TRIUMF — RESEARCH PROPOSAL

TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 22

Title of proposed experiment:

^{7}Be+p: elastic scattering

Name of group: Tactic

Spokesperson for group: L.Buchmann

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Members of the group (name, institution, status, per cent of time devoted to experiment)

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D. Gigliotti	UNBC	Graduate Student	40%
A. Laird	U. of York	Lecturer	20%
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C. Ruiz	SFU	Research Associate	30%
G. Ruprecht	TRIUMF	Research Associate	30%
J.M. Sparenberg	ULB	Research Associate	25%
P. Walden	TRIUMF	Senior Research Scientist	50%

Start of preparations: now

Date ready: 2006

Completion date: 2008

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
100 (^{7}Be)	ISAC-HE/TUDA	na

With more precise measurements becoming available for the ^{7}Be(p,γ)^{8}B reaction, the question of theoretical description and thus the extrapolation to low energies becomes more critical. Precision elastic scattering measurements of ^{7}Be on protons provide a tool to restrict the range of theoretical predictions as any theory describing ^{7}Be(p,γ)^{8}B also has to be capable of including the elastic scattering data. Elastic data can be obtained with high precision at relatively low beam intensities. We therefore propose a ^{7}Be beam-hydrogen scattering target experiment using the TACTIC chamber under development as the detector. Beam energies will cover nearly the full ISACI range (except for the lowest energies) and eventually be extended to ISACII energies. In addition, both the inelastic channel into the first excited state of ^{7}Be at 429 keV and the inelastic ^{3}He channel with a Q-value of -1.588 MeV will be explored. As calibration and independent measurement we also propose a ^{7}Li+p elastic scattering experiment.

Experimental area

ISAC-HE, TACTIC (TUDA)

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

p-beam on carbon target, 500 MeV

Secondary channel ISAC, TUDA

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

^{7}Be, ^{7}Li stable, 0.25-4.5 MeV/u, $\sim 5\times 10^{7}$ s^{-1} at TACTIC

TRIUMF SUPPORT:

A secondary stripper in the high energy beam line of ISACI is necessary. Safety measures like covering Faraday cups with foils; close co-operation with safety group. Some TRIUMF expertise for the development of TACTIC. Some financial infrastructure support. UV laser beam transport to the ISAC target.

NON-TRIUMF SUPPORT

Procurement of TACTIC (NSERC grant).

As ^{7}Be has a relatively long half life ($T_{1/2}$=53 d), it requires some precautions when running. However, only about 10% of the total ^{7}Be activity emit γ-radiation (478 keV). As a cautionary measure, points (beside the experiment) hit regularly by the beam by tuning or stripping, need to be covered by foil to be removed after the experiment. For a four week run the total activity brought into the experimental hall is estimated to be of the order of 5×10^{14} atoms of ^{7}Be, about two orders of magnitude less activity than the target we used in Seattle. See also the safety section in this report.

1 Introduction/Theory

With the advent of high precision measurements of the ^{7}Be(p,γ)^{8}B cross section [1], the question of extrapolation to low energies in this reaction has become more pronounced. Indeed, if one takes available theoretical prescriptions for extrapolations, the scatter in these extrapolations for $S_{17}(0)$[1] is as big as the error from experimental systematic uncertainties. Possible theoretical extrapolations from the data of Ref. [1] are shown in Fig. 1. However, while experimental systematic errors can be reasonably estimated, the scatter

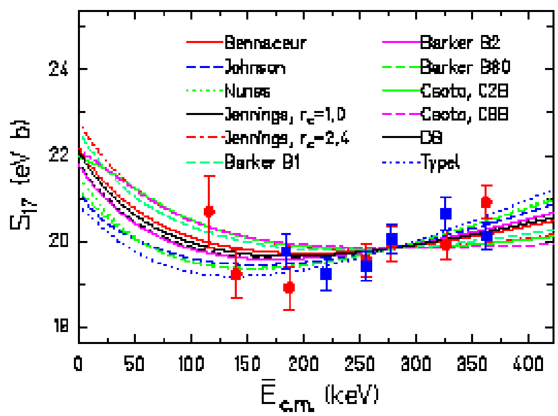

Fig. 1 Different theoretical extrapolations applied to the data of Ref. [1] as indicated in the figure. References to these different extrapolations can be found in Ref. [1].

in the theoretical extrapolation leads to a somewhat unsatisfactory error estimate as certainly extrapolations are of different quality and often based upon different experimental input parameters and different model approaches.

One profound way to adjust the nuclear part of theories in radiative capture is a precision measurement of the elastic scattering cross section of ^{7}Be+p. This ^{7}Be+p elastic scattering, in particular in the *s*-wave, is a very important ingredient for the theoretical description of the ^{7}Be+p radiative capture. In fact, the knowledge of elastic scattering is necessary both for the theoretical extrapolation of direct capture measurements to astrophysical energies and for the interpretation of Coulomb-dissociation data. In the absence of precise scattering data, phenomenological models like the potential or R-matrix ones generally deduce this information indirectly by assuming charge symmetry with the mirror system ^{7}Li+n, for which data and scattering lengths are known with high precision.

Recent ^{7}Be+p elastic-scattering experiments have, however, raised some doubts regarding this procedure: (i) the Louvain-la-Neuve experiment [2] (Fig. 2)[2] suggests that the ^{7}Be+p scattering length[3] for channel spin 1 is incompatible with the value expected from ^{7}Li+n in the framework of a charge-symmetric potential model; (ii) the Notre-Dame

[1] The cross section factor S of radiative capture of protons (A=1) on ^{7}Be (A=7) in the solar pp chain.

[2] It has come to our attention that another ^{7}Be elastic scattering experiment is in progress at Oak Ridge. To our knowledge it uses a similar set up as the LLN experiment.

[3] For a short introduction to the concept of scattering length, see the Appendix.

