TRIUMF - RESEARCH PROPOSAL

Experiment no.

Title of proposed experiment

Level structure of ^{21}Mg: nuclear and astrophysical implications

Name of group

University of Edinburgh/TRIUMF

Spokesperson for group

Alexander St.J. Murphy/John M. D'Auria

Email address

asmurphy@mps.ohio-state.edu / amurphy@ph.ed.ac.uk / dauria@sfu.ca

Members of group (name, institution, status)

(For each member, include percentage of research time to be devoted to this experiment over the time frame of the experiment)

A. St.J. Murphy	U. of. Edinburgh	Professor	50 %
J. D'Auria	Simon Fraser U.	Full Professor	50%
M. Aliotta	U. of. Edinburgh	Professor	20 %
R. Azuma	U of Toronto	Full Professor	10%
R. Boyd	Ohio State U.	Full Professor	20%
L Buchmann	TRUMF	Research Scientist III	20 %
A. Chen	TRIUMF	Research Associate	50 %
T. Davinson	U. of. Edinburgh	Research Fellow	20 %
B. Fulton	U. of York	Full Professor	20%
D. Hutcheon	TRIUMF	Research Associate	10 %
A. Laird	TRIUMF	Research Associate	20 %
A. Robinson	U. of. Edinburgh	Research Student	50 %
P. Walden	TRIUMF	Scientist	20 %
P. J. Woods	U. of. Edinburgh	Full Professor	20 %

Date for start of preparations: 03/2002

Date ready: 06/2002

Completion date: 12/2002

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
20 (^{20}Na)	2A/ISAC (TUDA, DRAGON)	NO
4 (^{20}Ne)	NA/ISAC (TUDA, DRAGON)	NO

Recently, radioactive beams of sodium have for the first time been accelerated at the TRIUMF facility. The proton rich isotopes available, coupled with the extraordinary abilities of the particle and gamma-ray detection facilities placed in the ISAC experimental hall, allow measurements relevant to many aspects of nuclear physics and astrophysics. In this paper we propose to make use of the world's first accelerated ^{20}Na beam, the unique capabilities of the TUDA and DRAGON systems, and a fortunate coincidence of nuclear physics properties, to allow measurement of the proton and gamma decay widths, angular momentum assignments and high precision excitation energy determinations for several states in ^{21}Mg.

The energy range available from ISAC, coupled with the high efficiency detection facilities of the TUDA system, allows detailed studies via elastic proton scattering. These will illuminate a region of excitation in ^{21}Mg in which one would expect there to be several states relevant to the astrophysically important ^{20}Na(p,γ)^{21}Mg reaction. Once identified in the (p,p) channel, we will attempt to observe, for the most favorable cases, using a hydrogen gas target, radiative captures with the DRAGON facility. Thus we will also determine the gamma decay widths. Studies similar to this latter objective were proposed in E908, presented to the EEC in December, 2000.

This reaction is an integral link in the path for breakout from the hot CNO cycle to the rp-process, and one resonance in particular, and very possibly more, is likely to play an important role. However, the data taken here will serve a wider purpose. These states in ^{21}Mg are expected to have isobaric analogues in the mirror ^{21}F nucleus. These fluorine states are rather well known, allowing detailed studies of the Coulomb energy shifts, and thus a test of a widely used technique for estimating resonance parameters in exotic nuclei. Indeed, the single previous measurement in this region of excitation in ^{21}Mg was, as is typical away from stability, via a multi-nucleon transfer reaction. Thus spectroscopic information extracted relied heavily on highly model dependent finite range DWBA analysis and comparison with the mirror nucleus. The simpler analysis afforded through the use of a radioactive beam will provide a much needed stringent test of complicated multi-nucleon transfer reaction techniques that previously have been used in studies of reactions near the drip lines. Especially relevant for the measurement proposed here, in the Kubono *et al.* investigation, it was noted that compatibility between the results of their analysis and the known mirror states required unexpectedly large level shifts, and indicated there may be missing s-wave resonances, leaving a strong chance that astrophysically important states have so far remained undetected. These data are also needed for shell model studies of nuclei near the drip lines, since the quality of such descriptions breaks down away from stability.

