TRIUMF — RESEARCH PROPOSAL

E810

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Title of proposed experiment:

First direct study of the ^{23}Mg(p,γ)^{24}Al reaction with a recoil mass separator (DRAGON)

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Start of preparations: January 2000

Date ready: July 2000

Completion date: 2002

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
50 (^{23}Mg)	2A/ISAC	no
10 (^{27}Al)	NA/ISAC	no
10 (^{23}Na)	NA/ISAC	no
5 (^{24}Mg)	NA/ISAC	no

The reaction ^{23}Mg(p,γ)^{24}Al plays a key role in the breakout from the NeNa to the MgAl cycle. Within this cycle the longlived ^{26}Al nucleus is produced, which was already observed by orbital γ-ray observatories, e.g. the Compton Gamma Ray Observatory (CGRO). Thus, nuclear physics data on ^{23}Mg(p,γ)^{24}Al will be extremly useful in the modelling of possible stellar site(s) for ^{26}Al nucleosynthesis.

In most of the astrophysical energy range of interest the reaction rate is dominated by the nuclear resonance at E_{cm} = 458 keV. Only at higher temperatures, which are unlikely to occur in novae, the E_{cm} = 651 keV can play a role. So far, the energies of this resonances have been determined by measuring the excitation energies of the relevant states in ^{24}Al via transfer reactions. Resonance parameters like widths and strengths have been concluded from analog states in ^{24}Na, Due to the uncertainty going along with this method, the ^{23}Mg(p,γ)^{24}Al reaction rate is still not well known at all temperatures.

We propose to measure the resonance strengths of the two astrophysically interesting resonances using the DRAGON facility in the high energy area of the ISAC experimental hall. The design features of the DRAGON facility should allow a determination of the resonance strengths with an accuracy of about 20 % already with ^{23}Mg beam currents in the $10^7 - 10^8$ s^{-1} range.

Experimental area

ISAC high energy hall (DRAGON)

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

proton (10 μA, 500 MeV)

Secondary channel ISAC

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

ISAC ion source: ^{23}Mg, 0.3 – 1.0 MeV/u

off-line ion source: ^{23}Na, ^{24}Mg, ^{27}Al, 0.15 – 1.5 MeV/u

TRIUMF SUPPORT:

- ISAC
- development of a ^{23}Mg ion source (on-line source)
- development of ^{23}Na, ^{24}Mg, and ^{27}Al ion sources (off-line sources)
- technical support for operating the extended windowless gas target
- technical support for operating the DRAGON facility
- data acquisition system

NON-TRIUMF SUPPORT

DFG (German Research Council) support will be sought for project support

- project support for students, travel, and consumables

NATO (North Atlantic Treaty Organization) support will be sought for travels

The safety concerns for this experiment are:

- radioactivity of the beam ^{23}Mg, of which most will be dumped within the DRAGON facility
- use of hydrogen gas in the gas target

Local shielding has to be arranged and proper local radiation monitors have to be installed. The gas target will not run in a recirculating mode, so an exhaust line to the atmosphere for the hydrogen has to be installed.

1 Scientific Justification

In binary systems with a degenerate object (e.g. white dwarfs or neutron stars) mass overflow and accretion from the binary companion can lead to explosive events like e.g. novae (on white dwarfs) or X-ray bursts (on neutron stars). The nuclear energy source is explosive hydrogen burning, ranging from hot CNO-cycles to long sequences of proton captures and beta-decays (rp-process) [1, and references there in].

