TRIUMF — RESEARCH PROPOSAL	Experiment no. 870	Sheet 1 of 16

Title of proposed experiment

Breakout from the hot CNO cycle via the $^{18}Ne(\alpha,p)^{21}Na$ reaction.

Name of group

TUDA

Spokesperson for group

A. Shotter & L. Buchmann

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. Shotter	University of Edinburgh	Full Professor	30%
L. Buchmann	TRIUMF	Senior Research Scientist	30%
T. Davinson	University of Edinburgh	Senior Research Fellow	30%
A. Ostrowski	University of Edinburgh	Professor	20%
P. Woods	University of Edinburgh	Professor	20%
A.N. Other	University of Edinburgh	Student	100%
F. Sarazin	University of Edinburgh	Research Fellow	50%
J. Görres	University of Notre Dame	Professor	20%
J. Daly	University of Notre Dame	Student	20%
M. Wiescher	University of Notre Dame	Full Professor	20%
P. Leleux	University Louvain-la-Neuve	Full Professor	20%
J. D'Auria	TRIUMF	Full Professor	20%

NOV - 2 2000

Date for start of preparations	August 1999
Date ready	October 2000
Completion date	October 2001

Beam time requested

12-hr shifts	Beam line/channel	Polarized primary beam?
22	ISAC-HE (TUDA)	NO

BEAM 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)

^{18}Ne energies:- 24 MeV, 21.5 MeV, 19.5 MeV.

Intensity at least 10^8 pps.

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.

SUPPORT REQUIREMENTS

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.

- ^{18}Ne production
- Bunched beam
- Data Acquisation
- Support to establish TUDA as reviewed in August 1999.

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 and detector systems will be provided by the Edinburgh group.

SUMMARY

Do not exceed one page.

This proposal concerns the measurement of a breakout reaction from the CNO cycle.

For high temperatures and densities the CNO cycle provides an efficient way to burn hydrogen to helium. However, a point can be reached where the temperature and densities are so high that breakout from the cycle can occur whereby the intermediate carbon, oxygen and nitrogen nuclei are converted by a series of (p, γ) and (α, p) reactions to heavy nuclei up to mass 60 and even beyond to mass 100. The main reactions that cause this breakout are thought to be $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{18}Ne(\alpha, p)\ ^{21}Na$. This proposal concerns the latter reaction.

The reaction $^{18}Ne(\alpha, p)\ ^{21}Na$ has been investigated at the radioactive beam facility in Louvain-la-Neuve in the c.m. energy range 2.5 to 3 MeV. From the resonances discovered in this region it is possible to determine upper bounds on temperature and density of the astrophysics environment for which breakout will occur via this reaction. The increased beam intensity at TRIUMF compared to Louvain-la-Neuve, will allow investigation of the reaction strength for $^{18}Ne(\alpha, p)^{21}Na$ below 2.5 MeV. This in turn will enable a more precise determination of the ρ, T parameters for which breakout is possible.

The experiment will be undertaken at the TUDA general scattering facility using a ^4He target gas cell and a ^{18}Ne beam. The reaction proton will be detected in large area silicon arrays.

1 Introduction

Explosive hydrogen burning is thought to be the main source of energy generation in novae and x-ray bursters, and also provides an important route for nucleosynthesis of material up to masses as high as the mass 100 region via the rp process [1]. Up to a temperature of $T \sim 0.2$ GK the burning with carbon takes place through the series of reactions,

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C$$

known as the hot CNO cycle. At higher temperatures, $T \sim 0.4$ GK, the ^{14}O waiting point is bypassed by the series of reactions

$$^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\beta^+)^{18}F(p,\alpha)^{15}O$$

with an increase in energy production. At still higher temperatures break-out from the cycle becomes possible.

The main reaction which determines the leak rate is thought to be $^{15}O(\alpha,\gamma)^{19}Ne$ [2]. However, it may be that other reactions provide alternative leak-out routes. In particular the reactions $^{18}Ne(\alpha,p)^{21}Na$ and $^{18}Ne(2p,\gamma)^{20}Mg$ have been suggested as possible candidates, although for the $2p$ reaction abnormally high densities would be required [3]. Any ^{19}Ne or ^{21}Na formed by these reactions acts as a seed for the rp process, where a series of charged particle reactions and β decays give mass flow to higher mass values. Thus the role of each possible breakout mechanism during such an event is vital in understanding the nucleosynthesis that would take place.

