A possible underground accelerator in the Dresden Felsenkeller

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Abstract. Typical energies in an astrophysical scenario lie far below the Coulomb barrier. Therefore the cross section is tiny, and in an in-beam experiment the experimental counting rate in $\gamma$ detectors is low. Often it is dominated by cosmic-ray induced background, even if suitable anticoincidence shields are applied. This problem can be overcome by placing the accelerator deep underground, where a sufficiently thick rock overburden attenuates cosmic rays. Based on the success of the LUNA 400 kV underground accelerator in Italy, several higher-energy underground accelerators are in the planning phase worldwide. All of them should be hosted in laboratories shielded by over 1000 m of rock, where cosmic-ray muons are negligible for the purposes of nuclear physics experiments. A preliminary background study indicates that a combined approach, using a shallow underground laboratory below 47 m of rock and an active shield to suppress surviving muons, results in a background level that is similar to deep underground sites.

The modeling of nuclear processes in astrophysical scenarios such as the Big Bang, stars, and stellar explosions requires a host of nuclear physics informations as input parameters, including precise cross sections of radiative capture reactions [1, 2, 3]. These reactions have generally been well-studied for energies above the Coulomb barrier. However, the astrophysically relevant energies lie far lower, and extrapolations are fraught with uncertainty. Therefore, it is desirable to measure the cross section directly at the energy of astrophysical relevance, or at least close to it. At these energies, the Coulomb barrier has to be penetrated by quantum mechanical tunneling, so the cross section values are very low. In turn, this results in very low experimental yields, so that the laboratory background counting rate in a detector becomes a limiting factor.

This difficulty can be overcome by placing the entire laboratory in an underground setting. Rock overburdens that are a few meters thick suffice to suppress the nucleonic part of the cosmic-ray induced background to negligible levels [4]. However, at these depths there remains a flux of cosmic-ray induced muons that is only slowly attenuated [5]. This remaining muon flux is troublesome because it leads to tertiary neutrons that are produced inside the shielding or the detector itself [6] and which are exceedingly difficult to suppress with active or passive shields.

In order for the background to become negligible for the purpose of nuclear astrophysics experiments, depths of about 1000 m rock are required. The only underground accelerator worldwide, the LUNA 400 kV machine, is located in the Gran Sasso laboratory in Italy, below 1400 m rock. It has been used with great success to study solar fusion and big bang nuclear
reactions [8].

However, a combined approach is conceivable where (a) a somewhat thinner rock overburden is used to reduce tertiary neutrons to a level that is comparable to the ambient neutron flux in Gran Sasso [7] and (b) the direct effects of secondary muons are vetoed by an active shield detector. In order to test this idea, the γ-ray background in one and the same actively vetoed high-purity germanium (HPGe) detector, a so-called "traveling" detector, has been studied at different sites: at the Earth’s surface, shallow underground at the Felsenkeller facility in Dresden/Germany below 47 m of rock [9], and deep underground at Gran Sasso.

The Felsenkeller facility is sited in the Plauenscher Grund former quarry in Dresden. In the 1850’s, a tunnel system was dug into the rock, in order to make ice cellars for a nearby, now decommissioned brewery. Since 1982, the Felsenkeller low-level counting facility is installed in one of the nine tunnels. It is presently operated by Verein für Kernverfahrenstechnik und Analytik Rossendorf (VKTA) and used mainly for analytics. The adjacent rock consists of hornblende monzonite, with a relatively high $^{232}$Th and $^{238}$U content. The low level counting facility hosts two shielded laboratories called Messkammer 1 and 2 (MK1 and MK2). The data reported here have been taken in MK2, which was constructed in 1995 and has 25 cm thick walls of iron and steel, in part pre-1945.

For the background study, a EURISYS Clover-type detector [10] has been used. It consists of four coaxial n-type HPGe detectors arranged like a four-leaf clover. The detectors are 71 mm long and have a tapered circular area of originally 51 mm diameter. The spacing between the crystals is only 0.2 mm, leading to a closely packed geometry. The virtual large detector formed by the four crystals in addback mode has 122% relative efficiency. In the present study, the Clover detector is always used in conjunction with a surrounding BGO scintillator. For the addback mode data, the BGO can act as a Compton suppression veto.

At Felsenkeller the data have been taken in the heavy shielded MK2, but no heavy shield have been applied during the surface and Gran Sasso runs. Therefore, no direct comparison can be made in the low energy region. However, the effect of the escape-suppression shield is most visible at $E_\gamma > 5.5$ MeV, where both the background from radioisotopes and α emitters in the crystal do not play a role any more (fig. 1). At LUNA the data was recorded during the stops of the running experiments. Therefore, the dynamic range of the detector have been set for the

![Figure 1.](image-url) (Color online) γ-ray background in a Clover HPGe detector: Earth’s surface, free-running (black dotted line) and with active muon veto (black dot-dot-dashed line). Shallow underground, free-running (red dashed line) and with active muon veto (red dot-dashed line). Deep underground [12, limited to 0-8 MeV], free-running (blue solid line) and with active muon veto (blue short dashed line).
experiment, and the spectra ended at 8 MeV. The recorded energy region is, however, relevant to a number of radiative-capture reactions of interest for astrophysics. For example, for the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction controlling the rate of the CNO cycles, at astrophysically relevant energies the three major transitions include $\gamma$-lines between 6 and 8 MeV $\gamma$-energy. In this energy range, the escape-suppressed counting rate of one and the same detector is only a factor 3 worse in Felsenkeller when compared to LUNA.

The science case for a higher-energy accelerator underground requires to move beyond the Sun and study reactions with higher-lying Gamow peaks that are inaccessible at the LUNA 0.4 MV facility. With a 2 MV underground accelerator the following reactions would be opened up for study:

- The $(\alpha,\gamma)$ reactions of stellar helium burning,
- the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reactions providing the neutrons for the slow neutron capture process, the so-called astrophysical s-process,
- $^{12}\text{C}$-induced reactions for stellar carbon burning, and
- selected supernova-related reactions, e.g. $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$

Presently, projects for underground accelerators of 2-4 MV acceleration potential are under discussion at Gran Sasso/Italy [11], Canfranc/Spain, Boulby/UK, and Homestake Mine/US. All these sites have rock overburdens of 1000 m of more and are expected to show background characteristics that are equal to or better than the known background at LUNA [12, and references therein].

However, constructing and maintaining an accelerator laboratory in any of these places requires considerable effort and lead-up time. Therefore, it is conceivable that a staged approach would accelerate progress: In an initial stage, the ease of access to a shallow-underground site like Felsenkeller would be exploited to gain low-energy cross-section data, while deep-underground facilities would still complete their preparatory phase. Subsequently, the even lower background there would be used to pursue the most promising projects, taking advantage of the experience gained shallow underground.

As it has been recognized by the community that it may be necessary to construct more than one underground accelerator (see white paper at http://www.hzdr.de/felsenkeller), the call for one or more underground accelerators has been highlighted in the NuPECC Long Range Plan 2010 (http://www.nupecc.org).

Acknowledgments
This work has been supported in part by the Herbert Quandt Foundation, DFG (BE 4100/2-1), and EuroGENESIS.

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