TRIUMF — RESEARCH PROPOSAL

Experiment no. **E 811**

BK-7

Title of proposed experiment:

A direct study of the $^{19}Ne(p,\gamma)^{20}Na$ reaction with a recoil mass separator (DRAGON)

Name of group: X-RAY BURSTS

Spokesperson for group: U. Greife (Colorado School of Mines)

E-Mail address: ugreife@mines.edu **Fax number:** 1 303 273 3919

Members of the group (name, institution, status, per cent of time devoted to experiment)

Name	Institution	Status	Time
J.M. D'Auria	Simon Fraser University	Faculty	50%
R.N. Boyd	Ohio State University	Faculty	15%
L. Buchmann	TRIUMF	Senior Research Scientist	tbd
A. D'Onofrio	INFN Napoli	Faculty	20%
S. Feldman	Colorado School of Mines	Graduate Student	100%
C. Galovich	University of Northern Colorado	Faculty	10%
U. Giesen	University of Notre Dame	Faculty	15%
L. Gialanella	INFN Napoli	Research Associate	20%
U. Greife	Colorado School of Mines	Faculty	50%
D. Hunter	Simon Fraser University	Research Associate	100%
A. Hussein	University of Northern BC	Faculty	tbd
D. Hutcheon	TRIUMF	Senior Research Scientist	100%
K.P. Jackson	TRIUMF	Senior Research Scientist	tbd
M. Junker	INFN Gran Sasso	Research Associate	tbd
J.D. King	University of Toronto	Faculty emeritus	10%
R. Korteling	Simon Fraser University	Faculty	tbd
A. Olin	TRIUMF	Senior Research Scientist	tbd
C. Rodriguez	Colorado School of Mines	Graduate Student	100%
C. Rolfs	Ruhr-Universitaet Bochum	Faculty	tbd
J. Rogers	TRIUMF	Senior Research Scientist	30%
G. Roy	University of Alberta	Faculty emeritus	tbd
A. Shotter	University of Edinburgh	Faculty	tbd
F. Strieder	Ruhr-Universitaet Bochum	Research Scientist	tbd
F. Terrasi	INFN Napoli	Faculty	20%
S. Theis	Ruhr-Universitaet Bochum	Graduate Student	tbd
M. Wiescher	University of Notre Dame	Faculty	tbd

Start of preparations: January 2000

Date ready: May 2001

Completion date: December 2002

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
60 (^{19}Ne)	2A/ISAC	no
10 (^{23}Na)	NA/ISAC	no
10 (^{19}F)	NA/ISAC	no
5 (^{20}Ne)	NA/ISAC	no

The hot CNO cycles and the rp process play an important role in the energy production and nucleosynthesis in a hot and explosive stellar environment. At high temperatures ($T_9 \geq 0.3$, $T_9 = T/10^9$ K) the reaction sequence $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$ may initiate a link between the hot CNO cycles and an element formation up to mass A = 56. This reaction sequence of proton captures and β-decays during explosive hydrogen burning may explain the observed abundance of isotopes between Ne and Al in nova ejecta. However, the reaction flow depends critically on the reaction rates of both capture processes ($^{15}O(\alpha,\gamma)^{19}Ne$ and $^{19}Ne(p,\gamma)^{20}Na$), which are still not well-known. Therefore, the actual temperature and density conditions for the breakout of the hot CNO cycles are not sufficiently defined.

In the subsequent text we propose to measure the important resonance parameters in the $^{19}Ne(p,\gamma)^{20}Na$ reaction. In previous experiments four excited states above the proton threshold in ^{20}Na were found in the energy region of interest with a center-of-mass energy of 447, 658, 787, and 857 keV, respectively. In most of the astrophysical scenarios the reaction rate is dominated by the resonance at E_{cm} = 447 keV, where a previous direct experiment at Louvain-la-Neuve found an upper limit of $\omega\gamma \leq 26$ meV (90 % C.L.). With the increased detection efficiency of the DRAGON setup (gas target and recoil separator) it should be possible to determine the strength of this important resonance with sufficient accuracy already with a ^{19}Ne beam current in the 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: ^{19}Ne, 0.3 – 1.0 MeV/u

off-line ion source: ^{19}F, ^{20}Ne, ^{23}Na, 0.15 – 1.5 MeV/u

TRIUMF SUPPORT:

- ISAC
- development of a ^{19}Ne ion source (on-line source)
- development of a ^{19}F, ^{20}Ne and ^{23}Na 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 ^{19}Ne, 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].

