PROCEEDINGS OF SCIENCE

Felsenkeller shallow-underground accelerator laboratory for nuclear astrophysics

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Underground, low-background accelerator-based experiments are an important tool to study nuclear reactions directly at energies relevant for astrophysical processes. This technique has been developed and proven at the 0.4 MV LUNA accelerator in the Gran Sasso laboratory in Italy, shielded from cosmic rays by 1400 m of rock. However, the nuclear reactions of helium and carbon burning and the neutron source reactions for the astrophysical s-process require higher beam energies. The same is true for the study of solar fusion reactions. Therefore, the NuPECC long range plan for nuclear physics in Europe strongly recommends the installation of one or more higher-energy underground accelerators.

Detailed background studies have shown that the Felsenkeller shallow-underground laboratory in Dresden, with a rock overburden of 45 m, has very low background in γ-ray detectors typical for nuclear astrophysics experiments when an additional active shield is used to veto the remaining muon flux.

A used 5 MV pelletron tandem with 250 μA upcharge current and external sputter ion source is currently being refurbished for installation in Felsenkeller. Work on an additional radio-frequency ion source on the high voltage terminal is underway. The project is fully funded, and the installation of the accelerator in the Felsenkeller laboratory is expected for the near future.

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1. Introduction

After the resolution of the solar neutrino problem by the discovery of neutrino flavour oscillations [1], a new problem regarding the Sun has arisen: The solar abundance puzzle [2]. The problem consists in the fact that the newly redetermined elemental abundances at the surface of the Sun lead to a standard solar model inconsistent with helioseismological observations [3].

In principle, the detection of solar neutrinos from the carbon-nitrogen-oxygen (CNO) cycle offers a way to directly determine the abundances of the elements carbon and nitrogen in the solar core [4]. However, for a correct interpretation of the possible CNO neutrino data, more precise cross sections of the solar fusion processes are required.

The field of solar fusion cross sections has benefited greatly from data obtained in recent years at the world's only underground ion accelerator, LUNA (Laboratory for Underground Astrophysics) [5]. This machine with 0.4 MV acceleration potential helped to improve the standard solar model [6]. Big Bang reactions were studied there, as well [7, 8]. The reason for this success story is the very low no-beam background. A rock overburden of 1400 m thickness suppresses the muon flux by six orders of magnitude and the neutron flux by three orders of magnitude [5].

However, the beam energy range at LUNA is limited, and several key solar fusion reactions actually require new data at higher energies to improve the overlap between underground and surface data and provide comprehensive data sets for extrapolations [6]. Due to this fact, a project

