LUNA PROPOSAL

2008-2012

COLLABORATION

Germany

BOCHUM, Inst. For Experimental Physics, Ruhr-Universitat:
C. Rolfs, F. Strieder, H.P. Trautvetter

DRESDEN, Inst. For Radiation Physics, Forschungszentrum Dresden-Rossendorf :
D. Bemmerer, M. Marta

Hungary

DEBRECEN, ATOMKI:
Z. Elekes, Zs. Fulop, Gy. Gyurky, E. Somorjai

Italy

GENOVA, Università degli Studi and INFN:
F. Confortola, P. Corvisiero, H. Costantini, A. Lemut, P. Prati

LNGS, Gran Sasso:
A. Formicola, C. Gustavino, M. Junker

MILANO, Università degli Studi, Ist. Di Fisica Generale Applicata and INFN:
R. Bonetti, A. Guglielmetti, C. Mazzocchi

NAPOLI, Università, Dip. Scienze Fisiche and INFN:
G. Imbriani, A. Di Leva, B. Limata, E. Roca, M. Romano, O. Straniero

NAPOLI, II Università, Dip. Scienze Ambientali and INFN:
F. Terrasi

PADOVA, Università degli Studi and INFN:
C. Broggini, A. Caciolli, R. Menegazzo, C. Rossi Alvarez

TORINO, Università, Dip. Fisica Sperimentale and INFN:
G. Gervino

1. LUNA: Underground Nuclear Astrophysics at Gran Sasso

Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak. The extremely low value of the cross-section inside the Gamow peak has always prevented its measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small because of cosmic ray interactions. In order to explore this new domain of nuclear astrophysics LUNA (Laboratory for Underground Nuclear Astrophysics) started in 1991 its activity by installing a 50 kV electrostatic accelerator underground at LNGS, followed in the year 2000 by a second 400 kV one. The qualifying features of both accelerators are a very small beam energy spread and a very high beam current even at low energy. After 16 years LUNA still remains the only underground accelerator facility existing in the world. The project of having an accelerator facility underground in the United States is now discussed in the frame of the DUSEL Project.

Outstanding results have been obtained on the cross-sections of $^{3}He(^{3}He,2p)^{4}He$ [Bon99] and $^{2}H(p,\gamma)^{3}He$ [Cas02], both measured within the Gamow peak of the Sun, and of $^{14}N(p,\gamma)^{15}O$, measured down to 70 keV [For04,Imb05,Lem06]. With these experiments LUNA has shown that, by performing the measurements underground with the typical techniques of low background physics, nuclear cross-sections can be measured down to the energy of the nucleosynthesis inside stars.

In particular, our result on $^{3}He(^{3}He,2p)^{4}He$ down to 16 keV (20 fbarn cross-section with a count rate of 2 events per month) has ruled out the astrophysical solution of the solar neutrino problem based on the existence of a narrow resonance within the Gamow peak of the Sun. On the other hand, the LUNA experiment on $^{2}H(p,\gamma)^{3}He$ has provided a precise measurement of an important reaction of Big-Bang nucleosynthesis (BBN).

The $^{14}N(p,\gamma)^{15}O$ reaction has been studied by LUNA with two different techniques: a germanium detector with solid target at 'high' energy and a BGO summing crystal with a windowless gas target down to 70 keV. Our measured cross-section is about a factor 2 smaller than the previous extrapolation in the NACRE compilation [Ang99]. The astrophysical consequences of such a reduction are significant: the CNO neutrino yield in the Sun is decreased by about a factor two [Inn04,Bah04], the age of the oldest Globular Clusters is increased by 0.7-1 Gyr to about 14 Gyr [Imb04] and the dredge-up of carbon to the surface of Aymptotic Giant Branch (AGB) stars is much more efficient [Her04].

At LUNA we have also measured the cross-section of $^{3}He(\alpha,\gamma)^{7}Be$ down to 93 keV. The data analysis was recently completed [Con07]. The uncertainty on this cross-section was the main nuclear limitation to the extraction of physics from the ^{8}B and

^{7}Be solar neutrino flux measurements. In addition, this reaction is the dominant channel for the BBN ^{7}Be production (and for the daughter ^{7}Li).

We have performed a high accuracy study by detecting the emitted prompt γ-rays and counting the produced ^{7}Be atoms. We obtain an extrapolated S-factor with a 3% error, thus reducing the uncertainty on the predicted ^{7}Be solar neutrino flux from 9.4% to 5.5% (from 12% to 10% for the ^{8}B flux). Nuclear physics does not give anymore a dominant contribution to the total uncertainty of the solar neutrino fluxes [Bem06,Gyu07,Con07]. This has great importance for the experiments, like BOREXINO, which are now starting a precise measurement of the ^{7}Be solar neutrino flux.

The 'non solar' phase of LUNA has already started with the experiment on ^{25}Mg(p,γ)^{26}Al. There are two reasons why this reaction is relevant for astronomy and astrophysics: the 1.8 MeV map taken by the satellites which look at the γ-sky and the anomalous meteoritic abundance of ^{26}Mg. This experiment is scheduled to finish by the end of 2007.

During all its activity, LUNA strongly benefited by the expertise and by the unique facilities available in Gran Sasso, in particular the laboratory for ultra-low background measurements.

2. The new phase of LUNA

In a study that lasted about one year we identified several nuclear reactions of great astrophysical relevance which can strongly benefit by an underground measurement (Tab.1).

Table 1. Candidate reactions for an underground measurement at LUNA. For each reaction the Q-value, the energy region important for astrophysics, the lowest measured energy and the lowest energy achievable in LUNA are given. The reactions discussed in this proposal are written in red, while in blue are those which require a new accelerator with higher voltage than the existing one. Energies are given in the centre-of-mass system.

Reaction	Q-value (MeV)	Burning energy (keV)	Lowest meas. energy (keV)	LUNA limit (keV, estimate)
$^{15}N(p,\gamma)^{16}O$	12.13	10-300	130	50
$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68
$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
$^{2}H(\alpha,\gamma)^{6}Li$	1.47	50-300	700 (direct) 50 (indirect)	50
$^{12}C(\alpha,\gamma)^{16}O$	7.16	300	950	500
$^{15}N(\alpha,\gamma)^{19}F$	4.01	364	536	364
$^{13}C(\alpha,n)^{16}O$	2.21	170-250	270	200
$^{22}Ne(\alpha,n)^{25}Mg$	-0.47	470-700	850	630

In this proposal we describe the scientific program we want to perform from 2008 to 2012 with the 400 kV accelerator already operating underground in the so called LUNA2 laboratory.

To study $^{12}C(\alpha,\gamma)\,^{16}O$, the 'Holy Grail' of nuclear astrophysics, $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)\,^{25}Mg$, the neutron sources inside stars, and other (α,γ) reactions a new accelerator of a few MV voltage installed in a dedicated space underground is required. Such project, which could produce an extremely important step forward in nuclear astrophysics, is the subject of a Letter of Intents to the Gran Sasso Scientific Committee.

3. Scientific program

In the following we outline the new scientific program of LUNA with the 400 kV accelerator. It consists in the measurement of a key reaction of BBN ($^2H(\alpha,\gamma)^6Li$) and in several thermonuclear reactions relevant for the synthesis of the elements inside the stars.

The first reaction we propose to study is $^2H(\alpha,\gamma)^6Li$, the main ^6Li production reaction during BBN. Existing experimental data reach E_{cm}= 700 keV while indirect measurements have been recently performed down to about 50 keV. The region of interest for BBN is between 50 and 300 keV. A strong discrepancy with extrapolations based on the direct data and theoretical predictions was found. This reaction will be studied with the existing 400 kV machine down to about 50 keV c.m. (150 keV laboratory beam energy).

