TRIUMF - RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 18

Title of proposed experiment

The hot CNO cycle and the $^{14}O(\alpha,p)^{17}F$ reaction

Name of group
TUDA

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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)

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P. Leleux	Louvain-la-Neuve	Professor	20 %
R. Azuma	University of Toronto	Professor	20 %

Date for start of preparations: January 2002

Date ready: September 2002

Completion date: September 2003

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
20	ISAC-HE	NO

Do not exceed one page.

This proposal addresses the experimental investigation of the $^{14}O(\alpha,p)^{17}F$ reaction cross section in the energy region E_{cm}=1.0-1.5 MeV. The reaction is thought to play an important role in the advanced stages of hydrogen burning, either as a way of bypassing the slow positron decay of ^{14}O in the hot CNO cycle, or as a starting point to break out the cycle through the subsequent $^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$ reactions.

At present no direct measurements are available. Information on the astrophysical S-factor is either obtained theoretically or from investigations of level properties of the compound ^{18}Ne nucleus, which are believed to contribute to the reaction rate.

Because of discrepancies in the spin and parity assignments of some critical resonances large uncertainties can be expected in the calculated reaction rate. The proposed experiment can help to put constraints on the available estimates of the S-factor, thereby shedding some light on the astrophysical implications.

The measurement will be undertaken at the TUDA facility using an ^{14}O beam and a ^{4}He gas cell. The reaction products will be detected in silicon detector arrays.

BEAM and SUPPORT REQUIREMENTS	

Experimental area

ISAC – high energy, TUDA line

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

Proton 500 MeV
ISAC production target

Secondary channel

High energy ISAC TUDA beamline

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

^{14}O energies: 5 - 10 MeV
Current at least 10^5 pps

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.

- ^{14}O production
- bunched beam

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.

The TUDA scattering facility, electronics, targets and detector systems will be provided by the Edinburgh group.

SAFETY	

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.

There is no special hazard using the TUDA system, other than the use of standard alpha particle calibration sources.

1 Motivation

The $^{14}O(\alpha,p)^{17}F$ reaction is believed to play an important role in hot (T_9 ~ 0.1 – 1.0) and dense (ρ ~ 10^2 - 10^5 g/cm^3) astrophysical environments, such as supermassive stars, novae and X-ray bursts. Here hydrogen burning initiates on pre-existing C, N and O nuclei (acting as catalysts) and proceeds through the so-called hot CNO cycle.

The energy generation rate in the cycle is limited by the β-decay lifetimes of ^{14}O ($t_{1/2}$ = 70.6 s) and ^{15}O ($t_{1/2}$ = 122 s). However, at sufficiently high temperatures and densities α captures on ^{14}O and ^{15}O can compete favorably with β decay [1]. For example, the **$^{14}O(\alpha,p)^{17}F$**$(p,\gamma)^{18}Ne(\beta^+\nu)^{18}F(p,\alpha)^{15}O$ reaction sequence can provide a pattern around the positron decay of ^{14}O thereby re-processing material into the hot CNO cycle. Alternatively, a breakout from the hot CNO cycle can occur if the **$^{18}Ne(\alpha,p)^{21}Na$** reaction is fast enough to compete with the β decay of ^{18}Ne. Similarly the breakout from the hot CNO cycle can also occur through the **$^{15}O(\alpha,\gamma)^{19}Ne$**$(p,\gamma)^{20}Na(p,\gamma)^{21}Mg(\beta^+\nu)^{21}Na(p,\gamma)^{22}M$… reaction sequence. Thereafter, a series of rapid proton captures (rp-process) can provide a route for the synthesis of nuclides in the A~60 mass region and beyond, as often observed in the spectra e.g. of novae remnants.

Under what physical conditions of temperature and density one reaction sequence dominates depends critically on the relative rates of the key reactions indicated above.

At present, none of α-capture processes on either oxygen isotope has yet been studied directly. Available information on their cross sections is based on theoretical predictions or obtained from the level structure of the respective compound nuclei (or their mirror analogs) via transfer or charge-exchange reactions. Although excitation energies are typically obtained with some keV precision, large uncertainties remain in the corresponding reaction rates as these depend exponentially on the resonance energies.

