TRIUMF - EEC SUBMISSION

Draft Submission

Progress Report

Exp. No.

S1156 - *Proposed*

Date Created:

2007-11-06 12:15:57

Title of Experiment:

Study of Alternative Extraction Methods for Phosphorus-30 Beams

Name of group:

BLT

Spokesperson(s) for Group

D.A. Hutcheon

Current Members of Group:
(name, institution, status, % of research time devoted to experiment)

D.A. Hutcheon	TRIUMF	Senior Research	50%
C. Ruiz	TRIUMF	Research Scientist	40%
C. Vockenhuber	TRIUMF	Research Associate	20%
L. Buchmann	TRIUMF	Senior Research	20%
A. Olin	TRIUMF	Research Scientist	15%
A.A. Chen	McMaster University	Associate Professor	15%
G. Ruprecht	TRIUMF	Research Associate	15%
U. Greife	Colorado School of Mines	Associate Professor	15%
J.M. D#Auria	Simon Fraser University-ORNL	Professor	10%
C. Wrede	Yale University	Student (PhD)	5%

Beam Shifts Used:

Beam Shifts Remaining:

New Beam Requests:

24 shifts
Comment: Blocks of 4 shifts, separated by approximately 1 weekBeamline 4A proton beam intensities up to 500 nA

Basic Information:

Date Created: 2007-11-06 12:15:57

Date Experiment Ready: 2008-07-02

Summary: Proton radiative capture competes with beta decay as a mode of destruction of P-30 formed in ONe novae. The strength of the capture reaction strongly influences the amount of Si-30 and of elements from S to Ca in the ejecta of hot ONe novae. It is closely tied to the Si-30/Si-28 ratio in presolar meteoritic grains coming from such novae. Experiment S1108 proposed a direct measurement of the capture strength. It received a High priority rating but no beamtime was allocated because a beam of the required intensity (>1E7) had not been produced.The combination of a SiC target, FEBIAD ion source and 70uA of proton beam did not produce measurable P-30 at the Yield station, despite an estimated production rate of 1E8--1E9 /s. ISAC Targets group plan to study release properties of a number of elements, including P. Identification of a suitable material would be followed by fabrication and testing at ISAC. Priority to actinide target development will mean a protracted timescale for testing of targets capable of producing P-30 with enough intensity for the DRAGON experiment. There is no guarantee that a high-temperature solid with suitable P release properties can be found. We propose a small, parallel investigation of production and trapping of P-30 produced in a chlorine gas target, to be carried out on beamline 4A. This studies key issues in a possible alternative method of P=30 release: a recycling boiling liquid target (BLT). Two BLT concepts are outlined, one based on liquid chlorine and the other on molten LiCl. The goal is to have tested the feasibility of the BLT concept as a backup, in the case that adequate P-30 production from a solid target has not been demonstrated within the next three years.

Plain Text Summary: We will test whether Phosphorus-30 can be produced in a target of chlorine gas and separated from the chlorine efficiently enough for a proposed experiment studying radiative capture of protons by Phosphorus-30 nuclei. The capture measurement could help to explain the ratio of Silicon isotopes found in certain presolar meteoritic grains.

Primary Beam Line: base4a

Secondary Channel

Base:

Primary / Secondary Beam

Proton Beam

Energy: 500 MeV

Intensity: 0.5 uA

Pulse Width:

Secondary Beam

Particle Type:

Energy:

Spot Size:

Intensity:

Special Characteristics:

Production Target

Meson Target:

Summary List of samples: Cl gas

μ*SR Spectrometers:*

TRIUMF Support (Resources Needed): BL4A operational (vacuum, magnets,extraction,safety). Design Office, Machine Shop for gas target and trap. Valves, gauges, shielding support stand. Safety equipment (exhaust, sniffer). Multiscaler with connection to network.

NSERC: Detectors previously purchased with NSERC funds

Other Funding:

Muon Justification:

Safety Issues: Chlorine is a toxic gas. P-32, P-33, Be-7 and Na-22 have multi-day half-lives. Detector high voltages.

