TRIUMF — RESEARCH PROPOSAL	Experiment no. 805	Sheet 1 of 19

Title of proposed experiment:

A Study of the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ Reaction with a $^{13}\mathrm{N}$ Beam

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*It is premature to project research time at this time.

Start of preparations:

Date ready:

Completion date:

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
≈ 34	ISAC/DRAGON	No

SUMMARY

A knowledge of the reaction rate for the $^{13}N(p,\gamma)^{14}O$ reaction for temperatures up to 10^9 K ($T_9 = 1$) is vital for understanding hydrogen burning in the hot CNO cycle and the conditions under which break-out into the rp-process may occur. Examination of the level scheme for ^{14}O indicates that proton capture on ^{13}N should be dominated at low energies by a resonance at 526 keV due to the $E_x = 5.155$ MeV $1^-, T = 1$ first excited state in ^{14}O. In addition, a non-resonant or direct capture contribution is also expected. A considerable effort has been expended in recent years in determining the parameters for the resonance via particle transfer reactions, resonant capture of ^{13}N in hydrogen targets, and Coulomb dissociation of high-energy ^{14}O beams in the field of a heavy nucleus. As a result, the resonance parameters are well-determined. However, the non-resonant component can only be calculated.

Breakout from the CNO cycle via the $^{13}N(p,\gamma)^{14}O$ reaction begins at about $T_8 = 1$. The peak temperature for a nova outburst is near $T_8 = 2.4$. This latter temperature serves as a convenient (and important) reference point to estimate the contributions to the S-factor from resonant and non-resonant capture and from the interference between them. The Gamow peak for the $^{13}N(p,\gamma)^{14}O$ reaction at this temperature is at 168 keV and has a width of 136 keV. At these energies the reaction rate has a significant dependence on the non-resonant component. Thus it is essential to make a direct determination of the non-resonant component of the reaction.

The ISAC facility should be able to produce a ^{13}N beam of 10^{10} s^{-1} (or more). With the proposed DRAGON recoil mass analyser serving as a detector with an efficiency of at least 10%, it should be possible to carry out a measurement of the $^{13}N(p,\gamma)^{14}O$ reaction in inverse kinematics over a center-of-mass energy range from 400 to 1000 keV within a reasonable period of time. This would allow a determination of the non-resonant component to an accuracy of better than 20%, leading to a much more secure extrapolation of the cross section to energies of astrophysical interest.

BEAM REQUIREMENTS	Expt # 805	Sheet 3 of 19

Experimental area

ISAC high-energy experimental area

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

500 MeV protons of $\approx 10\ \mu$A intensity, CW

Unpolarized

Zeolite primary target

Secondary channel ISAC

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

^{13}N, 60 keV, $\approx 10^{10}$ s^{-1}

TRIUMF SUPPORT:

Operation of the ISAC and DRAGON facilities and the gas target

Pool electronics (shared with other DRAGON experiments)

Mechanical and electrical engineering (shared with other ISAC experiments)

NON-TRIUMF SUPPORT

NSERC Project Grant

Normal procedures for the operation of ISAC/DRAGON and the gas target, as set out by the TRIUMF Safety Group, will be followed. Short-lived isotopes will be mass-separated and transported to the DRAGON experimental area where they will be monitored. Standard radioactive sources for calibration will be used.

1 Scientific Justification

1.1 Introduction

A knowledge of the reaction rate for the $^{13}N(p,\gamma)^{14}O$ reaction for temperatures up to 10^9 K ($T_9 = 1$) is vital for understanding hydrogen burning in the hot CNO cycle and the conditions under which break-out into the rp-process may occur. Examination of the level scheme for ^{14}O indicates that proton capture on ^{13}N should be dominated at low energies by a resonance at 526 keV due to the $E_x = 5.155$ MeV $1^-, T = 1$ first excited state in ^{14}O (see Fig. 1.1). (All energies are in the center-of mass system unless otherwise stated.) In addition, a non-resonant or direct capture contribution is also expected. A considerable effort has been expended in recent years to determine the parameters for the resonance. These include particle transfer reactions, resonant capture of ^{13}N in hydrogen targets. and Coulomb dissociation of high-energy ^{14}O beams in the field of a heavy nucleus. The present experimental situation is reviewed in two papers [1,2] from the group at Louvain-la-Neuve and in a review article on Coulomb dissociation studies [3].

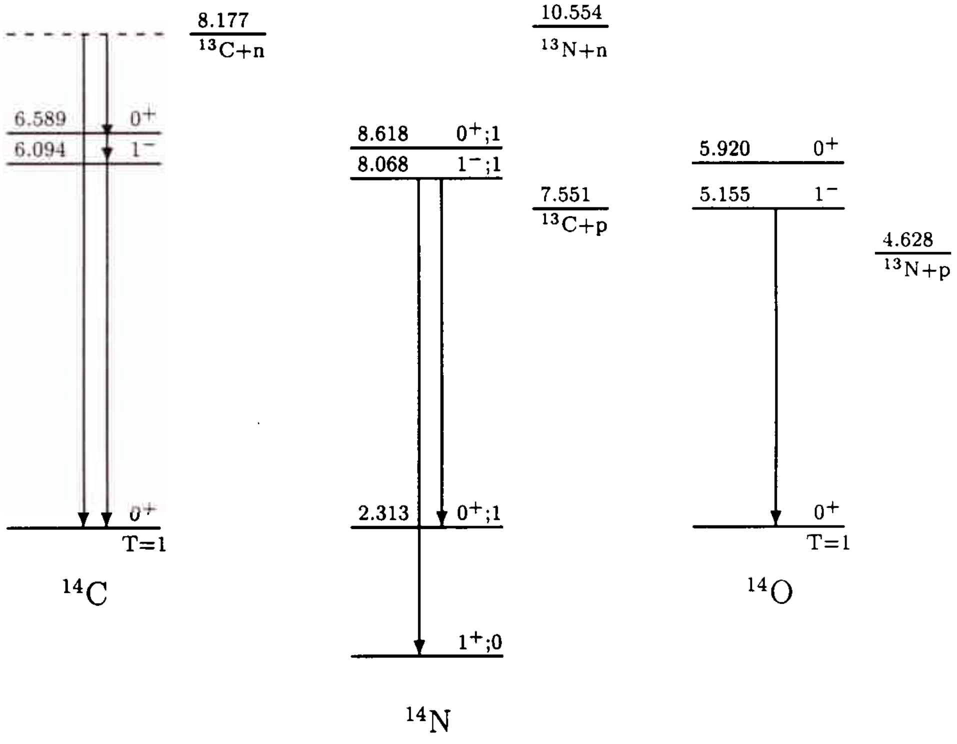

Fig. 1 Partial level schemes of mass 14 nuclei.