The proposed mode of running has already been adopted in the recent ^{21}Na(p,p)^{21}Na experiment (E879) during which a strong resonance was identified using TUDA and then subsequently measured in a short period of running on DRAGON as part of experiment E824, which studied the ^{21}Na(p,γ) reaction. It should be emphasized that we do not propose a comprehensive study of the level structure of ^{21}Mg, but rather a selective approach which aims to extract the most worthwhile aspects as efficiently as possible. In the present experiment we will require a total of 20 12 hour shifts to measure resonances in ^{21}Mg using TUDA and DRAGON, along with 4 shifts for calibration reactions using stable beams.

BEAM and SUPPORT REQUIREMENTS

Experimental area

ISAC high energy hall (TUDA and DRAGON)

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

Proton (20μA, 500MeV)

Secondary channel

TUDA
DRAGON

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

ISAC ion source: ^{20}Na, 300 –1500 keV/u, bunched beam, Δt =1ns, $\Delta E/E$ = 0.2%.
Minimum beam required: 2×10^6 pps for the ^{20}Na(p,p)^{20}Na studies with TUDA,
5×10^6 pps for the ^{20}Na(p,γ)^{21}Mg studies with DRAGON
Off-line source: ^{20}Ne, 200-1500 keV/u

TRIUMF SUPPORT:
Summarize all equipment and technical support to be provided by TRIUMF. If new equipment is required, provide cost estimates.
NOTE: Technical Review Forms must also be provided before allocation of beam time.

ISAC

Data acquisition support

NON-TRIUMF SUPPORT:
Summarize the expected sources of funding for the experiment.
Identify major capital items and their costs that will be provided from these funds.

Project support for students, support for travel.

SAFETY	Sheet 4 of 11

Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.

Radioactive: There are no safety concerns above and beyond the normal running of a radioactive beam in the ISAC experimental hall. Beam intensities of 5–50 x10^6 s^{-1} ^{20}Na ions are predicted. ^{20}Na is β^+ unstable with a half-life of roughly a half second, so no residual activity is expected after irradiation. Fields during RIB operation are not expected to exceed a few mSv/hr at 1m at any location due to this beam.

Chemical: An additional concern will be the hazards of using hydrogen as a target in DRAGON. This is not an unusual mode of operation and so these concerns have been addressed elsewhere.

Introduction

The objective of this proposal is to significantly advance knowledge of the nuclear level structure of ^{21}Mg. The properties of this nucleus are such that it is believed it may play an important role in several nucleosynthetic processes that occur in neutron stars and maybe white dwarfs. Also, from a strictly nuclear physics view point, the study of the structure of exotic nuclei has gained significant importance since the advent of radioactive beam facilities. These open up an invaluable means to experimentally access, for the first time, nuclei for which very little is known at present.

In what follows we shall outline the main motivations to study the $^{20}Na(p,p)^{20}Na$ and $^{20}Na(p,\gamma)^{21}Mg$ reactions and the level scheme of the unstable compound nucleus that they populate.

Astrophysical Relevance

Nucleosynthesis in Novae and X-ray bursts.

Heavy element production in extreme astrophysical environments, such as novae and x-ray bursts, is one of the most rapidly developing fields of nuclear physics. This is due not only to the advances in accelerator physics and detector arrays as witnessed at TRIUMF, but also to simultaneous advances in observational astronomy and advances in the theoretical treatment and understanding of explosive nucleosynthesis.

The objective of this proposal is first to locate and identify resonances in the $^{20}Na(p,p)^{20}Na$ reaction using TUDA, and then to take advantage of the ability to switch rapidly to the DRAGON facility to directly determine the astrophysically significant $^{20}Na(p,\gamma)^{21}Mg$ reaction rate. These measurements will help determine the exact mechanism for the energy generation and nucleosynthesis that occurs in novae and x-ray bursts.

Type-I x-ray bursts and novae are examples of binary stellar sites where accretion onto a degenerate partner can lead to an environment in which runaway energy generation produces large amounts of nucleosynthesis on a very short timescale (Boyd 1999). Consequently, the nuclei involved do not have enough time to beta decay, and thus completely different reaction pathways are involved from the nucleosynthesis that occurs over much longer timescales in more stable stellar environments.