D.A. Hutcheon: recent publications (last 5 years)

Refereed Journals

- C. Vockenhuber *et al.*, *Measurement of the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction relevant for supernova nucleosynthesis*, Phys. Rev. **C76** 035801 (2007).
- J. Zylberberg *et al.*, *Charge-State Distributions after Radiative Capture of Helium Nuclei by a Carbon Beam*, Nucl. Inst. Meth. **B254** 17 (2007).
- C. Matei *et al.*, *Radiative α capture on ^{12}C via the 6.049 MeV state of ^{16}O*, Phys. Rev. Lett. **97** 242503 (2006).
- C. Ruiz *et al.*, *Measurements of the $E_{c.m.}$=184 keV Resonance Strength in the $^{26g}Al(p,\gamma)^{27}Si$ Reaction*, Phys. Rev. Lett. **96** 252501 (2006).
- S. Engel *et al.*, *Commissioning the DRAGON facility at ISAC*, Nucl. Inst. Meth. **A553** 491 (2005).
- J.M. D'Auria *et al.*, *The $^{21}Na(p,\gamma)^{22}Mg$ reaction from $E_{c.m.}$=200 to 1103 keV in novae and x-ray bursts*, Phys. Rev. **C65** 065803 (2004).
- U. Greife *et al.*, *Energy loss around the stopping power maximum of Ne, Mg and Na ions in hydrogen gas*, Nucl. Inst. Meth. **B217** 1 (2004).
- A.K. Opper *et al.*,*Charge Symmetry Breaking in $np \rightarrow d\pi^0$*, Phys. Rev. Lett. **91**, 212302 (2003).
- S. Bishop *et al.*, *The $^{21}Na(p,\gamma)^{22}Mg$ Reaction and Oxygen-Neon Novae*, Phys. Rev. Lett. **90**, 162501 (2003).
- D.A. Hutcheon *et al.*, *The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC: design, construction and operation*, Nucl. Instr. Meth. **A498**,190-210 (2003).
- W. Liu *et al.*, *Charge state studies of low energy heavy ions passing through hydrogen and helium gas*, Nucl. Instr. Meth. **A496**, 198-214 (2003).

Study of Alternative Extraction Methods for Phosphorus-30 Beams

(a) **Scientific value of the experiment:**

TRIUMF experiment S1108 proposed a study of the ^{30}P(p,γ)^{31}S reaction at the DRAGON facility. The strength of this reaction is closely related to an astrophysical observable: the isotopic ratio A=30 to A=28 of Si in presolar meteoritic grains from ONe novae. It affects strongly, also, the abundance of elements between S and Ca in the ejecta of such novae. The EEC approved the proposal with High priority in July 2006. No shifts were allocated because beam availability at the requested intensity (>10^7 s^{-1}) had not been demonstrated.

Since then, the first Yield studies involving the FEBIAD ion source and targets of TiC or SiC have taken place. Previously-available surface and resonant laser ionization sources could not have produced a P beam because of the high ionization energy of phosphorus atoms. The FEBIAD source worked successfully, but no measurable amounts of ^{30}P reached the Yield station, even though the 70 μA beam on SiC should have produced it at a rate 10^8–10^9 s^{-1} through the ^{30}Si(p,n) reaction. The implication is that P was not able to diffuse and effuse out of the target material and into/through the transfer tube to the FEBIAD ion source.

The rate of diffusion in a grain of target material depends on the absolute temperature T as

$$D(T) = D_0 exp(-E_0/kT)$$

If the failure to extract ^{30}P (half-life 150 s) from the SiC target were entirely due to failure to diffuse out of grains of, say, 5 μm diameter, it would imply a diffusion coefficient <10^{-10} cm^2 s^{-1} at the operating temperature of the target. The strong dependence of diffusion and effusion rates on temperature is the reason ISOL solid targets are operated at as high a temperature as possible. However, sublimation rates also have a similar form of temperature dependence: the usefulness of a particular target material and geometry depends (in part) on whether useful diffusion rates are reached before the target is destroyed due to high sublimation rate (or other failure mode).