Present reaction rate information suggests that the gap between the hot CNO-cycles and nuclei beyond Neon can only be overcome by α-capture reactions at temperatures of a few 10^8 K. The most probable reaction sequence seems to be:

$$^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}(\mathrm{p},\gamma)^{20}\mathrm{Na}(\mathrm{p},\gamma)^{21}\mathrm{Mg}...$$

However, none of the reactions involved is well determined experimentally yet [2 and references therein]. The excitation energies of the relevant states in the compound nuclei have been measured via transfer reactions, but the critical physical parameters like widths or strengths have been estimated from the values of the analog states in mirror nuclei.

The present estimates suggest, that the probability of the above sequence is determined by the slowest reaction: $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$. The measurement of this reaction has already been proposed to the TRIUMF EEC.

Nevertheless, the uncertainties in the reaction rate estimates due to analog assignments from mirror nuclei call for a direct measurement of the resonance strengths with radioactive ion beams also for the other reactions. The reaction rate of the reaction $^{19}\mathrm{Ne}(\mathrm{p},\gamma)^{20}\mathrm{Na}$ in relevant stellar scenarios is believed to be dominated by a resonance at E_{cm} = 447 keV, which corresponds to the 2.64 MeV state in ^{20}Na (fig. 1).

The position of the energy levels in ^{20}Na were determined via the reaction $^{20}\mathrm{Ne}(^3\mathrm{He},\mathrm{t})^{20}\mathrm{Na}$ in several experiments [3-5]. The results of the most precise experiment [3] found four interesting excited states above the 2.199 MeV proton threshold in ^{20}Na corresponding to the resonance energies of 447 ± 5, 658 ± 5, 787 ± 5, and 857 ± 5 keV in the reaction $^{19}\mathrm{Ne}(\mathrm{p},\gamma)^{20}\mathrm{Na}$. Spin and parity assignments were made by Lamm et al. [4] and Kubono et al. [5] by comparing DWBA calculations to $^{20}\mathrm{Ne}(^3\mathrm{He},\mathrm{t})^{20}\mathrm{Na}$ angular distribution measurements. These assignments are depicted in fig. 1. Values for the partial proton and gamma widths of the resonances were then inferred from the proporties of their supposed mirror states (table 1).

Table 1
Resonance parameters for the $^{19}\mathrm{Ne}(\mathrm{p},\gamma)^{20}\mathrm{Na}$ reaction (Table 2 of ref. [3])

$E_x(^{20}Na)$ [MeV]	E_r [MeV]	$E_x(^{20}F)$ [MeV]	J^π	l	θ_l^2	Γ_p [eV]	$\Gamma_\gamma(^{20}F)$ [eV]	$\Gamma_\gamma(^{20}Na)$ [eV]	$\omega\gamma$ [eV]
2.646	0.447	3.173	1^+	0	<0.0001	<0.09			
				2	0.0063	0.078		0.0093	0.007
2.857	0.658	2.966	3^+	2	0.054	27	0.0109	0.01	0.02
2.986	0.787	2.865	(3^-)	3	0.0063	0.32		0.04	0.07
3.056	0.857	3.488	(1^+)	0	0.4	12200	0.0149	0.01	0.0075