The non-resonant component of the cross section has been calculated by several groups, either separately or as part of the calculation of the total cross section. References to theoretical studies can be found in refs. [1–3]. There are significant differences among the various calculations. Since the cross section at energies well below the resonance is required for the determination of the reaction rate at temperatures of astrophysical interest, it is desirable that an estimate of the non-resonant contribution based on experimental data be made, if possible.

We first review the existing data and find that the resonance parameters are well-determined. An estimate is then made of the possibility of measuring the cross section for the ^{13}N$(p,\gamma)^{14}$O reaction over a reasonably broad energy range using a ^{13}N beam from ISAC. Such a measurement would provide additional data on the resonance parameters and could reduce the uncertainty in the non-resonant contribution. It would also be an excellent test reaction for the ISAC radiative capture facility.

1.2 Resonance parameters

The width of the resonance is $\Gamma = \Gamma_\gamma + \Gamma_p \approx \Gamma_p$ since $\Gamma_\gamma \ll \Gamma_p$. A weighted average for Γ of 37.3 ± 0.9 keV is quoted in ref. [1], based on two measurements of 37.0 ± 1.1 and 38.1 ± 1.8 keV.

There have been several measurements of the radiative width both directly, using radioactive beams, or indirectly, via particle transfer. Experimental values of Γ_γ are tabulated in refs. [2,4]. Radiative widths obtained by the ^{13}N$(p,\gamma)^{14}$O reaction [2] and by Coulomb dissociation of ^{14}O [3] are of comparable accuracy and have lower uncertainty than those obtained via transfer reactions. A weighted average of $\Gamma_\gamma = 3.0 \pm 0.4$ keV is given in ref. [4].

The resonance energy has been determined accurately via elastic scattering to be 526.0 ± 1.0 keV [5]. This value is much lower than the previously accepted value of 545 ± 10 keV [6], but is in good agreement with a recent value of 528.8 ± 2.0 keV measured in a transfer reaction [7].

1.3 Calculation of the S-factor

The cross section can be written as

$$\sigma(E) = \frac{S(E)}{E} exp(-2\pi\eta)$$

where $S(E)$ is the astrophysical S-factor and η is the Sommerfeld parameter. The cross section (or S-factor) for the ^{13}N$(p,\gamma)^{14}$O reaction has been calculated [2,4] using the Breit-Wigner formalism in which the S-factor is written as

$$S(E) = S_R(E) + S_{DC}(E) + 2[S_R(E)S_{DC}(E)]^{1/2} cos\delta$$

where $S_R(E)$ and $S_{DC}(E)$ are the contributions from resonant and non-resonant capture, respectively. The final term in the expression describes the interference between resonant and non-resonant capture and contains the phase factor

$$\delta = tan^{-1}\left[\frac{\Gamma(E)}{2(E - E_R)}\right]$$

where E_R is the resonance energy and $\Gamma(E)$ is the energy-dependent resonance width.

The S-factor for the resonance is assumed to be described by a single-level Breit-Wigner shape, where the energy dependence of the partial widths Γ_γ and Γ_p and the total width Γ is taken into account. Thus, we have

$$S_R(E) = S_R(E_R)\left[\frac{exp(2\pi\eta(E))}{exp(2\pi\eta(E_R))}\right]\left[\frac{\Gamma_p(E)}{\Gamma_p(E_R)}\right]\left[\frac{\Gamma_\gamma(E)}{\Gamma_\gamma(E_R)}\right]\frac{[\frac{1}{2}\Gamma(E_R)]^2}{(E-E_R)^2+[\frac{1}{2}\Gamma(E)]^2}.$$

For the DC contribution, we have

$$S_{DC}(E) = C^2 S[S_{DC}(E)_{theory}]$$

where C is an isospin coefficient, S is the spectroscopic factor, and $S_{DC}(E)_{theory}$ is a theoretical calculation of the non-resonant S-factor.

From the above equations we see that $S(E)$ can be calculated if we have an experimental determination of the resonance parameters E_R, Γ_p and Γ_γ and of the spectroscopic factor S, and a calculation for $S_{DC}(E)_{theory}$.