We now come to thermonuclear reactions inside the stars. The temperature in the stellar interior is determined by the mass of the star. Low-mass stars like our Sun operate mainly on the proton-proton (pp) chain, while more massive stars produce energy through the operation of the Carbon-Nitrogen-Oxygen (CNO) cycles. However, in second generation stars, whose central temperatures are higher than those for the quiescent CNO cycle, additional cycles in the hydrogen burning stage can occur (NeNa, MgAl). Because of the higher Coulomb barriers involved in the processes, these higher burning cycles are relatively unimportant as a source of energy, but they are essential for the nucleosynthesis of elements in the mass $A \geq 20$ region.

Already in the past LUNA has studied the key processes of the pp chain and of the first CNO cycle. In this document we propose to explore the other cycles by measuring the (p,γ) reactions on ^{15}N, ^{17}O, ^{18}O, ^{22}Ne and ^{23}Na. Details of the measurements are described in the following subsections.

3.1. $^2H(\alpha,\gamma)^6Li$

Recently, the ^6Li isotope has been detected in a number of metal-poor stars [Smi93,Asp06]. These observations are significant because they suggest a ^6Li plateau similar to the well-known Spite plateau for ^7Li [Spi82]. The observed ^7Li abundance [e.g. Bon02 and Asp06] is a factor of 3 below the value predicted by standard big-bang nucleosynthesis based on the baryon-to-photon ratio from cosmic microwave background observations [Coc04]. The ^6Li data, however, are higher by as much as two to three orders of magnitude than the predicted big-bang production. This gives rise to a ^6Li problem in big-bang nucleosynthesis, in addition to the well-known ^7Li problem.

If the existence of the ^{6}Li plateau is confirmed, a pre-galactic source of ^{6}Li has to be introduced as an explanation. This could either be an extremely enhanced production in Big-Bang nucleosynthesis, mainly through the ^{2}H(α,γ)^{6}Li reaction, or nonstandard physics like the decay of relic gravitinos [Jed06]. It has been shown that ^{6}Li production through the pre-galactic interaction of energetic particles with the interstellar medium cannot explain the level of detected ^{6}Li [Pra06]. Most scenarios of pre-galactic ^{6}Li production, except for an enhanced ^{2}H(α,γ)^{6}Li cross-section, produce not only ^{6}Li but also ^{7}Li, therefore worsening the ^{7}Li problem. A sensitivity study of nuclear reaction rates for big-bang nucleosynthesis has shown that the nuclear uncertainty in the predicted ^{6}Li abundance is dominated by the uncertainty in the ^{2}H(α,γ)^{6}Li cross-section [Van00]. The reaction is dominated by d-wave capture to the first excited state in ^{6}Li and produces single γ-rays from ~1.6 to 2.2 MeV, see Figure 1. The Gamow peak ranges from 50 to 300 keV in the centre of mass. Because of its electric quadrupole nature the cross-section is predicted to be extremely small, few pbarn to few tens of pbarn in the energy range 50-100 keV.

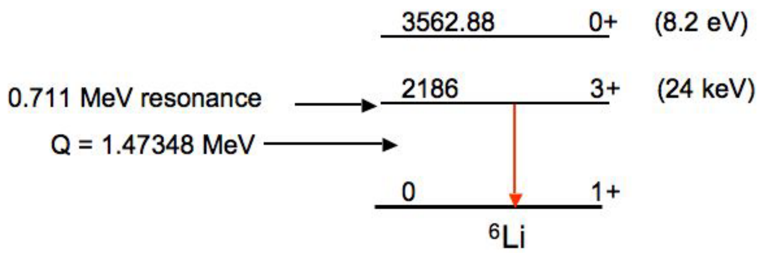

Figure 1. Level scheme of ^{6}Li

The cross-section of the ^{2}H(α,γ)^{6}Li reaction has been previously measured, in the energy range of Big-Bang nucleosynthesis, in a Coulomb dissociation study at Karlsruhe [Kie91]. Preliminary results from another Coulomb dissociation experiment at GSI [Ham06] indicate, with large uncertainties, a lower cross-section at similar energies (Fig.2). Theoretical calculations [e.g. Kha98] yield values that are systematically lower than the data [Kie91, Ham06]. The NACRE compilation consequently cites an uncertainty of a factor 3 in the rate at BBN temperatures.

The Q-values of ^{2}H(α,γ)^{6}Li (1.474 MeV) is similar to the one of ^{3}He(α,γ)^{7}Be (1.586 MeV), recently studied by LUNA. At big-bang energies, only capture to the ground state in ^{6}Li is energetically possible. Consequently, the observed γ-ray spectra from the LUNA ^{3}He(α,γ)^{7}Be study can be used to evaluate the feasibility of a ^{2}H(α,γ)^{6}Li measurement. An approximate spectrum, Fig.3, has been calculated with a beam energy E_α = 400 keV, using the measured laboratory background [Bem06] and the average S-factor for ^{2}H(α,γ)^{6}Li assumed in NACRE.

We propose to measure this cross-section with the presently available 400 kV accelerator in the lab energy range 150-400 keV corresponding to c.m. values of 50-130 keV. The corresponding rate of emitted photons at the lowest energy is 4 h^{-1} with an alpha beam of 100 µA and 10^{18} atoms/cm^2 target thickness.

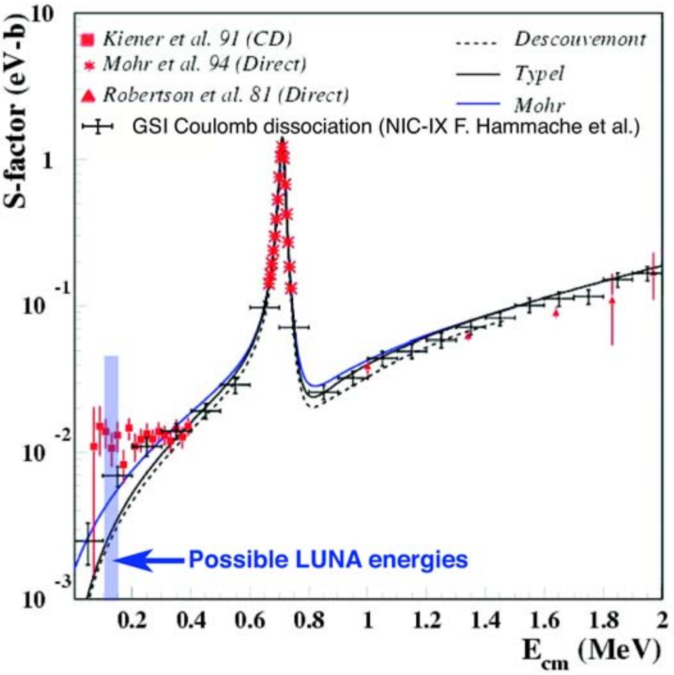

Figure 2. Existing results on the astrophysical factor of $^{2}H(\alpha,\gamma)^{6}Li$

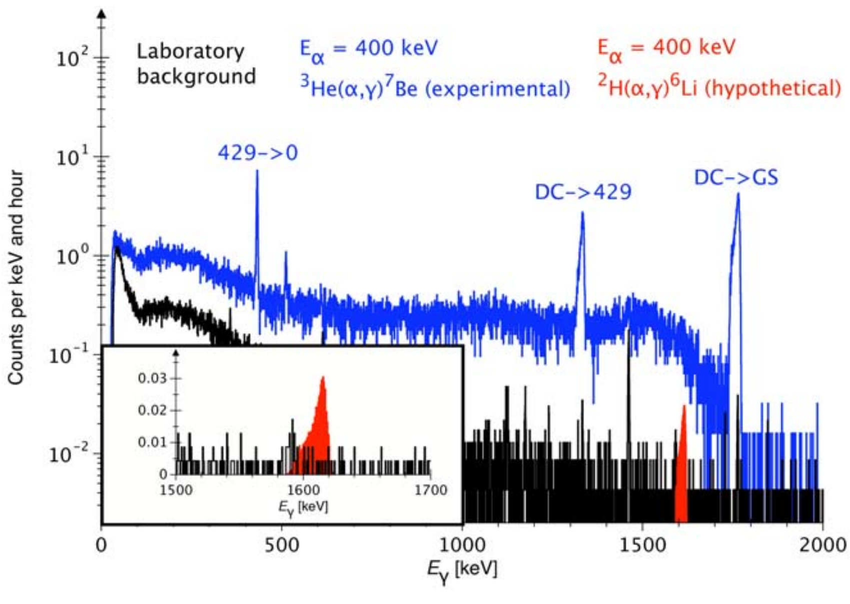

Figure 3. Spectra from the $^{3}He(\alpha,\gamma)^{7}Be$ experiment (top) and from the laboratory background (bottom) with the calculated peak due to $^{2}H(\alpha,\gamma)^{6}Li$ (in red; the gamma detection efficiency is the one measured in the $^{3}He(\alpha,\gamma)^{7}Be$ experiment)

In conclusion, this reaction could profit by the same set-up developed for the $^{3}He(\alpha,\gamma)^{7}Be$ reaction (gas target, shielding, detector, acquisition system) and, more important, is feasible only in an underground location such as LNGS.