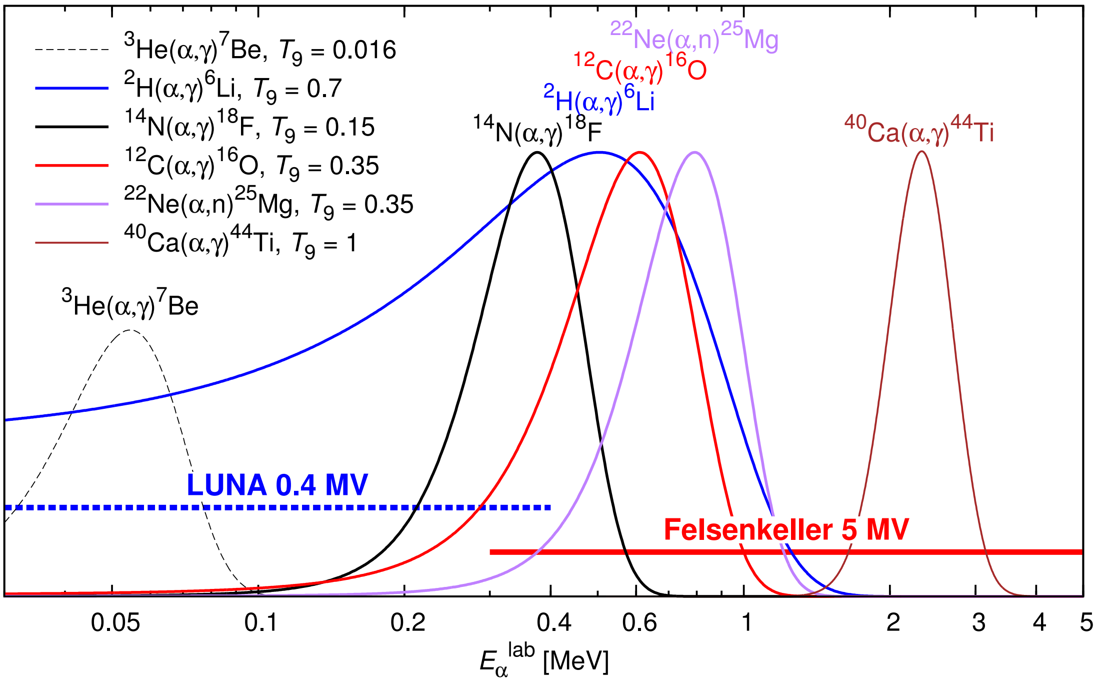

Figure 1: Gamow peaks of selected nuclear reactions, as a function of α beam energy in the laboratory: Solar fusion (^{3}He(α,γ)^{7}Be), Big Bang nucleosynthesis (^{2}H(α,γ)^{6}Li), stellar helium burning and s-process neutron production (^{14}N(α,γ)^{18}F, ^{12}C(α,γ)^{16}O, and ^{22}Ne(α,n)^{25}Mg), and the α-rich freezeout (^{40}Ca(α,γ)^{44}Ti). For each reaction, a temperature T_9 in GK corresponding to the related scenario is given in the legend.

for an additional, 3.5 MV accelerator is underway at LUNA (talk by Marialuisa Aliotta), and a high-current 5 MV underground accelerator is being developed at the Dresden Felsenkeller (this contribution).

In addition to complementing low-energy LUNA data on solar fusion and Big Bang nuclear reactions with higher-energy data, the new underground accelerators may open up scenarios such as helium [9] and carbon [10] burning and the neutron source reactions for the astrophysical s-process [11] to experimental study. Even nuclear reactions included in explosive scenarios such as the α-rich freezeout in supernovae [12] may benefit (fig. 1).

2. Site status and background studies

Inside the city limits of Dresden, Germany, there is a system of nine tunnels shielded by 45 m of hornblende monzonite rock. Since 1982, one of the tunnels hosts an underground laboratory for low-radioactivity measurements [13]. Two additional tunnels will be readied in 2015 for the installation of a 5 MV ion accelerator for nuclear astrophysics (fig. 2).

For nuclear astrophysics radiative capture experiments, the background in the 4-12 MeV γ-energy region is of decisive importance. In order to address this point, a background intercomparison was carried out using one and the same Compton-suppressed high-purity germanium (HPGe) detector system. This system was moved successively to several sites. The data show that with a muon veto, the background in the 6-8 MeV energy region is only a factor of 2-4 higher in Felsenkeller than deep underground at LUNA, enabling highly sensitive experiments [14]. The exercise was repeated with a 3” $\mathrm{LaBr_3}$ detector, and again the background in Felsenkeller was less than one order of magnitude higher than deep underground at LUNA, if a muon veto was used [14].

Recently, a muon background study and geodetic measurements were carried out at Felsenkeller. It was estimated that the rock overburden at the place of the future ion accelerator is equivalent to

