# ALNA - Accelerator Laboratory for Nuclear Astrophysics Underground

Working group for the development of an accelerator facility
for the Deep Underground Engineering and Science Laboratory (DUSEL)

## 1 Introduction

"We are all made of star stuff" is the famous quote by the late Carl Sagan, since each single atom in our body was processed through - on average - between fifty to hundred star generations before it condensed in our solar system - on earth - to form us. This means each atom experienced many times a supernova explosion and/or was dredged up from the interior of a deep convective low mass star to be blown into outer space, and/or was ejected in a thermonuclear explosion in a binary or massive star system before it got to us. The understanding of these nucleosynthesis processes which are driven by a large number of nuclear reaction and fusion processes is an important part for our quest about the origin of life in our universe.

The timescales of these nuclear processes set the ignition conditions of stellar burning, define the lifetime of stars and delineate the timescale of stellar explosions. The stellar life is composed by a sequence of stellar burning phases ranging from hydrogen burning - through the pp-chains for low mass stars $M<1.5M_{\odot}$ or the CNO cycles for massive stars $M>1.5M_{\odot}$ - to helium and carbon burning, followed by the rapid neon, oxygen, and silicon burning phases in the last years of stellar life. Despite 50 years of experimental efforts, none of the associated nuclear reactions which set the timescales and burning temperature conditions through stellar life has been measured yet. Present stellar model simulations rely on phenomenological or theoretical extrapolation of higher energy measurement which leads to considerable uncertainties in all aspects of stellar evolution. While there is a large number of reactions which impact stellar burning, theoretical modeling of stellar burning conditions allowed to identify a number of high priority reactions which need to be investigated. The reaction rates for these processes are so small that it requires nuclear accelerators shielded deep underground and state of the art detector arrays with high event to background sensitivities to provide the necessary experimental data.

The most daunting question over the last few decades was the solar neutrino problem which was closely associated with the extrapolation of the reactions in the pp-chains. Considerable uncertainties still haunt the low energy extrapolation of the $^{3}He(\alpha,\gamma)^{7}Be$ and the subsequent $^{7}Be(p,\gamma)^{8}B$ reaction cross section which still limit the reliability of the predicted solar neutrino flux. This question not only impacts the reliability of solar model predictions but also sets the uncertainty range for the theoretical interpretation of neutrino oscillations.

Hydrogen burning in more massive stars is defined by the CNO cycles, where the timescale is primarily set by the $^{14}N(p,\gamma)^{15}O$ reaction. The low energy cross section of this reaction relies on the extrapolation of experimental data using R-matrix theory to account for all possible low energy reaction contributions. Recent extrapolations of low energy data indicated discrepancies of up to nearly one order of magnitude [Ang01] in the extrapolation towards stellar energy conditions which translates into a significant uncertainty in the lifetime of massive stars [Imb04]. This is demonstrated in figure 1a. Recent efforts to expand the measurements towards lower energies were successful at the LENA underground facility. These results, coupled with other data at higher energies [Run05] reduce the uncertainty significantly to approximately 12% in the stellar energy range as indicated in figure 1b.