For x-ray bursts, where hydrogen is accreted onto the surface of a neutron star, current models suggest that the hot CNO cycles dominate the energy generation for temperatures T~0.4 GK (Wiescher 1998). The observed energy output however appears to be larger than these cycles are capable of producing. Thus it is thought that as the temperature and density increase, proton- and/or alpha–captures can become faster than the beta decays. This opens up the possibility of breaking out of the CNO cycles to the rp-process, which in turn determines a much larger energy generation as well as the explosive production of nuclei up to, perhaps, mass 100.

Current theory suggests the transition to breakout should occur above about T=0.6 GK (Wiescher 1999), proceeding via the reaction sequence $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na(p,\gamma)^{21}Mg$. While the alpha capture reaction is thought to determine the rate of this reaction sequence no direct data exists for the $^{20}Na(p,\gamma)^{21}Mg$ reaction. Although indirect data (Kubono 1992) seem to indicate levels within the Gamow window, only a direct determination of the $^{20}Na(p,\gamma)^{21}Mg$ reaction cross section at the relevant energies will confidently constrain the nucleosynthesis path. At higher temperatures still, current models suggest that the $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$ may dominate (Hahn 1996). However, this has yet to be confirmed and it is thoroughly possible that the initially mentioned reaction path may continue to dominate to higher temperatures. Given that barely any experimental data exists to confirm this picture, a measurement of a reaction that is located on the path to break out, and is indeed the first reaction in the chain of reactions after breakout, is clearly a high priority.

The $^{20}Na(p,\gamma)^{21}Mg$ reaction also plays a fundamental role in the energy generation and nucleosynthesis involved in novae explosions (Wiescher 1998), that is, when accretion from the hydrogen envelope of one star falls on to the surface of a white dwarf. In this case, the lower gravitational field of the white dwarf means that temperatures and pressures are insufficient to allow breakout to occur. Instead, it is thought that the NeNa and MgAl cycles will become the energy source. Of interest here is the NeNa cycle:

$$^{20}Ne(p,\gamma)^{21}Na(p,\gamma)^{22}Mg(\beta^+)^{22}Na(p,\gamma)^{23}Mg(\beta^+)^{23}Na(p,\alpha)^{20}Ne$$

This reaction paths cannot occur unless the ^{20}Ne seed nuclei are available. Since ^{20}Ne is the beta decay daughter of ^{20}Na, it becomes clear that the $^{20}Na(p,\gamma)^{21}Mg$ reaction is important in determining how quickly the ^{20}Na is depleted, thereby affecting the subsequent synthesis in the NeNa cycle.

Nuclear Relevance

Thomas Ehrman energy shift calculations

Apart from astrophysics, there are other areas of physics where reactions need to be studied which involve radioactive nuclei for which little information is known. A frequently used method for estimating the structure of such a nucleus is to make a comparison to the mirror nucleus which, by definition, has an inverted number of neutrons and protons. The isospin states of the two nuclei are thus equivalent, and the only differences should be due to the Coulomb force. However, these differences can mean that states that in one nucleus are unbound, can be bound in the mirror nucleus, and thus the mirror nucleus may have much more spectroscopic data available. To take into account the differences caused by the Coulomb force one has to account for the different spatial distributions of the protons within the nucleus compared to the neutrons in their isobaric analogue states. For this one can use the formalism of Thomas and Ehrman (Thomas 1952, Wiescher 1988).

This is of particular interest in the present case for two reasons. Firstly, the only data that currently exist seem to suggest an unexpectedly large shift for the (astrophysically important) states near the proton threshold. Indeed the shift for one state appears to be large enough to make bound a state which would otherwise be expected to be unbound. This presents the possibility that the states have been misidentified and thus there may be other states so far undiscovered. Another possibility is that the prescription of calculating the level shifts needs to be modified. This is the second reason of interest: a test here will provide a benchmark for the application of the Thomas-Ehrman energy-shift technique for other reactions near the drip line, many of which will be made at TRIUMF in the coming years. Two key parameters in determining the level shift are the angular momentum transfer involved, and the proton decay widths. The proposed measurements will provide high quality data relating to both of these.