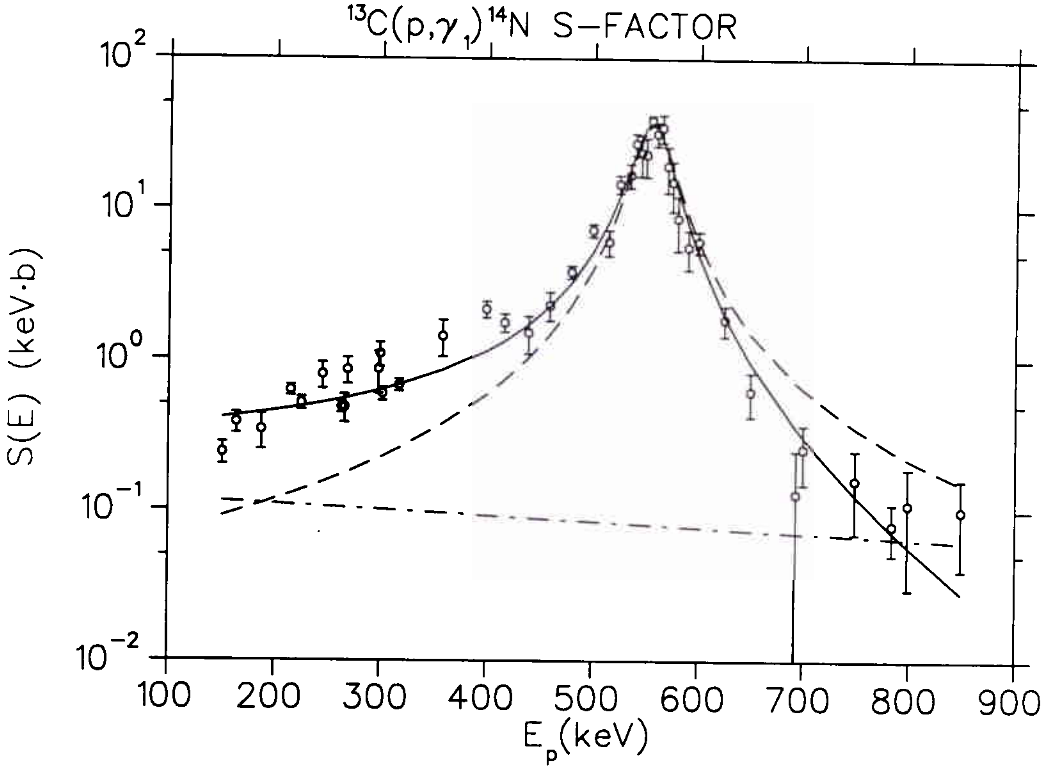

Fig. 2 Energy dependence of the S-factor for the $^{13}C(p,\gamma)^{14}N$ reaction populating the 2.313 MeV state in ^{14}N. See text for details.

1.4 Direct capture calculations

Two calculations of the theoretical DC S-factor have appeared recently [1,8]. They are presented in Table 1, along with a calculation carried out at TRIUMF [9], for the energy range from 0 to 1 MeV. The numbers in the second column are calculated directly from equation (15) of ref. [1]. The numbers in the third column are obtained from the equation for $S_{DC}(E)$ given on page 1898 of ref. [8] assuming that the spectroscopic factor used was $S = 0.45$ as inferred by their discussion and reference to the paper by Azuma *et al.* in ref. [10]. This paper showed a preliminary value of the spectroscopic factor for direct capture to the 2.313 MeV state in ^{13}C from a study of the $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ reaction (see Fig. 1.1). This is the analogue reaction to the direct capture in the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction and it is reasonable to assume that the spectroscopic factors are the same. The resonant and DC contributions to the S-factor for the analogue reaction are shown in Fig. 1.3. The final result for this spectroscopic factor was 0.43±0.09 [11].

There are considerable differences between the three calculations both in the magnitude of the S-factor and in its energy dependence.

Table 1 Theoretical direct capture calculations.

E(keV)	Ref. [1]	Ref. [8]	Ref. [9]
0	0.344	0.818	—
100	0.324	0.733	0.612
200	0.305	0.658	0.571
300	0.287	0.590	0.529
400	0.270	0.529	0.488
500	0.254	0.475	0.448
600	0.239	0.426	0.410
700	0.225	0.382	0.374
800	0.212	0.342	0.341
900	0.200	0.307	0.312
1000	0.188	0.276	0.287

1.5 The S-factor at $T_8 = 2.4$

Breakout from the CNO cycle via the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction begins at about $T_8 = 1$. The peak temperature for a nova outburst is near $T_8 = 2.4$. This latter temperature serves as a convenient (and important) reference point to estimate the contributions to the S-factor from resonant and non-resonant capture and from the interference between them.

The reaction rate is dependent upon an integral over energy of the product of the cross section (or S-factor) and a Maxwell-Boltzmann distribution of energy. The product of an exponentially decreasing tail from the MB distribution and an exponentially increasing cross section due to increasing penetrability restricts the contribution of this integral to a narrow range of energy determined by a characteristic energy E_0 and width ΔE_0 given approximately by [12]

$$E_0 = 0.122(Z_1^2 Z_2^2 A)^{\frac{1}{3}} T_9^{\frac{2}{3}} \text{ MeV}$$

$$\Delta E_0 = 0.237(Z_1^2 Z_2^2 A)^{\frac{1}{6}} T_9^{\frac{5}{6}} \text{ MeV}$$

where A is the reduced atomic mass. For the $^{13}N(p,\gamma)^{14}O$ reaction for $T_9 = 0.24$ we have $E_0 = 168$ keV and $\Delta E_0 = 136$ keV.

For $\Gamma_\gamma = 3.0 \pm 0.4$ eV and $\Gamma_p = 37 \pm 1$ keV we obtain $S_R(168) = 4.83 \pm 0.57$ keV·b. From the range of $S_{DC}(E)_{theory}$ values and for a range of spectroscopic factors from $S = 0.43 \pm 0.09$ [11] to $S = 0.90 \pm 0.23$ [2], we find $S_{DC}(168) = 0.26 \pm 0.15$ keV·b. Although the DC component is much smaller than the resonant component, the interference term is large and equals 2.18 ± 0.78 keV·b. Thus the S-factor becomes $S(168) = 7.3 \pm 1.0$ keV·b if errors are added in quadrature, or $S(168) = 7.3 \pm 1.5$ keV·b if absolute errors are added. Since some correlation is present because of the interference term, the error is somewhere between these two limits.