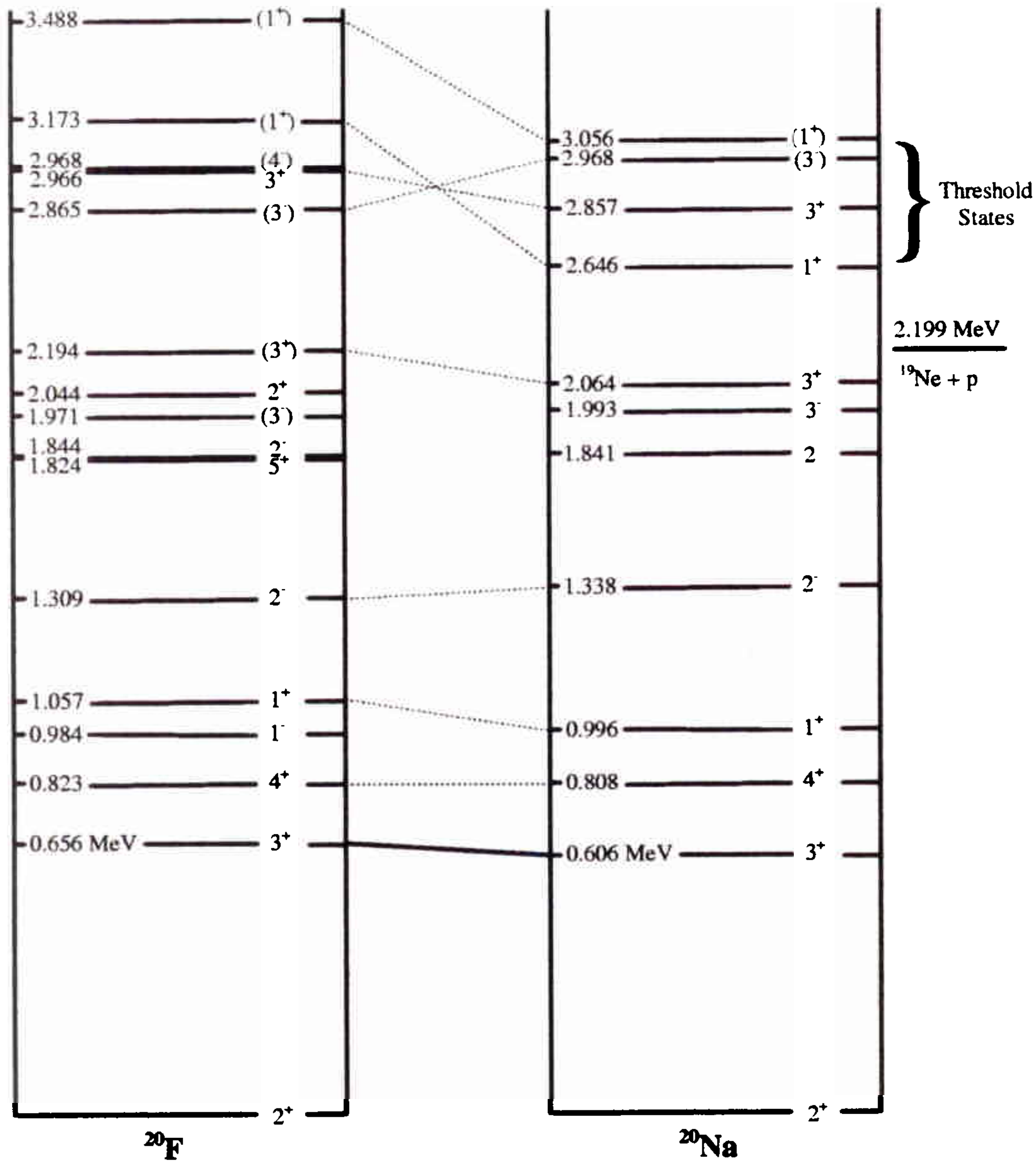

Fig. 1 . ^{20}Na and ^{20}F level diagram. The ^{20}Na excitation energies are taken from Lamm et al. [4] for levels below the 2.199 MeV ^{19}Ne + p threshold, and from ref. [3] for levels above the threshold. The ^{20}Na spins and parities are taken from Lamm et al. [4], while the ^{20}F energies and J^{π} values are taken from Ajzenberg-Selove [11]. The dashed lines indicate the analog assignments from Lamm et al. [4]. (Fig. 1 of ref. [3])