In novae the main energy source, after ignition via pp-reactions, is the hot CNO-cycle. As the gap between the hot CNO-cycles and nuclei beyond Ne can only be overcome (at least present reaction rate information suggests this) by α-capture reactions at temperatures which are unlikely to occur in novae, nucleosynthesis up to $A \sim 40$ (which is indicated by observations) can only happen due to proton capture reaction sequences on initial Ne and Mg abundances. To understand and interpret these observations, detailed measurements of low energy capture reactions on radioactive and stable isotopes in the Ne to Ca range are required. In the case of unstable nuclei these measurements have to be performed at radioactive beam facilities, while measurements of reactions on stable nuclei have to take place (due to the small cross sections) at low energy, high intensity accelerators in a background reduced environment, like e.g. at the Gran Sasso LUNA facility [2,3]. The nucleosynthesis and energy generation in X-ray bursts and black hole accretion disks is dominated by combined H- and He-burning at extreme temperatures and densities. Among the key nuclear informations needed are the reaction rates for proton capture on even Z $T_Z = -1/2$ nuclei like ^{23}Mg, ^{27}Si, ^{31}S, ^{35}Ar and ^{39}Ca where there is competition with β-decay. As their small reaction Q-values (less than 2 MeV) do not permit the application of statistical model cross sections, they have to be determined experimentally and are ideal targets for experiments with radioactive ion beams [1].

Of special current interest is the nucleosythesis of ^{26}Al, since it can be observed via γ-ray astronomy, e.g. with the Compton Gamma Ray Observatory (CGRO). A decision on the stellar site(s) of the ^{26}Al production cannot be made at present due to the lack of the necessary nuclear physics data. During static hydrogen-burning the ^{26}Al nuclides can be produced in the cold MgAl-cycle via ^{25}Mg(p,γ)^{26}Al, where resonances have been observed as low as 198 keV. From the known level structure of ^{26}Al one expects 4 additional resonances at lower energies, whose strengths can change the extrapolated reaction rates by several orders of magnitude. A search for these resonances will be carried out with stable targets at the underground Gran Sasso LUNA facility. However, nuclear material has to be processed from the NeNa to the MgAl cycle.

At low temperatures a leakage from the NeNa cycle is possible through the reaction ^{23}Na(p,γ)^{24}Mg. Due to the competing ^{23}Na(p,α)^{20}Ne this breakout is not very effective. At nova temperatures the two cycles are dominantly linked (fig. 1) by the nuclear reaction ^{23}Mg(p,γ)^{24}Al (in competition with the ^{23}Mg β-decay). Several reaction sequences can follow, which either produce or bypass the astronomically important ^{26}Al ground state nucleus.

Information on the structure of ^{24}Al for a prediction of the stellar reaction rate of ^{23}Mg(p,γ)^{24}Al has been predominantly derived from a study by S. Kubono et al. on the transfer reaction ^{24}Mg(^{3}He,t)^{24}Al. As the Q-value of the reaction ^{23}Mg(p,γ)^{24}Al is low (Q = 1.87 MeV), the cross section will be dominated by isolated resonances or the direct

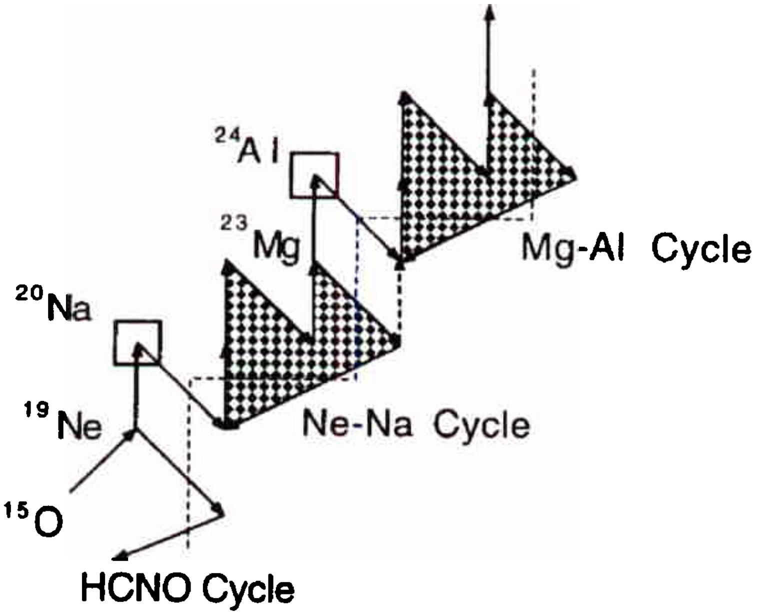

Fig. 1 . A schematic nucleosynthesis flow diagram for the leakout from the NeNa cycle to the next MgAl cycle, where the left-handed side of the dashed lines indicates proton-rich unstable nuclei. (Fig. 1 of ref. [4])