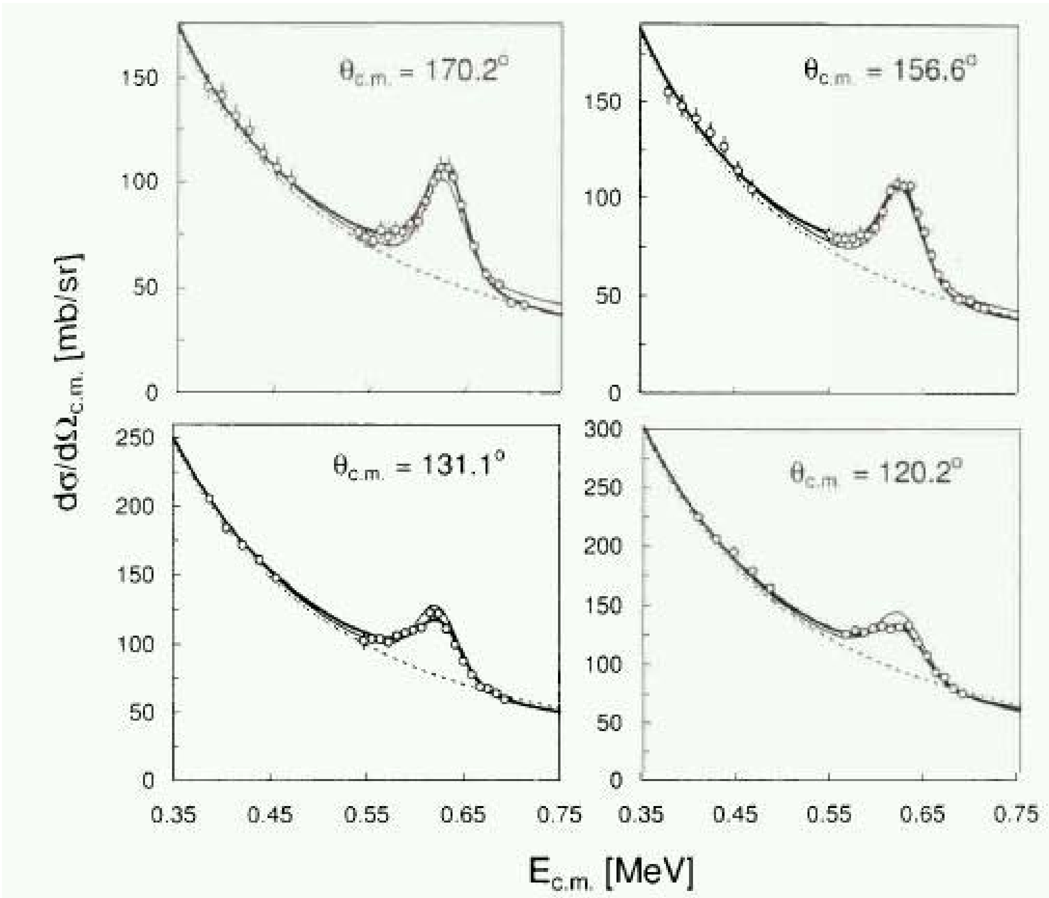

Fig. 2 Excitation function of the LLN ^{7}Be+p experiment. Two thick targets and LEDA detectors were used. Data were collected only at small forward laboratory angles, i.e. large cm angles.

experiment [3] (Fig. 3) is well described by an R-matrix formalism which is incompatible with the ^{7}Li+n scattering length for channel spin 2 [4,5]. A possible explanation for such a charge dependence could be the existence of wide *s*-wave states at an excitation energy of about 3.5 MeV in both the ^{8}Li and ^{8}B nuclei, corresponding to the ^{8}Be excited states seen in ^{7}Li+p elastic scattering [6]. For ^{7}Be+p, these states would be much above threshold (0.1375 MeV) and would only have a weak influence on scattering lengths. For ^{7}Li+n, they would be much closer to threshold (2.0328 MeV) and could strongly affect scattering lengths, which would therefore no longer show charge symmetry. The relative position of levels in the A=8 system is shown in Fig. 4. For all the data available, i.e., ^{7}Li+n, ^{7}Li+p and ^{7}Be+p very different potentials are then derived as shown in Fig. 5. At the moment it therefore looks as if charge symmetry is strongly broken.

Additional questions are: is charge independence with ^{7}Be+n and ^{7}Li+p fulfilled? No data are available for ^{7}Be+n and are not likely to be forthcoming soon (though some indirect method can be explored). On the other hand, ^{7}Li+p can and will be measured in the planned experiment as from kinematics and nearly all other conditions it will provide a

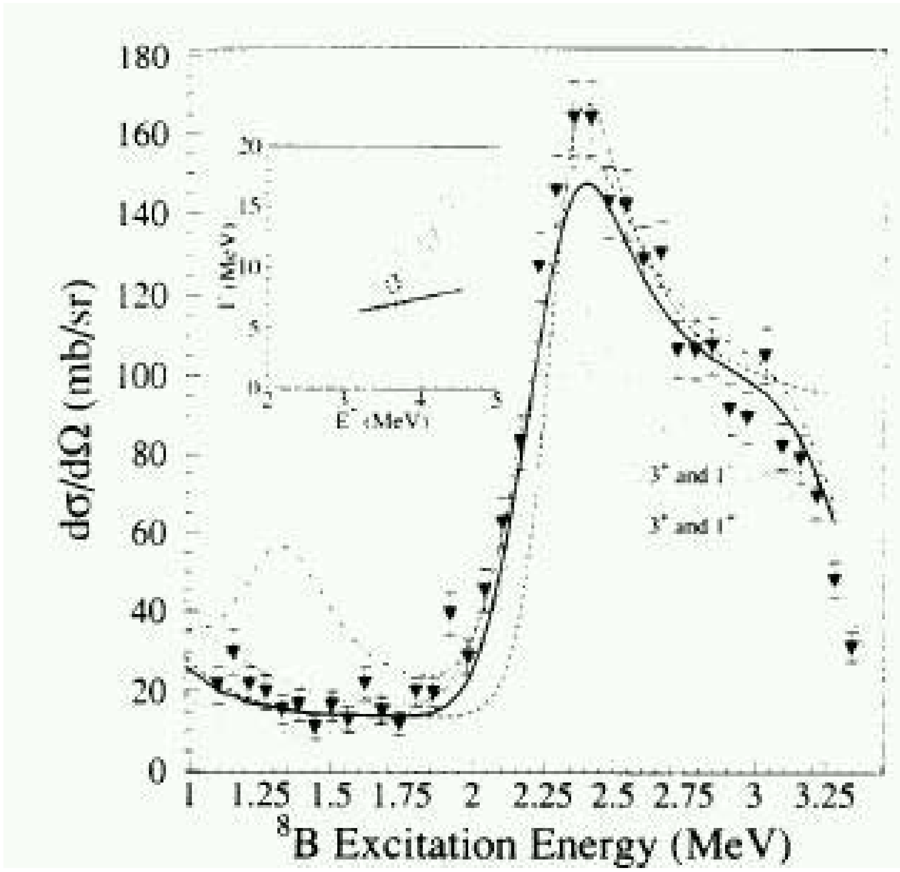

Fig. 3 Excitation function of the Notre Dame experiment showing a resonant like structure at about E=2.5 MeV and above with different R-matrix fits displayed. The insert shows an estimate of the position and width of a possible 2^- resonance.

thorough test of our detector (see below). From the experiment of Ref. [6] one gets rather imprecise scattering lengths, in rough agreement with the other systems for s=2 and in agreement with ^{7}Be+p for s=1 (green lines in Fig. 5). Therefore a simultaneous improvement in these data is desirable. For the channel spin s=2, which dominates the capture cross section, we thus expect the new experiment to confirm previous results of approximate charge symmetry, but with an improved precision. For s=1, the situation is much more open and both charge dependence or independence of the scattering length would be interesting results. Charge independence would reveal problems in previous experiments of ^{7}Li+n scattering, while charge dependence would be an interesting theoretical challenge (resonances close to thresholds might be an explanation).