These uncertainties can only be reduced by direct cross-section measurements with radioactive beams.

The $^{15}O(\alpha,\gamma)^{19}Ne$ is the main objective of the DRAGON facility, whereas a proposal presented by the Edinburgh group (TUDA collaboration) to study the $^{18}Ne(\alpha,p)^{21}Na$ has already been accepted at TRIUMF. Indeed the $^{14}O(\alpha,p)^{17}F$ reaction was already mentioned at that time as a natural extension of this kind of studies. This latter reaction represents also a very good candidate for investigations of (α,p) processes, for which the TUDA facility has mainly been built.

It is the aim of this proposal to investigate the $^{14}O(\alpha,p)^{17}F$ reaction. A direct measurement of its cross section in the energy region E_{cm} ~ 1.0 – 1.5 MeV (T_9 ~ 0.9 - 1.5) will put the determination of its astrophysical rate on firmer experimental ground.

The present state-of-the-art on its reaction rate is outlined in Section 2. Section 3 describes the proposed experiment. Beam time requests and future directions for a possible improvement of the measurement are detailed in Sections 4 and 5 respectively.

2 $^{14}O(\alpha,p)^{17}F$ reaction rate: state of the art

The $^{14}O(\alpha,p)^{17}F$ reaction rate depends sensitively on the properties of states in the compound nucleus ^{18}Ne in the energy range between the $^{14}O+\alpha$ threshold (E_x ~ 5 MeV) and E_x ~ 7 MeV, corresponding to stellar temperatures $T_9 \leq 2$.

Investigation of the ^{18}Ne level structure has been carried out mainly through the following reactions: $^{16}O(^{3}He,n)^{18}Ne$ [3,4], $^{12}C(^{12}C,^{6}He)^{18}Ne$ [3] and $^{20}Ne(p,t)^{18}Ne$ [3,5] and excitation levels have been identified up to E_x ~ 10 MeV. An overview of the resonance parameters is given in Tables 1 and 2 and in Fig. 1. However, disagreement remains among various authors as to the spin and parity assignments of some levels (as well as on their exact location and widths), with critical consequences on the calculated S(E)-factor.

2.1 The 5.1 MeV doublet

The 5.11 and 5.15 MeV levels in ^{18}Ne are expected to correspond to the 5.10 MeV ($J^{\pi}=3^{-}$) and 5.25 MeV ($J^{\pi}=2^{+}$) levels in the mirror nucleus ^{18}O. It is uncertain though which of the two in ^{18}Ne is the 3^{-} and which is the 2^{+}.

Early investigations by Wiescher et al. [6] based on Thomas-Ehrman shift calculation and by Funck et al. [7] on a microscopic multi-channel model agree in assigning values of $J^{\pi}=3^{-}$ and $J^{\pi}=2^{+}$ to the 5.11 MeV and the 5.15 MeV level respectively. It has been argued however that the two levels are too closely spaced for level-shift calculations to give reliable assignments of spin and parity [3]. Moreover, their experimental (proton) widths $\Gamma(5.11) = 45\pm5$ keV and $\Gamma(5.15) \leq 15$ keV have been taken as evidence that these spin and parity assignments should be reversed. Indeed, following penetrability arguments, a larger width and therefore a larger probability for proton emission would be expected for the level with lower *l*. On the basis of these considerations Hahn et al. [3] find $J^{\pi}(5.11) = 2^{+}$ and $J^{\pi}(5.15) = 3^{-}$. These latter assignments have recently been obtained also from angular distribution data of the $^{20}Ne(p,t)^{18}Ne$ reaction and related distorted-wave Born approximation calculations [5].

2.2 The 5.45 MeV level

Observed angular distributions and Coulomb shift calculations for this level have led to an unnatural parity assignment of $J^{\pi} = 2^{-}$ [3]. Because both particles in the entrance channel have spin zero this level cannot be populated and it therefore plays no role in the astrophysical S(E)-factor.