Structure of ^{21}Mg

The simple shell model description of the ground state of ^{21}Mg is expected to be a closed ^{16}O core plus 5 nucleons distributed as $<\pi 1d_{5/2}>^4<\nu 1d_{5/2}>$. States excited in proton scattering are thus likely to reflect unpaired nucleons in the $\pi 1d_{5/2}$, $\pi 2s_{1/2}$ and $\pi 1d_{3/2}$ shells. Additionally, negative parity states can be formed by promotion of a nucleon from the ^{16}O core. This appears to be confirmed by the level structure of the mirror nucleus, ^{21}F, where the ground state spin-parity is indeed $5/2^+$, the 1st excited state is $1/2^+$ and then there are several positive parity states above that with spins assignments of 1/2, 3/2, 5/2 and 7/2 and. A more sophisticated theoretical description of the structure of ^{21}Mg is at the current time difficult: whereas for nuclei in this mass region close to stability, theoretical shell model studies are generally able to describe nuclei very well using the W-interaction, closer to the drip lines they work rather less well. Indeed, this has led to significant recent desire for more data, such as those that would be gained from this experiment [Otsuka 2001].

Experimentally, knowledge of the level structure of ^{21}Mg above the proton threshold of 3.216 MeV is entirely based on the measurements of Kubono *et al.* (Kubono 1992). This study, populated states through the ^{24}Mg(^{3}He,^{6}He)^{21}Mg reaction. They observed around twenty states with excitation energies in the range 0-6 MeV, determining level energies to approximately 15 keV. Largely tentative transferred angular momentum values were determined for half of these, through comparison of the angular distributions to an exact finite range distorted wave Born approximation, and then tentative J^{π} values were assigned through comparison with the structure information available from ^{21}F, the mirror of ^{21}Mg. A summary of their findings relevant to this proposal is included in Figure 1. Of particular interest is that the first few excited states above the proton threshold were found to be much lower than the previous predictions (Wallace 1981, Langanke 1986). Additionally, the analysis of Kubono *et al.* indicated L_{tr}=2 transfer for the population of these states, whereas they had previously been assumed to be via L_{tr} =0 transfer.

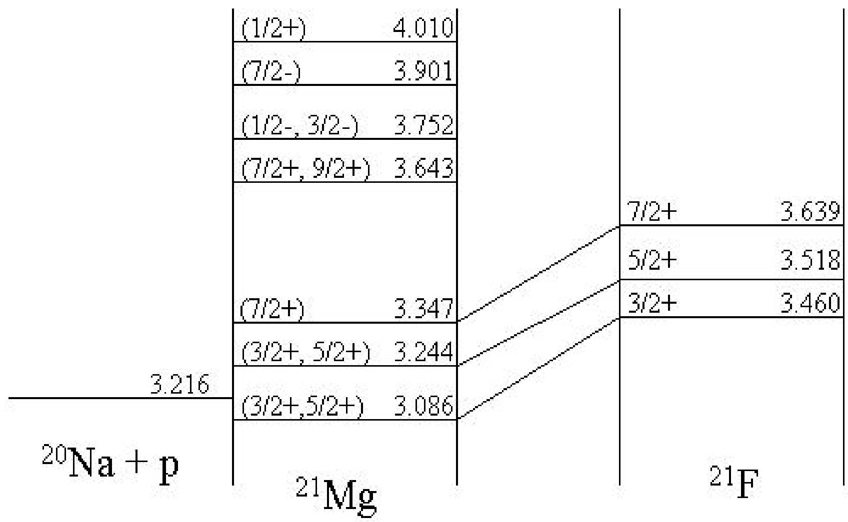

Figure. 1. Level structure of ^{21}Mg and ^{21}F near the ^{20}Na+p threshold

Table 1 then lists the resonance parameters that they inferred, based on assumptions of the spectroscopic factors and the exact spin assignments. Immediately apparent is that both the gamma and proton decay widths are rather small (under the assumptions made) for the lower lying of these states, thus making them likely unobservable. However, the state at E_x=4.010 MeV (E_r=0.794 MeV), if confirmed, should be readily detectable, apparently having both large proton and gamma decay widths. This resonance is expected to be a major contributor to the ^{20}Na(p,γ) reaction rate in the high temperature range (Kubono 1992). If the resonance parameters so far assumed turn out to be incorrect then others of the states may in fact be strong enough to also be observed. Moreover, there may well be strong resonances so far unobserved, due to the selectivity of the (^{3}He,^{6}He) transfer reaction. Also, the study of Kubono *et al.* was limited from observing states above an excitation of about 4.4 MeV by carbon contamination, and thus resonances above E_r=1.2 MeV may have been hidden. If new states should be observed, and have L_{tr}=0, they could be highly significant for astrophysical reasons.