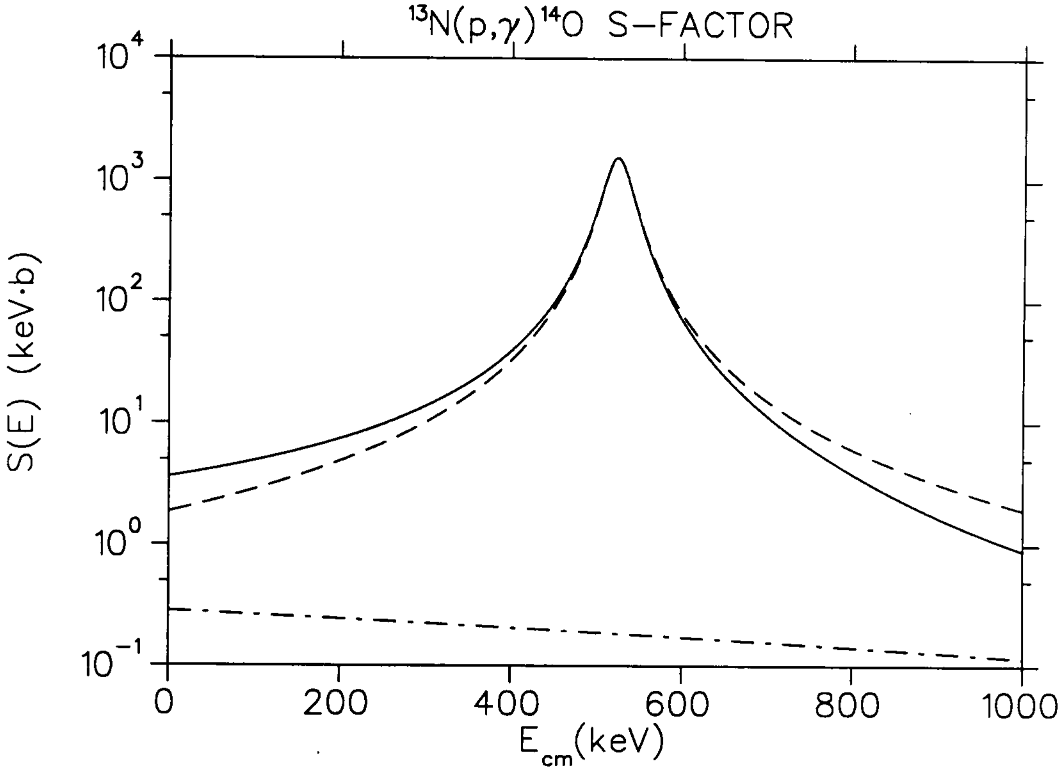

Fig. 3 Energy dependence of the S-factor for the $^{13}N(p,\gamma)^{14}O$ reaction. See text for details.

This calculation suggests that the S-factor is reasonably well-determined but that an experimental determination of the DC component could reduce the error somewhat. The possibility of making such a measurment with ISAC is discussed in the next section.

1.6 Conclusions

The resonance parameters for the $^{13}N(p,\gamma)^{14}O$ reaction are now quite well-determined as a result of recent experiments using radioactive beams. There is some uncertainty about the magnitude of the non-resonant contribution since this relies on a theoretical calculation of the cross section which then must be multiplied by a spectroscopic factor that is not well-known. There is also considerable variation among three recent theoretical calculations.

In Fig. 1.5 we show the S-factor for the $^{13}N(p,\gamma)^{14}O$ reaction where we have used the resonance parameters of section 1.2 and the direct capture calculation of ref. [9] with a spectroscopic factor of 0.45 to illustrate the energy dependence. The cross section curve derived from the total S-factor curve is shown in Fig. 1.6.

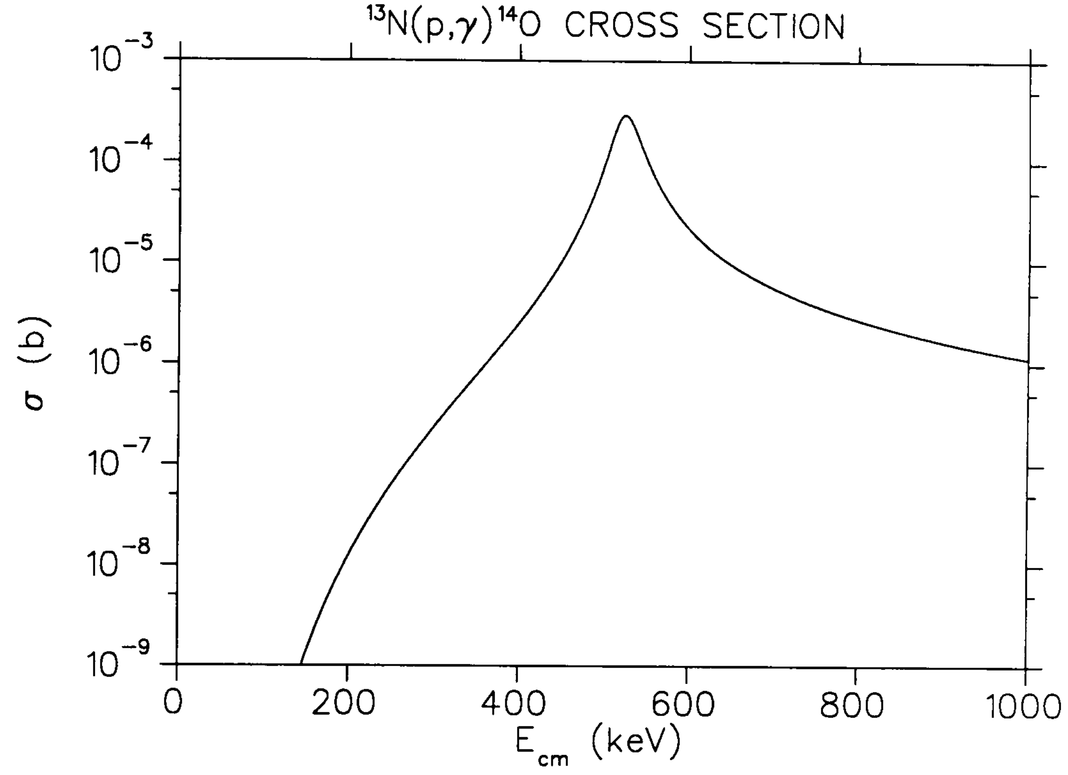

Fig. 4 Energy dependence of the cross section for the $^{13}N(p,\gamma)^{14}O$ reaction. See text for details.

The rate for the $^{13}N(p,\gamma)^{14}O$ reaction is determined, at temperatures relevant for the hot CNO cycle and break-out into the rp-process, by the S-factor at energies well below the resonance energy where the DC contribution is important. A direct measurement of the shape of the S-factor curve would improve the reliability of the extrapolation to the energies of astrophysical interest. Even though the DC contribution is not large at energies where measurements might be made, the interference term is much larger. Also, as shown in a study of the $^{13}C(p,\gamma)^{14}N$ reaction [11], it is essential to include all contributions to the cross section even when fits are made only over a broad resonance, if a good fit to the data is to be obtained. Such a measurement should be well within the capabilities of the ISAC facility provided that a ^{13}N beam $\approx 10^{10}$ s^{-1} and a high efficiency detection system are available.

The $^{13}N(p,\gamma)^{14}O$ reaction is of considerable astrophysical interest and is, in addition, the easiest radiative capture reaction involving a radioactive beam that could be studied with the radiative capture facility at ISAC. Therefore, it is an ideal reaction for the set-up and test of the facility.