The subject of this proposal is to investigate the breakout $^{18}Ne(\alpha,p)^{21}Na$ reaction. Before the recent work at Louvain-La-Neuve on this reaction (an Edinburgh-Louvain-La-Neuve-Notre Dame collaboration), no experimental information was available on the strength of this reaction. Indeed there was even limited information concerning the position of states in the compound system ^{22}Mg at and above the α particle threshold energy of 8.14 MeV. (However a recent Yale transfer reaction experiment leading to final states in the nucleus ^{22}Mg suggests there could be as many of 17 states in a 2.5 MeV energy range above this threshold energy [8].) The recent (α,p) experiment at Louvain-La-Neuve has been able to investigate the reaction over the energy range 2.5 to 3.0 MeV [4,5]. The aim of the present proposal is to extend measurements of this reaction to below 2.5 MeV.

Section 2 below outlines the recent results of the experiment undertaken at Louvain-La-Neuve. Section 3 proposes a method to measure the reaction in the lower energy region making use of the special features of the ISAC facility. Section 4 gives the expected experimental rates and section 5 gives details of beam request.

2 ^{18}Ne(α, p) in the C.M. Energy range 2.5 to 3.0 MeV

The investigation of the reaction at Louvain-La-Neuve was undertaken using the ^{18}Ne beam in a 3^+ charge state with a typical beam intensity at the target of 5 x 10^5pps. The experimental method used is illustrated in fig.1. Briefly, the target chamber was divided into two compartments, one under vacuum and the other containing ^{4}He gas at 500 mb pressure. The two compartments were separated with a 2 mg/cm^2 Ni foil. Protons originating from reactions of the ^{18}Ne beam with the ^{4}He gas were recorded in the forward direction by a solid state detector telescope (D1, D2, D3 see fig.1). This telescope system allowed identification of ejectile mass, measurement of energy and emission angle.

The geometry of the experiment as shown in fig.1 is not ideal mainly due to the extended nature of the target interaction region . The geometry results in considerable difficulties in determining absolute cross sections. Another problem with this geometry is that the detection system records a large yield of background proton events due to $p(^{18}Ne,p)^{18}Ne$ where the ^{18}Ne beam interacts with residual hydrogen atoms in the foils. This hydrogen is thought to be mainly due to H_2O molecules attached to foil surfaces, in particular the entrance window. While certain precautions can reduce this background contribution, it is very difficult to eliminate it. This background contribution to the proton spectrum is shown in fig.2. The main result of this background contribution is that it masks protons from resonances in the $^{18}Ne + \alpha$ channel below 2.5 MeV. The structure over background could be interpreted as due to resonances in the entrance channel above 2.5MeV. Reconstruction of the proton c.m. energy spectra, corrected for background and kinematic shift due to the angle of emission, enabled identification of 6 different proton groups. These six proton groups were identified with levels in ^{22}Mg and $(\alpha, p)\,\omega\gamma$ values are indicated in Table 1 and fig.3.

From the data contained in table 1 the stellar reaction rate of $^{18}Ne(\alpha,p)^{21}Na$ can be calculated from:

$$\langle \sigma v \rangle = \left(\frac{2}{\mu\pi}\right)^{\frac{1}{2}} \left(\frac{1}{kT}\right)^{\frac{3}{2}} \left(\frac{\hbar^2\pi}{\mu}\right) \sum_i \int \frac{\Gamma_i(\omega\gamma)_i \exp(-E/kT)}{((E-E_{Ri})^2+\Gamma_i^2/4)} dE$$

where the sum, i, is over all transitions shown in fig.3. T is the stellar temperature, μ the reduced mass, Γ_i the total resonance width and E_{Ri} the resonance position.

The question as to whether ^{18}Ne breaks out of the CNO cycle depends on the rate of destruction of ^{18}Ne, by the reaction $^{18}Ne(\alpha,p)^{21}Na$ compared to its β decay rate $^{18}Ne(\beta)^{18}F$ which returns this isotope back to the CNO cycle.