3.2. $^{15}N(p,\gamma)^{16}O$

The $^{15}N(p,\gamma)^{16}O$ and $^{15}N(p,\alpha)^{12}C$ reactions form the branching point from the first to the second CNO cycle (Fig.2) [Rol88]. The ratio of their respective reaction rates has been determined to be about 1:1000 at stellar energies [Rol74], directly influencing the nucleosynthesis yields of $^{16,17}O$ and ^{17}F and the rate of emitted ^{17}F neutrinos from the Sun. Furthermore, the $^{15}N(p,\gamma)^{16}O$ reaction plays an important role in the production of ^{19}F in AGB stars via CNO burning (Fig.4), as an alternative to the $^{15}N(\alpha,\gamma)^{19}F$ reaction or to the recently suggested n- process [Heg05]. The production process of ^{19}F is the subject of ongoing study in different stellar scenarios [Pal05] stimulated by many recent ^{19}F observations [Neu06].

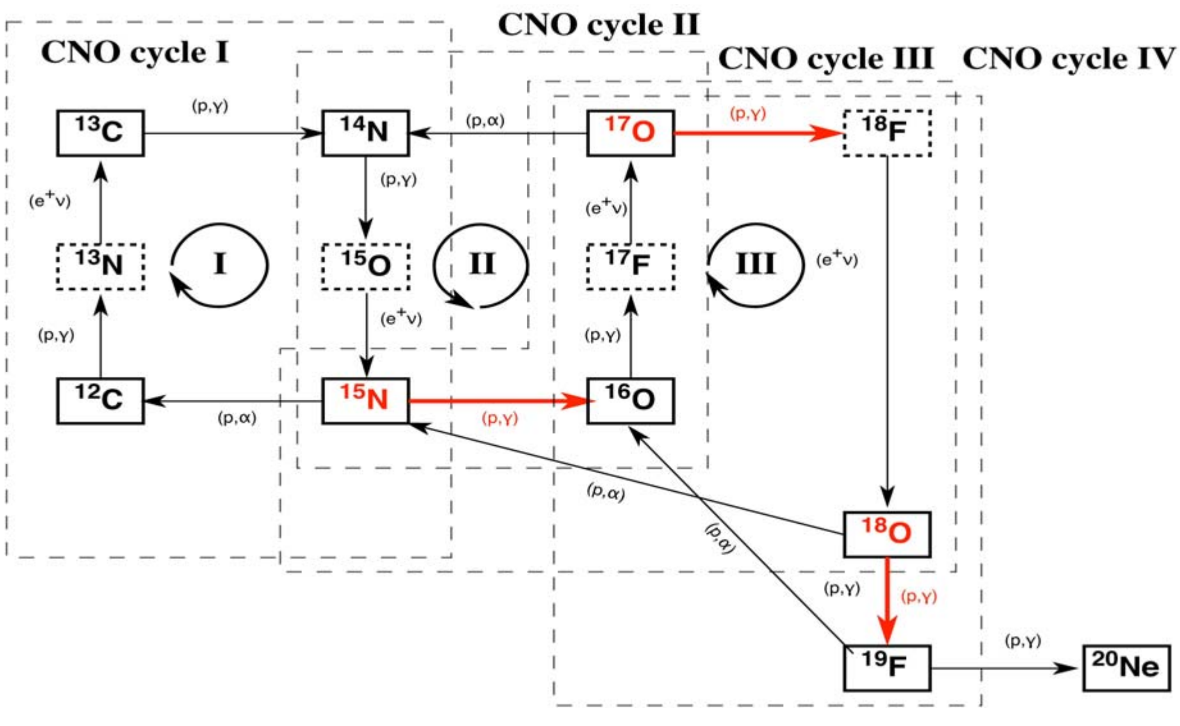

Figure 4. CNO cycles

The $^{15}N(p,\alpha)^{12}C$ reaction is the focus of ongoing experimental efforts elsewhere [Lac06]. For the $^{15}N(p,\gamma)^{16}O$ reaction (Q-value 12.127 MeV), it has been found that the broad resonance at E_p= 335 keV (E_x=12.442 MeV) and the resonance at E_p=1028 keV (E_x=13.091 MeV) decay with >90% branching to the 0^+ ground state in ^{16}O [Til93]. The previous extrapolation of the $^{15}N(p,\gamma)^{16}O$ cross-section to zero energy [Rol74,Ang99] was mainly based on data between the two resonances at E_p=335 and 1028 keV, with the direct capture component as a free parameter in the fit. Precision experimental data in this energy range will be an important test of the reliability of this extrapolation and will resolve the discrepancy between the only two works reporting low-energy data on this reaction. Even more, such data will make extrapolations for hydrogen burning in AGB stars unnecessary (Fig.5).

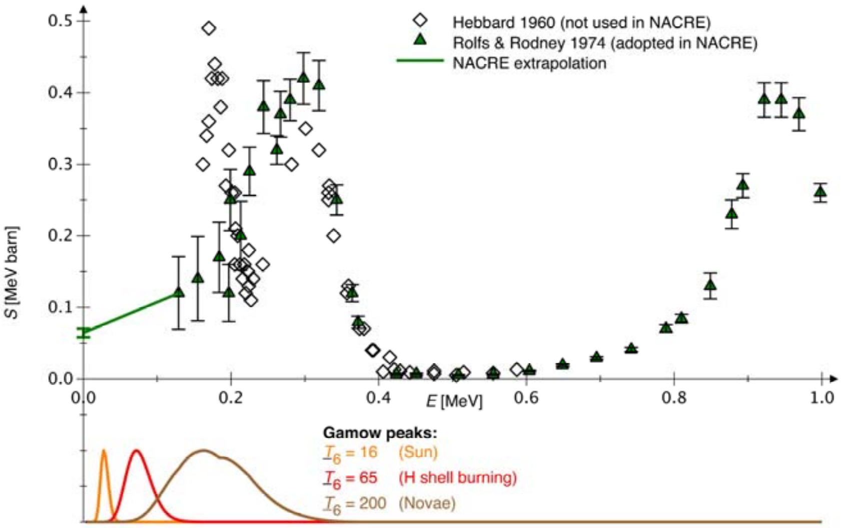

Figure 5. The astrophysical factor of $^{15}N(p,\gamma)^{16}O$ and the Gamow peak for different stellar temperature