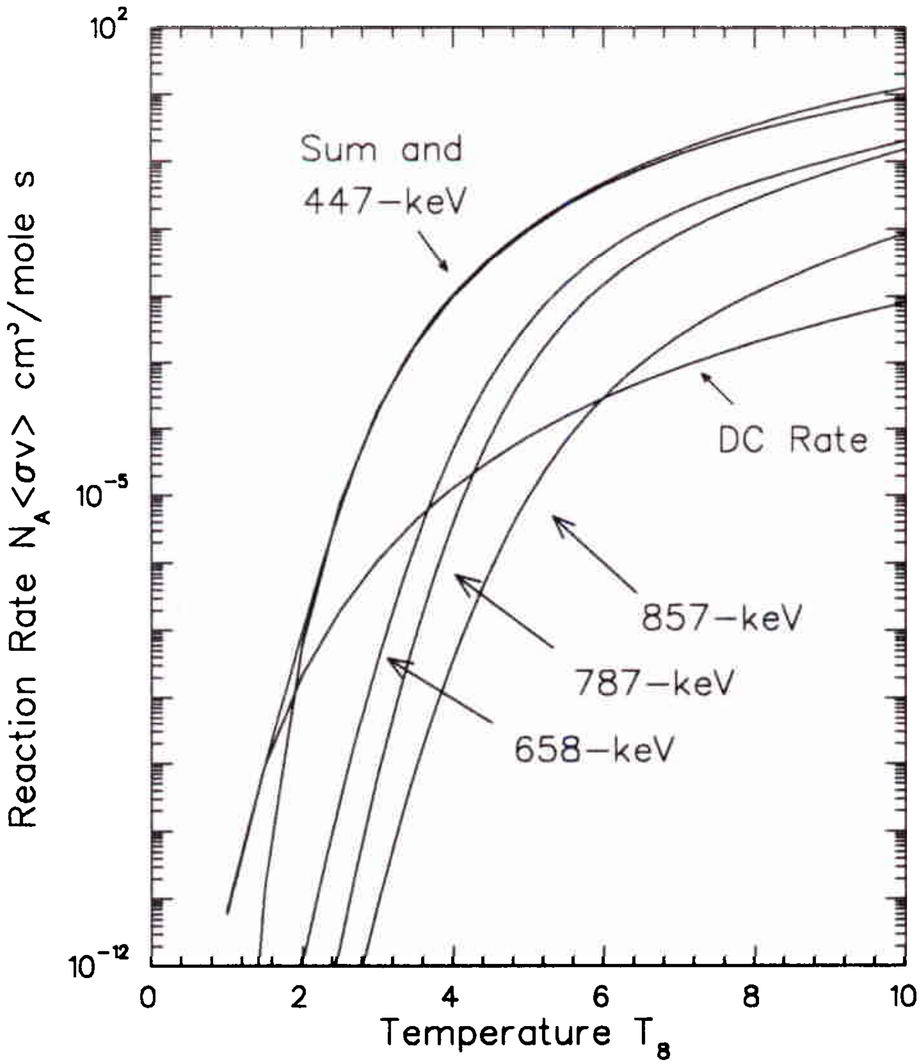

Fig. 2 . The ^{19}Ne(p,γ)^{20}Na resonant and direct capture (DC) reaction rate as a function of temperature for $1 < T_8 < 10$, for the case Γ_γ(447keV) = 9 meV. The 447 keV resonance dominates the total rate for $T_8 > 2$. (Fig. 3 of ref. [3])

Using this extracted resonance strengths $\omega\gamma$, one can calculate reaction rates as shown in fig. 2.

This calculation shows, that for nuclear astrophysics mainly the state at 2.64 MeV is of importance. Recently its 1^+ assignment has been called into question. Brown et al. [6] derive, taking into account coulomb shift calculations, a 3^+ assignment and thus use different nuclear properties from the new mirror state in ^{20}F. Thus the $\omega\gamma$ of the 447 keV resonance in ^{19}Ne(p,γ)^{20}Na would be about one order of magnitude larger ($\approx$ 80 meV) as assumed before.

There has already been one attempt to measure the resonance strength of this state directly with a ^{19}Ne radioactive ion beam [7]. At the radioactive ion beam facility of Louvain-la-Neuve a ^{19}Ne beam current of about 5×10^8 particles/sec was directed onto a polyethylene foil target. The ^{20}Na recoils were implanted together with the radioactive projectiles into catcher foils and moved in front of a particle detection system to monitor the β-delayed α-decay of ^{20}Na. With double sided silicon strip detectors or solid state track detectors detection efficiencies between 0.5 and 1.7 % were achieved. Due to background activities induced by a small deuterium contamination of the target (via the reaction ^{19}Ne(d,n)^{20}Na) and most probably intrinsic α-activity of the detectors and the surrounding material, this experiment was not able to measure the resonance strength $\omega\gamma$ of the 447 keV resonance. But they determined an upper limit of $\omega\gamma < 26$ meV (90 % C.L.), thus excluding (if the analog transfer of resonance properties from mirror states can be trusted — 80 meV for 3^+ assignment) already the 3^+ assignment of Brown et al. [6]. Nevertheless, for a trustworthy prediction of stellar reaction rates the $\omega\gamma$ of the 447 keV resonance in ^{19}Ne(p,γ)^{20}Na has to be measured and with the proposed facility at ISAC a direct experiment should be feasable.

2 Description of the Experiment

2.1 Determination of the ^{19}Ne(p,γ)^{20}Na 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 separate proposals. Assuming the resonance strengths $\omega\gamma$ from Smith et al. [3]:

$E_r = 447$ *keV* $\quad \omega\gamma = 7$ meV $\quad \Gamma \sim \Gamma_p = 0.09$ eV
$E_r = 658$ keV $\quad \omega\gamma = 20$ meV $\quad \Gamma \sim \Gamma_p = 27$ eV,
$E_r = 787$ *keV* $\quad \omega\gamma = 70$ meV $\quad \Gamma \sim \Gamma_p = 0.32$ eV
$E_r = 857$ keV $\quad \omega\gamma = 7.5$ meV $\quad \Gamma \sim \Gamma_p = 12.2$ keV,

one can estimate counting rates and a lower limit for the necessary ^{19}Ne ion beam current.