The LLN experiment gives a_{02} =-7 ±3 fm[4]. The value is derived by applying a simplified (not taking angular momentum mixing into account) R-matrix description. The large error results from the relative insensitivity of the fits, but not the scattering length, to the R-matrix interaction radius a. According to Ref. [7], this leads to an extrapolation error on $S_{17}(0)$ of about 1 eV b (5%). Figs. 3 and 4 of Ref. [7] illustrate this point. In his

[4] $a_{\ell s}$, with ℓ being the incoming angular momentum and s the channels spin.

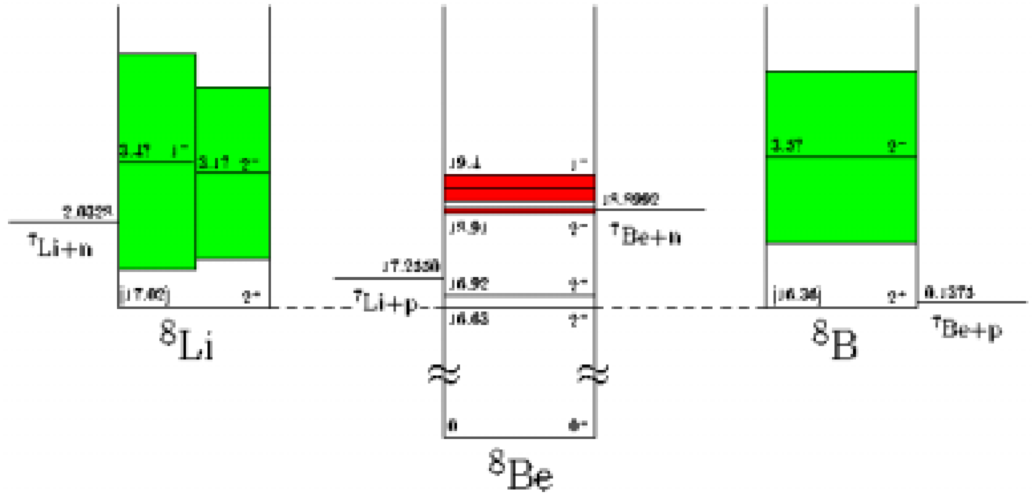

Fig. 4 The A=8 system in regard to proton and neutron capture at mass 7 nuclei.

new calculation (unpublished), Pierre Descouvement, ULB, has also tested the impact of the uncertainty on the scattering length on the astrophysical S-factor $S_{17}(0)$. He also gets errors of about 5%, which dominate the total error below 1 MeV.

From these correlations, one can estimate that an improvement in error to 10% on the scattering length would lead to an error of 1% on $S_{17}(0)$, which would be an acceptable error, since the experimental uncertainty is of the order of 5%. In addition, in a collaboration between TRIUMF and ULB, theorists will investigate in detail in the next few months, when the potential model is valid. First tests tend to show that the potential models used up to now are only valid below 1 MeV. Thus obtaining scattering data at higher energies (ISACI+II) in this experiments could thus allow to rule out some potential models (with good motivation), which is another way of reducing the theoretical uncertainty.

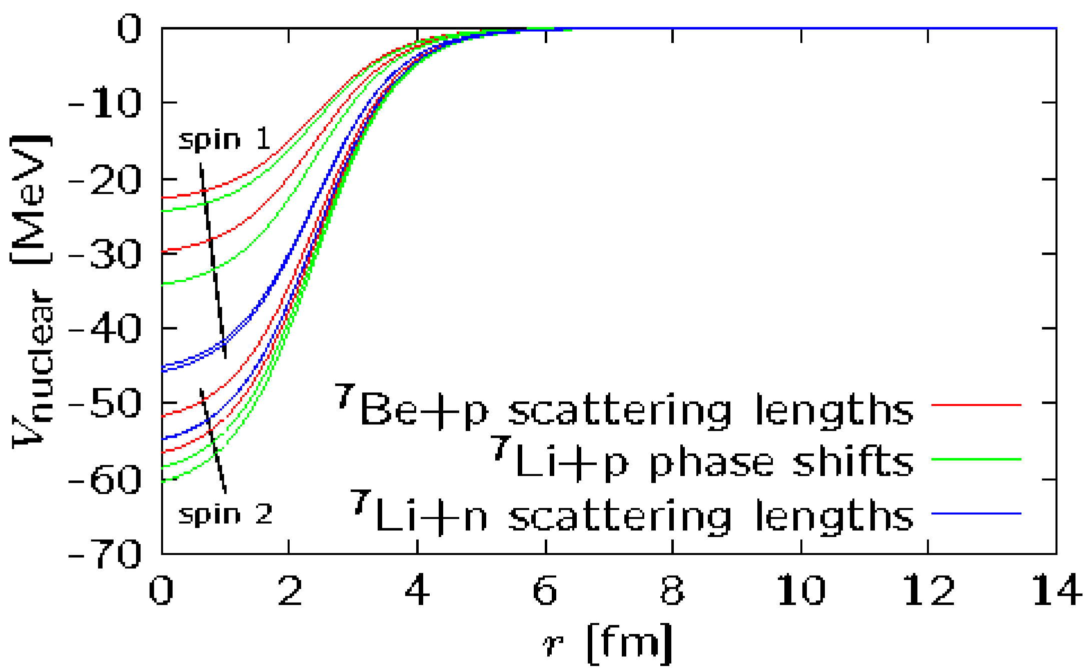

Fig. 5 Different optical potentials (Woods-Saxon) derived from different sets of elastic scattering data (radius 2.39 fm and diffuseness 0.65 fm).Shown are upper and lower limits for possible potentials.

2 The Experiment

2.1 Beamlines and stripping

Experimentally we will rely on the newly to be developed ISAC laser ion source to provide the necessary beam of ^{7}Be. Intensities of the order of 10^8 s^{-1} are requested and have been easily achieved at CERN-ISOLDE demonstrating at least the easy ^{7}Be release from target. The plans of the laser ion source group call for Fall of 2005 to deliver such beams provided TRIUMF funds the development of the laser system for beryllium beams (transport of short wavelength UV to the ion source). This agrees well with the TACTIC schedule (see below). The necessary frequency tripling of the initial solid laser frequency has been achieved. Still laser beam transport optics valued to about k$40 is missing[5] and needs to be provided by TRIUMF. In addition, the actual ionization scheme of beryllium still needs to be tested.

