TRIUMF - RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 20

Title of proposed experiment

Measurement of the ^{22}Na(p,γ) reaction rate

Name of group
DRAGON

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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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M. Trinczek	TRIUMF	Research Associate	25 %
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Date for start of preparations: April 2005

Date ready: June 2005

Completion date: April 2008

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
20 (^{22}Na)	HRMS	no
28 (^{23}Na)	OLIS+8pi or GP1	no
20 (^{1}H)	DRAGON	no

Do not exceed one page.

Sodium-22 is a long sought after but elusive cosmic gamma ray emitter. Some nova models using updated reaction rate libraries still show that ^{22}Na should be made prolifically in novae yet it has not been observed with orbiting gamma ray telescopes anywhere except in the central galactic bulge. This discrepancy may be resolved due to a recent measurement of ^{23}Mg structure which discovered a level that could have huge implications on the rate of ^{22}Na destruction via the ^{22}Na(p,γ)^{23}Mg reaction. It is therefore desirable to perform a direct (p,γ) measurement of the new resonance. It is proposed that a new ^{22}Na(p,γ) measurement is performed, with specific attention paid to the new resonance, using a ^{22}Na target made at TRIUMF-ISAC.

The experiment will consist of three phases: (1) target implantation and characterization study using stable ^{23}Na-implanted targets and low-energy proton beams (2) ^{22}Na target production and (3) measurement of the (p,γ) reaction rate. We propose the production of targets in a range of thicknesses and activities, not exceeding 20 mCi. Using ISAC's maximum beam current, it will only take 48 hours of continuous beam to produce a 20 mCi ^{22}Na target. To study the implantation process, two weeks of stable ^{23}Na beam at a range of energies (20-60 keV) will be needed, but not consecutively. Two weeks of 300-350 keV proton beams will also be required in a similar manner for the implantation study.

BEAM and SUPPORT REQUIREMENTS |

Experimental area

^{23}Na implantation: OLIS, port just before GP1 or 8pi and DRAGON target position
^{22}Na implantation: at exit of HRMS downstairs in ISAC-1
^{22}Na(p,γ): An outside laboratory, such as U.Washington or Notre Dame

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

^{23}Na beam (20-60 keV) on Ni, C, 1 pμA
^{22}Na beam (20-60 keV) on Ni, C, 50 pnA, just after high-res mass separator
^{1}H beam (300-350 keV) on Ni, Na, C, Ta, 5 nA; beam requirements are $\Delta E \leq 2$ keV

Secondary channel

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

none

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.

Secondary stripping is necessary following the DTL for the proton beams.
It will be necessary to work closely with the TRIUMF Safety Group to properly handle the radioactive targets, and obtain the necessary permits. Some machining and purchasing will have to be done (see below).

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.

It is estimated that all the capital support costs, including machining, will be borne by an NSERC project grant proposal (capital costs ~$85k, total grant request ~$350k)

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.

Radiation safety

The ^{22}Na targets will be a radiation hazard that will need substantial shielding. The targets will have up to 20 mCi of ^{22}Na, thus requiring thick lead shielding. In addition the targets should be handled remotely and kept in a well-shielded lead cask and stored appropriately when not in use. We plan to develop the techniques and handling procedures using low activity sources.

Chemical safety

The sodium will be implanted into targets under vacuum and therefore won't require any special procedures normally appropriate for handling of sodium metal. The implanted targets will be stored under vacuum. It is unlikely a hazard exists because the amount of sodium in the targets is small (a few micrograms at most).

Introduction and Scientific Justification: Why?

Explosive hydrogen burning and nucleosynthesis occur in novae, x-ray bursts and type II supernovae. Within the hot, dense, hydrogen-rich environment, a complex series of proton capture and β^+-decay reactions occur (the rp process), and elements heavier than helium are created and ejected into space. The proton capture reactions receiving the most attention recently are those which affect the abundances of cosmic gamma ray emitters, which have been observed in the ejected material of these explosions using orbiting gamma-ray telescopes. Understanding the rates of various reactions allows resulting isotopic abundances to be predicted, and provides insight into the process itself.

The study of explosive nucleosynthesis is one of the most active research fields in physics today. This situation has materialized largely due to two major occurrences: 1. gamma-ray telescope data have become available and 2. nuclear physics facilities are coming on line which can produce the short-lived nuclei which dominate the nuclear burning sequences in stars. One of the most exciting developments in the past 10 years has indeed been the detection of gamma rays coming from stellar explosions. These observations provide unprecedented evidence for active burning sites and provide a constraint on astrophysical explosion models.

Not all nuclei produced are candidates for observation by gamma-ray telescopes. The isotopes in question have to live long enough for the ejected debris to become transparent (~hours or greater), and they must emit characteristic gamma rays of sufficient energy ($\geq$1 MeV) at some point in their decay sequence. Two such nuclei have been the subject of much research over the past 5 years: ^{22}Na($T_{1/2}$=2.6y, E_γ=1.275 MeV) and ^{26}Al($T_{1/2}$=7.2x10^{5}y, E_γ=1.809 MeV). Of these two, only ^{26}Al has been identified in known burning sites. ^{22}Na has been identified only in the galactic bulge, but not from any one particular site.

This situation is puzzling to many scientists who believe that ^{22}Na should be made prolifically in nova and supernova; it is also the subject of some controversy. Some models predict ^{22}Na production equal to that of ^{26}Al, hence it should be readily detectable [1,2]. Other models indicate that the lack of detection is consistent with the production rates [3]. To resolve this discrepancy, knowledge of both the nuclear physics and the astrophysics of these production sequences must be advanced.