2.3 Excitation levels between 6.0-7.0 MeV

In addition to a doublet at E_x= 6.29 and E_x = 6.35 MeV, consistent with previous results [8], Hahn et al. report a previously unobserved state at E_x = 6.15 MeV [3]. From known properties of mirror levels in ^{18}O they adopt spin and parity assignments $J^{\pi}=3^{-}$, 2^{-} and 1^{-} for the three states respectively. It is worth noticing though that the assignments for the doublet states differ once again from those of Wiescher et al. ($J^{\pi}=3^{-}$ and 4^{+} respectively) [6], and those of Funck et al. ($J^{\pi}=3^{-}$ and 1^{-}) [7].

2.3 Excitation energies above 7.0 MeV

At excitation energies above 7 MeV seven new levels have been reported [3] (in addition to seven others already known). However, with the exception of the (previously unobserved) $J^{\pi}=1^{-}$ state at 7.35 MeV definite spins and parities for these new levels could not be assigned.

2.4 Astrophysical S(E) factor

The ambiguities summarized above have drastic consequences on the total astrophysical S(E)-factor of the $^{14}O(\alpha,p)^{17}F$ reaction.

In general, S(E) can be expressed as the sum of a direct reaction component $S_{DR}(E)$, a resonant contribution $S_{res}(E)$, and an interference term between these two mechanisms, that is:

$$S(E) = S_{DR}(E) + S_{res}(E) \pm 2(S_{DR}S_{res})^{1/2} \cos\left[\tan^{-1}\left(\frac{\Gamma(E)}{2(E-E_r)}\right)\right]$$

where E_r is the energy of the resonance and $\Gamma(E)$ its total width. The S factor for a particular resonance is given by the Breit-Wigner form and depends on the experimentally determined resonance energy, width and spin. Because of the uncertainties related to these parameters the $^{14}O(\alpha,p)^{17}F$ reaction rate as determined so far is still to be considered uncertain by large factors and possibly orders of magnitude.

Early calculations by Wiescher et al. [3] and Funck et al. [4] were largely based on theoretical expectations since experimental information on ^{18}Ne levels was very sparse at that time. For temperatures $T_9 \leq 0.3$ their reaction rates disagree by three orders of magnitude mainly because Funck et al. included the contribution from the 5.15 MeV level, which considerably enhances the stellar cross-section, being only ~40 keV above the $^{14}O + \alpha$ threshold.

However, according to the reversed spin-parity assignments of Hahn et al. the reaction rate as calculated by Funck et al. would be lower by three orders of magnitude at $T_9 \leq 0.3$ [3]. Indeed, Hahn et al. [3] find that the main contribution to the reaction rate arises from l=1 partial-wave direct reaction and its interference with the 6.15 MeV (1^-) state. (Interference term of the 7.35 MeV (1^-) state is claimed to be an order of magnitude lower because of its smaller resonance strength, narrower width and higher energy. Similarly interference of the 6.29 MeV (3^+) state would be an order of magnitude weaker than the 6.15 MeV state because of the higher l involved).

Fig. 2 shows the $S_{tot}(E)$-factor resulting from the summed resonant contributions of the 5.15 MeV ($J^{\pi}=3^-$), 6.15 MeV ($J^{\pi}=1^-$), 6.29 MeV ($J^{\pi}=3^-$), 7.05 MeV ($J^{\pi}=4^+$) and 7.35 MeV ($J^{\pi}=1^-$) states, together with the direct l=1 contribution and its constructive (+) and destructive (-) interference with the 6.15 MeV resonance [3]. For comparison the $S_{tot}(E)$ as determined by Funck et al. is also shown.

If results by Hahn et al. are confirmed the $^{14}O(\alpha,p)^{17}F$ reaction might provide a route to the breakout from the hot CNO cycle only at temperatures $T_9 \geq 0.5$, as shown in Fig. 3. At lower temperatures the breakout would be dominated mainly by the $^{15}O(\alpha,\gamma)^{19}Ne$ (Fig.3).

However, it should be stressed that at low temperatures both reaction rates depend critically on the properties of a single resonance. These have either been estimated theoretically or at most determined indirectly. As a consequence large uncertainties can be expected.