In this proposal, the entrance channel is to be ^{20}Na+p, and angular distribution of scattered protons should give definite values of angular momentum transfer. The channel spin of either 3/2 or 5/2 means that the final angular momentum of a state can then be derived from spectroscopic information of the mirror nucleus, as well as the possibility of γ-ray strength observations.

^{21}Mg (MeV)	E_r (MeV)	J^π	Γ_p (eV)	Γ_γ (eV)	$\omega\gamma$ (meV)
3.086	-0.130	(**3/2$^+$**, 5/2$^+$)	no data	0.188	no data
3.244	0.028	(3/2$^+$,**5/2$^+$**)	3.04×10^{-19}	0.0833	1.82×10^{-16}
3.347	0.131	(7/2$^+$)	1.23×10^{-6}	0.274	9.84×10^{-4}
3.643	0.427	(7/2$^+$,**9/2$^+$**)	1.58×10^{-4}	6.09×10^{-3}	1.54×10^{-4}
3.752	0.536	(1/2$^-$,**3/2$^-$**)	99.4	0.1	40
3.901	0.685	(7/2$^-$)	0.872	0.1	70
4.010	0.794	(1/2$^+$)	4720	0.439	88

Table 1. Resonance parameters adopted for the ^{20}Na+p reaction, reproduced from (Kubono *et al.*). Where more than one spin assignment is possible, the preferred choice is shown bold.

Description of the Experiment

This proposal intends to use a radioactive ^{20}Na beam delivered from the ISAC. The sodium beams that recently have been successfully accelerated allow a relatively firm estimate of a ^{20}Na current of at least 5×10^{6} s^{-1}. Stable beams of ^{20}Ne will also be required, for calibration, and will be extracted from the off-line source.

The accelerated beam will be delivered to the TRIUMF-UK Detection Array (TUDA) beam line via the main switching magnet. The recent completion of the first phase of TUDA marked the start of a collaboration between Canada and the UK dedicated to high efficiency charged particle detection, optimally suited for experiments like this that feature radioactive beams in inverse kinematics. Experiment E879 recently showed the capability of the detection array in a configuration largely identical to that we propose. Additionally, further instrumentation is being included to enhance the number of channels by about a factor of two.

In this proposal, we plan to perform an excitation function over the complete energy range of the Drift Tube Linac (0.3 – 1.5 MeV/u). The excitation energy of states probed in ^{21}Mg will be from 3.502 MeV to 4.644 MeV. This range of excitation will probe the states above and including the one at E_x=3.643 MeV. We believe that even if the tentative spectroscopic details attributed to the states below this are in reality more favourable, these states are still well beyond our hopes of sensitivity. However, there exists the possibility that there are other states that were not populated by the previous three-neutron transfer reaction, and to not consider that possibility risks missing perhaps the experiment's most important result. A polyethylene target (CH_2) will be used, and proton recoils will then be detected in the silicon LEDA arrays. As experiment E879 proved, measurement of just the recoil protons, given the known arrival time window provided by the RF, is sufficient to provide adequate background suppression.

LEDA-style silicon detector arrays will be used to cover laboratory scattering angles from about 10-50 degrees. This corresponds to ~20-100 degrees in the centre-of-mass system. Elastically scattered recoil protons from the CH_2 target will have energies from 2.83 MeV at forward angles, down to 1.20 MeV for the largest scattering; well above the detection thresholds. From consideration of the data taken recently in the ^{21}Na(p,p) measurement (E879) we believe that nuclei detected following the scattering of the ^{20}Na beam with carbon nuclei in the target will not be a serious problem because they have substantially higher energies and can therefore be removed in software.