However, the ISAC ^{7}Be beam will also likely contain ^{7}Li ions. As elastic scattering resulting from these two isotopes is hard to distinguish experimentally, we propose to use an additional stripper before the bending magnet into the DRAGON and hence the TUDA beamline (see below) for ISACI. For ISACII a stripper in front of the superconducting linac is planned in any case. The additional stripper allows to obtain a ^{7}Be^{4+} beam, a charge state not attainable for ^{7}Li. Fig. 6 shows the beryllium stripping probabilities according to Ref. [8]. For energies above 250 keV/u the stripping probability for the 4^+ state is above 10% which should allow us to obtain data. Such low energies are a region where Coulomb scattering is very dominant and the cross section therefore high. Moving towards higher energies the stripping probability for 4^+ quickly goes to close to 100%, while the elastic scattering cross section drops. For a ^{7}Li beam the surface ion source at OLIS can be used. ^{7}Li beams with the necessary intensities (0.1 nA) have already been extracted from OLIS.

2.2 TACTIC

Having obtained a pure ^{7}Be beam, only the recoil protons need to be observed in scattering. We propose to use the TACTIC detector for this purpose. Fig. 7 shows a schematic of the TACTIC detector under construction. TACTIC is a cylindrical ionization chamber, originally planned for the ^{8}Li(α,n)^{11}B experiment and also to be used in the ^{12}C+^{12}C experiment. It contains a cylindrical chamber in the centre which is not visible to the ion drift field outside that region. We are testing electron multiplying GEMs (Gas Electron Multipliers) for signal amplification close to the anode of the ionization chamber (Fig. 7) at the moment (see below). The inside chamber/cylinder contains the target gas which also can serve as an ionization chamber gas, if (as needed for ^{8}Li) the inner chamber is not separated by foil from the field region[6]. However, only observing recoil protons allows to separate the two chamber regions by a thin foil and therefore to operate both at different pressures and gases in both regions. This is necessary to obtain enough

[5] Information from Jens Lassen, the TRIUMF laser ion source specialist. Radioactive beryllium beams are also requested by the β-NMR group (private communication by R. Kiefl).

[6] There is a grounded grid providing shielding against the drift field. There is also a provision to repel beam induced ions away from the detection region.

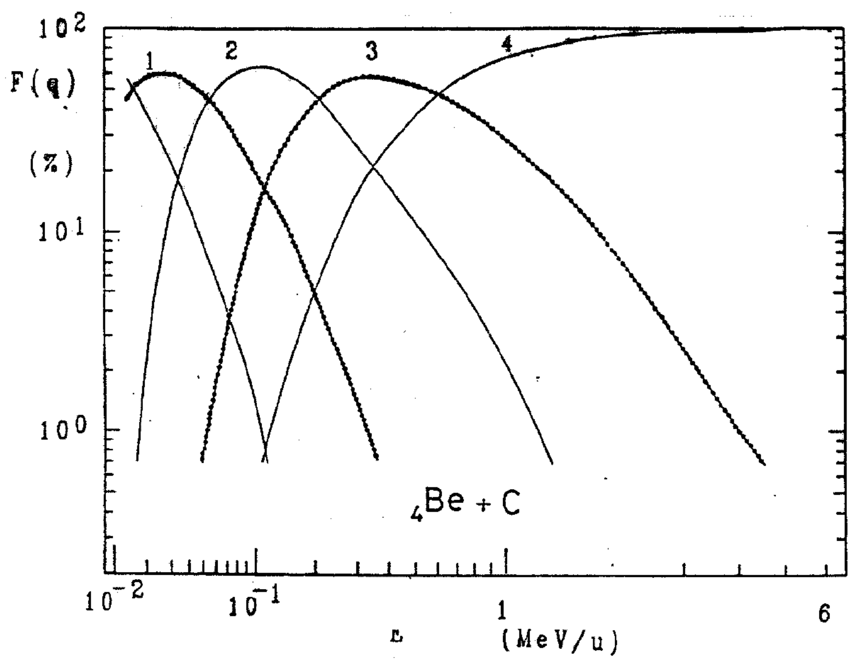

Fig. 6 Relative stripping probability for a beryllium beam on a carbon foil [8].

stopping power for the protons. Recoil protons from a few degree to close to 90° will be observed so that a nearly complete angular distribution can be obtained at any energy point (see below). The final chamber will consist of 3 concentric cylindric regions (Fig. 8). The inner region (1) is where the reaction takes part. Ejectiles (i.e. protons) travel to the drift region (2) where they are stopped in the detector gas.

The wires or the foil, respectively, act as the cathode for the drift region (2), where electrons move towards the anode starting from every point of the ejectile track. A Gas Electron Multiplier foil (GEM) is inserted in the drift region to gain a high amplification of the tiny electron currents. The GEM is a 50 μm thick isolating foil with a conducting (copper) layer on both sides, perforated by a grid of 50 μm large pinholes with 150 μm pitch. Applying a high voltage (∼450 V) between the layers bends the drift field through the holes. The high field inside the holes causes an avalanche effect. The amplification is about 100 which makes the pulses strong enough for further electronic amplification. Since the signals are already pre-amplified by the GEM, a single electronic board is sufficient to obtain signals ready for digitalization. These boards will be mounted directly on the outside of the chamber - there is no need to send weak signal over long distances, which further improves the signal/noise ratio.

The anode is divided into strips and the strips are divided into segments. This way we obtain pulses that enable us to reconstruct the track of the particles: The projection on the cylinder wall is given by the anode strip position and the radial position by the drift time of the electrons. Moreover, the integrated charge of the pulses gives us the energy loss per distance of the particle.

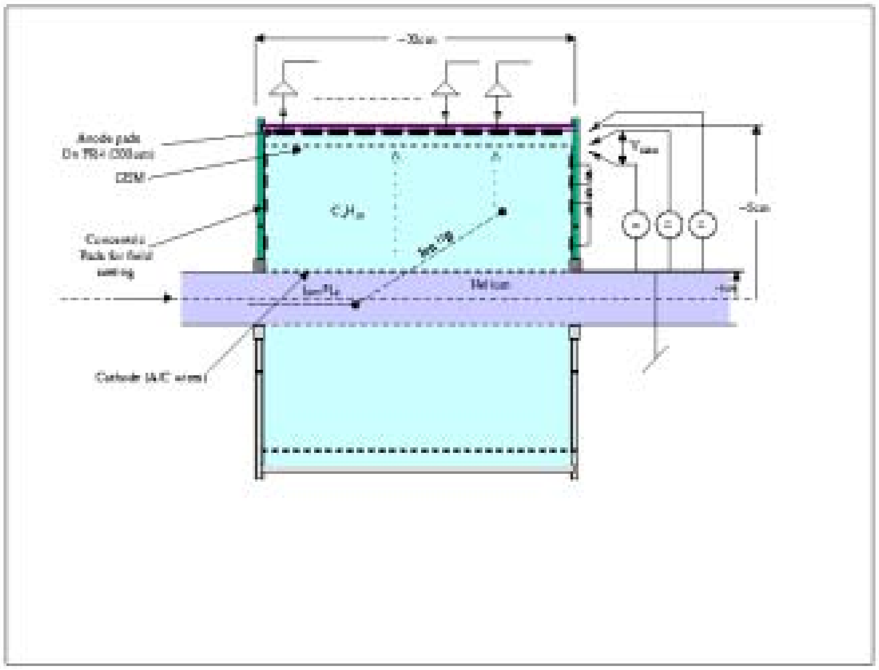

Fig. 7 The TACTIC detector under construction.