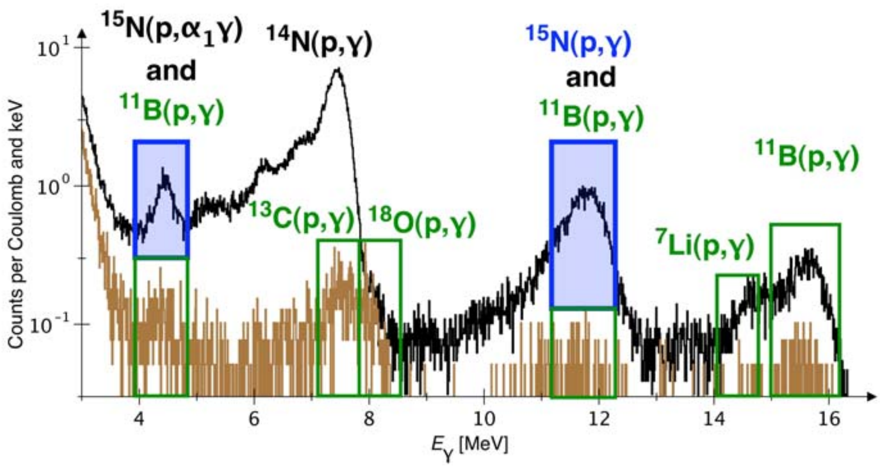

Figure 6. gamma spectra of the BGO detector with a 200 keV proton beam and different gas target: ^{14}N (top) and ^{4}He (bottom)

Qualitative data on this reaction have been already collected in our previous $^{14}N(p,\gamma)^{15}O$ gas target measurement [Lem06] due to the small ^{15}N content (0.4% isotopic abundance) in the target. From the high-energy part of the spectra, conclusions regarding the feasibility of a $^{15}N(p,\gamma)^{16}O$ study are possible (Fig.6). While the laboratory background is negligible (0.1 counts/day [Bem05]), the ion beam induced $^{11}B(p,\gamma)^{12}C$ background limits the extraction of $^{15}N(p,\gamma)^{16}O$ data from this previous study. However, it has been shown [Bem05] that this background arises from impurities independent on the gas pressure. Therefore, it will become negligible when using enriched ^{15}N gas. Based on this experience we propose a $^{15}N(p,\gamma)^{16}O$ experiment with a setup analogous to the one used in the $^{14}N(p,\gamma)^{15}O$ measurement[Lem06].

3.3. $^{17}O(p,\gamma)^{18}F$

In stars where temperature exceeds about 18 MK, matter is mainly processed through the CNO cycle, which is responsible for the synthesis of ^{14}N and of some of the carbon and oxygen isotopes, such as ^{13}C and ^{17}O. Large uncertainties remain in the reaction rates needed to understand stellar nucleosynthesis during the hydrogen burning phase. In particular, for $^{17}O(p,\gamma)^{18}F$ there is only the measurement of the 193 keV resonance in the energy region below 300 keV.

Standard description of the evolution of stars to the red giant branch predicts that the convective envelope will bring to the surface the material processed by the CNO cycle during the main sequence. The $^{16}O/^{17}O$ ratio in these stars may thus provide much information on the mixing (amount and location) due either to the first dredge-up process or to the slow mixing during the main sequence phase [Har84]. Such observations in the atmosphere of several evolved stars have been reported [Har84,Har84b]. In a variety of stars, the $^{16}O/^{17}O$ ratio ranges from 1100 to 160 [Har84b], thus revealing an important enrichment in ^{17}O relative to the solar value of 2485 [Cam73]. In more evolved carbon stars [Har85,Har87] this ratio is larger than the value expected from theoretical models of AGB stars. Unfortunately, the interpretation of all these observations suffers from the uncertainties on the $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ reaction rates at stellar energies.

The $^{17}O(p,\gamma)^{18}F$ cross-section is expected to be dominated at stellar energies by a resonance at E_p(lab)=70 keV, corresponding to the 5.673 MeV (1^-) state of ^{18}F. A subthreshold state at 5.605 MeV (1^-) could also play a significant role in the reaction rate through the high energy tail of the level and the possible interference effects with the 5.673 MeV state. The stellar temperature for red giants, AGB and massive stars is 20-100 MK and 100-400 MK for Novae. These ranges correspond to a Gamow peak energy from 26 keV to 140 keV and 70-370 keV, respectively. Present direct measurement of $^{17}O(p,\gamma)^{18}F$ extends down to 300 keV [Rol73], well above the range of interest for nuclear astrophysics, leaving open all extrapolation scenarios (Fig.7). The measurement of this reaction (Q=5606.5 keV) could be performed with the LUNA BGO detector [Cas02b], but a segmented detector with better energy resolution would be ideal to reduce systematic errors on the branching ratios and angular distributions.

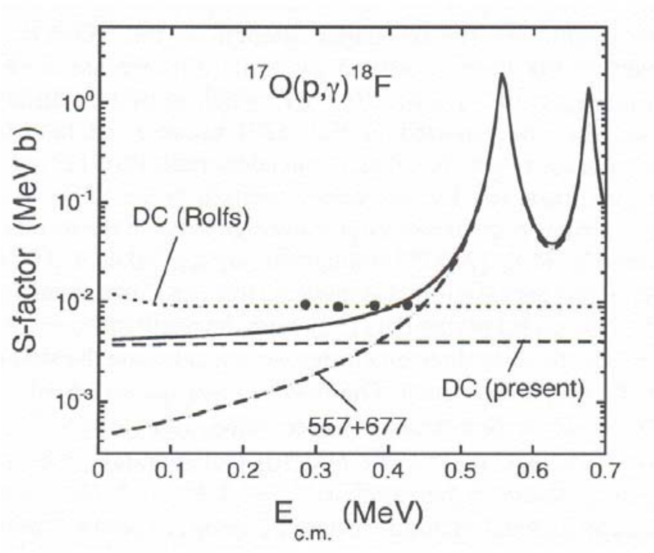

Figure 7. S-Factor data and extrapolation obtained by previous work [Fox05]. The contributions due to direct capture, 557 and 677 keV resonances are shown.

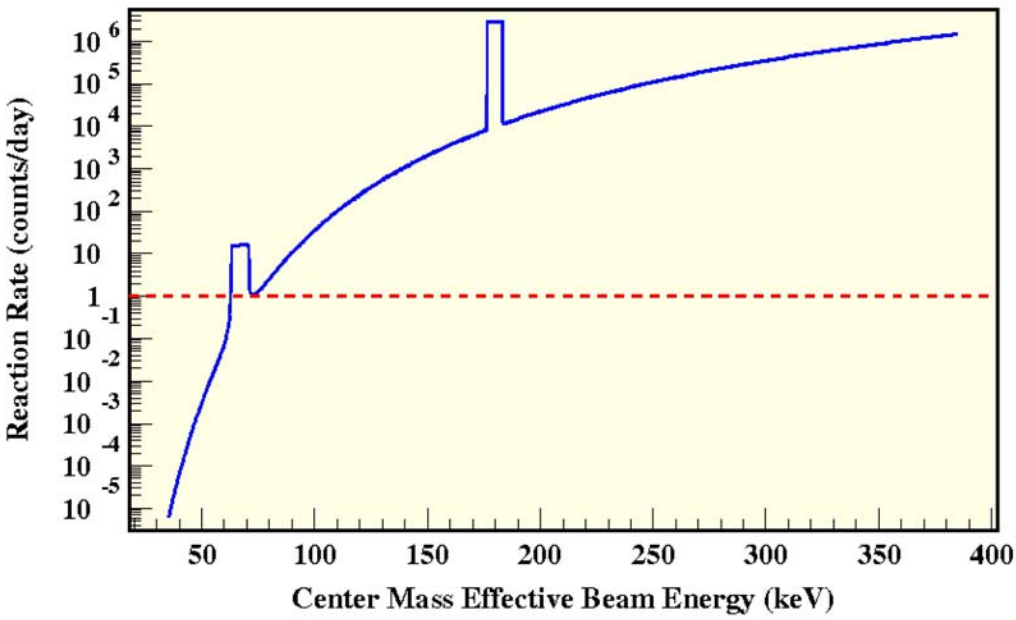

Figure 8. Count rate for the $^{17}O(p, \gamma)^{18}F$ reaction at LUNA (see text for details)

Figure 8 shows the expected counting rate assuming a typical target density of $5 \cdot 10^{17}$ Atoms/cm^2, beam current of 200 μA and 50% detection efficiency (no subthreshold state contribution has been taken into account). The laboratory background with the existing BGO detector is 30 counts/day (without shielding) to be compared with a $^{17}O(p,\gamma)^{18}F$ reaction rate of 30 counts/day at E_p=108.3 keV (E_{cm}=98.5 keV) and 1 count/day at E_p=80 keV (E_{cm}=71.9 keV). The expected rate at the E_p=70 keV resonance, which is of crucial importance for the determination of the stellar reaction rate, is about 16 counts/day, considering the cross-section obtained from the indirect measurement [Lan89].