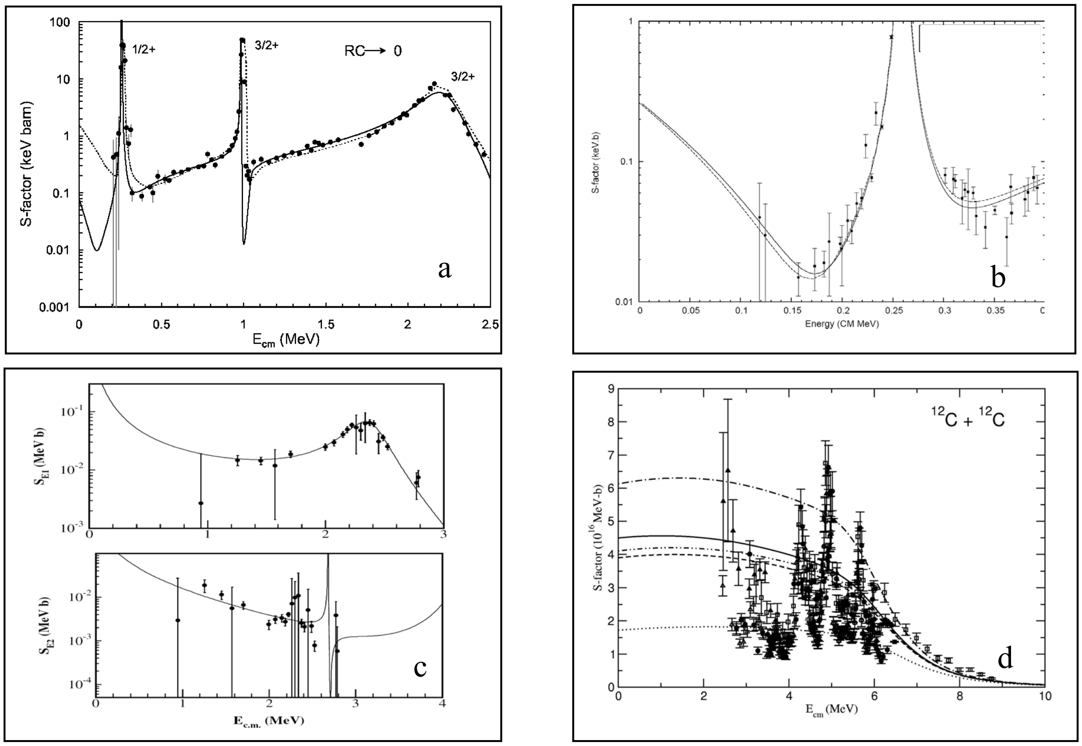


Figure 1: Low energy cross section (S-factor) data and predictions for $^{14}N(p,\gamma)^{15}O$ (a,b), $^{12}C(\alpha,\gamma)^{16}O$ (c), and $^{12}C+^{12}C$ (d). The lines indicate a variety of theoretical predictions for the extrapolation of the S-factor towards the critical low energy stellar burning range. The figure demonstrates the general uncertainty associated with present extrapolating techniques.

Stellar helium burning in red giant stars is characterized by the triple alpha process and the subsequent $^{12}C(\alpha,\gamma)^{16}O$ reaction. The reaction $^{12}C(\alpha,\gamma)^{16}O$ has been identified as one of the most critical nucleosynthesis reactions since it determines the ratio of carbon and oxygen in our entire universe: the abundance ratio of the element we are built from and the element we need to breathe [Wea93,Imb01]. Nuclear astrophysicists have tried in accelerator laboratories to determine that ratio for forty years using a large variety of experimental techniques (see [Rot99,Kun01,Plag05] and references there in). The results have been implemented in R-matrix calculations to extrapolate the reaction cross sections into the energy range of red giant stars [Bru99,Tis02,Buc05]. Figure 1c shows one example of the extrapolation for the E1 and E2 components of the reaction. This extrapolation clearly depends sensitively on the r-matrix parameters and the availability and accuracy of the low energy data. The predictions carry substantial uncertainties which not only impact the reliability of the predicted carbon oxygen ratio in our Universe but also affects the masses within the carbon and oxygen zones of a Type II supernova progenitor, thereby influencing the outcome of the core collapse (neutron star or black hole) and the explosive nucleosynthesis associated with the passage of the shock wave. It also determines the conditions of type Ia supernova explosions since it affects the carbon oxygen fuel abundances of the white dwarf material.

Slow neutron capture reactions along the line of stability (s-process) are responsible for the origin of approximately 50% of the isotopes above iron (Z>26). One of the proposed s-process sites are low mass asymptotic giant branch (AGB) stars, $M<5M_\odot$ which have been suggested as the site for the main s-process producing elements up to the lead region. The second site is stellar core helium and carbon burning in massive stars $M>8M_\odot$ which is responsible for the production of medium mass element up to the A=120 range. One of the open questions about s-process nucleosynthesis is the source for the stellar neutron flux. Several reactions have been proposed in the past, depending on the actual site conditions the most likely sources are $^{13}C(\alpha,n)$, $^{17}O(\alpha,n)$, and $^{22}Ne(\alpha,n)$. The strength of the neutron source depends on the low energy cross section of the reaction as well as on the $^{13}C$, $^{17}O$, $^{22}Ne$ fuel supply which is either provided through convective mixing processes from different burning zones ($^{13}C$) and/or by nuclear reaction sequences. Again, the low energy cross sections need to be determined to evaluate neutron flux and s-process efficiency at the different s-process sites.