Recently, a study of the $^{14}O(\alpha,p)^{17}F$ cross section has been carried out through its inverse reaction $^{1}H(^{17}F,\alpha)^{14}O$ at the Argonne National Laboratory using a radioactive ^{17}F beam [9]. Once again however disagreement has been expressed [10] as to the spin assignments of the states investigated, which in turn may significantly alter the results obtained so far.

In summary a direct determination of the $^{14}O(\alpha,p)^{17}F$ reaction cross section is highly necessary before decisive conclusions as to its stellar rate can be drawn.

3 The experiment

3.1 Objectives

It is proposed to study the $^{14}O(\alpha,p)^{17}F$ reaction cross-section in the energy range E_{cm} ~ 1.0-1.5 MeV, where a main contribution from the (1^-) 6.15 MeV excited state in ^{18}Ne is expected.

However, rather than investigating the properties of this (or any other) state, our aim is to measure the total cross section in order to establish experimentally which of the two calculated S-factors (if any) is appropriate. Indeed predictions of Hahn et al. differ from those of Funck et al. by at least one order of magnitude in most of the energy range shown in Fig. 2. It should then be possible to easily distinguish between the two. If calculations by Hahn et al. are confirmed, extension of the measurement up to E_{cm} ~ 1.5 MeV would enable us to determine the nature of the interference between the (1^-) 6.15 MeV state and l=1 partial-wave direct contribution. This piece of information is not trivial, as it determines the cross section at lower energies (i.e. at temperatures typical of the hot CNO cycle).

In the considerations which follow we shall work on the hypothesis of an astrophysical S-factor as calculated by Hahn et al.

The experimental setup will consist of arrays of silicon detectors installed in the TUDA scattering chamber and a ^{4}He gas target.

3.2 Experimental method

The method consists in the detection of both protons and ^{17}F from the $^{14}O(\alpha,p)^{17}F$ reaction. The setup is shown in Fig. 4a) and 4b). Briefly it will consist of a ^{4}He gas target, a LAMP detector array placed at forward angles (for proton detection at θ ~ 20^o-70^o) and a LEDA detector at very forward angles (between 6^o and 15^o) both for proton and heavy-ion detection (θ_{max} (^{17}F) ~ 11^o).

The gas target itself will consist of a small cubic cell (about 3x3x3 cm^3) with mylar windows to contain the ^4He gas. By making the entrance window just large enough to accommodate the beam it will be possible to maintain its thickness below 1 μm, thereby minimizing beam energy losses. The exit window on the contrary will have to allow for the widest possible angular aperture and might possibly require a higher thickness. This combination of windows should be capable of sustaining pressures P ~ 100-200 mbar, corresponding to a ^4He target thickness of ~ 10^{19} atoms/cm^2 (Δ_{cm} ~ 150 keV).

Measurement of the proton yield will be achieved mainly through 4 segmented silicon detectors (2.4x2.4 cm^2 each) placed inside the gas cell so as to form a box around the beam axis (Fig. 4b). Stopping foils will be used to protect the detectors from the elastically scattered particles.

As far as the background is concerned, the beam energy (E ~ 4.7 – 6.8 MeV) is well below the Coulomb barrier for contaminants such C or O in the mylar windows so that other channels with protons in the final state are closed. In any event, because of the very different Q-values involved in these reactions, kinematical discrimination of the detected protons would still be possible in the off-line analysis.

Similarly, elastically scattered protons (e.g. hydrogen in form of water vapor or as a component of the mylar windows) are not a serious concern because of their different kinematics.

4 Beam Request

The total beam time requested amounts to: 25 shifts with ^{14}O beam and 3 shifts with stable beams for calibration purposes. In particular, for the ^{14}O beam request the following assumptions have been made:

1) beam current of $5x10^5$ particles per second,
2) total cross sections as given in [3] at the relevant energies considered,
3) isotropic distribution for the reaction products in the laboratory system,
4) detection efficiency of 50%.

The measurement will be undertaken in three stages as outlined below and summarized in the table.

A first measurement (2 shifts) will be carried out at E_{cm} = 2.25 MeV. At this energy, corresponding to the resonance at E_x = 7.35 MeV (see Fig. 1 and 2), a relatively high yield is expected. It will therefore be straightforward to establish a good data point, thereby having an easy chance to confirm the calculations at this energy. At the same time this will give us the opportunity of setting up the whole detection system quickly and accurately with the radioactive ^{14}O beam.