The dominant nuclear uncertainties in the production of ^{22}Na have been identified and much progress has been made to reduce these uncertainties, through both indirect measurements [4-6], and direct measurements [7,8]. As pointed out in Starrfield *et al.* (2003), the ^{22}Na(p,γ) reaction rate has the largest effect on the ^{22}Na production. At nova temperatures, this reaction rate may be dominated by a single new resonance that was discovered very recently [6]. However, no direct measurement of the resonance strength has been performed. In addition, other key resonances have only been measured to ~50% accuracy (Table 1). Thus a new, direct measurement of this reaction rate, with particular attention focused on the new resonance, is required.

Table 1. ^{23}Mg levels above the proton threshold important for explosive hydrogen burning in novae (adopted from Jenkins *et al.*). The 7.769 MeV state recently discovered is highlighted in (blue) bold. Its strength has not been measured.

E_x [MeV]	E_p(lab)[keV]	$J^{\pi,i}$	$J^{\pi,f}$	E_γ [MeV	Branch [%]	ωγ [meV]
7.623	46	9/2+	5/2+	7.173	100	1.1×10^{-13}
7.647	70	3/2+	5/2+	7.196	100	7×10^{-10}
7.769	**198**	**(9/2-)**	**9/2+**	**5.055**	**58(8)**	**? (~0.4-4)**
			11/2+	**2.317**	**42(7)**	
7.780	209	(11/2+)	7/2+	5.729	33(6)	? 0.05(est.)
			9/2+	5.067	66(8)	
7.785	214	(7/2+)	5/2+	7.334	100	1.8(7)
7.801	232	5/2+				2.2(10)
7.852	284	(7/2+)	9/2+	5.138	100	15.8(34)
8.015	456	(5/2+-11/2+)	9/2+	5.300	71(16)	68(20)
			7/2+	5.967	29(12)	
8.160	607	5/2+	7/2+	6.110	100	235(33)

This new resonance was discovered in a gamma-ray spectroscopic measurement using the ^{12}C(^{12}C,n)^{23}Mg reaction with Gammasphere [6]. Excited state energies and gamma-ray intensities and energies were deduced (Table 1, Figure 1). Using mirror symmetry arguments, it was estimated that the new level at 7.769 MeV could have a resonance strength up to 4 meV based on a tentative J^π=9/2- spin assignment (p-wave). A resonance strength >0.4 meV would make the reaction rate larger than that of the E_p=214 keV resonance (Figure 2). Otherwise, the E_p=214 keV resonance dominates the reaction rate at nova temperatures (T=0.1-0.4 GK). Clearly, a direct measurement of the resonance strength of the E_p=198 keV state is needed. A re-measurement of resonance strengths of the E_p=214 keV and E_p=232 keV states is also desired to reduce the ~50% uncertainty in the rate.

Several direct measurements of the ^{22}Na(p,γ) reaction rate have been made in the past [9-12], but most recently by Stegmuller *et al.* [13]. With regards to resonances in the nova Gamow window, Stegmuller *et al.* measured resonance strengths down to E_p=214 keV, but the study did not extend far enough below that to see the E_p=198 keV resonance. To date, this resonance remains unmeasured. Experimental information available from direct measurements is therefore lacking and needs to be updated.

The Experimental Goals

The goals of the proposed experiment are two-fold. First the strength of the E_p=198 keV resonance will be measured. Second, the other resonances in the ~200 keV region will be measured better than currently known (~50%). The technique will not differ much from that presented in Stegmuller *et al.*; the only difference between that measurement and this one is that the E_p=198 keV resonance wasn't known at the time and therefore wasn't measured. However, it will be possible to improve upon the past measurements using (1) more target material and (2) segmented germanium detectors.