2 Description of the Experiment

2.1 Estimated rates

Rates for the $^{13}N(p,\gamma)^{14}O$ reaction were estimated in TRIUMF experiment proposal E311 using the data and theoretical calculations available in 1985. Here we update the estimates of E311 using the data described in the previous sections.

With a thin, windowless, gas-jet target of 10^{18} atoms/cm^2 [13], a ^{13}N beam of 10^{10} s^{-1}, and an estimated peak cross section of 330 μb (using the resonance parameters of sect. 1.2), the yields shown in column three of Table 2 would be obtained. Energy dependence of the partial widths is taken into account as described in sect. 1.3. The DC contribution has been taken to be that of ref. [9] with a spectroscopic factor of 0.45. The fourth column of the table shows the rates for the resonance contribution only. It is evident that the DC contribution has a marked effect on the projected rates at energies above the resonance where the cross section is relatively high because of the reduced effect of Coulomb repulsion.

Table 2 Expected thin target yield

E (keV)	$\sigma(E)$ (μb)	Resonance + DC Y (hr^{-1})	Resonance only Y (hr^{-1})
200	0.014	0.6	0.3
300	0.26	10	7
350	0.87	31	25
400	2.9	100	70
450	12	430	390
500	111	4.0×10^3	3.8×10^3
526	330	1.1×10^4	1.1×10^4
550	115	4.1×10^3	4.2×10^3
575	45	1.6×10^3	1.7×10^3
600	24	870	970
650	11	390	460
700	6.5	230	300
750	4.4	160	230
800	3.2	120	190
850	2.5	89	150
900	2.0	71	130
950	1.6	58	110
1000	1.3	48	100

The detection efficiency for this reaction could be 10% or better using the proposed DRAGON recoil mass separator [13]. Thus it would appear that the shape of the yield curve could be measured over the region from 400 to 1000 keV within a reasonable time ($\approx$ 100 counts per day at the extreme energies).

2.2 Set-up with a ^{13}C beam

The $^{13}C(p,\gamma)^{14}N$ reaction can be used to set up the ISAC accelerator, the windowless gas target, and the DRAGON facility for measurement of the $^{13}N(p,\gamma)^{14}O$ reaction. The $^{13}C(p,\gamma)^{14}N$ reaction has one broad resonance below 1 MeV occurring at 557.6 ± 0.5 keV in the laboratory frame and having a width of 40 ± 1 keV [11]. The center-of-mass energies are 517.5 and 37 keV, respectively, to be compared with the values of 526 and 37 keV for the $^{13}N(p,\gamma)^{14}O$ reaction. The state populated in the $^{13}C(p,\gamma)^{14}N$ reaction is the $1^-; T = 1$ state at 8.068 MeV in ^{14}N which is the analogue to the first excited state at 5.155 MeV in ^{14}O which is populated in the $^{13}N(p,\gamma)^{14}O$ reaction (see Fig. 1.1). The strength of the resonance in the $^{13}C(p,\gamma)^{14}N$ reaction is known to ±12% [11]. Since ^{13}C is stable, the experiment could be set up and calibrated using the off-line source.

2.3 Isobar contamination in the ^{13}N beam

The masses of ^{13}C and ^{13}N differ by only 1 part in 5,500. Therefore, the proposed mass analyzing system for the beam from the ion source will not have sufficient mass resolution to separate ^{13}N and ^{13}C ions. Experience with TISOL has shown that an ECR ion source will produce a large variety of molecular species. The first step in isobar contamination reduction will be to determine which mass beam has the highest $^{13}N/^{13}C$ ratio. In the "Red Giant" experiment [14], for example, the mass 30 beam was used since it provided the best $^{16}N/^{16}O$ ratio as well as the best $^{16}N/^{18}N$ ratio, where ^{18}N provided a background activity, and presumably appeared in a CN molecule.

Once the appropriate mass has been selected, there is nothing more that can be done with the primary beam. The DRAGON detector will not have sufficient resolution to separate ^{14}N and ^{14}O recoils which will be very close in mass and energy. However, the recoils should be separable in the $\Delta E - E$ detector at the end of the DRAGON system at least at the higher reaction energies. The details of the detector configuration are still under discussion. However, it appears that it may be possible to measure position and time-of-flight with good resolution at the detector [13]. This would aid in the identification of the desired ^{14}O ions in the presence of unwanted ^{14}N ions.

A γ-ray array around the target might not be of much assistance because of cascade γ rays from proton capture in ^{13}C that overlap in energy with the ground state γ ray from proton capture in ^{13}N [15], unless the high-efficiency segmented detector [13] is available. As the de-excitation γ ray for the $^{13}N(p,\gamma)^{14}O$ reaction is to the ground state (it is the only state available), there is a unique correlation between the γ-ray direction and the direction and momentum of the recoil. This would allow discrimination against the contaminant $^{13}C(p,\gamma)^{14}N$ reaction products where the angular correlation is different.

Finally, we note that the product nucleus of the $^{13}N(p,\gamma)^{14}O$ reaction is radioactive, while the product nucleus of the $^{13}C(p,\gamma)^{14}N$ reaction is stable. If isobar contamination proves too great a problem to be solved by one of the previously mentioned techniques, the activity of the ^{14}O product could be measured. The decay of the 70.6 s ^{14}O is mainly (99.3%) to the 2.313 MeV state in ^{14}N via positron emission. Detection of the positrons should be sufficient. If necessary, the 2.313 MeV γ ray could be detected, which would provide a clean signal, but at much lower efficiency.