Even though there are only 16 segments in both direction of the anode in the final chamber, we have 256 time and 256 charge values that have to be converted. Moreover, since the time resolution depends very strongly on the signal/noise ratio, the electronics has to be as close as possible to the chamber. Flash ADCs offer a good solution for these problems. They can be programmed to provide digitalized output for the differentiated (time) and integrated (charge) pulse.

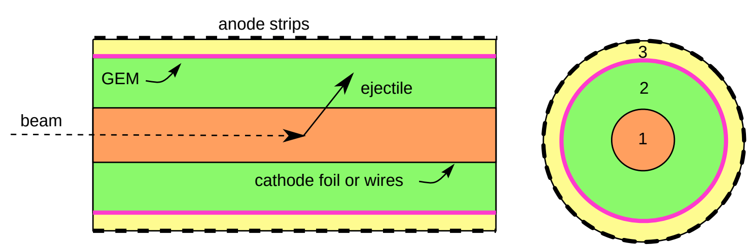

Fig. 8 Different cuts, parallel to the beam and perpendicular, through the TACTIC detector.

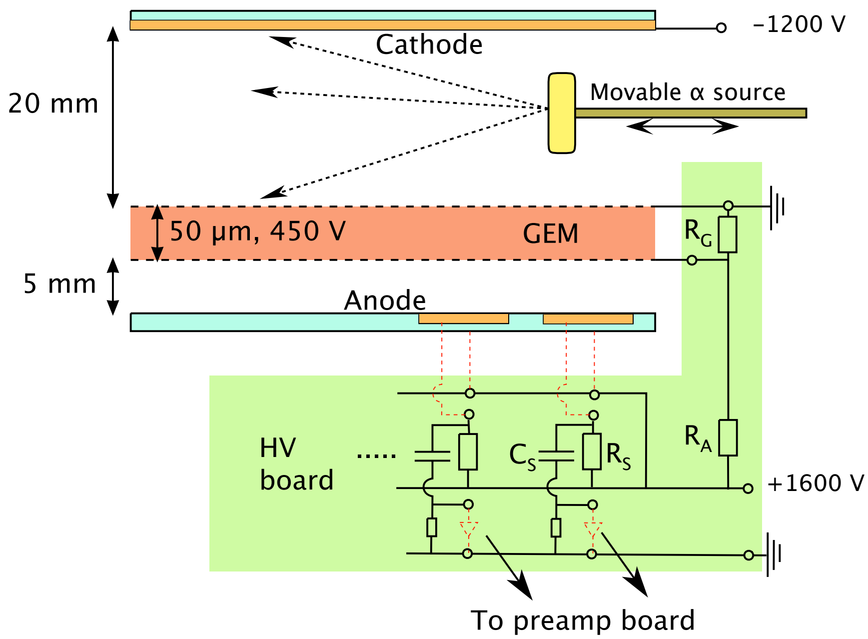

Fig. 9 Schematics of the TACTIC test chamber.

2.3 Experimental work at TACTIC so far

As mentioned above, a good signal to noise ratio is an important ingredient for the time resolution i.e. the radial position resolution. To test the signal we used a planar test chamber for different gas mixture and pressure dependence of the signal strength. The planar test chamber consists of different layers with dimensions of 20 cm x 20 cm (see Fig. 9). The upper and lower plate is for the gas inlet and outlet (not shown). Following are the cathode and, on the other side, the anode plate. The latter comprises 32 parallel strips for the localization of the particle (the perpendicular direction is not resolved in this set-up). The layer following the cathode is just a frame of 2 cm thickness. The space inside this frame acts as the drift region and an α source (^{241}Am, 5.5 MeV) is mounted on this frame. The α-particles are emitted along the drift region and perpendicular to the anode strips. The source position can be changed from the outside by adjusting screws. At last, the frame between drift region and anode strips holds the GEM foil.

Electrical contacts for each anode strips, the two GEM connectors as well as the cathode lead to the outside. A high voltage circuit board provides the needed cathode/anode and GEM voltage. GEM and anode have a common supply and the voltage ratio is fixed by divider resistors to 3.3.

The testchamber was flushed with a constant flow of 200 ccm/min of Ar/CO_2 and He/CO_2 gas mixtures: Fig. 10 shows the dependence of the signal/noise on the applied GEM+anode and drift voltage for different gases. As can be seen, the GEM works even better with helium and the operation is best with only a small amount of quenching gas. The latter result confirms the observations of other groups [26]. We finally operated the chamber for all further tests with a 90/10 He-CO_2 mixture. PHA spectra on single strips

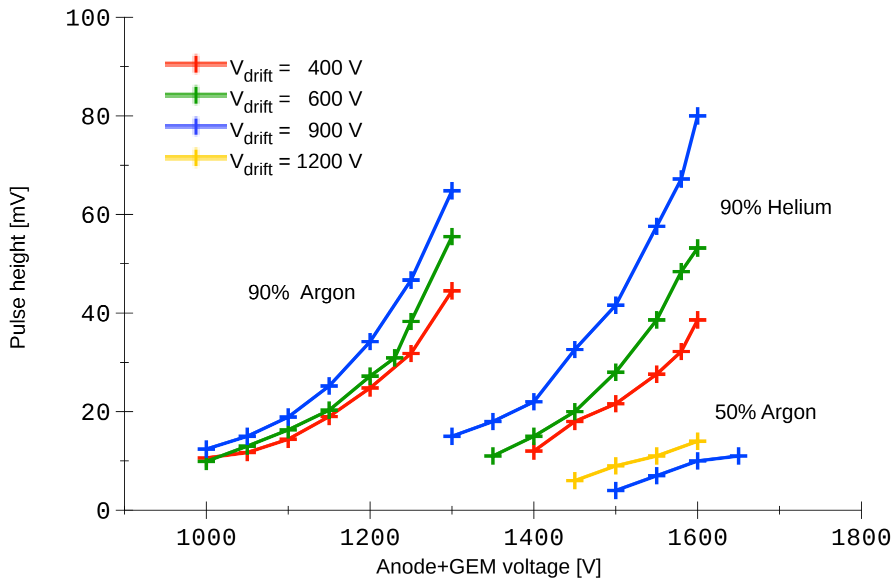

Fig. 10 Signal strength for different gases and voltages in our TACTIC test chamber.

show the expected simulated energy distribution for different positions of the source. The timing tests were performed with the currently available 4 channel preamplifier board (Fig. 5). Since we don't have a clear trigger signal (in the final detector we can use the RF beam signal as trigger) only the time differences to the strip signal can be analyzed. The angular range is limited by the cathode plate and the GEM and this range decreases with increasing distance between the source and the strips. Figure 11 shows the maximum and minimum time in dependence on the source distance. The asymmetry arises from as the source is not well centered. However, it is possible to estimate the electron drift times to about 2 cm/μs in agreement with the results of other groups [27]. A radial resolution of 0.2 mm can be estimated, which would be excellent for our final application.