For the low energy resonance a 8.94 MeV ^{19}Ne beam has to impinge on a windowless H_2-gas target. Following the tabulated stopping power values, which should be independent of the isotope, the stopping power of ^{19}Ne on a gaseous H_2 target at this energy is: $\epsilon = 72$ eV/(10^{15} atoms/cm^2). With a two sided, windowless H_2 gas target an areal target density of 8×10^{18} cm^{-2} can be achieved. The target thickness in the center of mass system is then $\Delta \cong 29$ keV, thus larger than the total width of the resonance, energy straggling of the beam in the target and the projected energy spread of 0.2 % of the projectiles from the accelerator. For an estimate one can use the formula for thick target yields [8]:

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

In the case of the 447 keV resonance this corresponds to:

$$Y_{max}(\infty) = 1.6 \times 10^{-11}. \tag{2}$$

This is the reaction yield per incoming ^{19}Ne projectile, and it should be noted that alone from the use of a gas target instead of a foil target, the gain in yield is about a factor 4. The yield also corresponds to the necessary beam suppression factor for the recoil mass

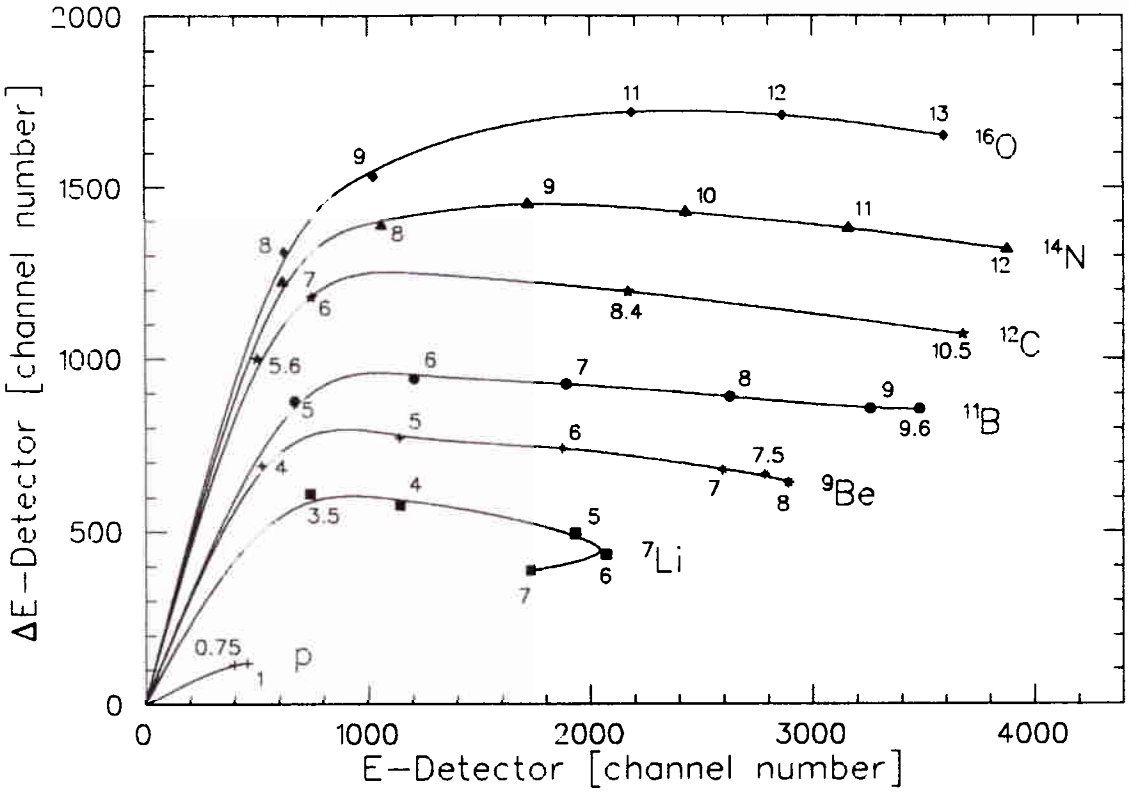

Fig. 3 . Observed matrix of the ΔE-E-telescope for ions between p and ^{16}O at the energies quoted (in units of MeV). The solid curves through the data points are to guide the eye only. Isotopes of a given element lie on the same curve shifted in energy by their mass ratios. (Fig. 3 of ref. [9])

separator. With the simple RMS setup of the NaBoNA experiment (**Na**poli-**Bo**chum-**N**uclear **A**strophysics Collaboration) at Naples [9,10], suppression factors of the order of 10^{-13} have already been achieved. Thus it should be possible to fulfill the requirements for the reaction ^{19}Ne(p,γ)^{20}Na with the state of the art recoil separator DRAGON at ISAC (it is designed for suppression ratios $\sim 10^{-15}$). In order to separate the ^{20}Na recoils from the ^{19}Ne "leaky beam" particles in the ΔE-E ionization counter at the last focus of the DRAGON facility, the existing detector from the NaBoNa experiment has to be improved for low energy particles. The ^{19}Ne(p,γ)^{20}Na experiment requires a good separation for particles with E ≅ 450 keV/amu (Fig. 3 shows the spectrum of the existing detector [9].) This can be done (and is already tested by the Bochum group) using very thin entrance windows and thus also lower gas pressure in the ionization chamber.