Stellar carbon burning is the third phase in stellar evolution. It is triggered by the $^{12}C+^{12}C$ fusion reaction with a small component of $^{12}C+^{16}O$ fusion. The low energy $^{12}C+^{12}C$ fusion cross section is one of the major enigmas in low energy fusion since it is characterized by resonance structures which have been interpreted as molecular resonances closely associated with the cluster structure of the $^{24}Mg$ compound nucleus [Gas05]. The low energy fusion cross section is important for determining the ignition conditions and the lifespan of the carbon burning phase in stellar evolution. A variety of predictions from different extrapolation techniques are shown in figure 1d. Also important is the relative branching between $^{12}C(^{12}C,\alpha)^{20}Ne$, and $^{12}C(^{12}C,p)^{23}Na$ since that ratio determines the final fuel abundance for the subsequent phase of neon burning [Pig06]. It also determines the efficiency of the s-process during carbon burning.

While there is a multitude of other critical reactions associated with stellar nucleosynthesis, the here listed examples carry the largest priority because they are directly associated with fundamental open questions about the nature and the characteristic of stellar burning scenarios and stellar evolution.

# 2 Accelerator Laboratory Underground

Low energy cross sections of charged particle reactions drop exponentially with energy because of the penetrability through the deflective Coulomb barrier. Typically low energy cross sections at stellar energies range are extremely low ($<<10^{-13}$ barn) and measurements with suitable statistics require weeks if not months of beam time. The main handicap for the experiments is, however, background events due to natural radiation background in detector arrays. Low energy room background can be successfully shielded.

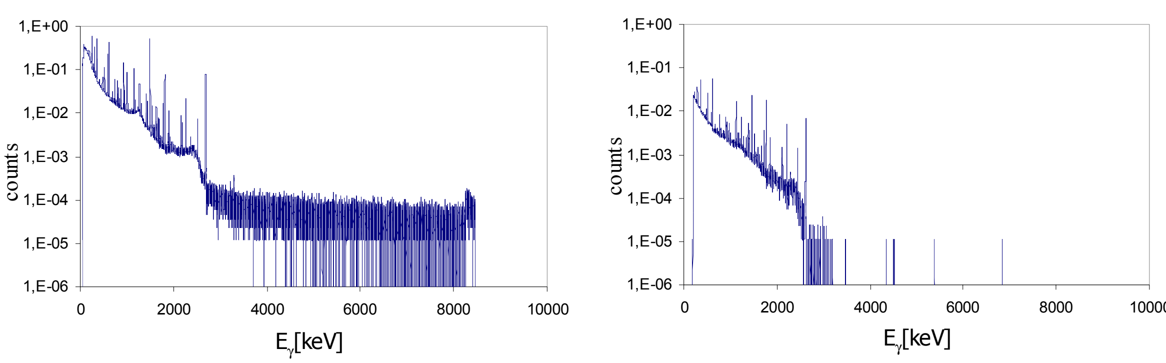


Figure 2: The comparison of a γ-spectrum form $^{14}N(p,\gamma)^{15}O$ taken at above ground laboratory conditions with a measurement at the LUNA underground accelerator facility. This translates into more than four orders of magnitude reduction of cosmic ray induced background

The remaining background source yields from cosmic ray induced muon and neutron radiation. This has to be removed by passive or active shielding techniques to improve the event to background conditions to the necessary level. A low energy accelerator underground does provide the necessary back ground reduction through passive shielding by several orders of magnitude.