3.4. $^{18}O(p,\gamma)^{19}F$

In second generation stars with masses $M \geq M_{Sun}$, hydrogen burning proceeds predominantly through the operation of the CNO tri-cycle [Rol88]. Hydrogen burning of ^{18}O, resulting from the β-decay of ^{18}F, can occur through two competing reactions: $^{18}O(p,\gamma)^{19}F$ and $^{18}O(p,\alpha)^{15}N$. The latter one dominates the hydrogen burning of ^{18}O leading to a recycling of the CNO catalytic material into the CN cycle [Lor78]. However, $^{18}O(p,\gamma)^{19}F$ may lead to small leakage from the CNO cycle and to the subsequent hydrogen burning of ^{19}F through $^{19}F(p,\gamma)^{20}Ne$. This could be the origin of the loss of catalytic materials from the CNO cycle and it would provide a link to the NeNa cycle. A better study of the nuclear processes involved is fundamental to proof the hypothesis of the closed CNO tri-cycle, but also to determine the amount of catalytic material lost by the cycle. Furthermore, the study of $^{18}O(p,\gamma)^{19}F$ is of interest for the precise location of the ^{19}F and of the Ne-Na nucleosynthesis sites.

At temperatures typical of quiet hydrogen burning ($T \leq 1$ GK) the $^{18}O(p,\gamma)^{19}F$ reaction (Q=7.994 MeV) is dominated by several resonances. Most of them have been directly measured [Wie80,Vog90] but at $T \leq 0.1$ GK there are still large uncertainties on the resonance strengths. In particular, the resonance at E_{cm}=89 keV has been directly observed only in the (p,α) channel while no direct evidence has been found in the (p,γ) channel and only upper limits for the resonance strength have been given.

We propose a measurement using the 400 kV LUNA accelerator and the existing BGO summing crystal with a Ta_2O_5 solid target placed in its centre. Such a system is very similar to the one we are now using for the $^{25}Mg(p,\gamma)^{26}Al$ study. The spectrum will be dominated by the full energy summing peak at $E_\gamma = Q + E_{cm}$, in a region where the experiment can take full advantage of the high background suppression of LNGS.

Considering a Ta_2O_5 solid target, a beam current of 200 μA and an absolute efficiency around 50%, the expected counting rate for low energy resonances at E_{cm}=89, 143, 205 and 260 keV is $3.4 \cdot 10^3$, $1.0 \cdot 10^8$, $4.0 \cdot 10^5$ and $2.6 \cdot 10^6$ counts/day, respectively (the rate of the E_{cm}=89 keV resonance is calculated considering the upper limit for the resonance strength [Vog90]). For comparison, the natural background measured underground with the unshielded BGO detector is 13 counts/day/MeV in the energy region around E_γ=7 MeV. Additional background can also arise from beam induced reactions on impurities in the solid target, in particular the 162 keV resonance of $^{11}B(p,\gamma)^{12}C$ and the 259 keV resonance of $^{14}N(p,\gamma)^{15}O$. For the measurement of the 89 keV resonance the beam induced background is under control, as previously observed in the $^{14}N(p,\gamma)^{15}O$ experiments [For04,Lem06].

Based on these estimates we propose to measure for the first time the resonance strength of the 89 keV resonance and, in addition, to reduce the error on the 143, 205 and 260 keV resonance strengths. Furthermore, LUNA can measure directly the low energy tail of the 143 keV resonance which is supposed to dominate the reaction rate at lower energies [Wie80]. This would significantly reduce the present uncertainty on the reaction rate.

3.5. $^{22}Ne(p,\gamma)^{23}Na$

The NeNa cycle is active in second-generation stars characterized by high burning temperatures. This cycle could play a role in understanding the highly enriched ^{22}Ne meteoritic samples. Furthermore, it is directly related to the anti-correlation between Na and O observed in globular clusters stars [Kra98,Car04]. Indeed, according to standard stellar models, surface abundances should not change as the star ascends the red giant branch, but the observed variation of surface carbon and oxygen led to a non convective mixing scenario driven by rotation. A possible by-product of this mixing is the change in the surface abundance of sodium. In this scenario the NeNa cycle operates episodically and the uncertainty in the $^{22}Ne(p,\gamma)^{23}Na$ reaction rate propagates to the final abundance of ^{23}Na. Finally, the $^{22}Ne(p,\gamma)^{23}Na$ reaction rate influences the abundance of ^{22}Ne in the ashes of the NeNa cycle, important for neutron production through the $^{22}Ne(\alpha,n)^{25}Mg$ reaction.

$^{22}Ne(p,\gamma)^{23}Na$ has a Q-value of 8.794 MeV and proceeds through numerous resonances and via direct capture at low energies. The direct capture contribution has been measured at higher energies [Rol75,Gor83] but resonant components have not been accurately determined yet. The lowest measured resonance is at E_x=9.211 MeV (E_{cm}=417 keV) but in the region of interest for astrophysics (T≤60 MK corresponding to $E_{cm}\leq$ 80 keV) lower energy states are considered as potential contributors. Several states have been recently observed via (^3He,d) spectroscopy giving an upper limit to (p,γ) resonance strengths [Hal01]. In particular, resonances at E_{cm}=68 keV and E_{cm}=100 keV seem to dominate the reaction rate at astrophysical energies.

We propose a measurement of this cross-section with the 400 kV LUNA accelerator and a windowless gas target re-circulating enriched ^{22}Ne. The setup is similar to the one used for the $^{14}N(p,\gamma)^{15}O$ study with the summing BGO detector[Lem06]. Considering a target density of $5\bullet10^{17}$ Atoms/cm^2 (1 mbar target pressure and 12 cm target length), a beam current of 200 μA, and an absolute efficiency around 60%, counting rates of 70 counts/day and $3\bullet10^4$ counts/day are expected, taking the upper limits from [Hal01] as value of the resonance strength, for the 68 keV and the 100 keV resonances respectively. The natural background measured underground with the unshielded BGO detector is 20 counts/day in the region of interest for the reaction. Possible background can also come from beam induced reactions on collimators or gas impurities but at E_p< 110 keV this contribution is almost negligible. Using the gas target-BGO technique and thanks to the background reduction, LUNA may either find the resonances or improve by several orders of magnitude the existing upper limits [Fig.9].