For the detection of the reaction products with the recoil mass separator DRAGON, the most abundant charge state of the ^{20}Na recoils has to be selected. Usually there is a charge state with at least 20 % probability. The momentum spread of $\Delta p/p = 0.71$ % and a recoil half angle $\Theta/2 = 0.41°$ 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 ^{19}Ne ion beam of:

$$N(^{19}Ne) = \frac{N_{\Delta E-E}}{\epsilon_{DRAGON} Y_{max}} = 9 \times 10^{7} \text{ ions/sec} \qquad (3)$$

is necessary. The next 2 resonances higher in energy are stronger and can thus be measured with the same beam current. The resonance at 857 keV poses a problem due to the large total width. It has to be estimated from the ^{19}Ne beam current which will be finally available if, due to the limited interest from nuclear astrophysical considerations, it will be worth to try to measure it.

The resonance strengths of the resonances will be measured relative to the elastic scattering cross section of ^{19}Ne 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 in this experiment. This way proper particle identification and reliability of the focussing elements can be ensured. Stable beams of ^{19}F, ^{20}Ne, and ^{23}Na 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.

2.3 Determination of the purity of the radioactive ^{19}Ne beam

The ΔM/M ratio between ^{19}Ne and its stable isobar ^{19}F is 1 : 5470. Thus the selectivity of the ISAC mass separator (1 : 10000) should be able to suppress a possible ^{19}F 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. A radioactive ^{19}Ne 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. ^{20}Ne as the reaction product of ^{19}F(p,γ)^{20}Ne will show up in another region of the ΔE-E spectrum as the ^{20}Na recoils of interest. However, to make sure the interpretation of the spectrum is correct, the reaction ^{19}F(p,γ)^{20}Ne should be measured at the energies of interest.

2.4 Measurement of the elastic scattering cross section of ^{19}Ne

As the reaction cross section of ^{19}Ne(p,γ)^{20}Na will be measured relative to the elastic scattering of hydrogen and ^{19}Ne, the scattering cross section has to be known. The easiest way is to measure the elastic scattering of ^{19}Ne 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