Table 1

Resonance parameters for ^{23}Mg(p,γ)^{24}Al (Table 2 of ref. [4])

No.	E_x [MeV]	E_{th}	J^π	l_p	θ_p^2	Γ_γ [eV]	Γ_p [eV]	$\omega\gamma$ [eV]
"1"	2.328	0.458	3^+	2	0.1	0.047	0.489	0.0268
"2"	2.521	0.651	4^+	2	0.02	0.16	1.815	0.1287
"3"	2.787	0.917	3^+	2	0.1	0.013	104.2	0.0114
"4"	2.876	1.006	2^+	0	0.1	>0.026	10040.0	0.0163
				2	0.1	>0.026	189.9	0.0163
"5"	3.002	1.132	1^+	0	0.1	>0.033	18100	0.0124
				2	0.1	>0.033	394	0.0124

capture process. Table 1 shows the resonance parameters derived from this experiment, together with information from analog states in ^{24}Na.

S. Kubono et al. assume that their energy determination of the excited states is accurate within 10 keV, thus giving a good basis for a search of these resonances in a direct experiment. But on the accuracy of their other resonance parameters they remark in their conclusions:

"However, it should be noted here that the present results are not conclusive at all, and the relative rate will only be meaningful since the proton and gamma widths of these states are not measured yet, which would affect dramatically the rate. The present work demonstrates how nuclear structure information is important. Thus, it is very interesting to study these physical parameters experimentally, possibly by using a radioactive nuclear beam of ^{23}Mg at stellar energies. ... There remains, however, a possibility of an alternative assignment to the analog states for the first two levels above the proton thereshold in ^{24}Al. ... This study is a first step for the investigation of the ^{23}Mg(p,γ)^{24}Al *process. The*

critical physical parameters, the proton and gamma widths of the resonances just above the proton thereshold should be determined by experiment, which is an interesting subject to be investigated with an unstable ^{23}Mg beam."

Nevertheless, one can use the extracted resonance strengths $\omega\gamma$ to give estimates on the possibility to pursue a direct experiment. Kubono et al. calculated from their results the stellar reaction rates as depicted in fig. 2.

