE)	40-60 MeV	10^4 pps
TAMU	10 MeV/u	4×10^5 pps [7]
DRAGON	0.15-1.5 MeV/u	10^8-10^9 pps

Table 3 The current status of ^{11}C unstable beam production.

The experiments or proposals to directly measure the ^{11}C(p,γ)^{12}N reaction are as follows:

- Louvain-la-Neuve 1996 (unsuccessful [27].)
- Louvain-la-Neuve 2003 (proposed [9].)

In the first attempt of direct measurement [27], a ^{11}CO beam with 8×10^{10} pps intensity was extracted from ECR ion source. This experiment focused on the detection of β-ray emission of ^{12}N, since it has a higher end point energy of 16.4 MeV. The experimenters tried to separate the ^{12}N rays from those of background by using a solenoid magnet and an energy degrader, a high detection efficiency of 10 % was expected to achieve. No further results and/or publications appeared later on. Perhaps the experiment encountered the difficulties caused by high background and identification of ^{12}N β-rays.

In the second proposal[9], they intend to use ARES recoil mass separator for measuring the ^{12}N recoils. In comparison with our proposal, their facility and setup do not provide the high intensity of ^{11}C beam and γ-detection capability. Furthermore, the solid target to be used will hinder them to extend the measurement down to the lowest possible energy.

Table 3 gives a summary of the ^{11}C beam production in the world. TRIUMF is able to provide the highest beam intensity in the energy range of astrophysical interest and has the unique DRAGON facility.

Clearly, this is an opportunity for TRIUMF to make an important contribution in the new research area.

2 Description of the Experiment

We propose to measure directly the cross section and the excitation function for the ^{11}C(p,γ)^{12}N reaction by using DRAGON spectrometer in recoil-γ coincidence mode. In this experiment, the S-factors for direct capture into the ground state and resonant captures into the 0.96 MeV and 1.19 MeV states in ^{12}N will be explored with the best precision so far, and the Γ_γ partial width of 1.19 MeV state can be extracted. A DSSSD detector will be used at focal plane for recoil energy and position measurements. The reaction kinematics is shown in Fig 4.

The center of mass energy range in which the measurements will be performed is shown in Fig. 5. If it is allowed to increase the ^{11}C beam intensity or beam time and extend

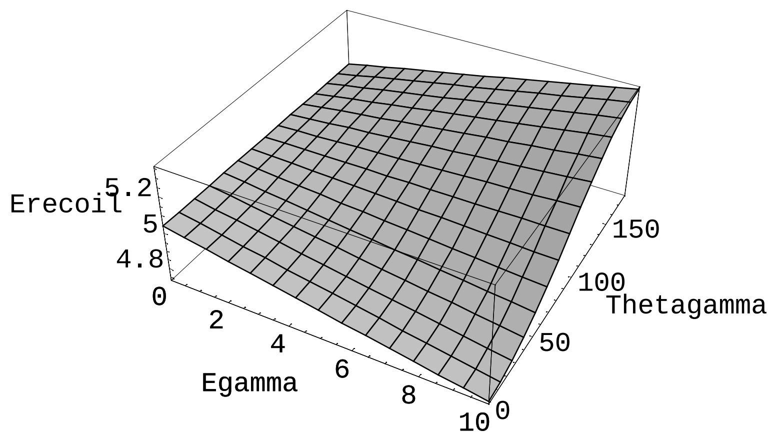

Fig. 4 The ^{12}N recoil energy (MeV) in $^{11}C(p,\gamma)^{12}N$ reaction , as a function of γ-ray energy (MeV) and γ-ray emerging angle. The ^{11}C beam energy is taken as 0.5 MeV/u.

the measurement down to the center of mass energy of 0.15 MeV(excitation energy 0.75 MeV), the properties of 0.96 MeV state in ^{12}N could also be extracted.

2.1 Experimental Arrangement

In order to ensure the reliability of the experimental results, we plan to implement the following measures in the experiment:

1. Make the coincidence of ^{12}N recoils with γ-rays to enhance the ratio of effect to background;

2. Use DSSSD detector to measure the ^{12}N recoils. The current experiment with DRAGON shows this detector is adequate to fulfill the requirements of both energy and position resolution.

3 Experimental Equipment

The DRAGON (See Fig. 6) is a powerful spectrometer with large acceptance, high γ-ray detection efficiency, position sensitive silicon detector at focal plane and windowless gas target that is necessary to perform a measurement down to the lowest possible beam energy. Thus ISAC-DRAGON provides the best experimental condition in the world to study the $^{11}C(p,\gamma)^{12}N$ reaction with a high background suppression ratio, namely

- High beam intensity, 10^8-10^9 pps to be expected;
- Windowless H_2 gas target, allowing low energy, background-free measurement;
- Coincidence measurement of ^{12}N recoil with γ-ray;
- Large acceptances of 25 mrad (see Fig. 7.)