First successful measurements have been performed at the LUNA facility at the Gran Sasso underground laboratory in Italy. The main focus was the experimental study of the $^{3}He(^{3}He,2p)^{4}He$ reaction for the pp-I chain [Bon99] and more recently the $^{14}N(p,\gamma)^{15}O$ reaction of the first CNO cycle [Imb05]. Both measurements were extremely tedious and challenging because of the low cross sections. While the success of these studies clearly demonstrated the advantages of an underground accelerator facility in comparison with above ground accelerator laboratories, they also showed that passive background reduction is not sufficient, since beam induced background is produced through scattering and reactions with low Z target impurities such as $^{2}H$, $^{6,7}Li$, $^{9}Be$, $^{10,11}B$. The experimental results and yield estimates indicate that the background level from beam induced radiation becomes significantly higher than the actual event rate towards lower energies. This required actual event identification to ensure effective beam induced background reduction. The existence of beam induced background reduces the depth requirements for an underground accelerator laboratory since cosmic ray induced background needs only be reduced below the level of beam induced background. This corresponds roughly to a depth of ~1500 m of rock for the laboratory location. On the other hand the existence of beam induced background increases the requirements on the detector facilities. The detector arrays need to be designed for maximum efficiency because of the low event rate and for unique event identification capability for active background reduction.

## 2.1 Accelerator facilities

The LUNA facility at the Gran Sasso laboratory operates a 50 kV and a 400kV low energy electrostatic accelerator for measuring reactions of relevance for stellar hydrogen burning. The energy is not sufficient for measuring reactions in stellar helium or carbon burning. The goal for the DUSEL accelerator laboratory is to have higher energy capabilities up to 1.5 MeV. This would permit the systematic study of reactions relevant for the understanding of helium burning in red giants and in AGB stars towards the low energy range. Measurements of heavy ion reactions such as $^{12}C+^{12}C$ would require substantially higher energies up to 8 MeV to map the critical excitation range.

The two options discussed by the accelerator working group are a small low energy accelerator for light ion beam forward kinematics experiments and a higher energy heavy ion machine for utilizing the inverse kinematics technique. The proposal is to first install a low energy single ended Singletron or Pelletron accelerator with 2 MV terminal voltage to perform a systematic study of $(\alpha,\gamma)$ and $(\alpha,n)$ reactions in forward kinematics at significantly reduced background conditions. These machines cover a wide energy range down to ~100 keV and would also be available for the measurement of $(p,\gamma)$ reactions. For the lower energy range the accelerator could be complemented for that by a small stand alone ECR source with post-acceleration in the 100 keV range. Such a device is presently under development at the LENA facility at the University of North Carolina. This facility would complement the LUNA laboratory which is designed primarily for reaction studies in stellar hydrogen burning conditions. It would have a considerably larger capability than LUNA since its considerably broader range in energy. The higher energy accelerator would allow the additional study of alpha capture reactions for the helium burning phase in stars but also the capture of proton capture processes on higher Z stable nuclei relevant for explosive hydrogen burning in novae.

In a second development step the laboratory should be equipped with a heavy ion accelerator with the capability of reaching energies of up to 1 MeV/u. This would be sufficient to provide the opportunity for inverse kinematics experiments at astrophysical relevant energies as well as for low energy fusion reaction studies. This technique is superior since it allows identifying and detecting the heavy ion recoil reaction products in a recoil separator. This considerably improves the background reduction capability and the overall sensitivity of the experiment. Inverse kinematics experiments require a windowless hydrogen/helium gas target system. Excellent beam emittance from the accelerator is crucial to reduce straggling and multiple scattering of the incoming beam particles in the gas target. This in turn will allow better separation between primary beam and reaction recoil particles in the separator. Presently two options for the accelerator are being discussed within the working group, a 1MeV/u RFQ/LINAC and a Tandem Tandetron or Pelletron accelerator. A design for the LINAC is presently being discussed with the accelerator design groups at Berkeley and Los Alamos. The main handicap is the limited beam quality and beam energy resolution from such an accelerator. A commercial Tandetron or Pelletron tandem would provide superior beam quality but may have limitations in beam intensity.

## 2.2 Detector facilities

A critical issue for an underground accelerator laboratory is the development of suitable detector facilities. The detectors need to have high efficiency for coping with the extremely low event rate but should also provide the possibility of event identification and active reduction of background events. In the case of forward kinematics experiments background reduction techniques need to be developed for capture gamma and low energy particle reaction products. Reducing background gamma radiation can either be done through coupling a high resolution Ge-detector with a $4\pi$ summing BGO or NaI detector array for Q-value gating. This is a very powerful technique which reduces the beam induced background by about three orders of magnitude as demonstrated in the example shown in figure 3. Not reduced is the Cosmic ray related background as can be seen in the energy range above the 12.8 MeV Q-value threshold for this particular example reaction.