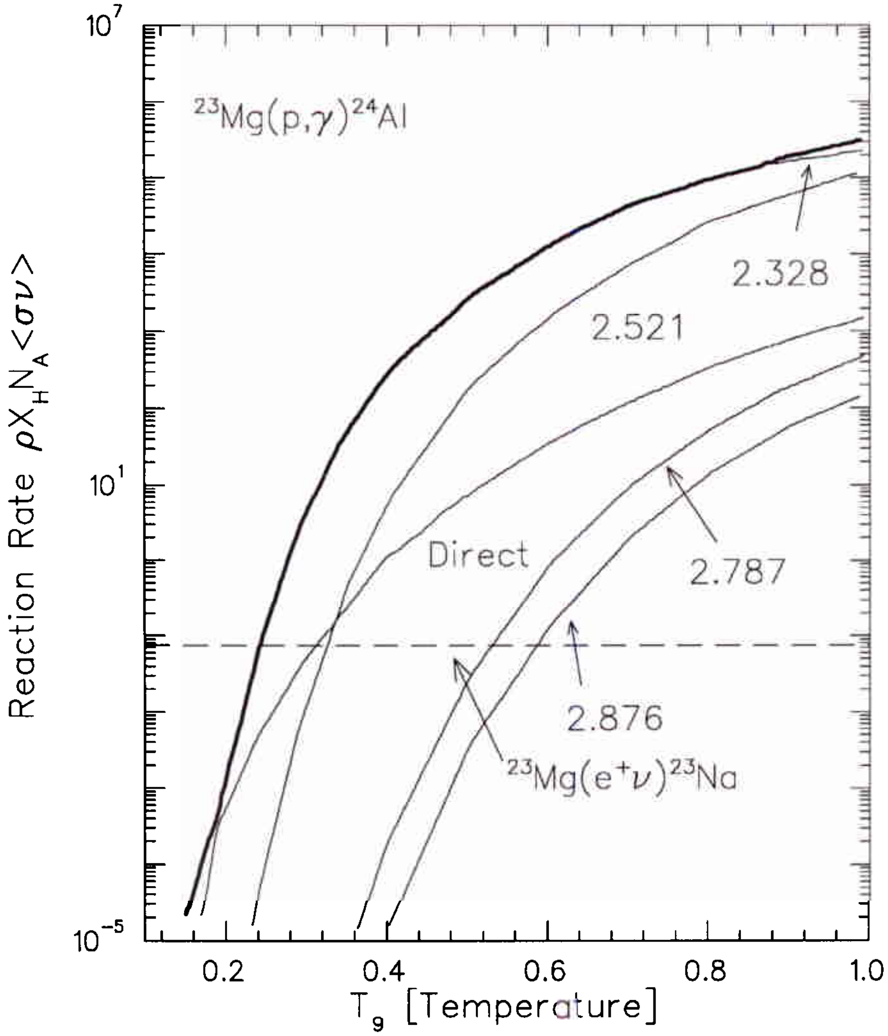

Fig. 2 . Each contribution to the stellar reaction rate $\rho X_H N_A < \sigma\nu >$ from the levels just above the proton threshold and from the direct capture process. (Fig. 8 of ref. [4])

This calculation shows that for nuclear astrophysics only the states at 2.328 and 2.521 MeV in ^{24}Al are relevant. Thus a direct investigation should concentrate on this two resonances at $E_{cm} = 0.458$ MeV and $E_{cm} = 0.651$ MeV, respectively.

2 Description of the Experiment

2.1 Determination of the ^{23}Mg(p,γ)^{24}Al reaction rate

The experiment has to take place at the planned recoil mass separator DRAGON at TRIUMF in combination with a windowless gas target. Both are described in a separate proposals. Assuming the resonance strengths $\omega\gamma$ from Kubono et al. [4]:

$E_r = 0.458\ MeV$ $\quad \omega\gamma = 26.8$ meV $\quad \Gamma \sim \Gamma_p = 0.49$ eV
$E_r = 0.651$ MeV $\quad \omega\gamma = 128.7$ meV $\quad \Gamma \sim \Gamma_p = 1.82$ eV,

one can estimate counting rates and a lower limit for the necessary ^{23}Mg ion beam current.

For the low energy resonance a 10.99 MeV ^{23}Mg ion beam has to impinge on a windowless H_2-gas target. At this energy the stopping power is: $\epsilon = 88$ eV/(10^{15} atoms/cm^2). With a two sided, windowless H_2 gas target an arial target density of 8×10^{18} cm^{-2} can be achieved. The target thickness in the center of mass system is then $\Delta \cong 30$ keV, so for an estimate the formula for thick target yields can be used [3].

$$Y_{max}(\infty) = \frac{\lambda^2}{2}\omega\gamma\frac{M+m}{M}\frac{1}{\epsilon} \tag{1}$$

In this case:

$$Y_{max}(\infty) = 7 \times 10^{-11}. \tag{2}$$

This is the reaction yield per incoming ^{23}Mg projectile, but gives also the necessary beam suppression factor for the recoil mass separator. With the simple RMS setup of the NaBoNA experiment (**Na**poli-**Bo**chum-**N**uclear **A**strophysics Collaboration) at Naples [6,7], suppression factors of the order of 10^{-13} have already been achieved, so that the requirements for the reaction ^{23}Mg(p,γ)^{24}Al should be possible to fulfill. In order to separate the ^{24}Al recoils from the ^{23}Mg "leaky beam" particles in the ΔE-E ionization counter at the end of the DRAGON facility, the existing detector from the NaBoNa experiment has to be improved for low energy particles. For this experiment a good separation at E $\cong$ 450 keV/amu has to be achieved. (Fig. 3 shows the spectrum of the existing detector [6].) This can be done (and is already tested by the Bochum group) by using very thin entrance windows and by lowering the chamber pressure.