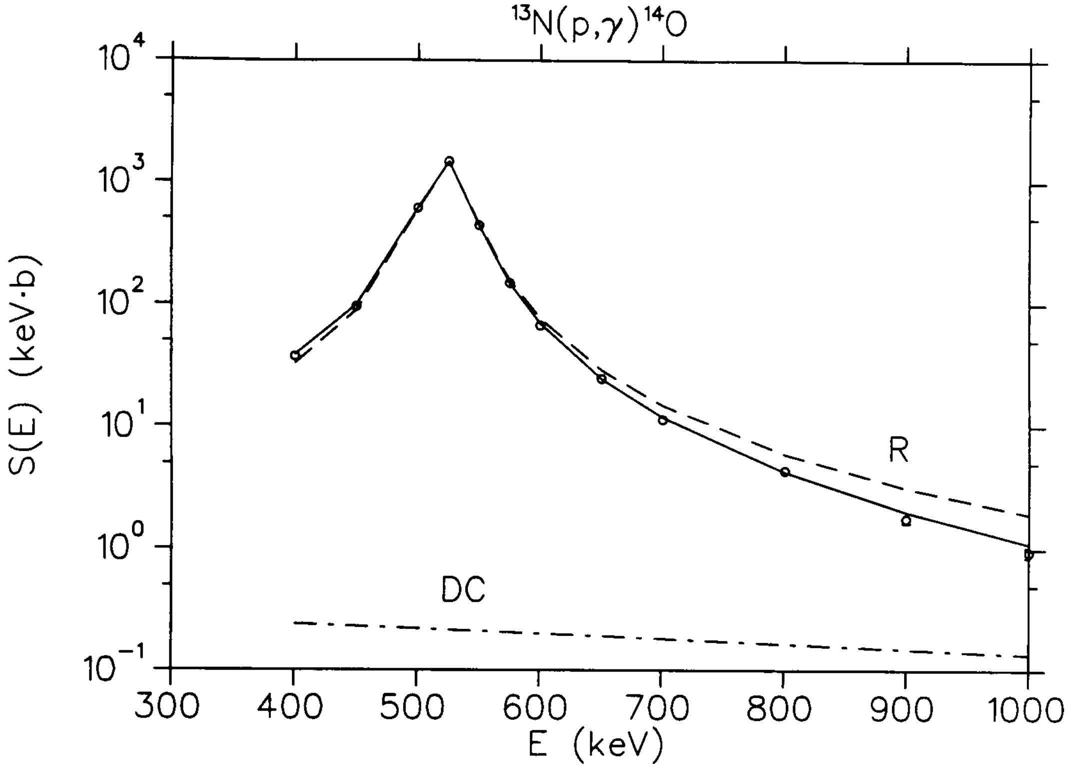

Fig. 5 Fit to the 12-point randomized yield curve. The fit parameters are given in Table 3.

2.4 Beam time required

If we take the yields from Table 2 and assume an overall detection efficiency of 10%, the number of events recorded per 24 hour period will vary from 24 at 300 keV to 2.6×10^4 at 526 keV, and down to 115 at 1000 keV. In order to estimate the beam time requirements for a good determination of both the resonant and DC parameters for the $^{13}N(p,\gamma)^{14}O$ reaction, randomized yield data were derived from Table 2 assuming a 24 hour data collection period and a 10% detection efficiency. There are 18 yield values in this data set from 300 to 1000 keV, inclusive. Fits were made to the complete data set, as well as to various subsets of the data set. The results are shown in Table 3, where the resonance energy, width and S-factor are given as well as the factor K which multiplies the DC contribution calculated from ref. [9].

The 8-point fit lacked sufficient data over the resonance peak region to adequately define the peak. However, once this region was better-defined in the 12-point fit, the resonance parameters were well-determined and the error in the magnitude of the direct capture was reduced to 19%. Adding more outlying points to the data set did not significantly alter the fit errors. In Fig 2.3 we show the fit to the 12-point yield curve and, in Fig. 2.4, the fit to the full 18-point curve for comparison.

A 12-point yield curve could be obtained in 24 12-hour shifts with the assumed beam intensity, target thickness and detection efficiency. We note that the projected ^{13}N beam

Table 3 Results of fits to randomized yield data.

No. of pts.	E (keV)	S_R (keV·b)	Γ_R (keV)	K	χ^2
8	525.33 ± 0.29	1480 ± 8	36.46 ± 0.42	1.13 ± 0.35	0.187
12	525.77 ± 0.09	1469 ± 4	37.19 ± 0.11	1.17 ± 0.22	1.21
14	525.76 ± 0.09	1469 ± 4	37.12 ± 0.10	1.08 ± 0.18	2.06
16	525.77 ± 0.09	1469 ± 4	37.11 ± 0.10	1.12 ± 0.18	1.55
17	525.80 ± 0.09	1469 ± 4	37.13 ± 0.10	1.20 ± 0.18	1.82
18	525.80 ± 0.09	1468 ± 4	37.14 ± 0.10	1.21 ± 0.18	1.69

intensity for ISAC for 10 μA of protons on target and with target release, ion source and stripping efficiencies taken into account is 1.9 x 10^{11} s^{-1} [16]. If this beam intensity can be realized, data collection time could be reduced significantly.