The mean lifetime of ^{18}Ne in a stellar environment due to destruction by helium nuclei depends upon the density, the temperature and reaction rate, and is given by the expression

$$\tau_m(He) = \frac{1}{N_{He}\langle\sigma\nu\rangle},$$

where N_{He} is the number density of helium nuclei. As this destruction via reaction competes with destruction via β^+ decay we have two regimes. One in which any ^{18}Ne formed β decays to ^{18}F and one in which the reaction $^{18}Ne(\alpha,p)^{21}Na$ allows mass flow out of the hot CNO cycle. This is illustrated in fig.4. The thick line is a locus for which the mean life time due to destruction via the reaction $^{18}Ne(\alpha,p)^{21}Na$ and the mean life time due to decay are equal. The thin lines are the upper and lower limits.

The density and temperature of certain stellar environments are thought to be able to reach $\rho \sim 10^6 \mathrm{gm/cm^3}$ and $T \sim 1-2\times10^9 K$.[6] Under such conditions fig.4 shows that ^{18}Ne is processed to ^{21}Na, rather than transforming to ^{18}F; the ^{21}Na can then be transformed by the rp process to heavier mass nuclei.

It should be emphasised that the locus calculated in fig.4 is based on the resonances measured in the $^{18}Ne(\alpha,p)^{21}Na$ reaction above 2.5 MeV. If there are any transitions below this energy, then the locus curve in fig. 4 would move towards lower densities and temperatures. If the evolution of such stellar environments is to be understood from a nuclear physics perspective it is important to locate the actual position of the locus in fig.4. This means that investigation of the $^{18}Ne(\alpha,p)^{21}Na$ in the energy c.m. range below 2.5 MeV is necessary.

3 ^{18}Ne(α, p) in the C.M. Energy Range below 2.5 MeV

3.1 Overview

The main problems to be overcome in measuring $^{18}Ne(\alpha,p)^{21}Na$ in the c.m. range below 2.5 MeV are: (1) background protons due to $^{18}Ne(p,p)^{18}Ne$, and (2) low yields due to small $(\omega\gamma)$ values from possible resonances.

In order to reduce the effect of the background protons, it is proposed that the detection system and target geometry be redesigned (compared to fig.1) in such a way that the proton detectors cannot see the probable sites where the background protons are being produced. Such a redesign is possible due to the excellent ISAC beam qualities. Obviously the increased ISAC ^{18}Ne beam compared to the Louvain-La-Neuve ^{18}Ne beam is essential to measure the lower values of $(\omega\gamma)$.

3.2 Experimental Method

The method proposed to measure the reaction $^{18}Ne(\alpha,p)$ in the energy range below 2.5MeV is shown in fig.5. It consists of two basic components: (1) a ^4He gas cell, and (2) a detection system comprising 2 LEDA detectors. The whole system will be contained within the TUDA reaction chamber[7].

The crucial factor in fig.5 is the design of the gas cell. With this design the proton detectors should not see protons scattered from any surface by the beam. The main reason why this design is possible at ISAC and not at Louvain-La-Neuve is due to the beam quality. In particular the ISAC beam target focus can go down to under 2×2mm and timing resolution is of the order 1 nsec. With this improved beam quality the gas cell entrance Ni foil window could be reduced to $500\mu g/cm^2$; however for safety reasons, a $1mg/cm^2$ window thickness will be used. The beam having passed through the ^4He gas will be stopped on Ta disc which will form part of the structure supporting the exit foil. The thickness of this disc must be such that no protons can be emitted from it. The exit foil, through which the protons pass, will probably be Ni foil of between 1 to $2mg/cm^2$. The gas pressure of the cell will be 500 mb. In order to ensure no protons emitted from Ni entrance foil can enter the proton detection system a collimator within the gas cell will be used. Details are shown in fig.5. The use of the internal collimator and exit stopping Ta disc will mean that the detector will not be equally sensitive to reactions along the beam path in the gas cell. It is straightforward to calculate this effect by a Monte-Carlo calculation, but the calculation will also be checked by using a small $^{241}Am\,\alpha$ source to record the α count rate in the detectors system for different source positions within the cell. (Measurement without the ^4He gas or exit Ni window).