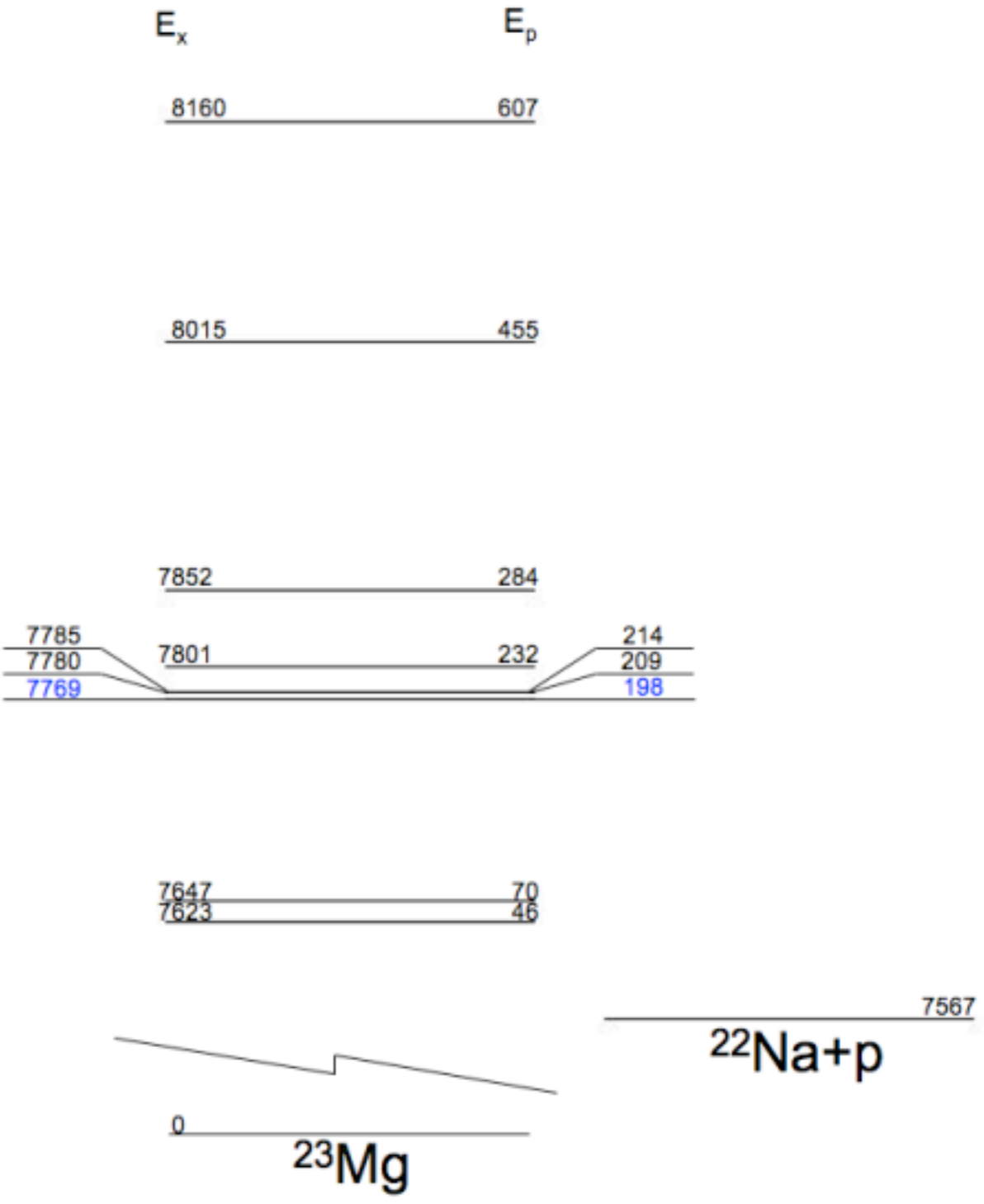

Figure 1. Level scheme of ^{23}Mg above the proton threshold. All energies are given in units of keV. The blue type shows a newly identified state that could be extremely important to the ^{22}Na(p,γ) reaction rate in novae.

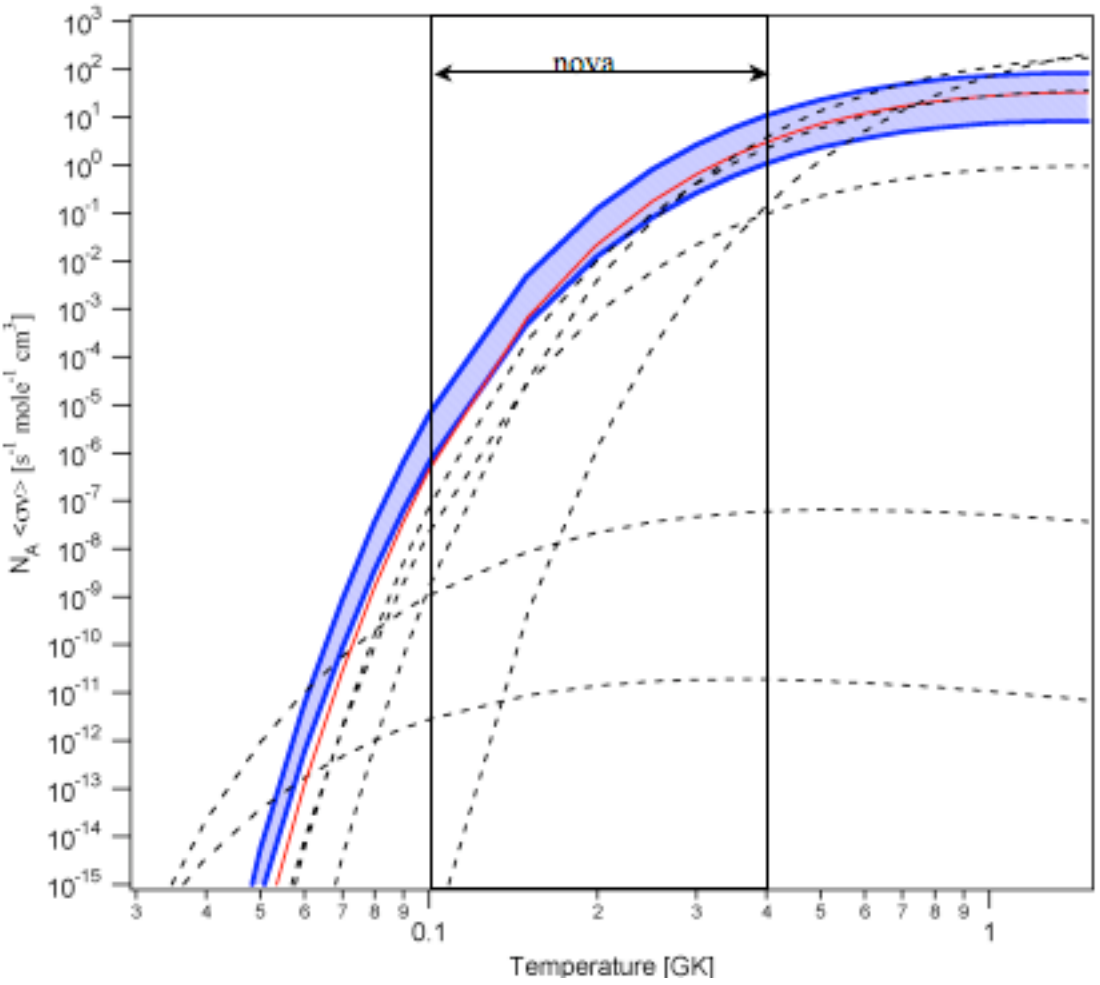

Figure 2. Proton capture reaction rates for all states E_r<500keV listed in Table 1. The solid (red) line is the E_p=214 keV resonance. The (blue) band is the E_p=198 keV resonance spanning the range of $\omega\gamma$=0.4-4 meV.

The Experiment

There are two ways that this reaction could be measured: Using a ^{22}Na beam and DRAGON, or using TRIUMF-ISAC to produce the ^{22}Na targets then perform the measurement elsewhere using a high current proton beam. Due to the high specific activity of the ^{22}Na and its long half life, and the possibility of activating the ISAC beamlines for their forseeable operating lifetime, it has been decided that it would be better to perform the direct measurement in normal kinematics elsewhere.