With carbide targets being counter-indicated for ^{30}P production, the ISAC Targets group is considering alternatives such as calcium oxide or zirconate as potentially better for release of P [1]. The reason for choosing a compound of Ca is clear from Figure 1, which shows the cross section for production of the various P isotopes from three different nuclides [2].
The cross section is largest when target and product nuclei are close in atomic number and when they are matched in neutron excess (A-2Z). The good elements from a cross section perspective (S, Cl and K) do not form compounds that have low vapor pressure at high temperature. Cross sections drop to millibarn and sub-millibarn values for elements beyond Ca. Studies of CeS have been made at HRIBF but ^{30}P has not been obtained from such targets.

Oxide targets generally have poor thermal conductivity compared to SiC and it is not clear, without making a direct measurement on the ISAC target system, what beam intensity they could handle and whether P would be released at a useful intensity. TRIUMF priority to actinide target development means there may be no more than one test in 2008 of a target capable of delivering ^{30}P. There is no guarantee that Nature has provided any material which can provide enough ^{30}P from a high-temperature solid target. ISAC Targets group plan measurements of release properties of P as the first step in selection of a target material for production of P.

In view of the protracted timescale for development of a conventional ISOL target for ^{30}P, it is

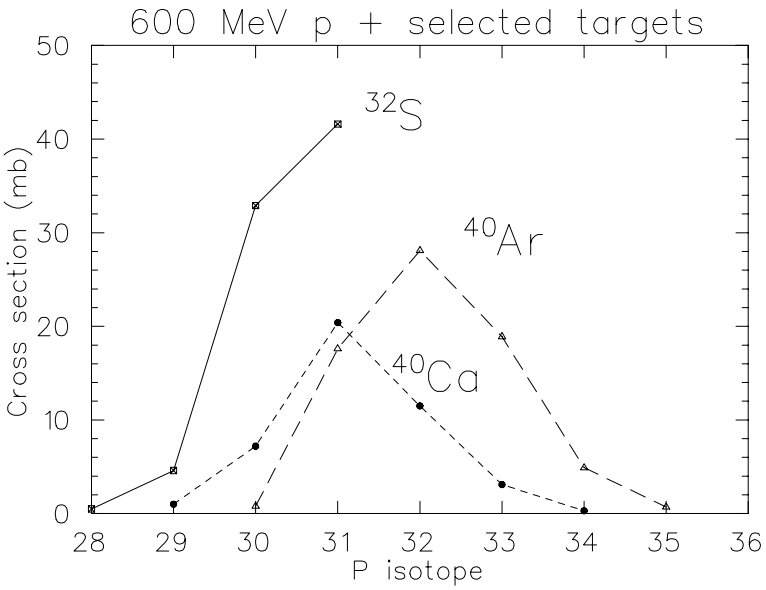

Figure 1: Production cross sections for phosphorus isotopes from targets of ^{32}S, ^{40}Ar and ^{40}Ca.

worth considering alternatives which might be investigated independently of the main thrust of ISAC target development. This proposal is to invest a modest effort in R&D on a possible "Plan B" for ^{30}P production. It should not be taken as advocating the abandonment of solid target development, but rather as an insurance policy against an unfavorable outcome; the preferred "Plan A" still is to make a workable high-temperature solid target.

The diffusion constant in a gas is of order D=1 cm^2 s^{-1} at 1 atm pressure [3]. Low energy facilities at TRIUMF and elsewhere have exploited this fact to extract radioactive product efficiently from a gas target. The BEARS facility at Berkeley has shown also that it is possible to transport the product rapidly across 350 m distance, separate it from the carrier gas and inject it into an ECR ion source [4]. The features of a BEARS demonstration of ^{11}C production include: 8-cm long target of nitrogen gas, plus 0.2% oxygen, at 22 atm; 30 μA beam of 10 MeV protons; target pressure rise to 50 atm under beam heating; product taking the form CO_2; after 5 min bombardment the target gas is transferred to a holding volume and then sent through an evacuated 3-mm polypropylene capillary, propelled by nitrogen gas at 6 atm; CO_2 trapped in a coil at LN2 temperature, other gases pumped away; trap warmed up and product sent to a small reservoir at the input to the ECR ion source (Figure 2).
In a demonstration of ^{14}O production, about 30% of the product nuclei were trapped and released [5].

TRIUMF experiment 955 demonstrated production of ^{11}C on the TR13 cyclotron and ionization by an ECR at the ion source test facility (but with transport by hand-carried lead pig, rather than capillary transfer line).