The proton widths of the resonances to be observed, even the wider ones, are narrow in comparison to the energy width of the target for the beams and energies involved. Similarly the ISAC beam should have an excellent energy resolution better than 0.2%. In order to cover the rather wide region of excitation in ^{21}Mg in as few runs as possible, a relatively thick target (~200μg/cm^2, ~10^{18} nuclei/cm^2) shall be used, which will cover about 200 keV in excitation. Thus, our event rates will be thick target yields. Given that the decay widths needed to accurately estimate the expected yield are unknown, the simplest, and perhaps most reliable method of estimating the yields, is to make a comparison with a previous experiments that used similar experimental configurations. The recently completed E879 run at TRIUMF is a good example. This experiment's data analysis is at an early stage, but states with proton widths around 10 keV were clearly observed online, with a rate limited current of ~1x10^7 ^{21}Na s^{-1}. Similarly, the measurement of the p(^{19}Ne,^{19}Ne)p reaction by Coszach *et al*. at Louvain-la-Neuve (Coszach 1994) also affords a suitable comparison. These data therefore lead us to believe any state with a width greater than 1 keV should be readily observable, and states with widths similar to or larger than the one reported by Kubono *et al.* at E_x=4.01 MeV (width 4.72 keV) should easily yield unambiguous L_{tr} values.

After a resonance has been identified with TUDA, and a measurement of the proton width determined, we will determine, for the most promising candidates, the gamma-decay width of the state. To do this we will set the switching magnet so as to deliver the beam to the Detector of Recoils and Gammas Of Nuclear reactions (DRAGON). This is a facility dedicated and optimised for the study of radiative proton and alpha capture reactions in inverse kinematics. The DRAGON features a windowless, differentially pumped gas target, BGO detectors to observe capture gamma-rays, a state-of-the-art electromagnetic mass separator, and an array of focal plane detectors to observe the recoils. Thus the DRAGON is ideally suited to the measurement of the ^{20}Na(p,γ)^{21}Mg reaction. Its excellent suitability to these measurements has been confirmed in the experiments conducted since construction was completed in 2001. Further details relating to DRAGON are given in NSERC 1997.

Once again, since we will operate the windowless gas target at a thickness of about 10^{18} atoms cm^{-2} we shall be measuring thick target yields. The yield from the widely spaced narrow resonances can be directly related to the resonance strength in the following way:

$$Y = 2\pi \mathrm{D}^2 \omega\gamma \, \frac{m_p + m_t}{m_p} \frac{n}{dE/dx} \int_{E_b-\Delta E}^{E_b} \frac{1}{\sqrt{2\pi}\sigma_b} \exp\left(-\frac{(E-E_r)^2}{2\sigma_b^2} \right) dE$$

where the masses of the projectile and target are m_p and m_t, λ is the reduced de Broglie wave length, n is the target density, dE/dX is the stopping per unit length, E_b is the beam energy and σ_b is the rms width of the beam. Using this equation, and numerically performing the integration, gives the yields in table 2. These yields were taken from proposal E908 (Chen 2000) and assume a ^{20}Na beam intensity of 5x10^7 p/s, an overall DRAGON transmission of 40% (includes charge state selection), and resonance strength values from Kubono *et al.* (Kubono 1992).

E_x in ^{21}Mg (MeV)	E_r (MeV)	ΔE (keV/cm)	$\omega\gamma$ (meV)	Yield (cph)
3.643	0.427	14.6	0.154	0.02
3.752	0.536	14.5	40	4.4
3.901	0.685	14.3	70	6.3
4.010	0.794	14.2	88	7.4

Table 2. Experimental parameters and predicted yields of events in DRAGON for several of the states of ^{21}Mg, assuming the resonance parameters listed in Table 1.

Readiness

Given the successes of experiments E824 and E879 we believe this experiment can be conducted as soon as beam time permits. We note that the complete instrumentation of TUDA in expected, resulting in roughly twice as many channels as used in the E879 proposal. This will allow an increase in the solid angle coverage and thus in detection efficiency. Given the ^{20}Na beam currents likely to be available, event rates of a few hundred Hz are expected, and thus we are not rate limited.