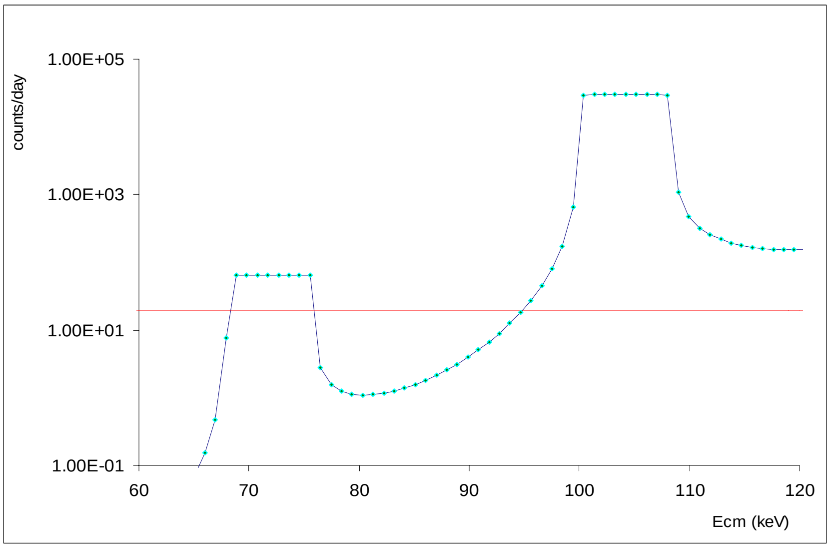

Figure 9. Expected counting rate for the $^{22}Ne(p,\gamma)^{23}Na$ reaction considering the resonances at E_{cm}=68 and 100 keV ($\rho=5\bullet10^{17}$ Atoms/cm^2, P=1mbar, L=12cm, I=200 μA). The horizontal line indicates the expected laboratory background rate

3.6. $^{23}Na(p,\gamma)^{24}Mg$

During the hydrogen burning phase at high temperature the nucleosynthesis path is likely to reach the sodium isotope ^{23}Na, where one expects a subsequent path either through the $^{23}Na(p,\alpha)^{20}Ne$ reaction, closing the NeNa cycle, or via $^{23}Na(p,\gamma)^{24}Mg$. The latter (p,γ) reaction transforms ^{23}Na to heavier elements and bypasses the NeNa cycle. Therefore, the important question for the nucleosynthesis of heavier isotopes is how much material is processed through the (p,α) or the (p,γ) channel [Rol88]. The quantity which needs to be determined with high precision is the reaction rate branching ratio, i.e. the ratio of $^{23}Na(p,\alpha)^{20}Ne$ versus $^{23}Na(p,\gamma)^{24}Mg$: $B_{p\alpha/p\gamma}=N_A<\sigma v>_{p\alpha}/\ N_A<\sigma v>_{p\gamma}$, where $N_A<\sigma v>$ is the thermonuclear reaction rate at given temperature T for each reaction [Row04].

Improved experimental data would influence the following items:
a) the galactic origin of the radioactive isotope ^{26}Al, which can be detected with modern γ-ray astronomy satellite telescopes, e.g. CGRO or INTEGRAL. Whereas supernovae Type II represented for a long time the accepted production site of this isotope, recent studies [Pra04] suggested the need of additional sources, i.e. Wolf-

Rayet stars or classical novae. As shown by [Row04] the abundance predictions of ^{26}Al are significantly affected by the large uncertainties, about 25 %, in the $^{23}Na(p,\gamma)^{24}Mg$ reaction rate.

b) the optical observation of magnesium and aluminium abundances in the shells of classical novae may significantly constrain theoretical models only if the nuclear physics inputs have smaller uncertainties than the observed abundance values. At present this not anymore the case due to the large improvements in the optical astronomy and the uncertainty on the reaction rates needs to be reduced.

c) the possible identification of pre-solar grains in primitive meteorites could be supported by the present studies of the NeNa cycle reactions [Row04]. Presolar oxide grains originating from novae are expected to condense in the ejected nova shells as spinel ($MgAl_2O_4$), corundum (Al_2O_3), or enstatite ($MgSiO_3$) [Jos04]. Unfortunately, these small size grains have not been discovered yet, but will significantly constrain the nova models through their precisely measured oxygen, magnesium, and aluminium isotopic ratios. For the prediction of the isotopic ratios through the models a precise knowledge of the nuclear physics data is necessary and as for the other mentioned implications one of the main source of uncertainty is the reaction $^{23}Na(p,\gamma)^{24}Mg$ [Row04].

The important stellar temperatures for the astrophysical sites are in the range of T=0.1 -1.0 GK, with a special focus on the novae region T=0.2-0.4 GK. The former temperature range corresponds to an energy window of E_{cm} = 100-600 keV. As for most of the nuclear reactions in this mass region the reaction rates of the reactions on ^{23}Na are dominated by narrow, isolated resonances and direct capture contributions are mostly negligible. The strengths of the involved resonances of the $^{23}Na(p,\alpha)^{20}Ne$ reaction are rather well constrained [Gor89] or can be determined in a laboratory on surface. On the other hand, the $^{23}Na(p,\gamma)^{24}Mg$ reaction (Q=11.693 MeV [Aud03]) is an ideal case for underground measurements. The resonances which need to be studied for the $^{23}Na(p,\gamma)^{24}Mg$ reaction are at E_p=309, 251, and 144 keV, with resonance strengths of $\omega\gamma$=107 ± 22, 0.6 ± 0.2 [Gor89], and $<1.5 \cdot 10^{-4}$ meV, respectively.

Due to the complex level structure (Fig.10) the $\omega\gamma$ can be measured with the present BGO detector. This experiment will benefit from the experiences gained in the $^{25}Mg(p,\gamma)^{26}Al$ experiment which is presently performed by LUNA. In this approach, an evaporated Na_2WO_4 target [Row04] is located in the centre of the BGO detector allowing for a very high γ-ray efficiency of approximately 50%. The obtained γ-ray spectra will be dominated by the full energy summing peak of the $^{23}Na(p,\gamma)^{24}Mg$ reaction at an energy of E_γ=Q + $E_{R,cm}$, a region of the spectrum where the experiment takes full advantage of the high suppression factor for cosmic-ray muons at LNGS. Therefore, the detection of the γ-rays from the reaction will be nearly background free and only hampered by beam induced background from $^{11}B(p,\gamma)^{12}C$ (Q=15.957 MeV), i.e. the strong resonance at E_p=162 keV, and $^{18}O(p,\gamma)^{19}F$ (Q=7.995 MeV), E_p=150 keV. The former background source could be avoided choosing a beam energy below this particular resonance and the latter will result in a summing peak below the region of interest ($E_\gamma \approx 9$ -12.5 MeV) in the spectrum.

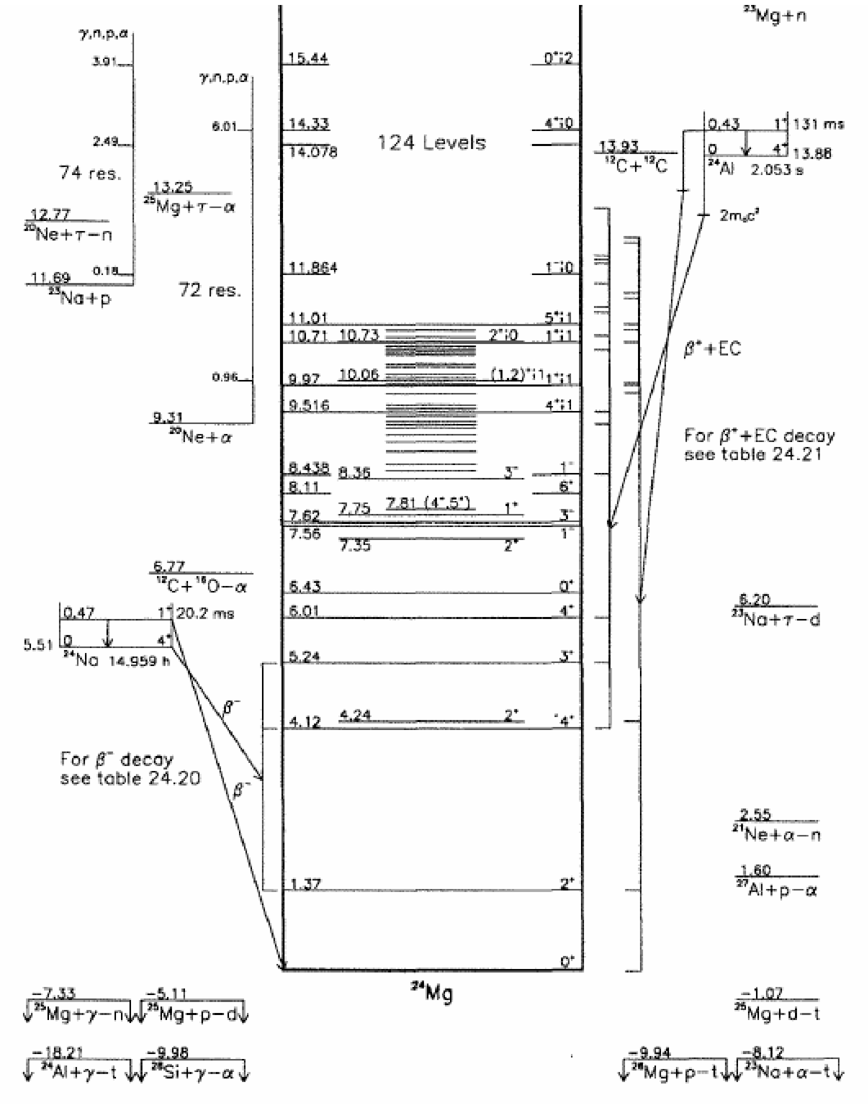

Figure 10. Level scheme of ^{24}Mg [End90]