One of the limiting factors at BEARS was the gas load which could be handled by the ECR ion source. Efficient and rapid cryo-separation of the product from the carrier gas depended on a wide separation between the boiling point of N_2 (-196C) and the CO_2 sublimation point (-78C), as well as proximity of the trap to high-speed pumps and to the ECR. At ISAC the FEBIAD source would impose a similar limit (estimated at 0.001 std-cc/min [6] which is $\approx 5\times10^{14}$ molecules/s: *major* changes to the ISAC target facility on beamline 2A would be

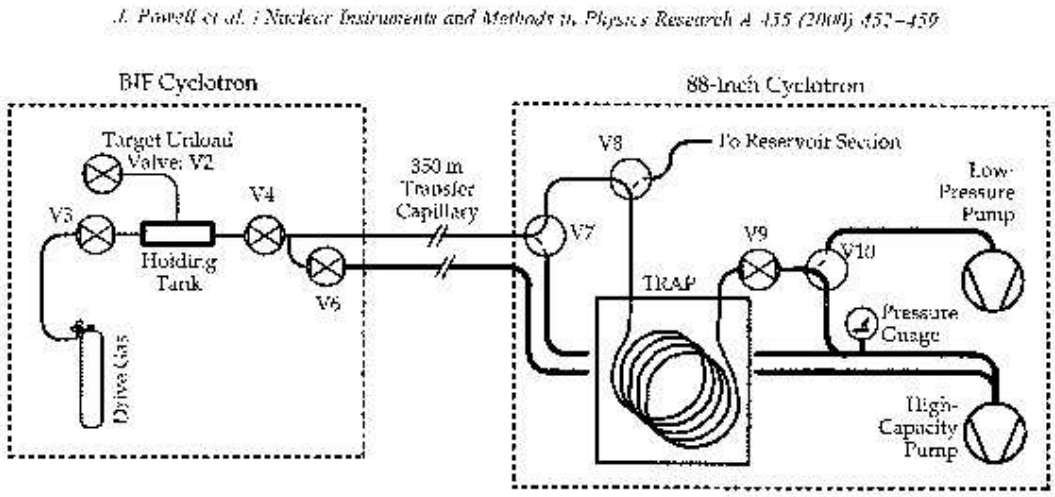

Figure 2: Transfer and separation radioactive product from a gas target at the BEARS facility, Berkeley.

required to achieve high pumping speeds near the input to the FEBIAD source. A lesser (but still not trivial) upgrade of pumping and shielding at the off-line ion source OLIS could permit delivery of ^{30}P beam to the ISAC accelerators. In addition, the production facility would have to be installed at BL2A or at another beamline at TRIUMF (which would require its own shielding and remote handling capability).

There would be great advantage if a target having the high diffusion rate of a gas could be mountd at the ISAC location on BL2A. A possible way to accomplish this is to have a liquid target which is vaporized by beam heating, product molecules are caught in a trap and the target vapor is re-condensed. To be workable, the method requires that hot-atom chemistry leads to formation of P-containing molecules which condense in the trap at temperatures that allow the target vapor to pass freely (or vice versa).

Figure 1 suggests that target liquids which include S or Cl would be best for production of ^{30}P. Potential target liquids such as SF_6 or H_2S might yield product molecules of PF_3 or PH_3, respectively, but the condensation temperatures of target and product are expected to be too close together for good cryo-separation. The exception may be phosphorus chlorides, provided their boiling temperatures are a reasonable guide to temperature of condensation in a trap. Two schemes appear to merit further study.

The first method is based on a target of liquid chlorine. As shown in Figure 3, the 500 MeV proton beam skims the surface of liquid, producing radioisotopes and vaporizing some of the liquid. The hot P atoms form PCl_3 and PCl_5. With valves V1 and V2 open and V3 closed, the P molecules are entrained by the Cl vapor into the trap, where they condense. The Cl vapor is re-condensed and returned to the target cell. After 1 minute V1 is closed, resulting in most of the Cl vapor in the trap being drawn into the condenser. V2 is then closed, V3 opened and the trap warmed up enough to release the phosphorus chlorides to a holding volume. V3 is then