For the detection of the reaction products with the recoil mass separator DRAGON, the most abundant charge state of the ^{24}Al recoils has to be selected. Usually there is a charge state with at least 20 % probability. The momentum spread of $\Delta p/p = 0.53$ % and a recoil half angle $\Theta/2 = 0.31°$ (including 0.20° recoil momentum spread and 0.11° straggling in the gas target, respectively) poses no problem for the acceptance of the DRAGON facility. Thus 100 % transmission of the selected charge state can be anticipated. A counting rate of 1 event/hour is easily separable from backgrounds (if there are any) in a ΔE-E detector. In order to achieve this, a ^{23}Mg ion beam of:

$$N(^{23}Mg) = \frac{N_{\Delta E-E}}{\epsilon_{DRAGON} Y_{max}} = 2 \times 10^7 \text{ ions/sec} \tag{3}$$

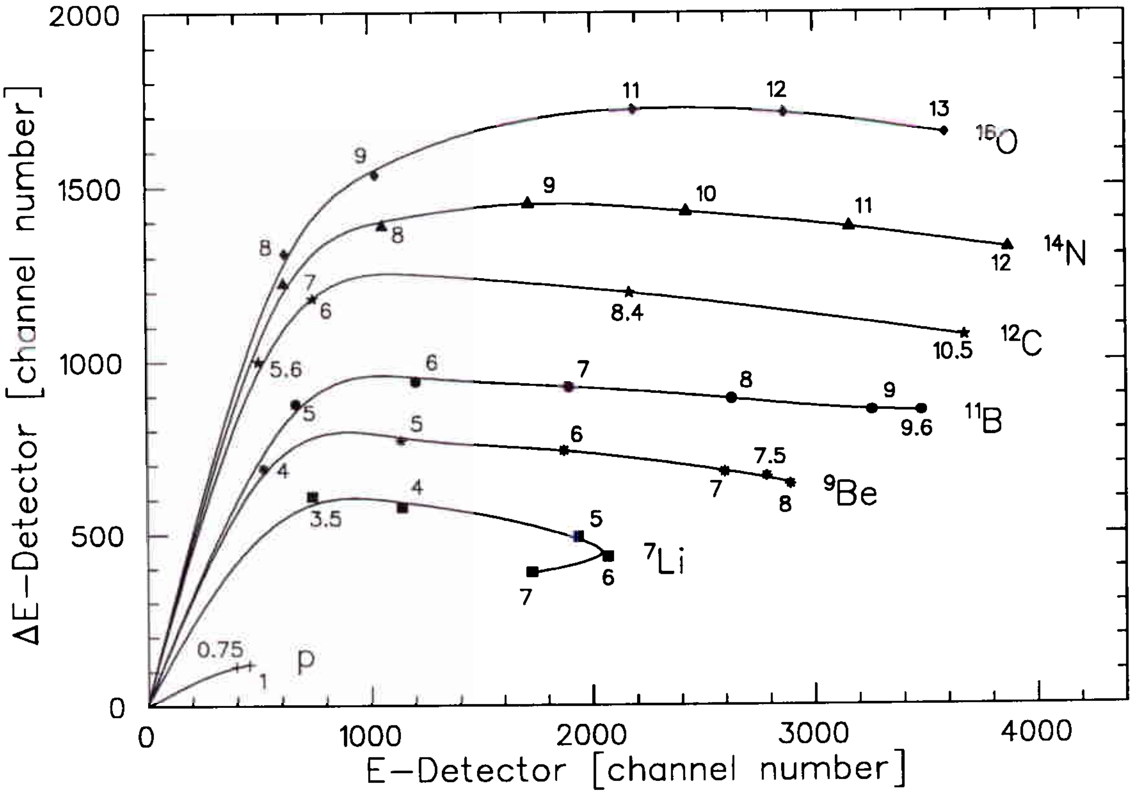

Fig. 3 . Observed matrix of the ΔE-E-telescope for ions between p and ^{16}O at the energies quoted (in units of MeV). The solid curves through the data points are to guide the eye only. Isotopes of a given element lie on the same curve shifted in energy by their mass ratios. (Fig. 3 of ref. [6])

is necessary. The resonance at E = 0.651 MeV is a factor of 5 stronger and can thus be measured with the same beam current.