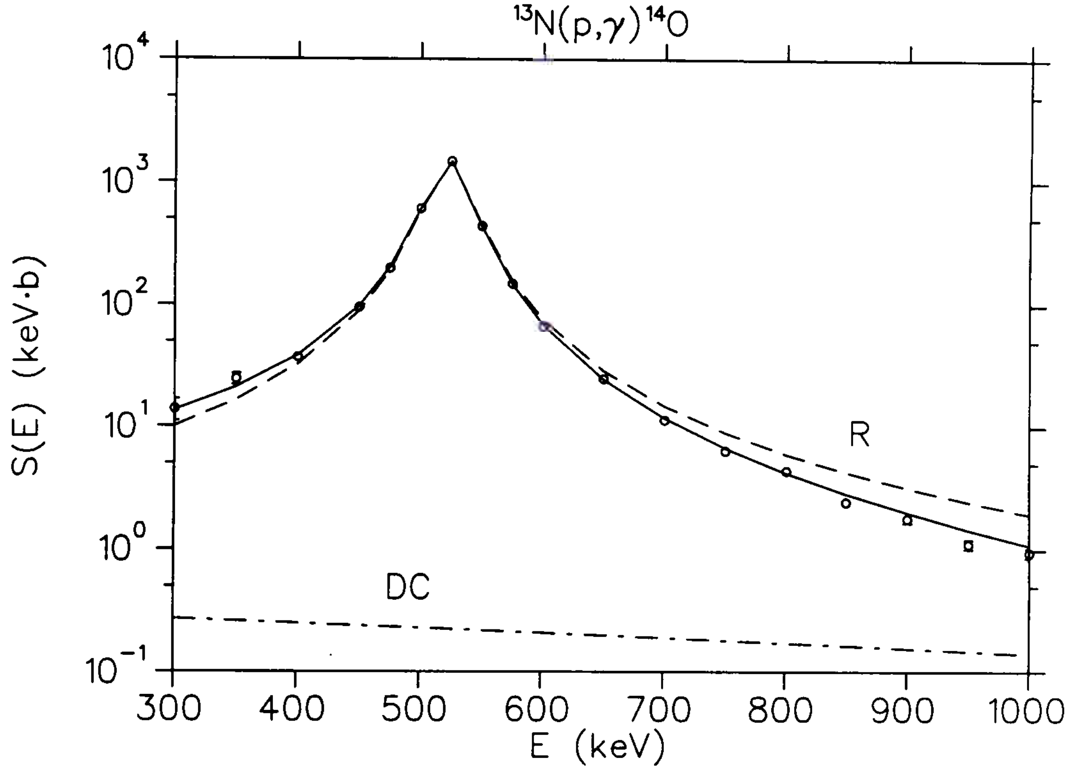

Fig. 6 Fit to the 18-point randomized yield curve. The fit parameters are given in Table 3.

Additional shifts will be required for determination of the beam mass for the best $^{13}N/^{13}C$ ratio and for set-up using a ^{13}C beam. The $^{13}C(p,\gamma)^{14}N$ reaction seems very good for initial testing of ISAC and the DRAGON detector system. If this were done, it would reduce the time necessary for set-up for the $^{13}N(p,\gamma)^{14}O$ reaction. A rough estimate of the additional shifts required for beam tests and for measurement of the resonance yield for the $^{13}C(p,\gamma)^{14}N$ reaction, for normalization of the $^{13}N(p,\gamma)^{14}O$ reaction strength, is 10 shifts, for a total of approximately 34 shifts for the complete experiment.

References

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

Refereed Journals

1. J.D. King, R.E. Azuma, C. Iliadis, A.C. Morton, L. Buchmann, M. Dombsky, K.P. Jackson, J.M. D'Auria, U. Giesen, G. Roy , T. Davinson, A. Shotter, W. Galster and R.N. Boyd. Investigation of the $^{12}C(\alpha,\gamma)^{16}O$ reaction via the β-delayed proton decay of ^{17}Ne. Nucl. Phys **A**, in press.
2. C. Iliadis, R.E. Azuma, J. Chow, J.D. King, A.C. Morton, L. Buchmann, M. Dombsky, K.P. Jackson, J.M. D'Auria, U. Giesen, J.G. Ross, H. Schatz and M. Wiescher. Decay studies of importance to explosive hydrogen burning. Nucl. Phys **A**, in press.
3. C. Iliadis, R.E. Azuma, L. Buchmann, J. Chow, J. D'Auria, M. Dombsky, U. Giesen, J.D. King, and A.C. Morton. Beta-delayed particle decay of ^{36}K. Nucl. Phys. **A609** (1996) 237-253.
4. R.E. Azuma, L. Buchmann, F. Barker, C.A. Barnes, J. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, J.D. King, R. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, T.R. Wang, S.S.M. Wong and P.R. Wrean. Constraints on the $^{12}C(\alpha,\gamma)^{16}O$ cross section at low energies from the β-delayed α-spectrum of ^{16}N. Phys. Rev. **C50** (1994) 1194-1215.
5. M. Dombsky, L. Buchmann, J. D'Auria, U. Giesen, K.P. Jackson, J.D. King, E. Korkmaz, R. Korteling, P. McNeely, J. Powell, G. Roy, M. Trinczek and J. Vincent. The β-delayed α-decay of ^{17}N. Phys. Rev. **C49** (1994) 1867-71.
6. S. El-Kateb, K.P. Jackson, W.P. Alford, R. Abegg, R.E. Azuma, B.A. Brown, A. Celler, D. Frekers, O. Häusser, R. Helmer, R.S. Henderson, K.H. Hicks, R. Jeppeson, J.D. King, G.G. Shute, B.M. Spicer, A. Trudel, K. Raywood, M. Vetterli and S. Yen. Spin-isospin strength distributions for *fp* shell nuclei: results for the $^{55}Mn(n,p)$, $^{56}Fe(n,p)$ and $^{58}Ni(n,p)$ reactions at 198 MeV. Phys. Rev. **C49** (1994) 3128-36.
7. U. Giesen, C.P. Browne, J. Görres, J.G. Ross, M. Wiescher, R.E. Azuma, J.D. King J.B. Vise and M. Buckby. The influence of low-energy resonances on the reaction rate of $^{18}O(\alpha,\gamma)^{22}Ne$. Nucl. Phys. **A567** (1994) 146-64.
8. J.D. King, R.E.Azuma, J.B. Vise, J. Görres, C. Rolfs, H.P. Trautvetter, and A.E. Vlieks. Cross section and astrophysical S-factor for the $^{13}C(p,\gamma)^{14}N$ reaction. Nucl. Phys. **A567** (1994) 354-76.
9. U. Giesen, C.P. Browne, J. Görres, S.M. Graff, C. Iliadis, H.P. Trautvetter, M. Wiescher, V. Harms, K.-L. Kratz, B. Pfeiffer, R.E. Azuma, M. Buckby and J.D. King. The astrophysical implication of low-energy resonances in $^{22}Ne+\alpha$. Nucl. Phys. **A561** (1993) 95-111.
10. L. Buchmann, R.E. Azuma, C.A. Barnes, J.M. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, J.D. King, R. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, S.S.M. Wong and P.R. Wrean. A study of beta delayed alpha emission from ^{16}N. Nucl. Instr. Meth. **B79** (1993) 330-34.
11. L. Buchmann, R.E. Azuma, C.A. Barnes, A. Chen, J. Chen, J.M. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, J.D. King, R. Korteling, P. McNeely, J. Powell,

G. Roy, M. Trinczek, J. Vincent, P.R. Wrean and S.S.M. Wong. The β-delayed α-spectrum of ^{16}N and the low-energy extrapolation of the p-wave $^{12}C(\alpha,\gamma)^{16}O$ cross section. J. of Phys. G: Nucl. Part. Phys. **19** (1993) S115-26.