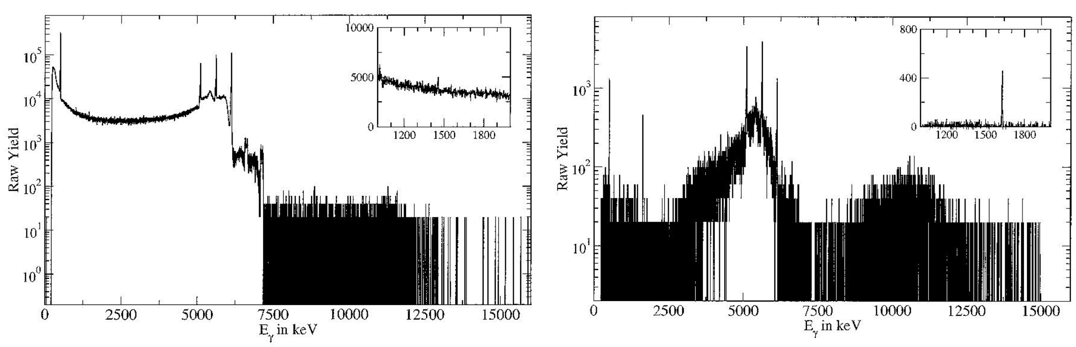


Figure 3: Beam induced $^{19}F(p,\alpha\text{-}\gamma)^{16}O$ background reduction through summing gating techniques for the 324 keV resonance in $^{19}F(p,\gamma)^{20}Ne$. Clearly to observe in the insert is the characteristic 1.63 MeV secondary transition in $^{20}Ne$. Also enhanced is the primary transition of 11.2 MeV.

This technique can be complemented by gamma tracking techniques to reduce uncorrelated background radiation. First calculations and simulations have been done with the GRETA group at LBNL to explore the suitability of this technique for high energy gamma radiation. Segmentation of the Ge-crystals and pulse shape discrimination offer additional possibilities for event identification and active back ground reduction.

Low energy particle processes such as (p,$\alpha$) and ($\alpha$,p) reactions are difficult to measure due to the large beam induced background from elastic and inelastic scattering. Particle identification techniques with telescope detector systems are of limited use because of the frequently low energies of the associated particles. Magnetic separation and focusing techniques such as superconducting solenoids with large acceptance angle can be used to deflect the elastically scattered particles and focus the reaction products onto a pixilated Si detector array. This can be complemented with time of flight separation techniques to further suppress background from multiple scattered particles.

Low energy measurements of ($\alpha$,n) reactions are notoriously difficult, due to the natural background from cosmic ray and fission induced neutrons but also due to beam induced neutron back ground from $^{13}$C impurities on the target. Neutron detection is difficult since in many cases the neutrons have very low energy which prohibits the use of scintillator detectors. In most cases the reaction neutrons are thermalized and detected with a $^{3}$He counter array. This techniques maximizes the detection efficiency but makes neutron background reduction difficult because of the loss of energy and timing information. The situation is exemplified in figure 4 which shows the excitation curve for the $^{22}$Ne($\alpha$,n) reaction. The left hand figure shows the neutron yield measured with a 4$\pi$ neutron counter, the right hand figure displays the measurement with high resolution $^{3}$He spectrometer. The latter method is superior in reducing neutron counts from background rejection but suffers from extremely low efficiency.