The gas cell will be electrically isolated so the beam charge can be recorded during an experimental run. While recording the current from the gas cell may give a reasonable relative measurement of the beam intensity, it may not be a good absolute measurement. Therefore we will adopt the arrangement used at Louvain-La-Neuve and use two upstream detectors to measure elastic scattering of ^{18}Ne from a gold flash on the Ni gas cell window (fig.1. shows the arrangement of detectors D_1, D_2 which measured such back scattering with the Louvain-La-Neuve arrangement.

The proton detector system will consist of 2 LEDA detector systems, with a total of 16 sections or 256 separate channels. The LEDA detectors will be placed in tandem separated by 1 cm. Each detector sector will have a silicon thickness of 300 μm.

For protons between the energies of 6 to 9 MeV, the 2 LEDA system will identify protons by the normal $\Delta E \times E$ method. For proton energies below 6 MeV the protons will not penetrate the first LEDA detector so for these slower protons time of flight will be used to identify the protons. (A development of the method shown in figure 5 would be to use a thin CD detector somewhere between the gas cell and the LEDA detectors. This would have the advantage of not only identifying the protons to low energy, but also of defining the proton trajectory more precisely.)

The ^{18}Ne beam energy for the initial search for $^{18}Ne(\alpha,p)^{21}Na$ transitions below 2.5 MeV centre of mass energy will be 24 MeV. For 500 mb ^4He gas pressure this will place reactions taking place for a c.m. energy between 2.6 and 2.25 MeV in the most sensitive region in the gas cell. For 19.5 MeV beam energy the most sensitive region will be 1.8 to 2.1 MeV in the c.m.

4 Limits of measurement

The resonances measured for the reaction $^{18}Ne(\alpha,p)^{21}Na$ at Louvain-La-Neuve in the energy range 2.5 to 3.0 MeV have $\omega\gamma$ values in the region of several keV, see table 1. The increased detector efficiency for the proposed detector configuration shown in fig. 5 together with the increased ^{18}Ne beam intensity of ISAC should enable $\omega\gamma$ values to be measured to significantly smaller values. This is an important point, since for resonances below 2.0 MeV c.m. energy, $(\omega\gamma)$ values will fall rapidly due to decreasing alpha penetrability.

An estimate of the lowest $\omega\gamma$ that can be measured is based on the following conditions and parameters:

(1) Assume a resonance occurs in the gas volume at the most sensitive position as viewed by the proton detectors.

(2) A first order calculation of the probability of detecting a proton from such a resonance in the LEDA detectors (assuming isotropic emission in the c. of m.) gives a value of 0.14.

(3) Assume a ^4He gas pressure of 500 mb. The width of the resonance within the gas extends over 1 or 2 mm, ignoring beam energy straggling.

(4) Assume a beam intensity of 10^8 ^{18}Ne particles per second.

Under such conditions, if a resonance has an $\omega\gamma$ value of 1 keV then in one shift (12 hours) about 450 protons will be recorded. This would indicate that in a 5 shift run about 20 protons would be recorded for a resonance which has an $\omega\gamma$ of 10 eV. Whether such proton events could actually be used to determine such low values of $\omega\gamma$ will depend on the intensity of background events; obviously all precautions will be taken to reduce background events, however it is almost impossible to predict beforehand the severity of this problem.

Background considerations aside, if the beam intensity of ^{18}Ne could be increased beyond 10^8 pps in the future then it should be possible in principle to determine lower values of $w\gamma$, perhaps even down to leV. This would enable the reaction rate to be determined more accurately in the lower temperature stellar range.

If the maximum beam intensity was 10^6 pps then this TRIUMF experiment would be still about 20 times more sensitive than the Louvain-la-Neuve experiment. Below a beam intensity of 10^5 pps probably no new data could be obtained.