The experiment will consist of three phases: (1) target implantation study using stable ^{23}Na (2) ^{22}Na target production and (3) measurement of the (p,γ) reaction rate. We propose the production of targets in a range of thicknesses and activities, not exceeding 20 mCi. This choice allows maximum freedom in performing the experiment. Using ISAC's maximum beam current, a 20 mCi ^{22}Na target will only take 48 hours of continuous beam to produce. Hence we request 10 days of beam time, which should be sufficient to carry out all the implantation needed. To study the implantation process, two weeks of stable ^{23}Na beam at a range of energies (20-60 keV) will be required.

This reaction will be measured using a well-established technique equivalent to that of Stegmuller *et al.* in their ^{22}Na(p,γ) measurement. A 0.19 mCi ^{22}Na target, implanted in a Ni substrate, was bombarded by protons of energies 0.2-0.6 MeV. A 100% germanium detector was used to measure the

resulting gamma rays. A 5 cm-thick lead brick was placed between the target and the detector to reduce the high rate of 511 keV and, to a lesser extent, 1.275 MeV gamma rays emitted from the target. A small diameter target was used, and the proton beam was rastered over the entire area of the target. Using this approach reduces the uncertainty regarding the luminosity, from ~10% due to the uncertainties on beam spot size and target nonuniformity, to ~1% due to uncertainty on the integrated beam flux [13-15]. This method also allows constant monitoring of the amount of target material remaining by simply measuring the activity of the sample.

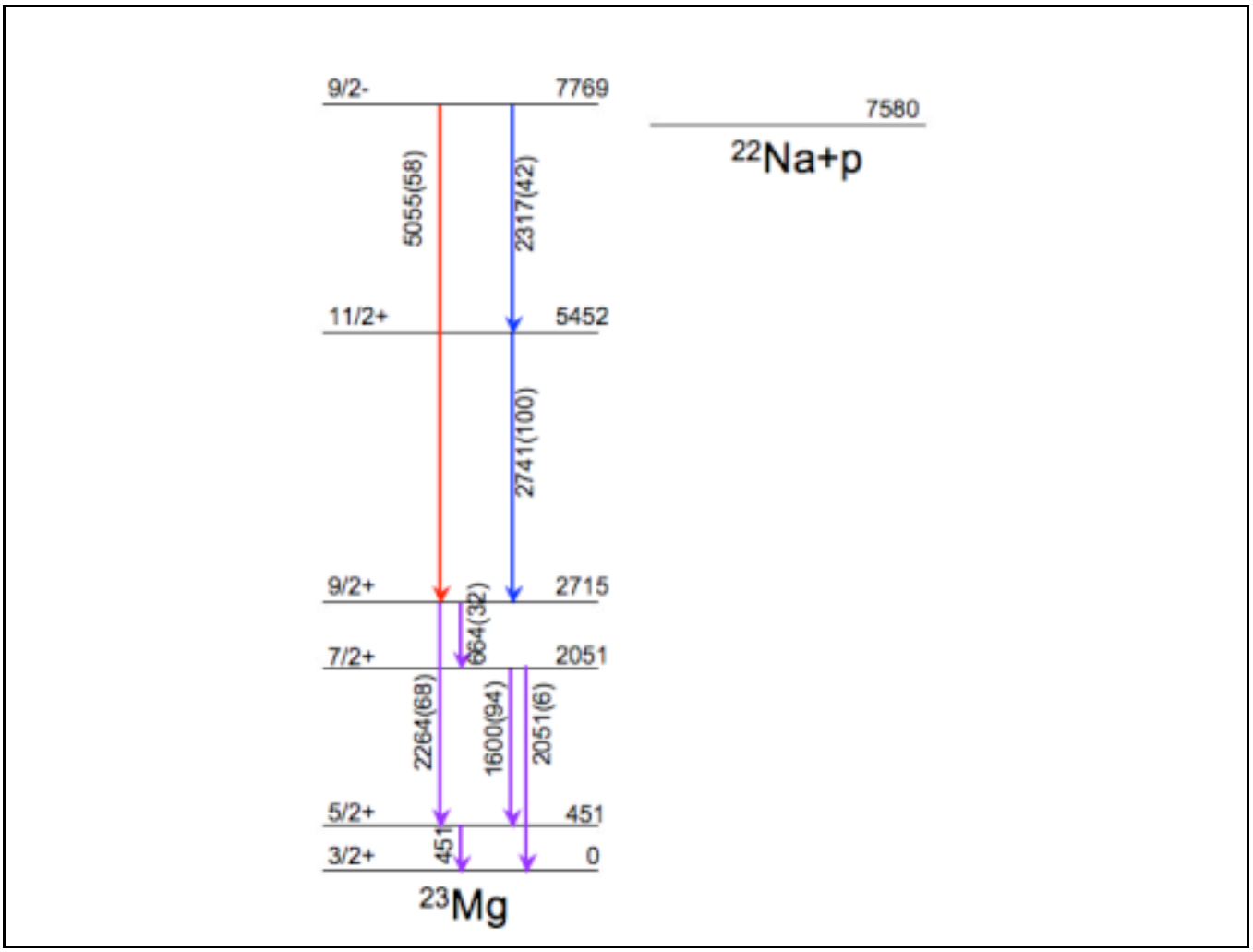

Figure 3. Decay scheme of the E_p=198 keV resonance. Each transition is labeled by its gamma ray energy [keV] and branching ratio [%].