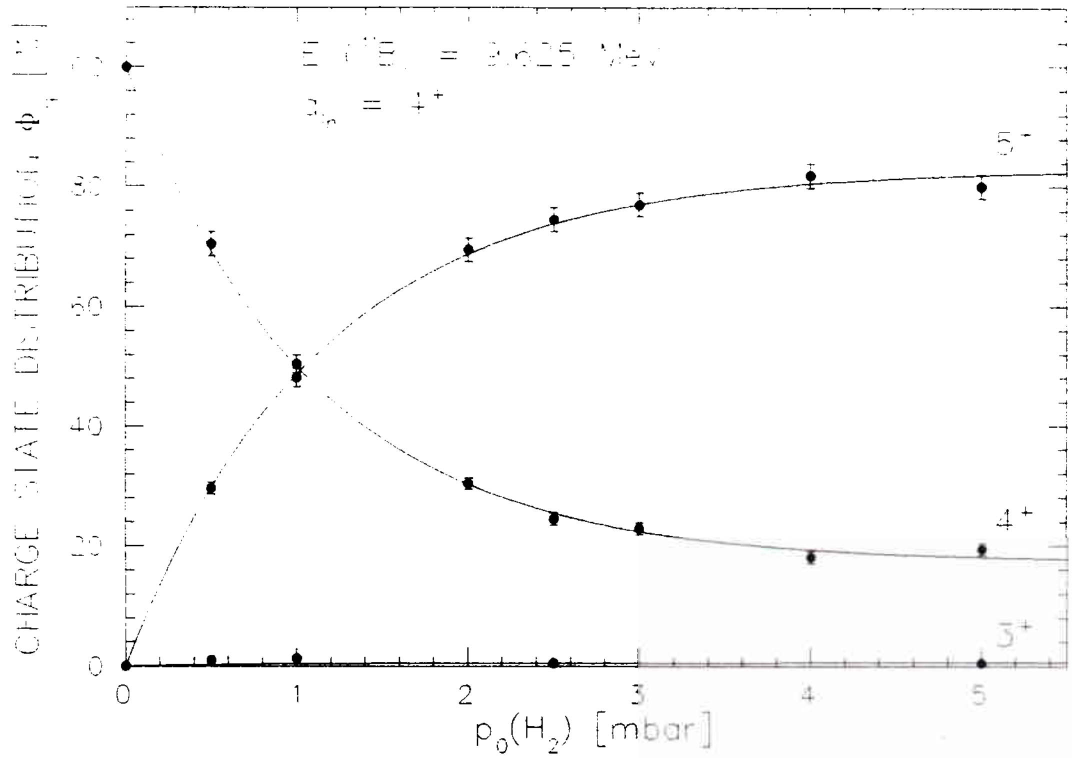

Fig. 4 . Charge state distribution of 9.625 MeV ^{11}B projectiles in H_2 gas, as a function of gas pressure. The figure shows the result for an incident charge state $q_{in} = 4^+$. The curves through the data points are fits using exponential functions.

controlled with a stable ^{19}F 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 Na 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 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 $^{8}B^{5+}$ probability after the two sided gas target (fig. 4).

These measurements can be done with ^{23}Na as there should be no isotopic effect in the charge state distributions.

2.6 Determination of the influence of deuterium contamination of the target

The recent experiment of Page et al. [7] with a radioactive ion beams had shown the possible influence of the (d,n) reaction channel on a proper determination of the (p,γ) reaction rate. In their experiment (on the reaction ^{19}Ne(p,γ)^{20}Na) the recoiling ^{20}Na were caught directly after the production foil and moved in front of a detection device. However, also all reaction products of the contaminant reaction ^{19}Ne(d,n)^{20}Na were collected. Due to the different Q-value and recoil kinematics, the recoil mass separator would select only a fraction of the recoiling nuclei from the (d,n) reaction. The total amount has to be determined by Monte Carlo calculations. Nevertheless, a test measurement should be made. As the walls of the gas target will be contaminated using D_2 gas, the proper way will be probably to use a deuterated foil target instead of the gas cell. If measurements with gas prove to be necessary, the contamination can be removed by outgassing the beam elements in an oven and by changing all lubricants of the vacuum pumps.

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:

  ^{19}F, ^{20}Ne, ^{23}Na — 5 shifts each (off-line source)

- Determination of the beam purity of the radioactive ^{19}Ne beam (ΔE-E detector and probably resonance in ^{19}F(p,γ)^{20}Ne):

  ^{19}Ne — 5 shifts
  ^{19}F — 5 shifts (off-line source)

- Measurement of the elastic scattering cross section of ^{19}Ne on hydrogen relative to the scattering of ^{19}Ne on heavy noble gases:

  ^{19}Ne — 5 shifts
  ^{19}F — alternating (off-line source)

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

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

- Measurement of the resonance strengths of the E = 447 keV resonance:

  ^{19}Ne — 10 shifts

- Measurement of the resonance strength of the E = 651 and 787 keV resonances:

  ^{19}Ne — 20 shifts

- Off-resonance runs (at 3 energies):

  ^{19}Ne — 20 shifts

5 Data Analysis

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

References

1. Nuclear and Particle Astrophysics, Report for the NUPECC committee, conven. F.K. Thielemann, unpublished 1997

2. S. Kubono, Progress of Theoretical Physics 96 (1996) 275

3. M.S. Smith, P.V. Magnus, K.I. Hahn, A.J. Howard, P.D. Parker, A.E. Champagne, and Z.Q. Mao, Nucl. Phys. A 536 (1992) 333

4. L.O. Lamm, C.P. Browne, J. Görres, S.M. Graff, M. Wiescher, A.A. Rollefson, and B.A. Brown, Nucl. Phys. A 510 (1990) 503

5. S. Kubono, N. Ikeda, M. Yasue, T. Nomura, Y. Fuchi, K. Kawashima, S. Kato, H. Orikasa, T. Shimozuka, H. Oknuma, H. Miyatake, and T. Shimoda, Z. Phys. A 331 (1988) 359

6. B.A. Brown, A.E. Champagne, H.T. Fortune, and R. Sherr, Phys. Rev. C 48 (1993) 1456

7. R.D. Page, G. Vancraeynest, A.C. Shotter, M. Huyse, C.R. Bain, F. Binon, R. Coszach, T. Davinson, P. Decrock, Th. Delbar, P. Duhamel, M. Gaelens, W. Galster, P. Leleux, I. Licot, E. Lienard, P. Lipnik, C. Michotte, A. Ninane, P.J. Sellin, Cs. Sükösd, P. van Duppen, J. Vanhorenbeeck, J. Vervier, M. Wiescher, and P.J. Woods, Phys. Rev. Lett. 73 (1994) 3066