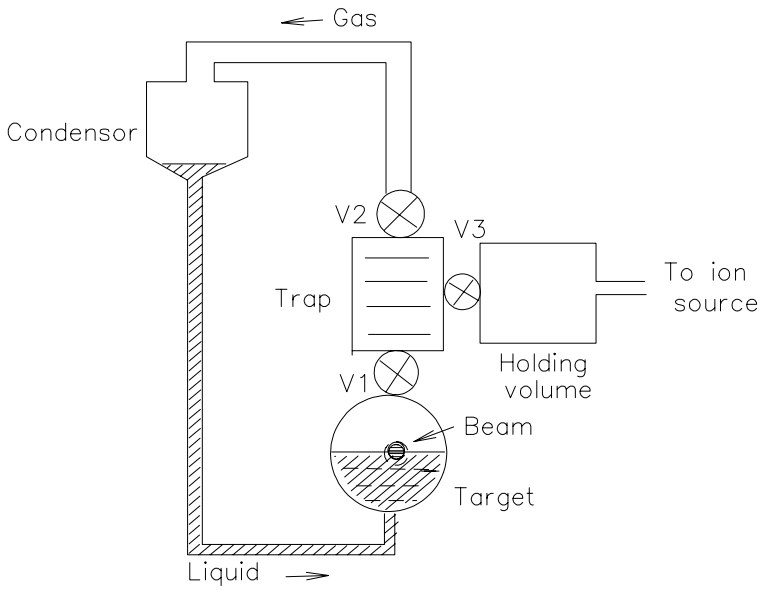

Figure 3: Concept for a boiling liquid target based on liquid chlorine.

closed, V1 and V2 opened and the production cycle is repeated.

A production rate of $\mathbf{10^{10}\ s^{-1}}$ **for** $^{30}\mathbf{P}$ (assuming >0.1% efficiency for trapping, release, ionization and acceleration, to provide $>10^7$ s^{-1} at DRAGON) is predicated on the following assumptions:

- Target length 6 cm
- Cross section 10 mb
- Beam-in-liquid 500 nA
- Liquid temperature -88C
- Pressure above target 0.1 atm
- Beam power loss in Cl target 24 W
- Vaporization rate 54 atm-cm^3/s
- Trap conductance 6 l/s
- Condenser temp (V1 closed) -150C

A Cl target should be favorable for the formation of phosphorus chlorides. It has the drawback that the target material is corrosive and toxic. The condenser should have a cooling power >100 W at -100C and be able to achieve a "low load" temperature of -150C.

The second method uses a target of LiCl heated to just above its melting point (613C), with the proton beam skimming the surface of the liquid (Figure 4). Again, there is a requirement that product P atoms form chlorides through hot-atom chemistry.
The LiCl vapor is re-condensed in a trap held at the same temperature as the liquid, a temperature at which the LiCl vapor pressure is 0.03 Torr. Phosphorus chlorides pass through the open valve V1 to a trap at -80C, where they condense. Any chlorine gas produced in the target will pass through the second trap and the open valve V2, to be pumped away. (A long, low-conductance line should provide enough pumping speed.) After a period of accumulation,

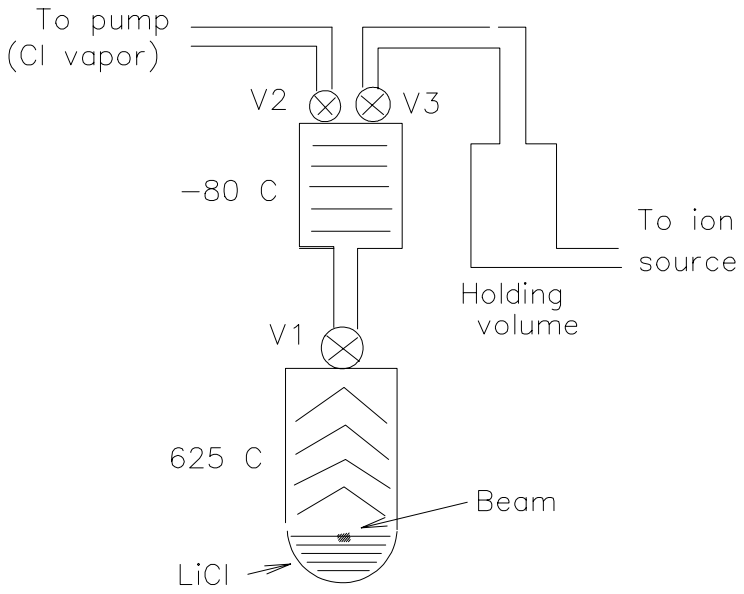

Figure 4: Concept for a boiling liquid target based on liquid lithium chloride.

valves V1 and V2 are closed, V3 opened and the upper trap is warmed up to release product to the ion source.