For the proposed experiment, a very similar setup will be used. Proton beams of up to 50 μA will be used (higher currents will cause rapid ^{22}Na loss from the target [13]), thus it will be necessary to attach the target to a water-cooled mount. The measured gamma-ray flux, measured with a germanium detector, will be used in conjunction with the knowledge of the gamma-ray energies and branching to determine the resonance strengths. For the E_p=198 keV resonance, the 5.055 MeV gamma ray (58% branch) will be used because it is in a region of the gamma-ray spectrum that is cleaner than the location of the 2.317 MeV gamma ray (42% branch) (Figure 4).

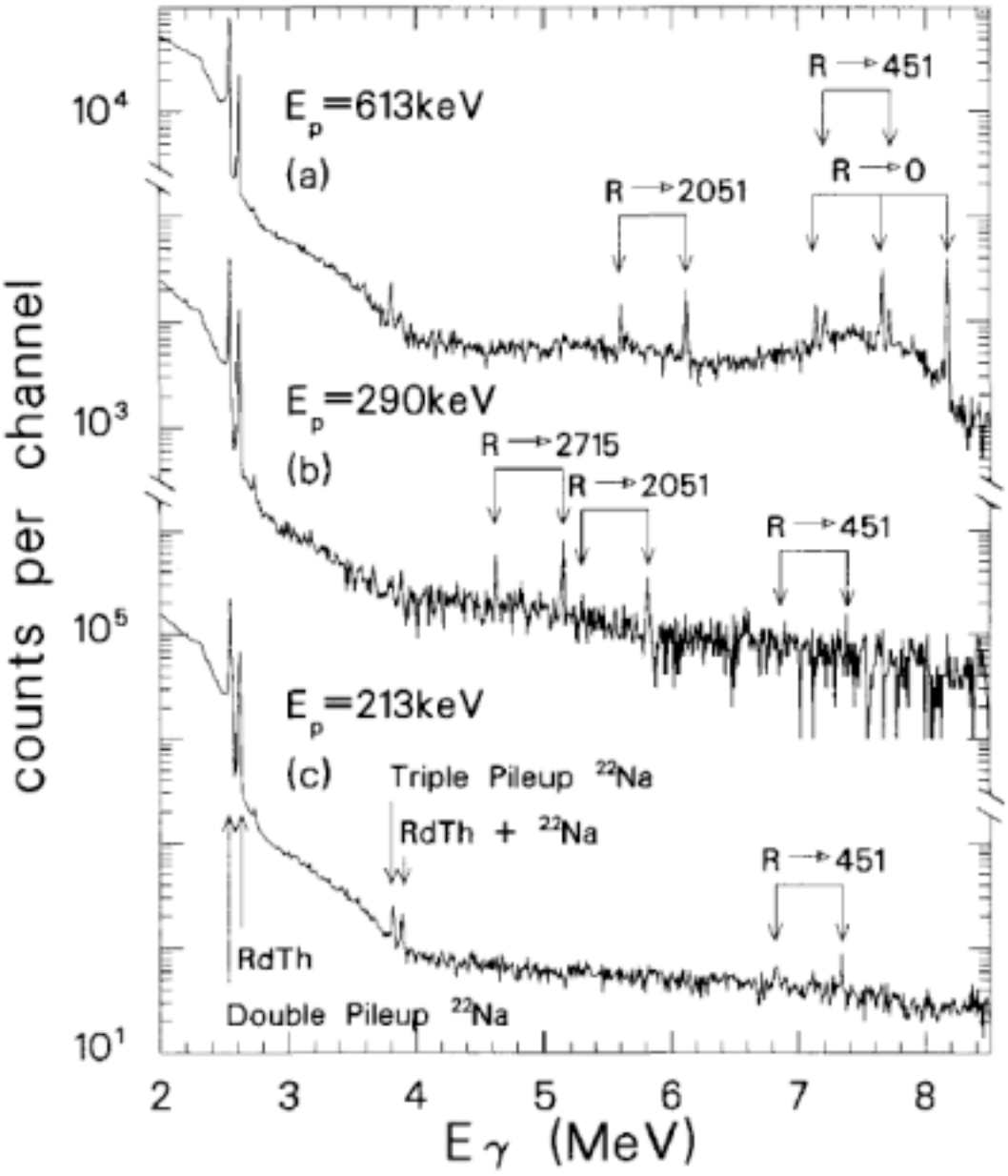

Figure 4. Gamma-ray energy spectrum measured for three resonances in the ^{22}Na(p,γ) reaction (taken from Stegmuller *et al.*), illustrating the cleanliness of the gamma-ray spectrum at 5 MeV compared to ~2.3 MeV. This figure, in particular the E_p=213 keV measurement, also shows the clear advantage of using germanium detectors for gamma-ray measurement.

Despite the apparent simplicity of the experiment, it will be challenging. First, the ^{22}Na is released from the implanted targets under proton bombardment and will consequently contaminate the chamber; thus a dedicated chamber and pumping system will have to be obtained. Second, the ^{22}Na decay produces a 1.275 MeV gamma ray 99% of the time, in addition to the annihilation radiation. While this is beneficial for monitoring the amount of ^{22}Na over time, the expected high activity of the target will swamp the gamma-ray detectors used to perform the experiment. Consequently, the detectors will have to be placed some distance from the target to reduce this rate to tolerable levels, which will reduce the efficiency of the gamma detection system, or thick lead shielding will be required to reduce the high rate

of 511 keV gamma rays to tolerable levels, as in Stegmuller *et al.* A single clover Ge detector with a BGO shield can be borrowed and would be ideal for this measurement. Alternatively, a large (≥100%) HPGe detector could be used. High rate amplifiers (such as the ORTEC 973U) will be required for each germanium detector used (or each segment of a germanium detector used).