8. C. Rolfs and W.S. Rodney, Cauldrons in the Cosmos, University of Chicago Press (1988)

9. L. Gialanella, F. Strieder, K. Brand, L. Campajola, A. D'Onofrio, U. Greife, E. Huttel, F. Petruzzuolo, V. Roca, C. Rolfs, M. Romano, M.Romoli, S. Schmidt, W.H. Schulte, F. Terrasi, H.-P. Trautvetter, and D. Zahnow, Nucl. Instr. Meth. A 376 (1996) 174

10. L. Campajola, L. Gialanella, K. Brand, A. D'Onofrio, U. Greife, E. Huttel, R. Kubat, G. Oliviero, H. Rebel, V. Roca, C. Rolfs, M. Romano, M. Romoli, S. Schmidt, W.H. Schulte, F. Strieder, F. Terrasi, H.-P. Trautvetter, and D. Zahnow, Z. Phys. A 356 (1996) 107

11. F. Ajzenberg-Selove, Nucl. Phys. A 475 (1987) 1

Include publications in refereed journal over at least the previous 5 years.

1. C. Arpesella, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, U. Greife, C. Gustavino, M. Junker, J. Lambert, P. Prati, W.S. Rodney, C. Rolfs, H.-P. Trautvetter, D. Zahnow, and S. Zavatarelli, Phys. Lett. B 389 (1996) 452

2. L. Campajola, L. Gialanella, K. Brand, A. D'Onofrio, U. Greife, E. Huttel, R. Kubat, G. Oliviero, H. Rebel, V. Roca, C. Rolfs, M. Romano, M. Romoli, S. Schmidt, W.H. Schulte, F. Strieder, F. Terrasi, H.-P. Trautvetter, and D. Zahnow, Z. Phys. A 356 (1996) 107

3. F. Strieder, L. Gialanella, U. Greife, C. Rolfs, S. Schmidt, W.H. Schulte, H.-P. Trautvetter, D. Zahnow, F. Terrasi, L. Campajola, A. D'Onofrio, V. Roca, M. Romano, and M. Romoli, Z. Phys. A 355 (1996) 209

4. L. Gialanella, F. Strieder, K. Brand, L. Campajola, A. D'Onofrio, U. Greife, E. Huttel, F. Petrazzuolo, V. Roca, C. Rolfs, M. Romano, M. Romoli, S. Schmidt, W.H. Schulte, F. Terrasi, H.-P. Trautvetter, and D. Zahnow, Nucl. Instr. Meth. A 376 (1996) 174

5. C. Arpesella, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, U. Greife, C. Gustavino, M. Junker, A. Lanza, P. Prati, C. Rolfs, D. Zahnow, and S. Zavatarelli, Nucl. Instr. Meth. A 360 (1995) 607

6. U. Greife, F. Gorris, M. Junker, C. Rolfs, and D. Zahnow, Z. Phys. A 351 (1995) 107

7. U. Greife, C. Arpesella, C.A. Barnes, F. Bartolucci, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, F. Gorris, C. Gustavino, M. Junker, R.W. Kavanagh, A. Lanza, G. Mezzorani, P. Prati, P. Quarti, W.S. Rodney C. Rolfs, W.H. Schulte, H.-P. Trautvetter, D. Zahnow, Nucl. Instr. Meth. A 350 (1994) 327

8. P. Prati, C. Arpesella, F. Bartolucci, H.W. Becker, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, F. Gorris, U. Greife, C. Gustavino, M. Junker, C. Rolfs, W.H. Schulte, H.-P. Trautvetter, and D. Zahnow, Z. Phys. A 350 (1994) 171

9. H.W. Drotleff, A. Denker, H. Knee, M. Soine, G. Wolf, J.W. Hammer,U. Greife, C. Rolfs, and H.-P. Trautvetter, Astroph. J. 414 (1993) 735

10. S. Engstler, G. Raimann, C. Angulo, U. Greife, C.Rolfs, U. Schroeder, E. Somorjai, E. Somorjai, B. Kirch, and K. Langanke, Z. Phys. A 342 (1994) 471

11. S. Engstler, G. Raimann, C. Angulo, U. Greife, C.Rolfs, U. Schroeder, E. Somorjai, E. Somorjai, B. Kirch, and K. Langanke, Phys. Rev. Lett. B 279 (1992) 20