Beam time required

We intend to cover the excitation energy region in ^{21}Mg from 3.50 – 4.65 MeV. For the (p,p) measurements made with TUDA we will do this in 5 steps, each of 200-250 keV using thick targets. Once identified, promising resonances will then become the focus of (p,γ) studies using DRAGON. In this way we expect to an initial break down of the beam time required for this study using both TUDA and DRAGON is as follows: The numbers of shifts indicated include those required for calibration with stable beams.

Radioactive beam:		Stable beam	
TUDA Studies	10 x 12 hour shifts	TUDA Studies	2 x 12 hour shifts
DRAGON Studies:	10 x 12 hour shifts	DRAGON Studies:	2 x 12 hour shifts

References

[Boyd 1999] R.N. Boyd, Heavy Elements and Related New Phenomena, ed. by R. Gupta and W. Greiner, World Scientific, Singapore, (1999), p. 893

[Wiescher 1998] M. C. Wiescher, H. Schatz and A. E. Champagne, Phil. Trans. R. Sc. Lond. A **356** (1998) 2105 [Otsuka 2001] T. Otsuka *et al*. Bull. Am. Phys. Soc. (2001)

[Wiescher 1999] M. C. Wiescher, J. Görres and H. Schatz, J. Phys. G **25** (1999) 133

[Kubono 1992] S Kubono, Y. Funatsu, N. Ikeda, M. Yasue, T. Nomura, Y. Fuchi, H. Kawashima, S. Sato, H. Miyatake, H. Orihara and T. Kajino . Nuclear Physics **A537** (1992) 153

[Hahn 1996] K.I Hahn, A. Garcia, E. G. Adelberger, P. V. Magnus, A. D. Bacher, N. Bateman, G. P. A. Berg, J. C. Blackmon, A. E. Champagne, B. Davis, A. J. Howard, J. Liu, B. Lund, Z. Q. Mao, D. M. Markoff, P. D. Barker, M. S. Smith, E. J. Stephenson, K. B. Swartz, S. Utku, R. B. Vogelaar and K. Yildiz, Phys. Rev. C **54** (1996) 1999

[Thomas 1952] R.G. Thomas, Phys. Rev. **88** (1952) 1109

[Wiescher 1988] M. C. Wiescher, J. Görres and F.K. Thielemann, Ap. J. **326** (1988) 384

[Otsuka] Bull. Am. Phys. Soc. 2001, Talk presented at the APS/JPS meeting, Maui, 2001.

[Wallace 1981] R. K. Wallace and S. E. Woosley, Astrophys. J. Suppl. **45** (1981) 389

[Langanke 1986] K. Langanke, M. Wiescher, W. A. Fowler and J. Görres, Astrophys. J. (1986) 629

[Coszach] R. Coszach, Th. Delbar, W. Galster, P. Leleux, I. Licot, E, Lienard, P. Lipnik, M. Michotte, A. Ninane, J. Vervier, C. R. Bain, T. Davinson, R. D. Page, A. C. Shotter, P. J. Woods, D. Baye, F. Binon, P. Discouvemont, P. Duhamel, J. Vanhorenbeech, M. Vinke, P. Decrock, M. Huyse, P. Van Duppen, G. Vancraeynest and F.C. Barker, Phys. Rev. C. **50** (1994) 1695

[NSECR 1997] NSERC Major Installation Grant Report for DRAGON (1997)

[Chen 2000] A. Chen and J.M. D'Auria, Proposal E908 submitted to TRIUMF EEC meeting of Dec. 2000.

Association of the ^{12}C+^{12}C breakup states in ^{24}Mg with the quasi-molecular resonances,
N. Curtis, N. M. Clarke, B. R. Fulton, S. J. Hall, M. J. Leddy, A. St.J. Murphy, J. S. Pople, R. P. ward, W. N. Catford, G. J. Gyapong, S. M. Singer, S. P. G. Chappell, S. P. Fox, C. D. Jones, D. L. Watson, W. D. M. Rae and P. M. Simmons, Phys. Rev. C **51** (1995) 1554.