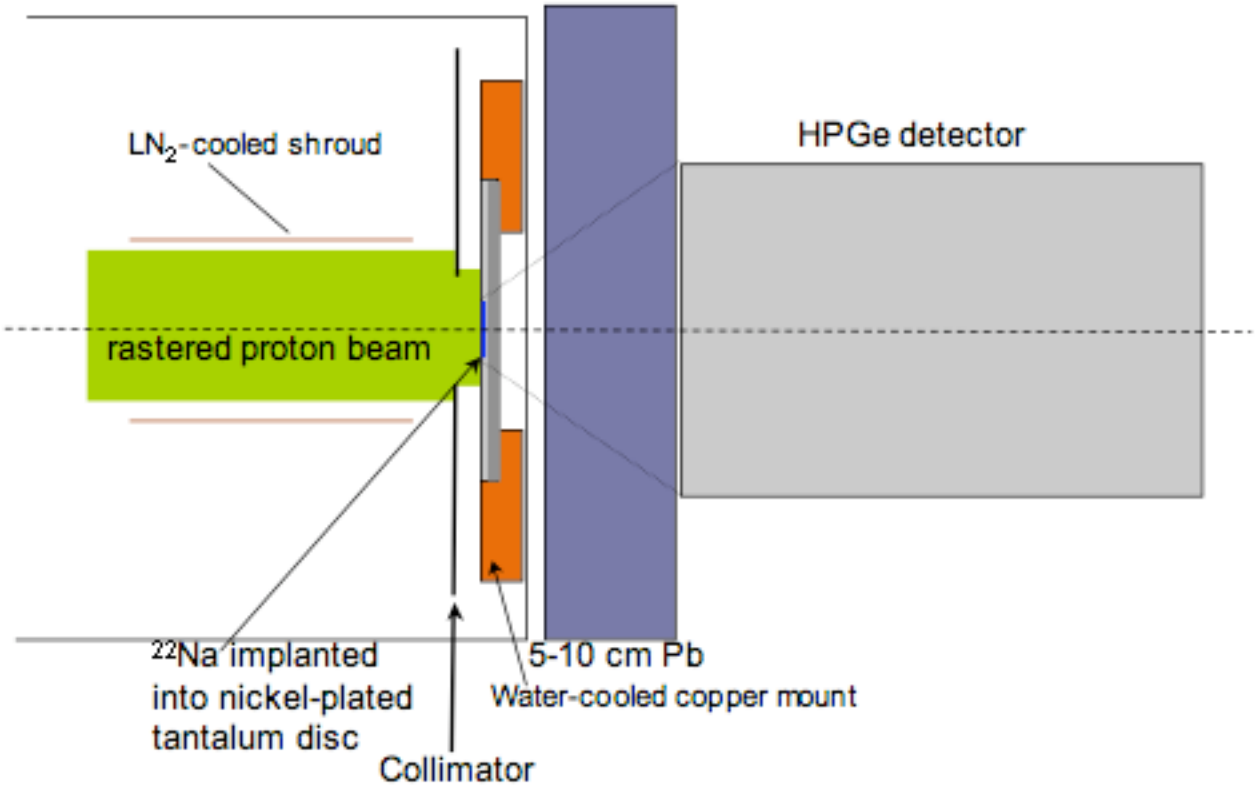

Figure 5. Closeup of proposed experimental setup

Target Production

Sodium target production is not a trivial matter, but fortunately it has been studied extensively with this specific application in mind [9-13]. To summarize, implanted targets are superior to electrodeposited targets. Implantation has the advantages that the beam is pure, the targets can be made in a variety of thicknesses, enormous amounts of sodium (10^{19} atoms) can be implanted, and implanted sodium targets have been made and shown to perform well in (p,γ) experiments. The sodium is also confined to the substrate during transport, and is more stable under proton irradiation. It is for these reasons that we have chosen to use an implanted target.

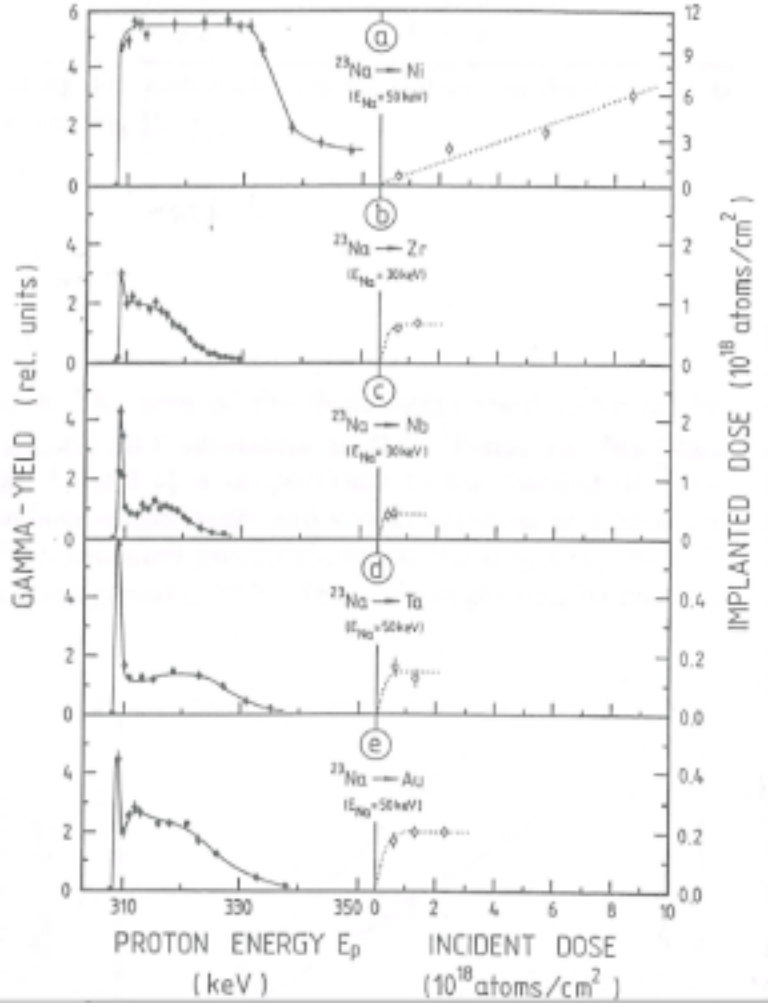

Figure 6. Sodium implantation results from Seuthe *et al.* [10] showing the advantage of using the nickel substrate over other possible materials.