A gas handling system to allow operating under less than atmospheric pressure has already been designed for the testchamber. This is necessary to check the quality of the signals under lower pressure conditions. For the ^{8}Li experiment the final chamber will be operated at 20-50 mbar to reduce the energy loss of the ^{11}B recoils. The signals will be lower and the gas mixture presumably has to be changed. However, for the ^{7}Be recoil protons we have a wide variety of ranges, leading to even the use of xenon at atmospheric pressure for high beam energies. A 16-channel amplifier is ready for operation. This is already very close to the final set-up. We have to check how far the time and charge information can be extracted from this. A GEANT4 simulation is also in preparation. For the ^{8}Li(α,n)^{11}B measurement and inelastic ^{7}Be scattering we want to observe γ-rays emitted from different excitation positions. The GEANT simulation will show, how much the γ-rays are attenuated by the chamber and the surrounding electronics. No γ-detection is required for elastic scattering experiments; however, when implemented the detection of inelastic scattering to the first excited state of ^{7}Be (E_x=429 keV) will provide additional information about the ^{7}Be+p reaction mechanism. It is planned to use the DRAGON BGO array for γ-detection, with the detectors positioned outside the chamber.

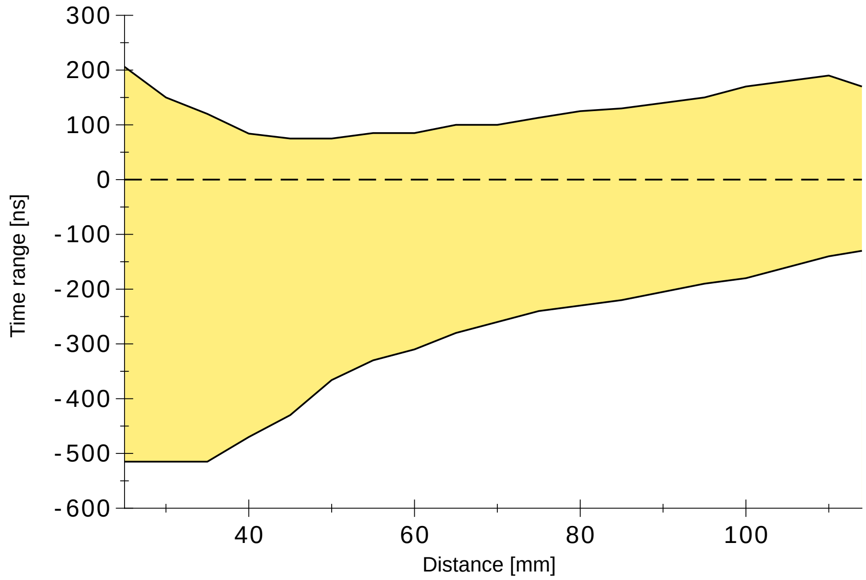

Fig. 11 Time range of signals in dependence from the distance to the source in our testchamber.

2.4 Stopping powers and ranges

We will run with entry and exit windows at the TUDA position and eventually an ISACII position. As the ^{7}Be beam looses energy both in the secondary stripper and the entry window, the beam energy at the active target region would have to be estimated by stopping power calculations. These can be checked by performing other elastic proton scattering measurements with stable beams. If the secondary stripper is mounted before the HE DRAGON take off, the energy loss in the stripper can also be measured by DRAGON. Stopping power calculations show that for the lowest energies, a very thin entrance window will be required. We are gaining at presence such experiences at the DRAGON ionization chamber with S_3N_4 windows. As we are dealing with beam, entrance windows do not need to be large in diameter. However, pressures in the drift region have to be kept low then too, typically between 1 and 10 T. In addition, as we know the angle and the energy of the recoil proton, we can reconstruct the energy of the individual ^{7}Be responsible for the scattering. The precision of this reconstruction needs to be tested. We will also keep the option open to run at the windowless gas target at DRAGON.

As far as the recoil proton range in the chamber is concerned it depends on the beam energy and angle and covers a wide range. In general, events close to 90° will have little energy and are stopped or considerably slowed down by the separation foil. Recoil protons close to zero degree have rather high energies but at least at the start of the chamber, also a long way to go. Fig. 12 shows the recoil proton energy in dependence from the angle for ^{7}Be energies of 0.25, 1.5, and 4.5 MeV/u, respectively. Obviously the distribution follows a cosine dependence making even for the highest energies observation close to 90° impossible. If one takes 200 keV as the minimum observable proton energy, then the maximum observable angle for the three cases is 59° (0.25 MeV/u), 78° (1.5 MeV/u), and

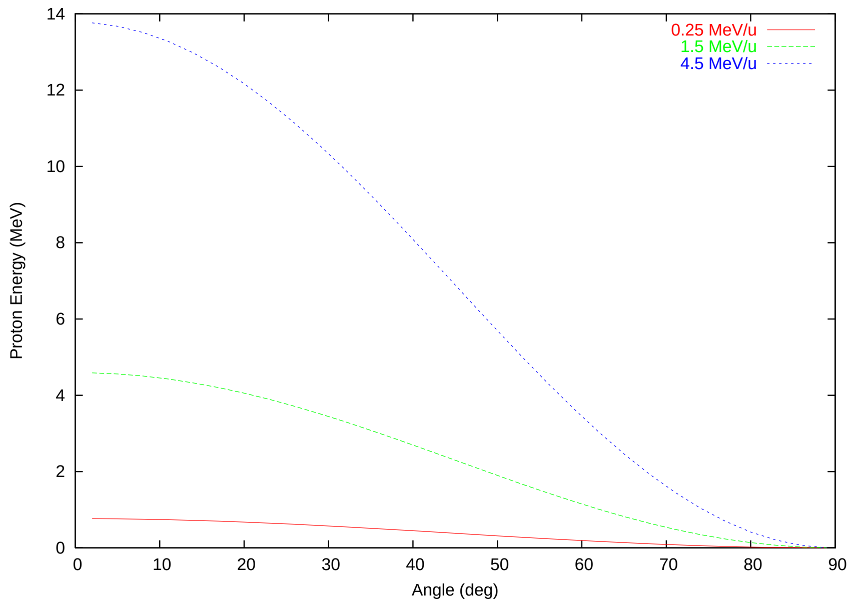

Fig. 12 Recoil proton energy for a ^{7}Be beam of 0.25, 1.5, and 4.5 MeV/u, respectively, in dependence of the scattering angle.

83° (4.5 MeV/u).