Assuming a proton beam current of about 200 μA one expects a thick-target yield of about $2 \cdot 10^8$, $1.4 \cdot 10^6$, and 600 (upper limit) counts/h, for the $^{23}Na(p,\gamma)^{24}Mg$ resonances at E_p=309, 251, and 144 keV, respectively. These numbers show that it is possible to determine for the first time the resonance strength of the low energy E_p=144 keV resonance or at least to reduce the upper limit to a value where the claim that this resonance does not play any role is justified. This would reduce significantly the present uncertainty on the reaction rate at low temperatures and fix the ratio between the $^{23}Na(p,\alpha)^{20}Ne$ and $^{23}Na(p,\gamma)^{24}Mg$ reactions (Fig.11).

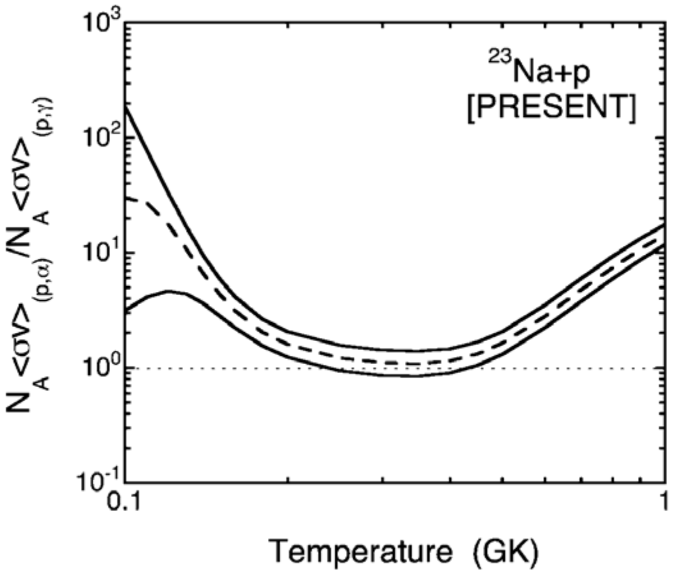

Figure 11. Ratio of the reaction rates for $^{23}Na(p,\alpha)^{20}Ne$ and $^{23}Na(p,\gamma)^{24}Mg$ [Row04]

4. Experimental setup and schedule

The LUNA 400 kV accelerator has been installed at Gran Sasso in the year 2000. It is an electrostatic machine (High Voltage Engineering, Europe BV) which accelerates protons and alphas produced by an RF ion source mounted on its high voltage terminal. The terminal voltage is generated by an inline-Cockcroft-Walton power supply capable to handle a beam of 1 mA at 400 kV. The absolute energy is determined with a precision of ±300 eV with a spread smaller than 100 eV and a long term stability of 5 eV per hour [For03]. The accelerator is imbedded in a tank (1 m diameter and 2.8 m long) which is filled with N_2/CO_2 insulation gas at 20 bar (Fig.12).

Until summer 2006 the accelerator was equipped with only one beam line. Since then we have a second line (the two lines can be used alternatively). On the first beam line we have mounted a fully shielded HPGe detector and a windowless gas target set-up, whereas on the second one we have a solid target set-up (Fig.13).

The program described in this proposal can be performed without major modification of the experimental set-up we already have. In particular, the solid and gas target systems developed in the past can be entirely used. We almost have all the required detectors: two high efficiency (125-135%) ultra-low background HPGe, two 105% efficiency HPGe and a large summing BGO detector. In order to perform angular distribution measurements and reach even lower energy regions we are planning to

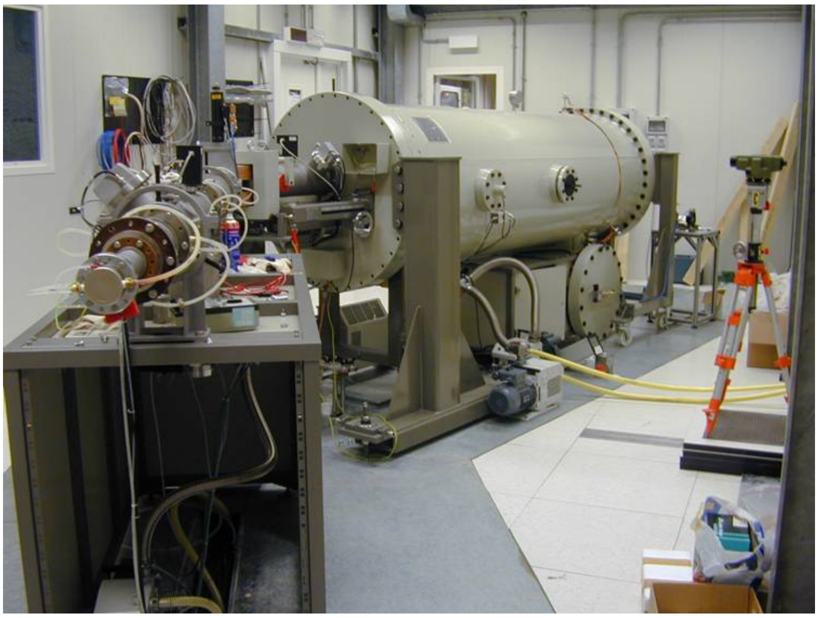

Figure 12. The LUNA 400 kV accelerator in the year 2002

acquire in the future high efficiency crystals with higher granularity and better energy resolution than the existing BGO. Such detectors, made of NaI, CsI or the recently developed $LaBr_3$, could become part of a large array to be used in future experiments with a new high voltage (few MV) accelerator.

Extrapolating from the LUNA budget of the last years we estimate 150 kEuro/year expenses for running costs and for equipment and detector maintenance. The new segmented detector with good energy resolution would require an additional investment of about 200 kEuro. The cost of the experiment will be shared among the different participating institutions according to the Memorandum of Understanding.

The experimental program will start with the $^{2}H(\alpha,\gamma)^{6}Li$ reaction in 2008 followed by $^{15}N(p,\gamma)^{16}$ in 2009. The schedule of the experiments, from 2010 to 2012, will be defined in 2009 also considering the updated scientific situation.