Search for ^{16}O-^{16}O-^{16}O structure in ^{48}Cr,
A. St.J. Murphy, R. A. Le Marechal, N. M. Clarke, N. Curtis, M. Freer, B. R. Fulton, S. J. Hall, M. J. Leddy, J. S. Pople, G. Tungate R. P. Ward, W. D. M. Rae P. M. Simmons W. N. Catford, G. J. Gyapong S. M. Singer S. P. G. Chappell, S. P. Fox, C. D. Jones, P. Lee, and D. L. Watson, Phys. Rev. C. **53** (1996) 1963.

Evidence for a deformed band in ^{16}O+^{16}O breakup of ^{32}S,
N. Curtis, A. St.J. Murphy, N. M. Clarke, M. Freer, B. R. Fulton, S. J. Hall, M. J. Leddy, J. S. Pople, G. Tungate, R. P. Ward, W. N. Catford, G. J. Gyapong, S. M. Singer, S. P. G. Chappell, S. P. Fox, C. D. Jones, D. L. Watson, P. H. Regan and V. F. Pucknell, Phys. Rev. C. **53** (1996) 1804.

^{12}C+^{12}C and ^{16}O+^{8}Be Decay of ^{24}Mg States Excited in the ^{12}C(^{16}O,^{24}Mg)α Reaction,
M. Freer, N. M. Clarke, B. R. Fulton, J. T. Murgatroyd, A. St.J. Murphy, S. P. G. Chappell, R. L. Cowin, G. Dillon, D. L. Watson, W. N. Catford, N. Curtis, M. Shawcross and V. F. E. Pucknell, Phys. Rev. C **57**, (1998) 1277.

Can breakup reactions be used to probe high-lying inelastic channels in ^{12}C+^{12}C scattering?
S. J. Hoad, N. M. Clarke, N. Curtis, M. Freer, B. R. Fulton, S. J. Hall, M. J. Leddy, A. St.J. Murphy, J. S. Pople, G. Tungate, R. P. Ward, S. P. G. Chappell, S. P. Fox, C. D. Jones, D. L. Watson, W. D. M. Rae, P. M. Simmons, W. N. Catford, G. J. Gyapong and S. M. Singer, J. Phys. G **24** (1998) 167.

Measurements of Proton Radiative Capture Cross Sections Relevant to the Astrophysical rp- and γ-Processes,
F. R. Chloupek, A. St.J. Murphy, R. N. Boyd, A. L. Cole, J. Görres, R. T. Guray, G. Raimann, J. J. Zach, T. Rauscher, J. V. Schwarzenberg, P. Tischhauser, and M. C. Wiescher, Nucl. Phys. **A 652** (1999) 391

The Observatory for Multiflavor Neutrinos from Supernovae,
R. N. Boyd and A. St. J. Murphy for the OMNIS collaboration, Nucl. Phys. **A 688** (2001) 386

Proton radiative capture cross sections on ^{102}Pd at energies of astrophysical interest
N. Özkan, A. StJ. Murphy, R. N. Boyd, A. L. Cole, R. deHaan, M. Famiano, J. Göerres, R. T. Güray, M. Howard, L. _ahin and M. C. Wiescher, Nucl. Phys. **A 688** (2001) 459

Evidence for a highly deformed band in ^{12}C+^{16}O breakup of ^{28}Si
N. I. Ashwood, J. T. Murgatroyd, N. M. Clarke, M. Freer, B. R. Fulton, A. St.J. Murphy, S. P. G. Chappell, R. L. Cowin, D. L. Watson, W. N. Catford, N. Curtis, and M. Shawcross, Phys. Rev. C. **63** (2001) 034315

Optimisation of the Design of OMNIS, the Observatory for Multiflavor Neutrinos from Supernovae,
J. J. Zach, A. StJ Murphy, D. Marriot and R. N. Boyd, Accepted, Nucl. Instr. Meth. A (2001)

Measurement of the cross section of the ^{8}Li(d,α)^{6}He reaction of possible relevance to Big Bang Nucleosynthesis,
L. _ahin, R. N. Boyd, A. L. Cole, M. Famiano, R. T. Güray, A. StJ. Murphy, N. Özkan, J. J. Kolata, V. Guimarães and M. Hencheck, Accepted, Phys. Rev. C, (2001)