The general advantage of TACTIC over previous experiments is that we will use a thin target gas cell of pure hydrogen for a target (no target deterioration) with tracing capabilities, simultaneous energy resolution and particle identification. The point is illustrated in Fig. 13 showing how degraded events can be excluded. In fact, it is our experience that the polyethylene targets used in Louvain or Oak Ridge deteriorate rapidly even at ion currents of 10^7 s^{-1}. While there is some equilibrium reached after a short bombardment, the stoichiometry of the target (which would not be trustworthy to start with) is unknown. The LLN measurements are therefore normalized to a ^{7}Li(p,p)^{7}Li measurement of 1953 [9]. However, different target stoichiometries and intial degredation in both the ^{7}Li and the ^{7}Be measurements will still influence the results. In addition, we will cover

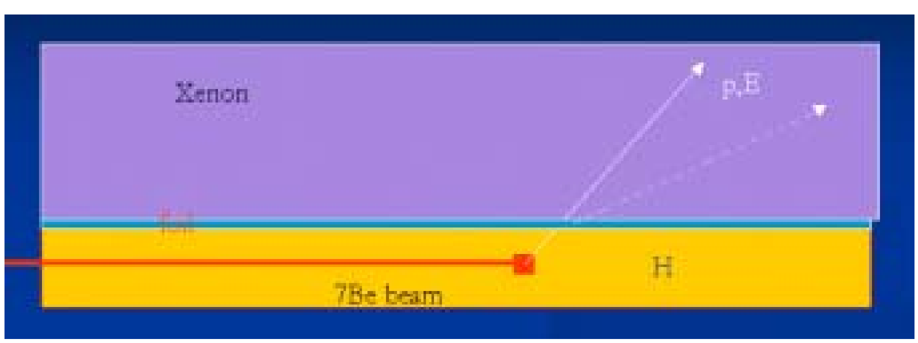

Fig. 13 Detection of degraded events in Tactic.

a far more extended angular range than previous experiments and will also measure inelastic scattering channels that indeed influence the elastic channel above their respective thresholds.

3 Beam energies and number of shifts

ISACI can provide ^{7}Be energies of close to 2 MeV/u. It is therefore proposed to run the first phase of the experiment at ISACI. Since there are claims of a *s*-wave resonance in ^{7}Be+p [3] at higher energies it would be desirable, however, to extend the energy range to 4.5 MeV/u. Since ISACII is supposed to be online shortly after the time when our experiments commences, this should pose no problem, except the general one, which yet has to be worked out, how beam energy determinations are made at ISACII.

The aim of this precision experiment is to obtain good elastic angular distributions for many energies. Covering this excitation function requires extensive running for several weeks with at least two running periods. Several stable and unstable runs will be required as well to test TACTIC and obtain some ^{7}Li scattering data. All in all, the request can be estimated to about 100 shifts[7] of ^{7}Be beam and similar amounts of stable beam.

4 Safety

In the past there have been some safety concerns about running the relatively long-lived ($T_{1/2}$=53 d) ^{7}Be. However, the proposed beam intensities for elastic scattering hardly warrant such concerns. Most points where most of the activity is dumped in the ISAC hall can be easily covered and the activity be removed after the experiment. Given the amount of ^{7}Be dumped, tweasers should be sufficient to handle these foils. Fig. 1 4 shows these points in the ISAC hall. The total activity collected for all runs will be about 1/100 of that of the Seattle ^{7}Be target. Since the runs extend over quite some period, even that level will never materialize. In addition, at many points the γ-rays (478 keV) will be quite attenuated, e.g. in the RFQ by the massive steel tank, and at the ISACI stripper by a future lead shielding (planned for ages, but never installed). When beamlines are opened in the ISAC hall, swiping procedures detecting contaminations are already in place. As the ^{7}Be beam is always at some velocity in the ISAC hall, it will be implanted into the stopping material therefore not causing easily removable surface contaminations. We will produce an extensive safety report to cover these points. There should be also a reminder that isotopes like ^{56}Ni with far higher specific activities and biological hazards have been proposed to be available as beams at ISACII and no concerns about radiation levels have been raised in these cases.

[7]ISAC energy changes take at best several hours to a maximum of day (character wisebest for Miltonists).

Fig. 14 Points in the ISAC hall where likely most of the ^{7}Be activity will be dumped.

5 Appendix: Scattering length

For non-charged particles the phaseshift δ at low energies can be expressed in a wavenumber k dependent expression as

$$k \cot \delta_{\ell s} = \frac{1}{a_{\ell s}} + \frac{1}{2} r_\ell^2 k^2 + \cdots \tag{1}$$

where $a_{\ell s}$ is the scattering length and r_ℓ the effective range. For $k \rightarrow 0$ this scattering length has a finite, non zero value. A negative value indicates then a potential that does not have bound states while a positive scattering length indicates the presence of at least one bound state in the potential.

For charged particles, where the concept is generally less used, the scattering length is modified by Coulomb terms to

$$2P_0 k \cot \delta_{\ell s} + 2k\eta h(\eta) = \frac{1}{a_{\ell s}} + \frac{1}{2} r_\ell^2 k^2 + \cdots \tag{2}$$

with η the Sommerfeld parameter and the penetrability factor for the s wave

$$P_0 = \frac{2\pi\eta}{e^{2\pi\eta} - 1} \tag{3}$$

and the h-function given by

$$h(\eta) = \eta^2 \sum_{j=1}^{\infty} \frac{1}{j(j^2 + \eta^2)} - \ln \eta - \gamma \tag{4}$$

with γ=0.5772... being the Euler constant. The scattering length and effective range can then replace the phase δ in the fits, as was done in Ref. [2].

References

1. A. Junghans et al., Physical Review C, **68** (2003) 065803.
2. C. Angulo et al., Nucl. Phys. A **716** (2003) 211
3. G.V. Rogachev et al., PRC 64 (2001) 061601
4. F. Barker and A.M. Mukhamezhanov, NPA 673 (2000) 526
5. JM. Sparenberg, to be published and private communication (2004)
6. L. Brown et al., NPA 206 (1973) 353
7. B. Davids and S. Typel, PRC 68 (2003) 045802
8. K. Shima et al., At. Dat. Nucl. Dat. Tabl. **51** (1992) 173
9. W.D. Warters, W.A. Fowler, C.C. Lauritsen, Phys. Rev. **91** (1953) 917

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

1. J.M. D Auria, R.E. Azuma, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J. José, J. King, A.M. Laird, M. Lamey, R. Lewis, W. Liu, A. Olin, D. Ottewell, P.D. Parker, J. Rogers, C. Ruiz, M. Trinczek, and C. Wrede, "The 21Na(p,γ)^{22}Mg Reaction from Ecm = 200 to 1103 keV in Novae and X-ray Bursts", Phys. Rev. C 69 065803 (2004).