5 Beam Request

There is limited reliable information on the states in ^{22}Mg between the energies 8.1 to 10.6 MeV corresponding to the $^{18}Ne+\alpha$ entrance energy of 0 to 2.5 MeV. Therefore in this experiment it is important to carefully scan the c.m. energy region from 2.5 to 1.75 MeV. Below 1.75 MeV the $\omega\gamma$ values of any resonances are likely to be below 10eV and therefore at the limit of measurement. For a gas pressure 500 mb, the sensitive region of the gas cell scans about 300 keV at a centre of mass $\alpha+^{18}Ne$ energy of 2 MeV. This suggests the experimental investigation is undertaken in three stages as outlined below.

^{18}Ne beam energy(MeV)	c.m. scan (MeV)	beam shift
24	2.2 - 2.6	5
21.5	2.3 - 2.0	5
19.5	2.1 - 1.8	10

The beam shifts requested for each scan must be considered as best estimates based on experience gained at Louvain. However, it should be emphasised that this experiment is investigating unknown territory so these estimates can only be taken at face value.

In addition to 20 shifts of data collection, 2 shifts are requested for setting up the experiment with a beam. Experience has shown at Louvain-la-Neuve that 2 shifts is the minimum set-up time for this type of experiment.

6 Readiness

The installation of TUDA has been extensively discussed with the TRIUMF management. In summary, it is planned that the detector array including the chamber and electronics is machined, bought and assembled at the University of Edinburgh and shipped to TRIUMF in the period from March to early summer 2000. At the same time an instrumentation cabin to shield from electronic noise and to provide stable temperature conditions will have been constructed by TRIUMF. It is envisaged that after two months the system will be ready for tests with α-sources. Even with generous leeway for problems, TUDA will be operational and ready for stable and radioactive beam by September 2000.

7 Data Analysis

The plans for a data acquisition system for TUDA are in hand. The system will be based on VME coupled to CAMAC and is expected to handle event rates of up to 50 kHz. Events will be written both onto disk and tape (DLT) from a PC based system. Analysis of the data can be undertaken both at Edinburgh and TRIUMF.

8 Future Directions

Following the measurement of the $^{18}Ne(\alpha,p)$ reaction, we intend to investigate the reaction $^{14}O(\alpha,p)$. This reaction is important since it can speed up the CNO process by bypassing the ^{14}O waiting point through the reaction sequence: $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\beta^+)^{18}F(p,\alpha)^{15}O$. Clearly this reaction sequence is also the production source of ^{18}Ne, through which CNO breakout can occur. For $^{14}O(\alpha,p)$ there is little direct experimental data concerning the reaction in the astrophysical energy region.

The production of an ^{14}O beam at TRIUMF and the use of similar experimental techniques developed for the $^{18}Ne(\alpha,p)$ reaction, would enable resonance $w\gamma$ values down to 10 eV to be measured for ^{14}O beam intensities of 10^8 pps and to 1keV for beam intensities of 10^6 pps.

We request that development of a ^{14}O beam be given some priority to enable the $^{14}O(\alpha,p)$ reaction to be measured.

9 References

(1) A.E. Champagne and M. Wiescher Ann. Rev. Nucl. Part. Sci. 42(1992)39

(2) K.Langanke et. al. J. Astro. 301(1986)629

(3) J. Görres et. al. Phys. Rev C51(1995) 392

(4) W. Bradfield-Smith et. al. Phys Rev 59C(1999) 3402

(5) W. Bradfield-Smith et. al. NIM. A425 (1999) 1

(6) M. Wiescher et. al. Phil. Trans. R. Soc. London A356 (1998) 2105

(7) A.C.Shotter Letter of intent, TRIUMF, July 1998

(8) A. Chang, Private communication

Proton group	Level assignment in ^{21}Na (MeV)	$\omega\gamma$ (keV)	State in ^{22}Mg (MeV)
1	3.544	$2.8^{+3.0}_{-1.7}$	10.99
2	1.716	$7.1^{+3.0}_{-2.5}$	10.58
	2.425	$26^{+30.0}_{-10.0}$	11.05
3			
4	g.s.	$0.77^{+.35}_{-0.3}$	10.6
	0.332	$1.0^{+0.7}_{-0.5}$	10.82
5	g.s.	$3.82^{+3.9}_{-1.5}$	10.91
	0.332	$8.7^{+9.2}_{-5.0}$	11.13
6	g.s.	$4.24^{+4.0}_{-2.5}$	11.13

TABLE I $\omega\gamma$'s for the various possible assignments. The level that would be accessed, for each assignment, in the compound nucleus is also shown.