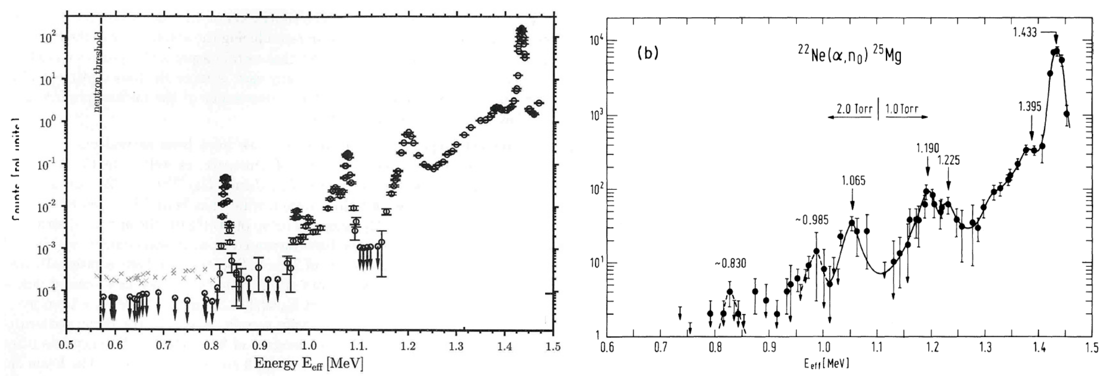


Figure 5: Low energy range of the $^{22}$Ne($\alpha$,n) excitation curve. The left hand panel shows the total neutron yield measured with a 4$\pi$ neutron counter. The upper limits in the low energy range demonstrate the present level of neutron background (above ground). The right hand panel shows the $n_0$ neutrons populating the ground state of $^{25}$Mg. The identification has been achieved by using a high resolution but low efficiency $^{3}$He spectrometer array. The right hand panel demonstrates better

Several resonances are anticipated for the energy range below 800 keV but are concealed by the natural neutron background if a neutron counter is used. A detector system utilizing time of flight techniques for low energy neutrons needs to be developed to reduce the remaining natural neutron background underground from natural fission and beam induced neutrons.

Inverse kinematics techniques are the main tool for measuring low energy reactions with radioactive beams. The crucial instrument for separating and detecting the heavy recoil reaction products are recoil mass separator such as the Daresbury separator at HRIBF in Oak Ridge or the

DRAGON separator at ISAC in TRIUMF.  Experiments with radioactive beam require a overall beam to recoil reduction of $10^{-15}$ to single out the reaction products from the beam induced background. Inverse reaction techniques with low energy stable beams are much more demanding since the cross section at stellar burning conditions is significantly lower than cross sections for explosive burning. The measurement of the low stellar cross section requires high beam intensity and therefore necessitates a considerably improved reduction ratio of down to $10^{-20}$ for the recoil separator facility. First inverse kinematics measurements with stable beams have been successfully performed for higher energy conditions but pilot studies for $^{4}$He($^{12}$C,$^{16}$O) at DRAGON at ISAC [Buc05], at ERNA at the DTL in Bochum, Germany [Sch05], and the RMS at KUTL in Kyushu, Japan [Sag05] have achieved beam to recoil reduction of $10^{-18}$ but they also demonstrated the necessity for improved RMS acceptance and separation capabilities.

The goal is to develop a recoil separator system to be used in conjunction with the DUSEL heavy ion accelerator. A design study has been completed and is shown in figure 6. The design was optimized for large acceptance angle and an overall mass resolution of 200  for heavy ion beams up to mass A=40 in the energy range of 0.2 to 1.0 MeV/u for proton and alpha capture reactions. A pilot facility is presently being build at Notre Dame to demonstrate the versatility of the design.