The second step will involve investigation of the region around the 6.15 MeV state (E_{cm} = 1.05 MeV) where a rate of 3 counts/h is expected at the top of the resonance. A yield of 150 counts can then be achieved over 4 shifts, which also implies that the measurement is still feasible even for beam currents of 10^5 pps.

Finally 16 shifts will be devoted to the measurement at E_{cm} = 1.50 MeV. Here a total of 80 (8) counts are expected for destructive (constructive) interference. It will therefore be possible to establish the nature of the interference.

Additional 3 shifts (one at each energy) are required to measure the background from an empty gas cell.

E_{cm} [MeV]	rate [counts/h]	# shifts [12 h]
2.25	3000	2
1.05	3	4
1.50	0.05	16

In summary, the requested beam time will allow us to establish the resonant behaviour in a region of astrophysical relevance, around E_{cm} = 1.05 MeV. This will provide, for the first time, direct experimental information on the astrophysical S(E)-factor, thereby reducing the uncertainties associated with theoretical calculations. Moreover, by establishing the sign of the interference at E_{cm} ~ 1.5 MeV a very important piece of information will be obtained for the lower energy regime, which is otherwise not accessible to a direct investigation with present techniques.

5 Future Directions

A second stage of this measurement can be foreseen, where an improvement in terms of energy resolution can be obtained by replacing the gas target with a solid ^{4}He target implanted in an Al substrate (see e.g. [11,12] and references therein). The setup would still be similar to the one described above, except that a second LAMP array would be added for backward proton detection.

This setup would allow for the following improvements:

- well defined energy and location of interaction (target thickness Δ_{cm} ~ 40 keV)
- angular distribution information available, albeit with low resolution
- sensibly reduced energy losses and straggling for heavy ions (i.e. ^{14}O and ^{17}F) and hence better discrimination through time-of-flight technique.

However, the intrinsically low ^{4}He content of the solid target (at most 5×10^{17} atoms/cm^2 [11]) means that the feasibility of this approach will depend on yields from the present experiment and on relatively higher beam intensities than presently considered here.

6 Readiness

Following the highly successful ^{21}Na+p (E879) experiment of September/October 2001, TUDA is generally ready for further experiments.

Assuming the proposed experiment is approved, the following tasks would need to be completed to be ready for the ^{14}O(α,p) experiment:

1) Purchase of additional (2.4x2.4cm^2) silicon strip detectors. The typical lead time for silicon strip detectors is ~16-18 weeks.
2) Installation of the TUDA VME-based data acquisition system. Some of the major components to the TUDA data acquisition system (VME Crates, CPU, TDCs)have already been delivered. The VME-based data acquisition is important a) to provide large number of channels (512 ADCs and 512 TDCs), and b) to enable significantly higher rates (>20kHz)

Currently, it is expected that the ECR source will be available from the Autumn 2002. This provides more than sufficient time to complete the tasks identified above.

6 References

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[12] L. Weismann et al., Nucl. Instr. & Meth. B 170 (2000) 266-275 Lett. to the Editor.

$^{16}O(^{3}He,n)^{18}Ne$		$^{12}C(^{12}C,^{6}He)^{18}Ne^{a}$	$^{20}Ne(p,t)^{18}Ne^{b}$		
E_x (MeV±keV)	Γ (keV)	E_x (MeV±keV)	E_x (MeV±keV)	Γ (keV)	J^{π}
4.520±7	9±6		4.520^{c}		1^{-d}
4.561±9	25^{e}				3^{+}
4.589±7	4±4		4.589^{c}		0^{+d}
5.106±8	50±10		5.106^{c}	49±6; 45±5^{f}	2^{+}
5.153±8	≤20		5.153^{c}	≤20; ≤15^{f}	3^{-}
5.454±8	≤20	5.45^{g}			2^{-}
6.15±10	≤40	6.15±20			(1^{-})
6.30±10			6.286±10	≤20	(3^{-})
6.35±10			6.345±10	45±10	(2^{-})
7.07±10	200±40				
(7.05±30)	(≤120)				(4^{+})
(7.12±30)	(≤120)	7.12±20			
7.35±18	≤50	7.35±20			(1^{-})
		7.62±20			
7.72±10	≤30	7.73±20			
7.94±10	40±10	7.94±20	7.92±20	70±20	
8.11±10	≤30	8.11^{g}			
		8.30±20			
		(8.45±30)			
		8.55±30			
		8.94±20			
		9.18±20			
		9.58±20			

Table 1

Energy levels of ^{18}Ne as determined through the reactions indicated (from ref. [4]).