2. U. Greife, S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, J.M. D Auria, S. Engel, D. Gigliotti, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, A.M. Laird, M. Lamey, W. Liu, A. Olin, D. Ottewell, J. Rogers, and C. Wrede, "Energy loss around the stopping power maximum for Ne, Mg, and Na ions in hydrogen gas", Nucl. Inst. Meth. B 217 1, 1 (2004).

3. A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Casandjian, H.E. Swanson, L. Buchmann, S.H. Park, A. Zyuzin, A. Laird, "Precision measurement of the ^{7}Be(p,γ)^{8}B" S-factor", Phys. Rev. C., 68 (2003) 065803

4. S. Bishop, R.E. Azuma, L. Buchmann, A.A. Chen, M.L. Chatterjee, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, M. Hernanz, D. Hunter, A. Hussein, D.A. Hutcheon, C. Jewett, J.Joseé, J. King, S. Kubono, A.M. Laird, M. Lamey, R. Lewis, W. Liu, S. Michimasa, A. Olin, D. Ottewell, P.D. Parker, J.G. Rogers, F. Strieder, and C. Wrede, "^{21}Na(p,γ)^{22}Mg reaction and Oxygen-neon novae", Phys. Rev. Let., 90 (2003) 162501

5. D.A. Hutcheon. S. Bishop, L. Buchmann, M.L. Chatterjee, A.A. Chen, J.M. D'Auria, S. Engel, D. Gigliotti, U. Greife, D. Hunter, A. Hussein, C.C. Jewett, N. Khan, M. Lamey, A.M. Laird, W. Liu, A. Olin, D. Ottewell, J.G. Rogers, G. Roy, H. Sprenger, C. Wrede,"The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC: design, construction and operation", Nucl. Inst. Meth. A, 498 (2003) 190

6. W. Liu, G. Imbriani, L. Buchmann, A.A. Chen, J.M. D'Auria, A. D'Onoforio, S. Engel, L. Gialanella, U. Greife, D. Hunter, A. Hussein, D.A. Hutcheon, A. Olin, D. Ottewell, D. Rogalla, J. Rogers, M. Romano, G. Roy, F. Terassi, " Charge state studies of low energy heavy ions passing through hydrogen and helium gases", Nucl. Inst. Meth. A, 496 (2003) 198

7. J.C. Chow, J.D. King, N.P.T. Bateman, R.N. Boyd, L. Buchmann, J.M. D'Auria, T. Davinson, M. Dombsky, E. Gete, U. Giesen, C. Iliadis, K.P. Jackson, A.C. Morton, J. Powell, and A. Shotter, "β-delayed particle decay of ^{17}Ne into $p + \alpha$ ^{12}C through the isobaric analog state in ^{17}F", Phys. Rev. C, 66 (2002) 064316

8. A.C. Morton, J.C. Chow, J.D. King, R.N. Boyd, N.P.T. Bateman, L. Buchmann, J.M. D'Auria, T. Davinson, M. Dombsky, W. Galster, E. Gete, U. Giesen, C. Iliadis, K.P. Jackson, J. Powell, G. Roy, and A. Shotter, "Beta-delayed particle decay of ^{17}Ne", Nucl. Phys. A, 706 (2002) 15

9. C. Ruiz, F. Sarazin, L. Buchmann, T. Davinson, R.E. Azuma, A.A. Chen, B.R. Fulton, D. Groombridge, L. Ling, A. Murphy, J. Pearson, I. Roberts, A. Robinson, A.C. Shotter, P. Walden, and P.J. Woods, "Strong resonances in elastic scattering

of radioactive ^{21}Na on protons", Phys. Rev. C (Rapid Communications), 65 (2002) 042801(R)

10. D. Anthony, L. Buchmann, P. Bergbusch, J.M. D'Auria, M. Dombsky, U. Giesen, K.P. Jackson, J.D. King, J. Powell, and F.C. Barker, "Beta Delayed Deuteron emission from ^{6}He", Phys. Rev. C, 65 (2002) 034310

11. P. Tischhauser, R.E. Azuma, L. Buchmann, R. Detwiler, U. Giesen, J. Görres, M. Heil, J. Hinnefeld, F. Käppeler, J.J. Kolata, H. Schatz, A. Shotter, E. Stech, S. Vouzoukas, and M. Wiescher," Elastic α-^{12} scattering and the ^{12}C(α,γ)^{16}O $E2$ S-factor", Phys. Rev. Let., 88 (2002) 072501

12. A. Zyuzin, S.H. Park, L. Buchmann, K.R. Buckley, A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, and J. Vincent, "The fabrication of metallic ^{7}Be targets with a small diameter for ^{7}Be(p,γ)^{8}B measurements", Nucl. Instr. Meth. B, 187 (2002) 264

13. A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Casandjian, H.E. Swanson, L. Buchmann, S.H. Park, A. Zyuzin, "^{7}Be(p,γ)^{8}B" astrophysical S-factor from precision cross section measurements", Phys. Rev. Let., 88 (2002) 041101

14. L. Buchmann, "Radiative cascade transitions and the ^{12}C(α,γ)^{16}O $E2$ cross section to the ground state of ^{16}O", Phys. Rev. C., 64 022801(R) (2001)

15. N. Bateman, K. Abe, G. Ball, L. Buchmann, J. Chow, J.M.D'Auria, Y. Fuchi, C. Iliadis, H. Ishiyama, K.P. Jackson, S. Karataglidis, S. Kato, S. Kubono, K. Kumagai, M. Kurokawa, X. Liu, S. Michimasa, P. Strasser, and M.H. Tanaka, " Measurement of the ^{24}Mg(p,t)^{22}Mg reaction and implications for the ^{21}Na(p,γ)^{22}Mg stellar reaction rate", Phys. Rev. C, 63 (2001) 035803

16. L.Buchmann, E.Gete, J.C.Chow, J.D.King, and D.F. Measday, "The β-delayed particle decay of ^{9}C and the A-9, T=1/2 nuclear system; R-matrix fits, the A=9 nuclear system, and the stellar reaction rate of ^{4}He(αn,γ)^{9}Be", Phys. Rev. C., 63 (2001) 034303

17. E.Gete, L.Buchmann, R.E.Azuma, D.Anthony, N.Bateman, J.C.Chow, J.M.D'Auria, M.Dombsky, U.Giesen, C.Illiadis, K.P.Jackson, J.D.King, D.F. Measday, and A.C.Morton, "The β-delayed particle decay of ^{9}C and the A-9, T=1/2 nuclear system; Experiment, data and phenomenological analysis", Phys. Rev. C., 61 (2000) 064310

18. A.Y.Zyuzin, L.R.Buchmann, J.S.Vincent, K.R.Buckley, N.O.Bateman, K.A.Snover, J.M.Csandjan, T.D.Steiger, E.G.Adelberger, and H.E.Swanson, "Metallic beryllium-7 target of small diameter", Nucl. Inst. Meth., A438 (1999) 109