Title of proposed experiment:

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

Name of group: X-RAY BURSTS

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

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Fax number: 1 303 273 3919

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

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<th>Institution</th>
<th>Status</th>
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Start of preparations: January 2000

Date ready: May 2001

Completion date: December 2002

Beam time requested:

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<th>12-hr shifts</th>
<th>Beam line/channel</th>
<th>Polarized primary beam?</th>
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<tr>
<td>60 ($^{19}$Ne)</td>
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<tr>
<td>10 ($^{20}$Na)</td>
<td>NA/ISAC</td>
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<td>10 ($^{19}$F)</td>
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<td>5 ($^{20}$Ne)</td>
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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 \((T_\theta \geq 0.3, T_\theta = T/10^9 \text{ K})\) the reaction sequence \(^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}(p, \gamma)^{20}\text{Na}\) 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 \(\beta\)-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 \(^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}\) and \(^{19}\text{Ne}(p, \gamma)^{20}\text{Na}\), 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 \(^{19}\text{Ne}(p, \gamma)^{20}\text{Na}\) reaction. In previous experiments four excited states above the proton threshold in \(^{20}\text{Na}\) 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 \(E_{\text{cm}} = 447\) 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 \(^{19}\text{Ne}\) 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, emittance, intensity, beam purity, target, special characteristics)*

  ISAC ion source: $^{19}\text{Ne}$, 0.3 – 1.0 MeV/u

  off-line ion source: $^{19}\text{F}$, $^{20}\text{Ne}$, $^{23}\text{Na}$, 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 $\alpha$-capture reactions at temperatures of a few $10^8$ K. The most probable reaction sequence seems to be:

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

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: $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$. 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 $^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$ in relevant stellar scenarios is believed to be dominated by a resonance at $E_{\text{cm}} = 447$ keV, which corresponds to the 2.64 MeV state in $^{20}\text{Na}$ (fig. 1).

The position of the energy levels in $^{20}\text{Na}$ were determined via the reaction $^{20}\text{Ne}(^{3}\text{He}, t)^{20}\text{Na}$ 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 $^{20}\text{Na}$ corresponding to the resonance energies of 447 ± 5, 658 ± 5, 787 ± 5, and 857 ± 5 keV in the reaction $^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$. Spin and parity assignments were made by Lamm et al. [4] and Kubono et al. [5] by comparing DWBA calculations to $^{20}\text{Ne}(^{3}\text{He}, t)^{20}\text{Na}$ 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 properties of their supposed mirror states (table 1).

<p>| Table 1 | Resonance parameters for the $^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$ reaction (Table 2 of ref. [3]) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
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<th>$E_x^{(20}\text{Na)}$ [MeV]</th>
<th>$E_r$ [MeV]</th>
<th>$E_x^{(20}\text{F)}$ [MeV]</th>
<th>$J^+$</th>
<th>$\theta^2$</th>
<th>$\Gamma_p$ [eV]</th>
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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$^\pi$ 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$(p,\gamma)^{20}$Na resonant and direct capture (DC) reaction rate as a function of temperature for $1 < T_8 < 10$, for the case $\Gamma_\gamma(447\text{keV}) = 9$ 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$(p,\gamma)^{20}$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 $5 \times 10^8$ 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 mon-
itor the \( J\)-delayed \( \alpha \)-decay of \(^{20}\text{Na}\). 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 \(^{19}\text{Ne}(d,n)^{20}\text{Na}\)) and most probably intrinsic \( \alpha \)-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 \( \omega \gamma < 26 \text{ meV (90 \% C.L.)} \), 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 \(^{19}\text{Ne}(p,\gamma)^{20}\text{Na}\) has to be measured and with the proposed facility at ISAC a direct experiment should be feasible.

2 Description of the Experiment

2.1 Determination of the \(^{19}\text{Ne}(p,\gamma)^{20}\text{Na} \) 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]:

\[
E_r = 447 \text{ keV} \quad \omega \gamma = 7 \text{ meV} \quad \Gamma \sim \Gamma_p = 0.09 \text{ eV} \\
E_r = 658 \text{ keV} \quad \omega \gamma = 20 \text{ meV} \quad \Gamma \sim \Gamma_p = 27 \text{ eV}, \\
E_r = 787 \text{ keV} \quad \omega \gamma = 70 \text{ meV} \quad \Gamma \sim \Gamma_p = 0.32 \text{ eV} \\
E_r = 857 \text{ keV} \quad \omega \gamma = 7.5 \text{ meV} \quad \Gamma \sim \Gamma_p = 12.2 \text{ keV},
\]

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

For the low energy resonance a 8.94 MeV \(^{19}\text{Ne}\) beam has to impinge on a windowless \( \text{H}_2 \)-gas target. Following the tabulated stopping power values, which should be independent of the isotope, the stopping power of \(^{19}\text{Ne}\) on a gaseous \( \text{H}_2 \) target at this energy is: \( \epsilon = 72 \text{ eV} / (10^{15} \text{ atoms/cm}^2) \). With a two sided, windowless \( \text{H}_2 \) gas target an areal target density of \( 8 \times 10^{18} \text{ cm}^{-2} \) can be achieved. The target thickness in the center of mass system is then \( \Delta \equiv 29 \text{ keV} \), 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]:

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

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

\[
Y_{\text{max}}(\infty) = 1.6 \times 10^{-11}.
\]

This is the reaction yield per incoming \(^{19}\text{Ne}\) projectile, and it should be noted that 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 16O 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 (Napoli-Bochum-Nuclear Astrophysics 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 19Ne(p,γ)20Na 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 20Na recoils from the 19Ne "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 19Ne(p,γ)20Na experiment requires a good separation for particles with E \approx 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 20Na recoils has to be selected. Usually there is a charge state with at least 20% probability. The momentum spread of Δp/p = 0.71% and a recoil half angle θ/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 19Ne ion beam of
\[ N(19\text{Ne}) = \frac{N_{\Delta E-E}}{\epsilon_{\text{DRAGON}} V_{\text{max}}} = 9 \times 10^7 \text{ ions/sec} \] (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 19Ne 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 19Ne 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 \( \Delta E-E \) ionization chamber have to be calibrated with stable beams relevant in this experiment. This way proper particle identification and reliability of the focusing elements can be ensured. Stable beams of 19F, 20Ne, and 23Na with beam currents in the region of pA can be guided with Faraday cups between the various elements and in front of the \( \Delta E-E \) 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 19Ne beam

The \( \Delta M/M \) ratio between 19Ne and its stable isobar 19F is 1 : 5470. Thus the selectivity of the ISAC mass separator (1 : 10000) should be able to suppress a possible 19F 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 19Ne beam of several tens of pA can be focussed as described in the previous section onto the Faraday cup in front of the \( \Delta E-E \) detector and after reducing the beam current the contamination can be monitored directly. 20Ne as the reaction product of 19F(p,\( \gamma \))20Ne will show up in another region of the \( \Delta E-E \) spectrum as the 20Na recoils of interest. However, to make sure the interpretation of the spectrum is correct, the reaction 19F(p,\( \gamma \))20Ne should be measured at the energies of interest.

### 2.4 Measurement of the elastic scattering cross section of 19Ne

As the reaction cross section of 19Ne(p,\( \gamma \))20Na will be measured relative to the elastic scattering of hydrogen and 19Ne, the scattering cross section has to be known. The easiest way is to measure the elastic scattering of 19Ne 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 $^{19}$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 $^8\text{B}^{5+}$ 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 D₂ 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


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


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