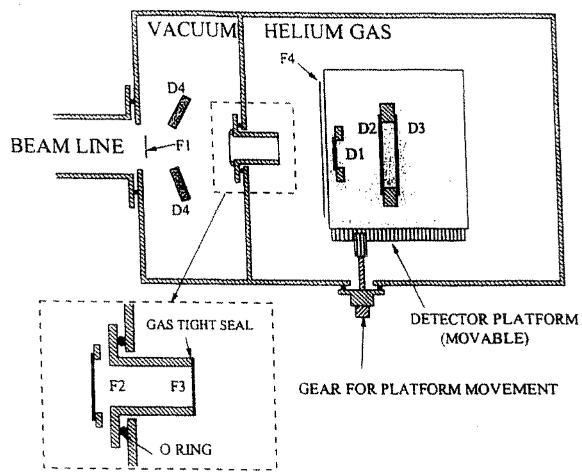

FIG. 1. A schematic view of the scattering chamber and detectors used at Louvain-la -Neuve to study the reaction $^{4}He(^{18}Ne,p)^{21}Na$. The detectors D1,D2 and D3 were double sided silicon strip detectors allowing the protons to be identified and their energy and trajectory to be measured.

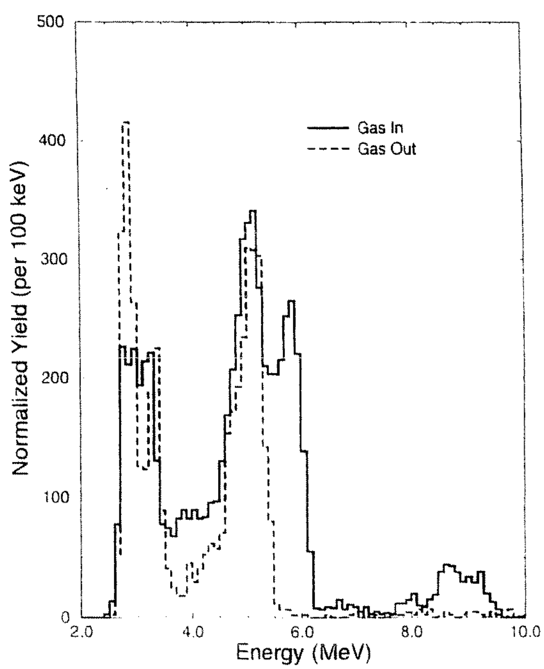

FIG. 2 Raw proton energy spectra for the target volume filled with helium gas, and gas evacuated. The protons observed with no gas target are mainly due to elastic scattering of protons from H_2O molecules on the surface of foils such as the window between the vacuum chamber and the helium gas.

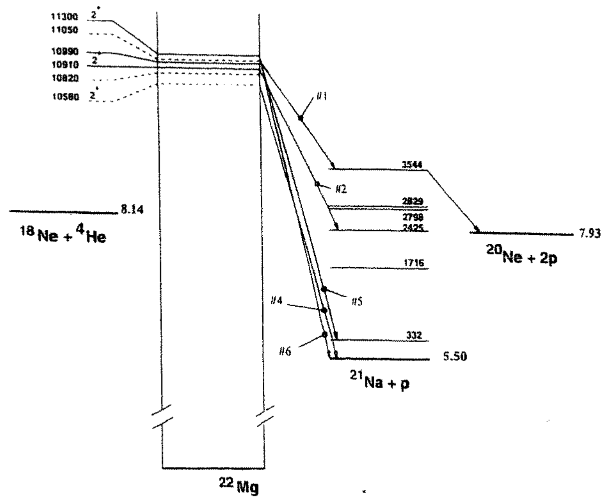

FIG. 3 Reaction transitions deduced for the reaction ^{18}Ne(^{4}He,p)^{21}Na. Dotted line levels represent a lower assignment confidence than full line levels. The strengths of transitions for the different proton groups 1-6 are given in table 1.