12. L. Buchmann, R.E. Azuma, C.A. Barnes, J. D'Auria, M. Dombsky, U.Giesen, K.P. Jackson, J.D. King, R. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, T.R. Wang, S.S.M. Wong and P.R. Wrean. The β-delayed α spectrum of ^{16}N and the $^{12}C(\alpha,\gamma)^{16}O$ cross section at low energies. Phys. Rev. Lett. **70** (1993) 726-29.
13. J.D. King. Branching ratios for the decay of the 8.78 and 8.91 MeV states of ^{14}N. Can. J. Phys. **69** (1991) 828-29.
14. J.D. King, D. Frekers, R. Abegg, R.E. Azuma, L. Buchmann, C. Chan, T.E. Drake, R. Helmer, K.P. Jackson, L. Lee, C.A. Miller, E. Rost, R. Sawafta, R. Schubank, S.S.M. Wong, S. Yen and X.Q. Zhu. Excitation of the 10.957 MeV 0^-;T=0 state in ^{16}O by 400 MeV protons. Phys. Rev. **C44** (1991) 1077-80.
15. C. Iliadis, U. Giesen, J. Görres, S. Graff, M. Wiescher, R.E. Azuma, M. Buckby, J. King, C.A. Barnes and T.R. Wang. The reaction branching $^{31}P(p,\gamma)/^{31}P(p,\alpha)$ in the rp-process. Nucl. Phys. **A533** (1991) 153-169.

Conference Proceedings

1. J.D. King, R.E. Azuma, J. Chow, C. Iliadis, A.C. Morton, L. Buchmann, M. Dombsky, K.P. Jackson, J.M. D'Auria, U. Giesen, G. Roy, T. Davinson, A. Shotter, W. Galster and R.N. Boyd, 1997. The beta-delayed proton decay of ^{17}Ne and the rate of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, in *Proceedings of the international workshop on the physics of unstable nuclear beams,* World Scientific, New Jersey, in press.
2. J.D. King, R.E. Azuma, L. Buchmann, F.C. Barker, C.A. Barnes, J.M. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, R. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, T.R. Wang, S.S.M. Wong and P.R. Wrean, 1994. The β-delayed α-particle spectrum of ^{16}N and the $^{12}C(\alpha,\gamma)^{16}O$ cross section at low energies, in *Proceedings of the third international conference on radioactive nuclear beams*, ed. D. J. Morrissey, Editions Frontières, Gif-sur-Yvette Cedex, pp. 483-87.
3. U. Giesen, L. Buchmann, R.E. Azuma, C.A. Barnes, J.M. D'Auria, M. Dombsky, K.P. Jackson, J.D. King, R. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, S.S.M. Wong and P.R. Wrean, 1993. The β-delayed α spectrum of ^{16}N and the extrapolation of the p-wave $^{12}C(\alpha,\gamma)^{16}O$ cross section to low energies, in *Proceedings of the first symposium on nuclear physics in the universe*, eds. M.W. Guidry and M.R. Strayer, IOP Publishing, Bristol, pp. 343-51.
4. L. Buchmann, J.S. Vincent, J.M. D'Auria, J. King and R.E. Azuma, 1990. Proposals and estimates for an experimental program at ISAC, in *Proceedings of the first international conference on radioactive nuclear beams*, eds. W.D. Myers, J.M. Nitschke and E.B. Norman, World Scientific, New Jersey, pp. 46-58.

Talks

(i) Invited

1. The beta-delayed proton decay of ^{17}Ne and the rate of the $^{12}C(\alpha,\gamma)^{16}O$ reaction. International Workshop on the Physics of Unstable Nuclear Beams, Serra Negra, São Paulo, Brazil, August 28-31, 1996.
2. Experimental techniques in nuclear astrophysics (Five lectures). Summer Nuclear Institute at TRIUMF, July 22-August 2, 1996.
3. The use of radioactive decay to solve a nuclear reaction problem in stellar evolution. CAP 51st Annual Congress, Ottawa, 16-19 June, 1996.
4. Cross section and S-factor for the $^{13}N(p,\gamma)^{14}O$ Reaction. Presentation to a joint session of the ISAC Workshop and the Lake Louise Winter Institute, Lake Louise, Alberta, 21 February, 1994.
5. The Red Giant Experiment. Nuclear Physics Seminar, Ohio State University, 31 January, 1994.
6. The Red Giant Experiment. Physics Department Colloquium, U. of Guelph, 19 October, 1993.
7. The β-delayed α-decay of ^{16}N and its relevance to stellar evolution and nucleosynthesis. Physics Department Colloquium, U. of Toronto, 25 March, 1993.
8. The β-delayed α-spectrum of ^{16}N and its astrophysical significance. Eastern Regional Nuclear Physics Conference, Pembroke-Chalk River, 5-7 March, 1993.
9. Experiments in nuclear astrophysics with radioactive beams. Triumf Summer Nuclear Institute, July 28, 1992.

(ii) Contributed

1. Investigation of the $^{12}C(\alpha,\gamma)^{16}O$ reaction via the β-delayed proton decay of ^{17}Ne. International Conference on Nuclei in the Cosmos, University of Notre Dame, 20-27 June, 1996.
2. Beta-delayed proton decay of ^{17}Ne to excited states in ^{16}O. Division of Nuclear Physics of the American Physical Society, Bloomington, Indiana, Oct. 26, 1995.
3. The β-delayed α-particle spectrum of ^{16}N and the $^{12}C(\alpha,\gamma)^{16}O$ cross section at low energies. Contributed oral presentation to the Third International Conference on Radioactive Nuclear Beams, Michigan State University, 24-27 May, 1993.
4. Determination of the $\beta\alpha$ decay spectrum of ^{16}N. Symposium on the Production and Utilization of Radioactive Beams, American Chemical Society, San Francisco, 5-10 April, 1992.
5. Cross section and astrophysical S-factor for the $^{13}C(p,\gamma)^{14}N$ reaction. Eastern Region Nuclear Physics Conference, McMaster University, 16-17 May, 1991.
6. Excitation of the 10.957 MeV 0^-;T=0 state in ^{16}O by 400 MeV protons. Eastern Region Nuclear Physics Conference, McMaster University, 16-17 May, 1991.