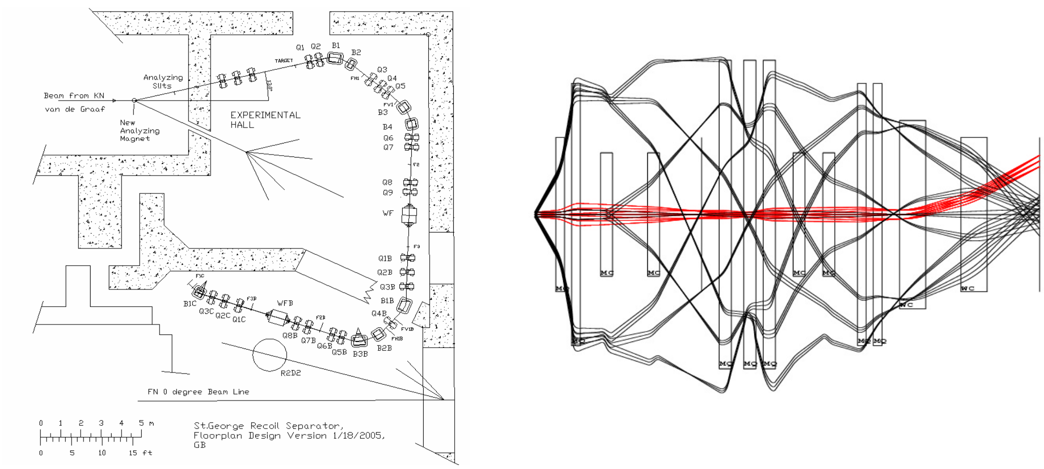


Figure 6: Shows the floor plan of the pilot project St. George for the DUSEL recoil separator system

The design of a recoil separator would be a crucial instrumentation for the heavy ion accelerator at DUSEL which would be proposed as part of the second phase of the construction of a DUSEL underground laboratory.

# 3   Requirements for an Underground Accelerator Laboratory

No formal proposal has been developed or submitted for an underground accelerator laboratory at DUSEL. At this time we want to present to the DUSEL collaboration the important motivations for an Underground Accelerator Lab and to lay-out the scope of the space, infrastructure, and ancillary equipment that will be needed for such a facility.  These requirements, listed below, are necessary for the design and construction of an internationally competitive underground accelerator facility

### 3.1 Depth and Space

As discussed above the depth requirements for an underground accelerator laboratory are not as stringent as for other underground projects proposed for DUSEL. A depth of 4000 m.w.e. (corresponding to about 1500 m of rock) would be sufficient for the operation of such a facility. Locating the accelerator laboratory at a different depth level would have the advantage that low level neutrino detection facilities would be shielded against any (low level) beam induced neutron or neutrino background originated in the course of the long term experiments.

The laboratory needs sufficient space for accelerator halls and target halls which should be shielded against each other. Based on the present plan the accelerator hall requires space for locating two machines, a low energy single ended accelerator and a heavy ion machine. The space needs have been estimated to 15x10x5 $m^3$. Additional space is needed for auxiliary systems for $SF_6$ gas storage and gas handling as well as for power supply, cooling water, and cryogenic equipment 10x10x5 $m^3$. The target halls need space for the different beam line components, the windowless gas target, and detector support stands, in particular ample space is needed for the recoil mass separator device. The space needs were estimated for 20x15x5 $m^3$ with additional space of 5x10x5 $m^3$ for housing the necessary power supply units for magnetic and electric beam optics systems. Additional space of approximately 8x8x5 $m^3$ for the accelerator and experiment control room as well as computational facilities is required. Laboratory space is needed for general use such as experiment preparation, detector testing and target preparation; a space of 10x10x5 $m^3$ would be sufficient. Finally space for a small shop (5x5x5 $m^3$) will be necessary for immediate repairs of accelerator and detector equipment. Some of the support laboratory space can be located at above ground building facilities.

### 3.2 Infrastructure

Accelerator halls as well as target rooms need to be equipped with overhead crane systems for transporting and positioning heavy equipment such as dipole and quadrupole magnets or other beam line systems. Accelerator and target halls as well as the associated underground laboratory space needs to be equipped with de-ionized cooling water. This is essential for accelerator and beam line equipment operation. Electrical power requirements are quite demanding, in the first stage of the project a total power of 50kW would be sufficient for operating the small accelerator and the associated beam line and detector systems. The second stage, which includes the second accelerator as well as the recoil separator system, requires a power of ~200 kW. The entire underground laboratory needs to be air-conditioned.

### 3.3 Auxiliary Equipment

Extensive auxiliary equipment needs to be part of the proposal. Listed above are a windowless re-circulating gas target, a Ge-NaI detector array, a number of Si strip detector systems, and finally a heavy ion recoil separator. Sufficient experience in the design and operation of such equipment is available within the working group. There is also close overlap with the design requirements for similar equipment for nuclear astrophysics experiments at RIA.

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* In some cases, a report may combine several working groups under one title; when applicable, please name the working group before you list its members.

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