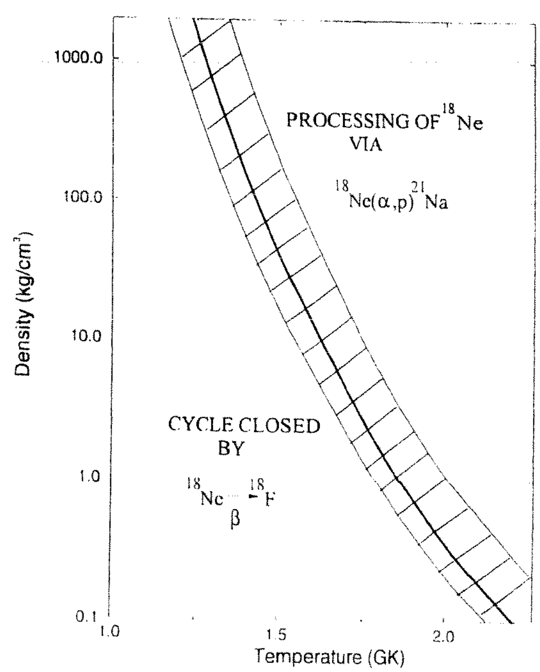

FIG. 4 The division locus separating the processing of ^{18}Ne by the (4He,p) reaction or by beta decay.

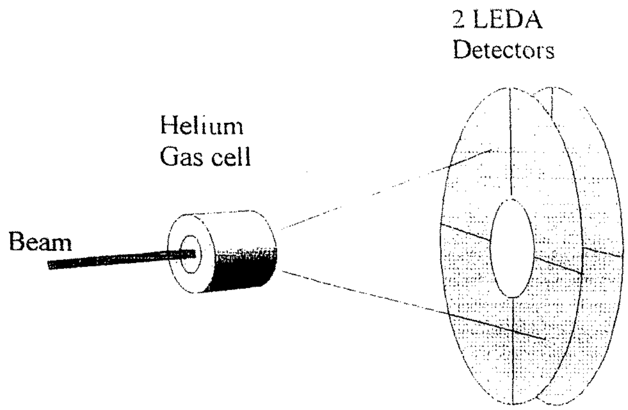

FIG 5a A schematic view : gas cell and detector system

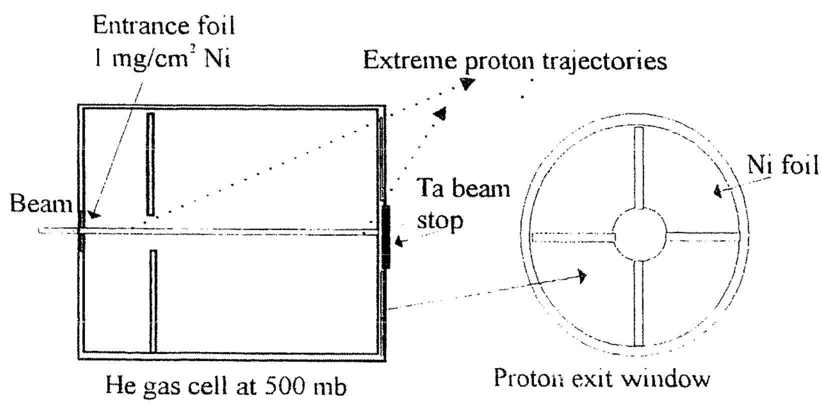

FIG 5b Details of gas cell

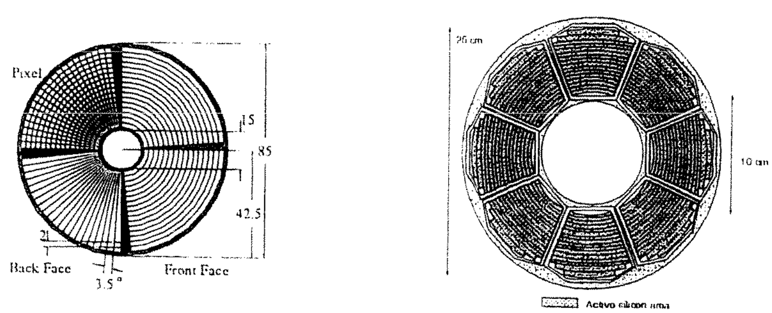

FIG 5c LEDA (right), CD (left)