Previous result [6]		Our work	
E_x (MeV±keV)	Γ (keV)	E_x (MeV±keV)	Γ (keV)
4.520± 7	9±6		9±6
4.589± 7	4±4		2±6
5.106± 8	49±6, 45±5		45±7
5.153± 8	≤20, ≤15		8±5
5.454± 8	≤20	5.467±5^{a}	6±6
6.286±10	≤20	6.305±4^{a}	8±7
6.345±10	45±10	6.358±5^{a}	18±9

Table 2

Comparison between energy levels as obtained in [4] (left) and [5] (right) (from ref. [5]).

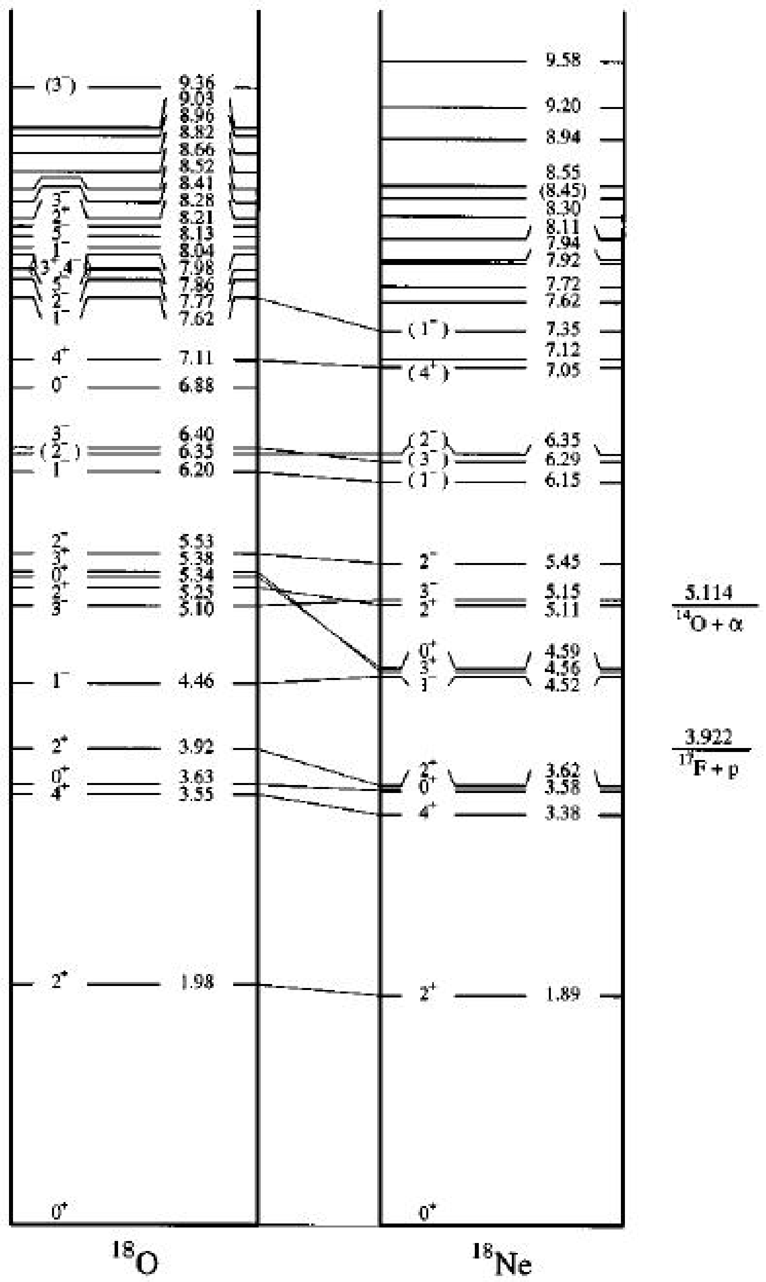

Fig. 1 Energy levels of ^{18}Ne as given in [4]. For comparison analog states in ^{18}O are also shown.