The resonance strengths of the resonances will be measured relative to the elastic scattering cross section of ^{23}Mg on hydrogen. This cross section has to be determined separately by using heavy noble gas admixtures to the target gas.

2.2 Calibration of the DRAGON facility

The elements of the recoil mass separator and especially the ΔE-E ionization chamber have to be calibrated with stable beams relevant to this experiment. This way proper particle identification and reliability of the focussing elements can be ensured. Stable beams of ^{23}Na, ^{24}Mg, and ^{27}Al with beam currents in the region of pA can be guided with Faraday cups between the various elements and in front of the ΔE-E detector. Reducing the beam current by closing the beam diagnostic slits allows at the same time a test of the ionization chamber.

Table 2
Resonance parameters for ^{23}Na(p,γ)^{24}Mg (Table 24.17 of ref. [8])

E_R [MeV]	E_x [MeV]	Γ [keV]	$\omega\gamma$ [eV]
0.426	12.1171	< 2	< 0.0013
0.491	12.1814	< 0.05	0.09
0.567	12.2579	< 0.06	0.24
0.649	12.3391	< 0.07	0.64
0.693	12.3830	7	< 0.004

2.3 Determination of the purity of the radioactive ^{23}Mg beam

The ΔM/M ratio between ^{23}Mg and its stable isobar ^{23}Na is 1 : 5280. Thus the selectivity of the ISAC mass separator (1 : 10000) should be able to suppress a possible ^{23}Na contamination coming from the ion source. Nevertheless, the actual contamination has to be known in order to ensure a reliable interpretation of the measurement of the elastically scattered particles corresponding to the number of incident beam particles. To achieve this a radioactive ^{23}Mg beam of several tens of pA can be focussed as described in the previous section onto the Faraday cup in front of the ΔE-E detector and after reducing the beam current the contamination can be monitored directly. ^{24}Mg as the reaction product of the background reaction ^{23}Na(p,γ)^{24}Mg will show up in another region of the ΔE-E spectrum as the ^{24}Al recoils of interest. However, to make sure the interpretation of the spectrum is correct, the reaction ^{23}Na(p,γ)^{24}Mg should be measured at the energies of interest. Known resonances are displayed in table 2.

2.4 Measurement of the elastic scattering cross section of ^{23}Mg

As the reaction cross section of ^{23}Mg(p,γ)^{24}Al will be measured relative to the elastic scattering of hydrogen and ^{23}Mg, the scattering cross section has to be known. The easiest way is to measure the elastic scattering of ^{23}Mg on hydrogen compared to the scattering from a noble gas, e.g. Argon or Xenon, which is supposed to be pure Rutherford cross section at the energies of interest. The amount of the admixture can be determined and controlled with a stable ^{23}Na beam, where the elastic scattering on hydrogen is known or can be determined with a high precision (e.g. with a beam calorimeter) at other accelerator laboratories (e.g. DTL Bochum).

2.5 Determination of charge state probabilities of Al ions emerging from the gas target

As the efficiency of the recoil detection is governed by the probability of the selected recoil charge state, the relevant probabilities have to be known. The nuclear reaction can take place anywhere within the gas target. Thus not all recoils pass enough matter to reach the equilibrium charge state distribution before entering the recoil mass separator. In principle one can place a foil stripper at the entrance of the RMS to ensure equilibrium, but at low energies one would like to avoid any additional straggling process. Recoil particles produced at different depths in the gas target have to pass through different