Nickel and carbon are by far the best substrates for implanting significant quantities of sodium [9,10]. Implantation of up to ~10^{19} atoms into a thick nickel foil is possible. The capacity of carbon foils is even higher. The capacity of both substrates is only limited by their thickness, and the sodium depth profile is rather flat and featureless, a very desirable characteristic of the target (Figure 5). The target amount (thickness) will be limited by the experimental requirement that close resonances are resolved. Specifically, a target that is ~2-3 keV thick @ E_p=198 keV would be preferred for measuring the strengths of the 209 and 214 keV resonances. A slightly thicker (~5-10 keV) target can be used for the other interesting resonances.

Target development and characterization will constitute a major portion of the work for this experiment. The implantation process will be perfected using beams of stable sodium-23. There are many uncertainties associated with the implantation process, including which implantation energy to use and the migration behavior of the sodium in the substrate. The depth profiles as well as the lateral extent and migration of the implanted targets will be measured using the narrow (Γ < 20 eV) 309 keV resonance in the ^{23}Na(p,γ)^{24}Mg reaction ($\omega\gamma$=2.2eV). Once the production technique has been studied and perfected, ^{22}Na targets will be made.

The ^{22}Na target will be produced at ISAC. Remarkably high-intensity ^{22}Na beams are available at ISAC (up to 77 pnA) using a silicon carbide ISOL target in conjunction with a surface ionization source.

The ^{22}Na will be deposited into a metallic disc over a small area (~5mm diameter). It is planned that many targets will be made, in the range of 0.1-20 mCi ($4.4x10^{14}$-$8.8x10^{16}$ atoms). The discs will consist of a fairly thick (~1 mg/cm^2) layer of nickel electrodeposited onto a thick sheet of tantalum. The ^{22}Na implantation will take place just after the high-resolution mass separator located downstairs in the ISAC-1 facility. A small chamber will be built and used for implanting the ^{22}Na (Figure 7). The chamber will have the target mounted on the end of a long rod that that will enable remote handling of the target and extraction of the target from the vacuum chamber. Once removed from the implantation station, the small chamber will be sealed off using a thick steel plate, then placed in a rolling lead cask for transport.

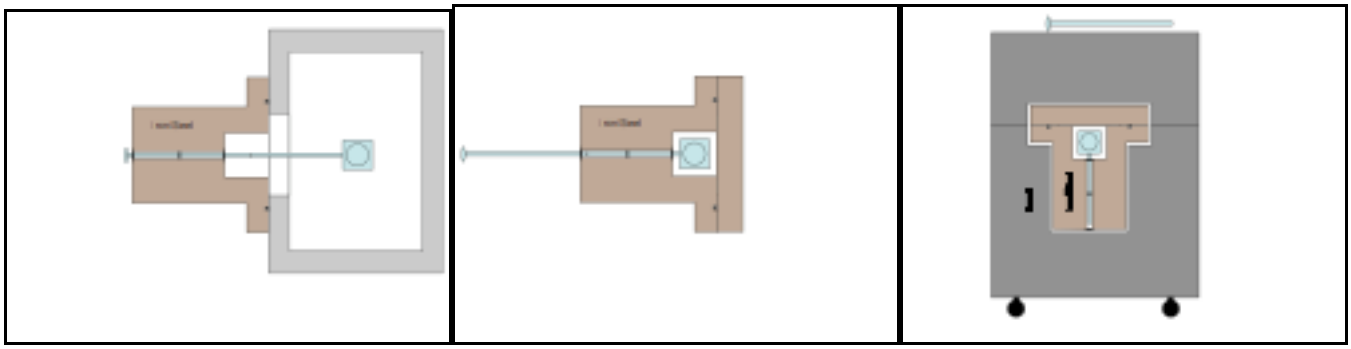

Figure 7. Chamber for implantation and transport. Left, during implantation: Sodium is implanted into sample on the end of long rod (beam perpendicular to page). Middle, just after implantation: Sample is retracted into well, then sealed off using thick steel plate. Right, ready for transport: Rod extension is unscrewed, chamber is placed into rolling lead cask and a thick lead cap is added.

The ^{22}Na targets will likely have the same three-dimensional profiles as the ^{23}Na test targets, but this will have to be verified. The lateral extent and migration of the ^{22}Na targets will be mapped by measuring the 2D profile of the gamma rays viewed (by a HPGe detector) through a narrow (~1mm) collimator. The depth profile of the ^{22}Na targets will be measured using the strong 607 keV resonance, though it is expected that it will be the same as the ^{23}Na targets.

In addition, it will be necessary to identify the contaminants in the target to determine the potential background induced in the measurement. We plan to use the target chamber at the other facility to identify the target contaminants in the ^{22}Na targets by using large-angle, low energy (p,p) scattering (measured with silicon surface-barrier detectors). Because of the production technique (SiC ISOL target combined with the surface-ionization source), it is unlikely that there will be significant isobaric contamination in the implanted target. ^{22}Mg is unlikely to be produced very efficiently, but nevertheless it decays to ^{22}Na in a matter of seconds and will be of no concern. Because the surface ionization source is used, virtually no ^{22}Ne will be present in the beam, but it will be present as the daughter of ^{22}Na. Fortunately there are no ^{22}Ne(p,γ) resonances in the vicinity of the ones to be measured.