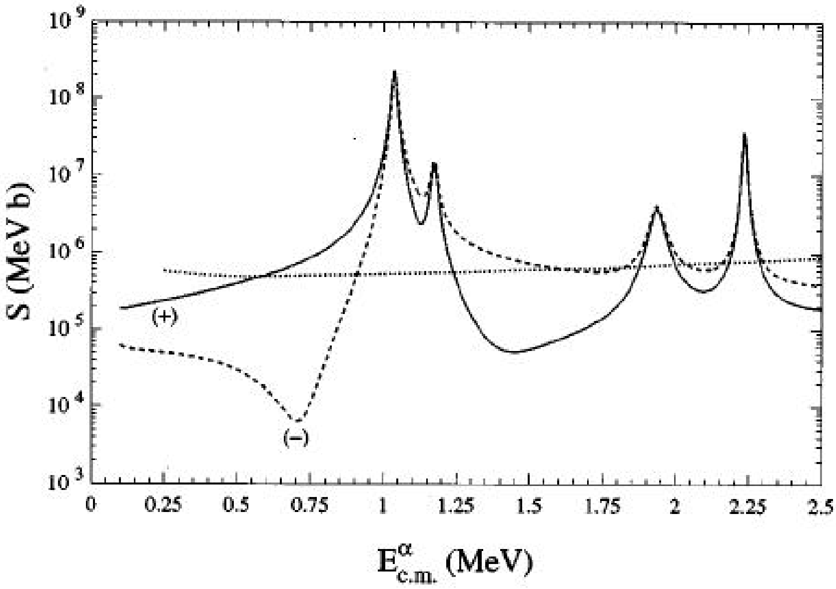

Fig. 2 Total S(E) factor as calculated by [3]. Constructive (+) and destructive (-) interference between the $J^{\pi}=1^{-}$ 6.15 MeV state and the direct $l=1$ partial wave contribution is shown. The dotted line represents the total S(E)-factor given in [7].

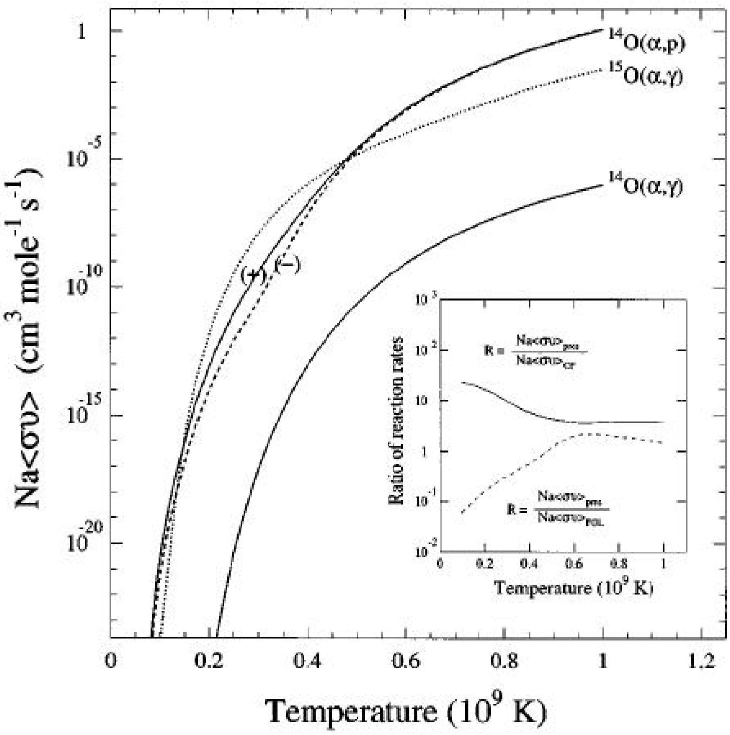

Fig. 3 Comparison of reaction rates vs. temperature. According to [3] the $^{14}O(\alpha,p)$ reaction dominates over the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction only at $T \geq 0.5x10^9$ K.