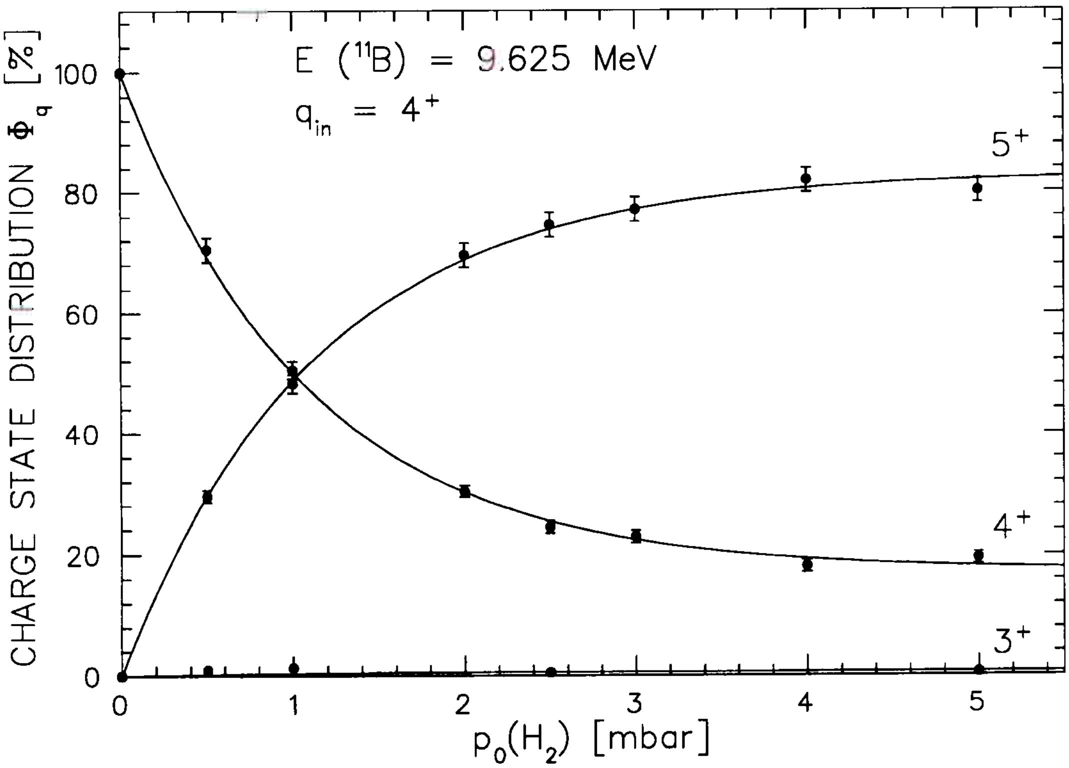

Fig. 4 . Charge state distribution of 9.625 MeV ^{11}B projectiles in H_2 gas, as a function of gas pressure. The figure shows the result for an incident charge state $q_{in} = 4^+$. The curves through the data points are fits using exponential functions.

amounts of target matter; this effect can be simulated by varying the gas pressure in the target zone. Integrating over the resulting probabilities gives the charge state distribution of the reaction products. This technique was successfully used in the NaBoNA project to determine the $^8B^{5+}$ probability after the two sided gas target (fig. 4).

These measurements can be done with ^{27}Al as there should be no isotopic effect in the charge state distributions.

3 Experimental Equipment

This experiment needs the recoil mass separator DRAGON and the extended gas target. As the recoil cone of this reaction is small compared to the acceptance of the DRAGON facility, it would be possible to lengthen the interaction zone of the extended gas target in order to achieve the proposed target density. The ΔE-E detector must be able to distinguish neighbouring elements at energies around 400 keV/amu.

4 Beam Time required

Our requirements of beam time are:

- Calibration of the recoil mass separator DRAGON and the ΔE-E detector with stable beams:

^{23}Na, ^{24}Mg, ^{27}Al	5 shifts each (off-line source)

- Determination of the beam purity of the radioactive ^{23}Mg beam (ΔE-E detector and probably resonances in ^{23}Na(p,γ)^{24}Mg):

^{23}Mg	5 shifts
^{23}Na	5 shifts (off-line source)

- Measurement of the elastic scattering cross section of ^{23}Mg on hydrogen relative to the scattering of ^{23}Mg on heavy noble gases:

^{23}Mg	5 shifts
^{23}Na	alternating (off-line source)

- Determination of charge state probabilities of Al ions emerging from the gas target:

^{27}Al	5 shifts (off-line source)

- Measurement of the resonance strengths of the E = 0.458 MeV resonance:

^{23}Mg	10 shifts

- Measurement of the resonance strength of the E = 0.651 MeV resonance:

^{23}Mg	10 shifts

- Off-resonance runs (at 2 energies):

^{23}Mg	20 shifts

5 Data Analysis

The data analysis can be done partly at TRIUMF and at the home institutions of the participants.

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