Even with an aperture of only 3 mm at the exit of the high-temperature trap, a LiCl vapor pressure of 0.03 Torr would result in the loss of 6 g of target material per day into the upper trap. Therefore, periodic heating of the upper trap (with valves V2 and V3 closed) would be necessary, to drive the LiCl back down into the production cell.

If the rate of production of chlorine gas should prove low enough that it could be handled by the ion source, a non-cycling mode of operation becomes possible. Valve V2 is closed, the upper trap is held at 100–150C and valves V1 and V3 are open, allowing steady flow of the phosphorus chloride vapor into the ion source. Given the low boiling point of $AlCl_3$ (183C), it is possible that the short-lived isotopes ^{25}Al and ^{26m}Al might be extracted from a LiCl target. It is possible also that 0.84 s ^{34}Ar could be created by the (p,2n) reaction, with useful quantities delivered to the ion source in continuous mode if the free volume (most notably the holding volume) were minimized.

Many questions have to be answered before we could be confident that a boiling liquid target will produce 10^9 s^{-1} of ^{30}P at the input of an ion source at the ISAC BL2A target location:

- Do product atoms form the desired compounds?
- Are product atoms entrained efficiently by target vapor?
- Are entrained products trapped efficiently?
- Can product molecules be transferred efficiently to the ion source?
- Do valves and target enclosure materials stand up to beam, heating and corrosion?
- Can sufficient refrigeration power be generated at the ISAC target module?

This proposal is to carry out experiments with a chlorine gas target to address aspects of

the first three questions. It would be done on beamline 4A with a 500 MeV proton beam of sub-microamp intensity. Stage 2 approval is requested at this time.

(b) **Description of the experiment:**

The apparatus is sketched in Figure 5.