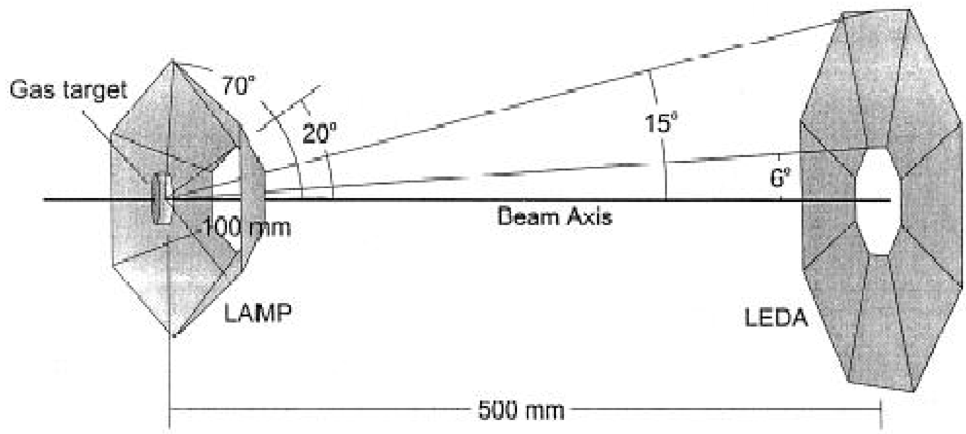

Fig. 4 a) Experimental setup (sketch from ref. [11]).

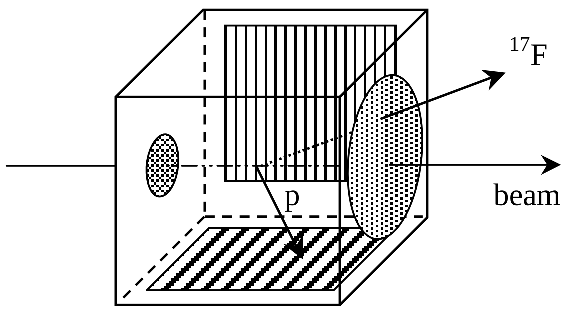

Fig. 4 b) Schematic view of the gas cell. Two of the four silicon strip detectors are also shown.

1 *The* $^{12}C(^{12}C,^{8}Be_{gs})^{16}O_{gs}$ *reaction at* E_{cm} *= 27 to 36 MeV*

M. Aliotta, S. Cherubini, E. Costanzo, M. Lattuada, S. Romano, C. Spitaleri, A. Tumino, D. Vinciguerra, M. Zadro

Zeitschrift für Physik A354 (1996) 119 – 120.

2 *Indirect measurements of nuclear reaction cross sections at astrophysical energies*

G. Calvi, S. Cherubini, M. Lattuada, S. Romano, C. Spitaleri, M. Aliotta, G. Rizzari, M. Sciuto, R.A. Zappalà, V.N. Kondratyev, Đ. Miljanić, M. Zadro, G. Baur, O.Yu. Goryunov, A.A. Shvedov

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3 *Gamma-ray detection with a* 4π *NaI spectrometer for material analysis*

M. Merhoff, M. Aliotta, I.J.R. Baumvol, H.-W. Becker, M. Berheide, L. Borucki, J. Domke, F. Gorris, S. Kubsky, N. Piel, G. Roters, C. Rolfs, W.H. Shulte

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4 *Detection of breakup fragments in inverse Coulomb dissociation experiments*

M.C. Morone, G. Oliviero, L. Campajola, A. D'Onofrio, L. Gialanella, M. La Commara, V. Roca, M. Romano, M. Romoli, F. Terrasi, R. Barnà, D. De Pasquale, M. Aliotta, S. Cherubini, M. Lattuada, S. Romano, C. Spitaleri

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5 *Low-energy radioactive ion beam induced nuclear reactions*

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