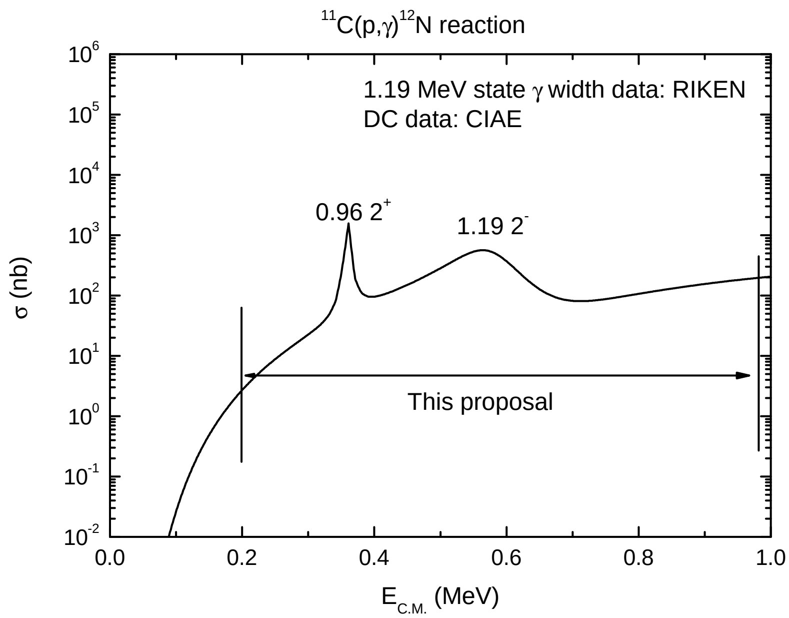

Fig. 5 The estimated energy dependence of the $^{11}C(p,\gamma)^{12}N$ cross section, together with the energy range to be covered in our proposal.

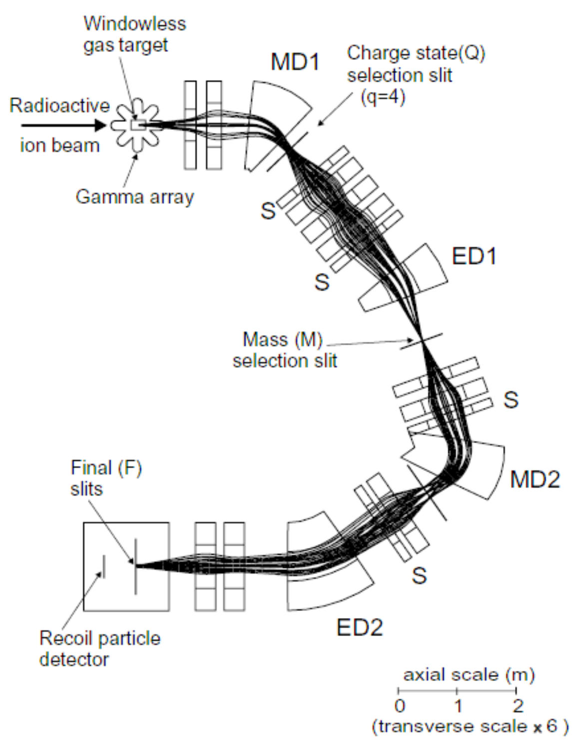

Fig. 6 Schematic representation of the DRAGON layout with typical ion trajectories.

4 Readiness

The desired beam time is 2004-2005, this is a compromise to worldwide competition and the readiness of our experimental preparation.

The DRAGON facility is in good condition. The ^{11}C on-line ion-source is under development, which should be much benefited by the experience of ^{11}C production in TISOL and in Louvain-la-Neuve. Also an estimation of ^{11}C beam production was presented in ORNL.

There were experiments in TISOL [29], using ECR ion source and 13.1 g/cm^2 zeolite target to produce carbon beams like ^{10}C. The resultant production rate were 1.2×10^7/s/μA.

Based on this data and SHIELD spallation code, and assuming a uniform target material distribution, we expect that ECR ion source will be able to deliver a ^{11}C beam intensity up to 2×10^9 pps, with a 40 μA proton beam. An accelerated ^{11}C beam with intensity up to 2×10^8 pps is then expected, assuming a 10 % transmission efficiency of ISAC. Of course, it is possible to enhance ^{11}C beam intensity by increasing proton beam intensity, as the progress in target-ion source technology.

5 Beam Time required

The request for beam time depends on the event rate estimate that is related to the ^{11}C beam intensity and cross section of ^{11}C(p,γ)^{12}N reaction. The uncertainty of cross section can be seen from Fig. 1, and this is the very topic to be solved in present proposal.

It is feasible to achieve an acceptable experimental precision within an affordable beam time, by using DRAGON spectrometer. A reasonable estimate can be given according to the following realistic condition:

- 10^8-10^9/sec ^{11}C ions impinge on the H_2-gas target;
- Using 8 torr H_2-gas target, the equivalent areal density 10^{18} atom/cm^2;
- 25 % overall efficiency (γ(50%)*+DRAGON(50%))
- 100-1000 nb cross section

*The real gamma detection efficiency may be lower due to the high background of 511 keV γ-rays.

We have carefully calculated ^{12}N acceptance in DRAGON, based on the reaction kinematics and measured DRAGON acceptance data. As can be seen from Fig. 7, a full transmission of ^{12}N recoils in a single charge state can be achieved in DRAGON.