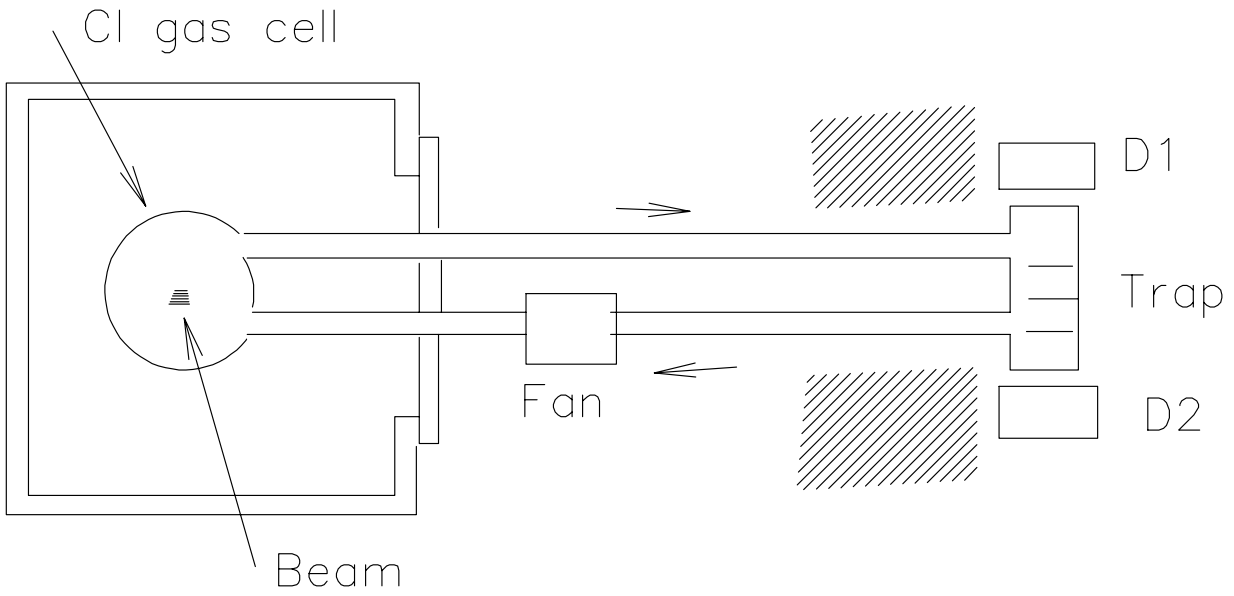

Figure 5: Sketch of the chlorine gas target and trap to be used in the proposed experiment on BL4A.

Beam passes through a 6-cm long cell containing Cl gas at a fraction of 1 atm pressure. Tubes connect the production cell to a trap cell, with a fan to draw gas through the trap. Decay rate of ^{30}P in the trap is measured by a pair of fast scintillation detectors (D1, D2) which detect the pair of 511-keV gamma rays from its positron decay (half-life 150 s).

The rate of formation of condensable P product would be studied as a function of the beam intensity, the gas pressure and the temperature of the gas. The trap performance would be studied as a function of the trap temperature and of the material of the trap surfaces.

Decay rate *vs* time after interruption of beam gives a clear indication of ^{30}P: only ^{15}O has a similar lifetime and decay mode. Sodium isotopes, whether in the form of Na or NaCl, will have very low volatility at the planned target temperatures and should stick in the gas cell walls.

Assuming a production cross section 10 mb, target pressure 0.1 atm at 0C and a beam intensity 100 nA gives a production rate of 2×10^5 s^{-1}. A positron detection efficiency of no worse than a few percent would allow a sensitive measure of the ^{30}P content of the trap.

Measurements would consist of a brief period of bombardment, comparable to the product half-life of 150 s, followed by a beam-off period during which the positron decays in the trap would be counted. During beam-on the positron detectors would see mostly room background (neutrons, gammas) and positron decays would be counted only during beam-off times.

Chlorine gas will require special precautions: it is toxic in low concentrations and can corrode many materials. These issues must and will be addressed in Technical and Safety documents.

(c) **Experimental equipment:**

The gas cell and trap require heating/refrigeration source(s) that allow independent variation of temperature. Planned temperatures span -30 to +120C for the target cell and -80 to +50C for the trap. It is proposed to mount the experiment near the end of BL4A in the vacuum box which housed the TISOL target assembly. The Cl gas cell would be mounted on a removable side plate, as indicated in the sketch. It would require valves to allow pump-down, gas filling and venting. Safety issues concerning chlorine gas may dictate addition of an "anti-hood" with forced air flow to be mounted below the apparatus. The design and manufacture of the gas cell, trap and connecting vacuum lines are to be provided by TRIUMF.

Detectors and associated coincidence detection electronics will be assembled by the experimental group.

Beamline 4A has not received beam for several years. Proper operation of its extraction probe, magnets, vacuum system and diagnostics must be verified. Hardware to satisfy Prompt Radiation Hazard regulations must be tested.

(d) **Readiness:**

November–December 2007: check BL4A readiness (TRIUMF Ops)
January 2008: Technical and Safety reviews; BL4A repairs (if any)
February–March 2008: Design of target/trap (Design Office, experimenters)
April–May 2008: Order equipment (experimenters) and manufacture gas cell/trap (Machine Shop)
June 2008: Assemble and test equipment
July–August 2008: Beam delivery to experiment

(e) **Beam time required:** We request 24 shifts, in blocks of 4 shifts approximately 1 week apart. This allows time to replace trap material due to build-up of long-lived contaminant activity or to test a different material. All the time would be as prime user on BL4A. Beam tuning is expected to take 2–3 hours at the start of each block of time. The distinction between "adjustment of apparatus" and "production" is not clear for this type of experiment.

(f) **Data analysis:** Data collection requires a multiscaler capable of logging coincidence counting rates vs time for periods of up to 1000 s. The data must be transferred to a desktop computer capable of a least-squares fit involving several exponential functions. It is not expected that these data processing needs will impact the TRIUMF central computing resources in any visible way.

References

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