Experimental equipment required

For the implantation testing phase of the experiment, existing beamlines and experimental apparatus (GP1 or 8pi) can be used, and OLIS will provide the ^{23}Na beam. For characterizing the ^{23}Na-implanted targets, the DRAGON target position will be used with a proton beam, if available. Otherwise, the targets will be tested at the other facility. ISAC has experience making ^{22}Na sources, thus during implantation of the ^{22}Na, the implantation station already constructed for that purpose will be used. The storage chambers and casks will be obtained and tested prior to ^{22}Na implantation.

For performing the (p,γ) measurement, an expendable target chamber and pumping system will be acquired. The experimental apparatus will have to be effectively disposable, kept permanently at the chosen laboratory or discarded safely by some other means upon completion of the experiment, due to the

expected magnitude of contamination. Therefore, a simple chamber will be constructed, and a small cryo-pump and mechanical roughing pump will be obtained. A cryo-pump is preferable to exhausted pumps (e.g. turbomolecular pumps) because, in case of catastrophic target failure, the radioactivity is contained within the cryo-pump and chamber. The use of liquid nitrogen-cooled beamline shrouds will be necessary to keep the sputtered ^{22}Na from contaminating the upstream beamlines. Two small silicon detectors will be required for the proton scattering target characterization. Lead casks will be acquired for shielding during transport and target storage. A segmented germanium detector and its associated electronics can be borrowed, but the high-rate spectroscopy amplifiers will still need to be purchased. The tantalum discs will be purchased and the electroplating will be done at TRIUMF (unless a more suitable supplier can be found).

Experimental beam requirements

Phase 1: Implantation study

The first phase of the experiment will be the ^{23}Na implantation study. For this purpose, a ^{23}Na beam from OLIS will be sent to either the general-purpose 1 station (more precisely a small port just upstream of GP1) or to the target position of the 8pi spectrometer. The beam will be collimated to produce a 5mm diameter implantation spot. The Na will be implanted in varying doses ranging from 4.4×10^{14} to 8.8×10^{16} atoms (which would correspond to 0.1-20mCi of ^{22}Na). The time to make these targets ranges from 70 seconds to 234 minutes at 1 particle-μA. At 50 pnA, the time will range from ~0.4-80 hours. Implantation energy will be varied from 20-60 keV in 10 keV steps to determine the best implantation energy. The implantation will be in the low energy area and therefore won't be subject to limitations imposed by the RFQ or the drift-tube LINAC (DTL), therefore it is expected that at least 100 pnA can be delivered. It is likely that there will be three stages of implantation, each more refined than the previous one, thus requiring three separate blocks of beam time.

Between each set of implantations, the targets will be characterized using the 300-350 keV proton beam. The beam energy will be varied and the depth profile will be mapped using the strong (2.2 eV) resonance at 309 keV in ^{23}Na(p,γ), similar to Figure 6. Because the resonance is so strong, only a few nA will be needed to measure the profile. The beams will have to be varied in energy in 2 keV steps to achieve an accurate depth profile and each measurement (assuming a 1% efficiency and 1 pnA) will take about 20 minutes. It is assumed that one such measurement can be run per two hours, allotting time for beam energy changes. Thus, for the thin targets (ΔE=3 keV for Ep=198 keV protons) it will take 20 hours, and for the thick targets (ΔE~10 keV) it will take roughly three days, meaning almost 4 days per implantation set. For three sets, we will therefore require 12 days of 300-350 keV proton beam at ~1 nA. It is more convenient to perform the tests here, provided a suitable proton beam can be delivered to DRAGON. If not, then these tests will be conducted at the other laboratory.

Phase 2: ^{22}Na target production

The ^{22}Na implantation will occur in an implantation station immediately downstream of the high-resolution mass separator, located one floor below ground level in the ISAC-1 experimental hall. At least four targets, a thin one, a thick one and two spares will be produced. The exact activities of these targets won't be known until the implantation study is finished. However it is expected these targets will be in the range of 0.1-20 mCi. The maximum beam listed on the ISAC production page corresponds to 77 pnA. Assuming 50 pnA is delivered, it will take 23 minutes to produce a target of 0.1 mCi, and 78 hours to produce a 20 mCi target. Regardless of what we find in the implantation study, for safety reasons, we will limit the target activities to ~20 mCi. Once the targets are made their activities will be measured and appropriate radiation safety steps will be taken according to their activity. It is anticipated that each target will require its own chamber as in Figure 7, so four will have to be constructed. The chambers will be stored in a safe place chosen by the TRIUMF Safety Group.

Phase 3: ^{22}Na(p,γ) resonance strength measurement

There are several laboratories in the world that are capable of this kind of measurement. However, laboratories either in Canada or in the USA are preferred because it will be easier to transport the radioactive targets. It is preferred to do the measurement as close as possible to TRIUMF to minimize the transportation. The two closest laboratories capable of this measurement are the University of Washington (Seattle) and the University of Notre Dame (South Bend). These laboratories are exceptional research facilities. However, due to the potential difficulties resulting from the significant radiation hazards of the targets, it may be more favorable to do the experiment at the facility that is best equipped for and has the most experience with radioactive targets. At this stage it is not clear which is the better choice and the evaluation process is underway.

Special safety precautions

Due to the high target radioactivity, special precautions must be taken for safety reasons. Special lead casks will have to be constructed to keep and transport the targets in case they break, releasing ^{22}Na. The targets must also be mounted on long arms to enable safe handling. Rolling lead shields and lead gloves will be used when handling the target-containing chamber. There is experience for this type of target handling at TRIUMF; a ~350 mCi ^{7}Be target was produced for the ^{7}Be(p,γ) study. However, the decay of ^{7}Be only produces a 478 keV gamma ray 10% of the time. Gamma rays of this energy are shielded efficiently by thick sheets of Pb. Because the ^{22}Na emits one 1.275 MeV gamma ray and two 511-keV gamma rays 100% of the time, it will require much more lead shielding than the ^{7}Be targets did.

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