The event rate estimate with the assumed condition is plotted in Fig. 8. As a result, we expect 2-100 events/day in the proposed energy range. For the sake of measurement reliability, we require 60 shifts for the measurement of an excitation function from 0.2 to 1.0 MeV in center of mass frame, with 50 keV step in 0.2-0.3 MeV for measuring direct

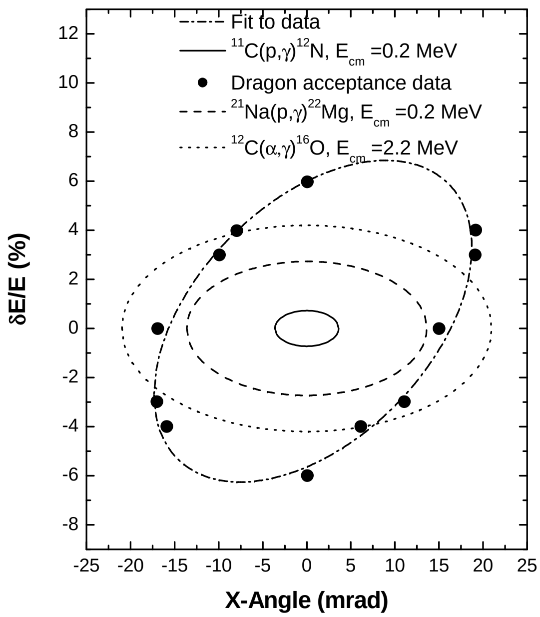

Fig. 7 The acceptance calculation of $^{11}C(p,\gamma)^{12}N$ reaction for specified experimental conditions, shown as DRAGON acceptance as the functions of energy difference and recoil angle. Points are the measured points where transmission of a beam was 50% of maximum, circle represent the ^{12}N acceptance.

Beam energy (MeV)	Energy step (keV)	focus	Shifts required
0.2-0.3	50	DC	6
0.3-0.4	10	2^+	20
0.4-0.7	20	2^-	20
0.7-1.0	50	DC/interference	14

Table 4 The beam time requirement of ^{11}C unstable beam with respect of center of mass beam energy .

capture, 10 keV step in 0.3-0.4 MeV for 2^+ 0.960 MeV resonance, 20 keV step in 0.4-0.7 MeV for 2^- 1.191 MeV resonance and 50 keV step in 0.7-1.0 MeV for direct capture and determination interference sign. The large proton widths of 2^+ and 2^- resonances make it easy to scan the peaks in large energy steps, to accommodate the relatively low beam intensity. Table 4 gives a summary on ^{11}C beam time request corresponding to different center of mass energies.

In this way, we expect to derive the S-factor with 10-30 % uncertainties. In case of lower ^{11}C beam intensity (10^8 pps), we will focus on the most important energy interval, from 0.4-0.7 MeV, and from 0.7-1.0 MeV, to measure 2^- resonance and determine the interference sign, respectively. In this case, the arrangement of shifts will be changed correspondingly.

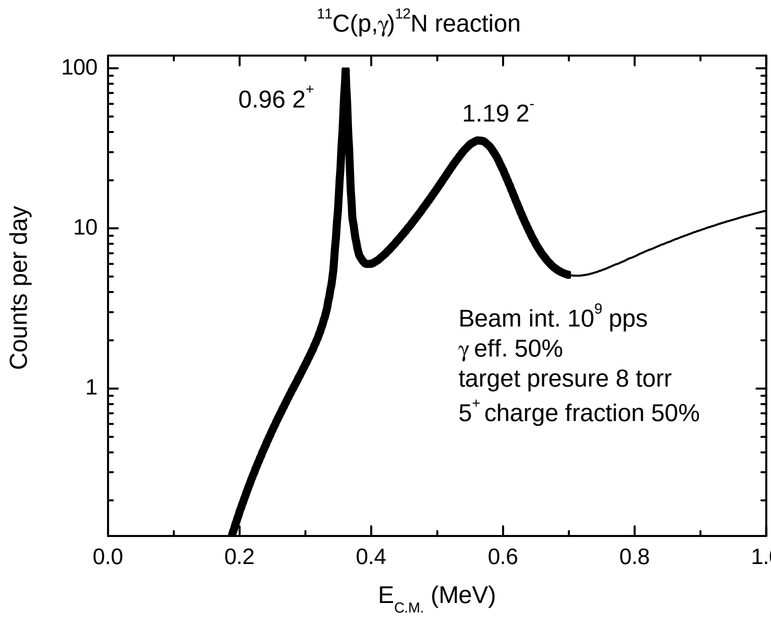

Fig. 8 The counting rate estimation of $^{11}C(p,\gamma)^{12}N$ reaction for specified experimental conditions.

6 Data Analysis

The data will be analyzed at CIAE by using the Linux PC station powered of ROOT software. The excitation function will be derived based on the ^{12}N recoil-γ coincidence and recoil energy spectra, from which the contributions of direct capture and resonant captures can be extracted, respectively. The data will be used for the astrophysical network calculation.

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