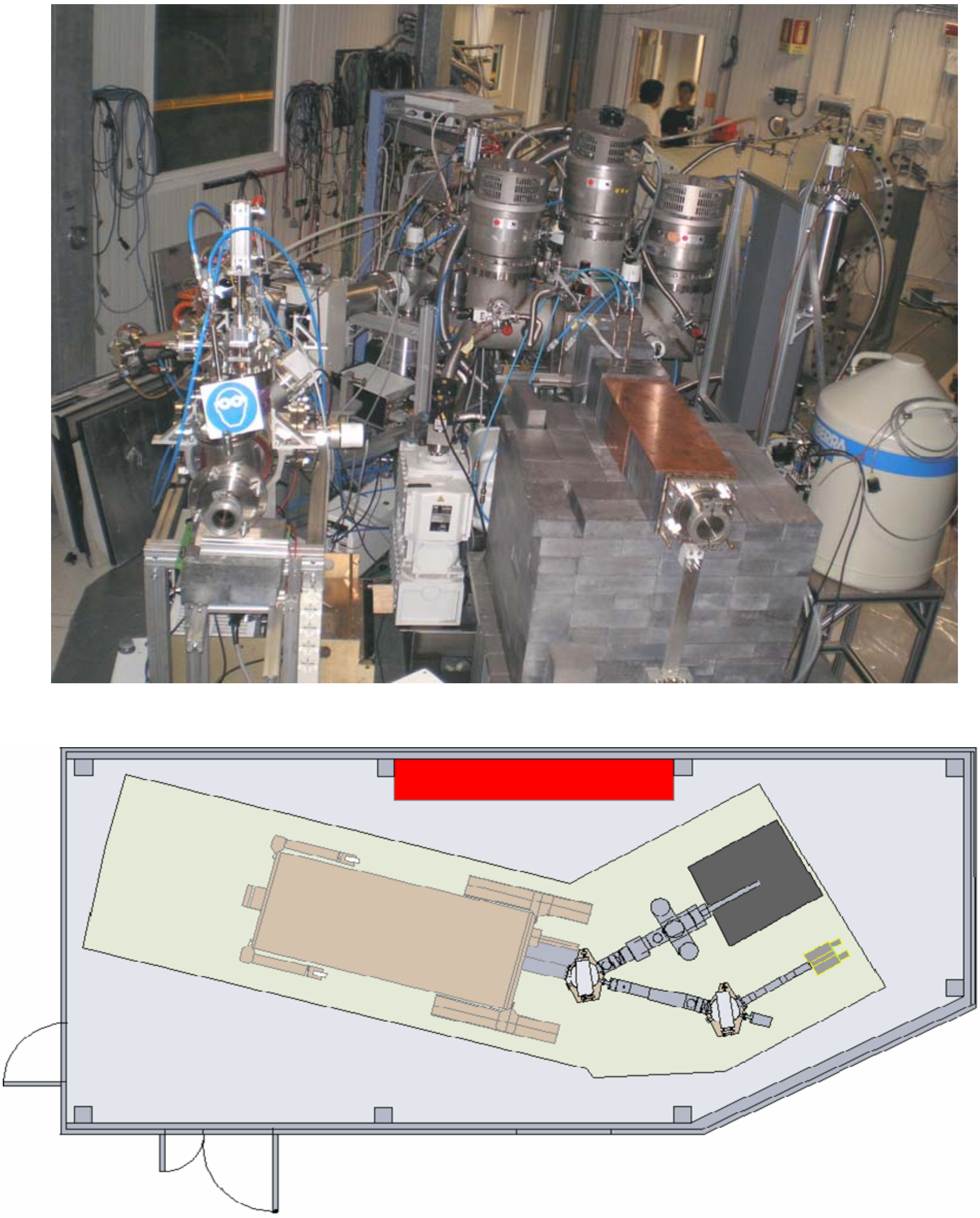

Figure 13. The LUNA experimental set-up in February 2007, with the gas target of the $^{3}He(\alpha,\gamma)^{7}Be$ experiment on the right and the second beam line on the left (in the photo)

Bibliography

[Ang99] C. Angulo et al., Nucl. Phys. A 656(1999)3
[Asp06] M. Asplund et al., Astrophys. J. 644(2006)229
[Au03] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. A 729(2003)337
[Bah04] J.N. Bahcall et al., Phys. Rev. Lett. 92(2004)121301
[Bem05] D. Bemmerer et al., Eur. Phys. J. A 24(2005)313
[Bem06] D. Bemmerer et al., Phys. Rev. Lett 97 (2006)122502
[Bon02] P. Bonifacio et al., Astron. Astrophys. 390(2002)91
[Bon99] R.Bonetti et al., Phys. Rev. Lett. 82(1999)5205
[Cam73] A.G.W. Cameron, Space Sci. Rev. 15(1973)121
[Car04] E. Carretta et al. Astrophys. J. Lett. 610(2004)L25 - L28
[Cas02] C.Casella et al., Nucl. Phys. A 706(2002)203
[Cas02b] C.Casella et al., Nucl. Instr. Meth. A 489(2002)160
[Coc04] A. Coc et al., Astrophys. J. 600(2004)544
[Con07] F. Confortola et al., submitted for publication
[End90] P.M. Endt, Nucl. Phys. A 521(1990)1
[For03] A. Formicola et al., Nucl. Instr. Meth. A 507(2003)609
[For04] A. Formicola et al., Phys. Lett. B 591(2004)61
[Fox05] C. Fox et Al., Phys. Rev. C 7(2005)055801
[Gor04] J. Görres, M. Wiescher, and C. Rolfs, Astrophys. J. 343(1989)365
[Gor83] J. Görrres et al. Nucl. Phys. A 408(1983)372
[Gyu07] Gy. Gyurky et al, Phys. Rev. C 75(2007)035805
[Hal01] S. E. Hale et al. Phys. Rev. C 65(2001)15801
[Ham06] F. Hammache et al., PoS(NIC-IX)013 (2006)
[Har84] M.J. Harris and D.L. Lambert, Astrophys. J. 281(1984)739
[Har84b] M.J. Harris and D.L. Lambert, Astrophys. J. 285 (1984) 674
[Har85] M.J. Harris, D.L. Lambert and V.V. Smith, Astrophys. J. 299(1985)375
[Har87] M.J. Harris et Al., Astrophys. J. 316(1987)294
[Heg05] A. Heger et al., Phys. Lett B 606(2005)258
[Her04] F. Herwig et al., Astrophys. J.613(2004)L73
[Imb04] G. Imbriani et al., Astronomy and Astrophysics 420(2004)625
[Imb05] G. Imbriani et al., Eur. Phys. J A 25(2005)455
[Inn04] S. Degl'Innocenti et al., Phys. Lett. B 590(2004)13
[Jed06] K. Jedamzik, Phys. Rev. D 74(2006)10309
[Jos04] J. Jose et al., Astrophys. J. 612(2004)414
[Kha98] A. Kharbach and P. Descouvemont, Phys. Rev. C 58(1998)1066
[Kie91] J. Kiener et al., Phys. Rev. C 44(1991)2195
[Kra98] R. P. Kraft et al. Astrophys. J. 115(1998)1500

[Lac06] M. La Cognata et al., Eur. Phys. J. A 27(2006)249
[Lan72] V. Landre et Al., Phys. Rev. C 40(1989)1972
[Lem06] A. Lemut et al., Phys. Lett. B 634(2006)483
[Lor78] H Lorenz-Wirzba et al. Nucl. Phys. A 313(1978)346
[Mak80] H-B. Mak et Al., Nucl. Phys. A 343(1980)79
[Neu06] D. Neufeld et al., Astron. Astrophys. 454(2006)L37-L40
[Pal05] A. Palacios, M. Arnould and G. Meynet, Astron. Astrophys. 443(2005)243
[Pra04] N. Prantzos, Astron. Astrophys. 420(2004)1033
[Pra06] N. Prantzos, Astron. Astrophys. 448(2006)665
[Rol73] C. Rolfs, Nucl. Phys. A 217(1973)29
[Rol74] C. Rolfs and W. Rodney, Nucl. Phys. A 235(1974)450
[Rol75] C. Rolfs et al. Nucl. Phys. A241(1975)460
[Rol88] C.Rolfs W.S.Rodney, "Cauldron in the cosmos", Un. of Chicago Press
[Row04] C. Rowland et al., Astrophys. J. 615(2004)L37
[Smi93] V. Smith et al., Astrophys. J. 408(1993)262
[Spi82] F. Spite and M. Spite, Astron. Astrophys. 115(1982)357
[Til93] D. Tilley, H. Weller and C. Cheves, Nucl. Phys. A 564(1993)1
[Van00] E. Vangioni-Flam et al., Astron. Astrophys. 360(2000)15
[Vog90] K. B. Vogelaar et al. Phys. Rev. C 42 (1990)753
[Wie80] M. Wiescher et al. Nucl. Phys. A 349(1980)165