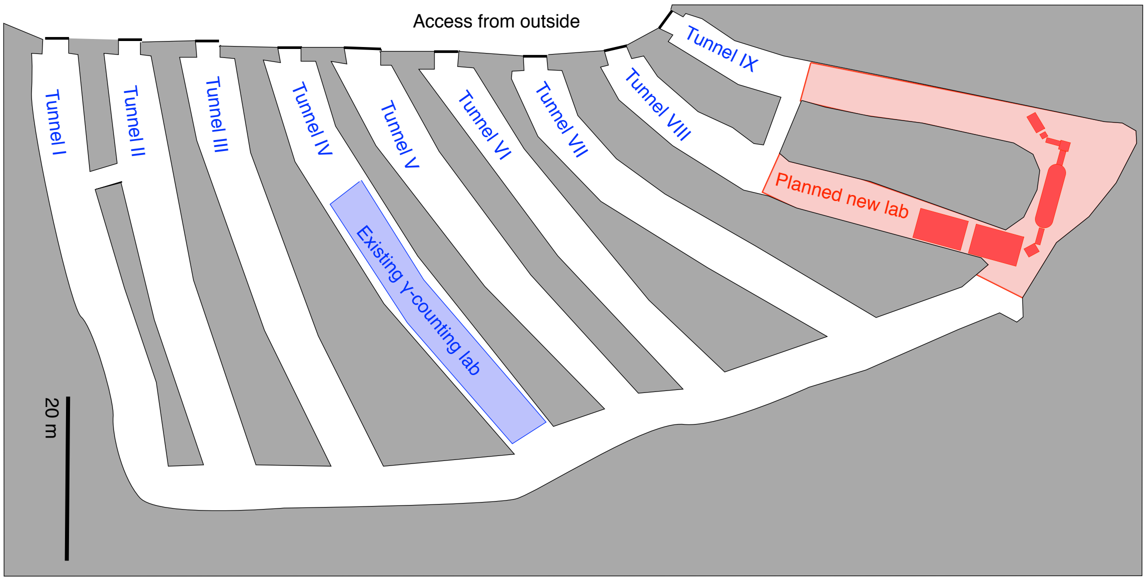

Figure 2: Layout of the Felsenkeller underground facility with the existing [13] and the planned new laboratory.

130 m of water. The maximal directional muon flux measured, 2.5 $m^{-2}sr^{-1}s^{-1}$, was found to come from the direction of the tunnel entrance [15].

3. The 5 MV Pelletron accelerator

For the purpose of the project, a used accelerator mass spectrometry system consisting of a 5 MV Pelletron with double charging chains (250 μA upcharge current, high-current MC-SNICS sputter ion source for hydrogen and carbon beams) was recently bought and transported to Dresden. The accelerator is undergoing refurbishment at HZDR, applying necessary maintenance to components that have been running for twelve years, such as the pellet chains and motor, vacuum generating systems, pressurized gas systems, and external sputter ion source. A possible upgrade of the automated control system of the accelerator is under study.

In addition, a radio frequency ion source is projected to be added to the high voltage terminal. This additional ion source is based on a model that has been running successfully at HZDR for many years [16] and shall enable the generation of intensive helium beams. The ions will be injected at an angle of 30° into the acceleration tube. Therefore the tandem mode of operation will be kept in addition to the terminal ion source.

As a result, intensive beams of ^{1}H, ^{4}He (from the terminal ion source), and ^{12}C will be provided at astrophysically relevant energies. Additional beams available in tandem mode include ^{14,15}N.

4. Example for an astrophysical application

As an example for an astrophysical application, an in-beam spectrum from an experiment on the $^{12}C(p,\gamma)^{13}N$ reaction is shown. The data have been taken at the HZDR 3 MV Tandetron on the Earth's surface (fig. 3, [17]). Despite the satisfactory carbon beam intensity, the massive lead shielding (12 cm, close to the optimum for a surface-based detector) and the muon veto, the signal is already close to the no-beam background at a center-of-mass energy of 190 keV. When running at 100 keV instead, the signal is expected to drop by a factor of 70, making a surface-based measurement impossible. However, the background at Felsenkeller is low enough that such a study would be possible there, once the accelerator is installed.

5. Outlook

The Felsenkeller accelerator will be a versatile tool able to address solar fusion and Big Bang reactions at energies higher than those available at LUNA, as well as the nuclear reactions of carbon and helium burning and the neutron sources for the astrophysical s-process (fig. 1).

In addition, also a large, well-shielded HPGe detector for offline counting will be included in the new laboratory, enabling activation experiments as well as material selection for dark matter studies.

The fact that an existing, immediately available accelerator is used means that at Felsenkeller important hands-on experience may soon be collected, aiding the preparation of deeper-underground

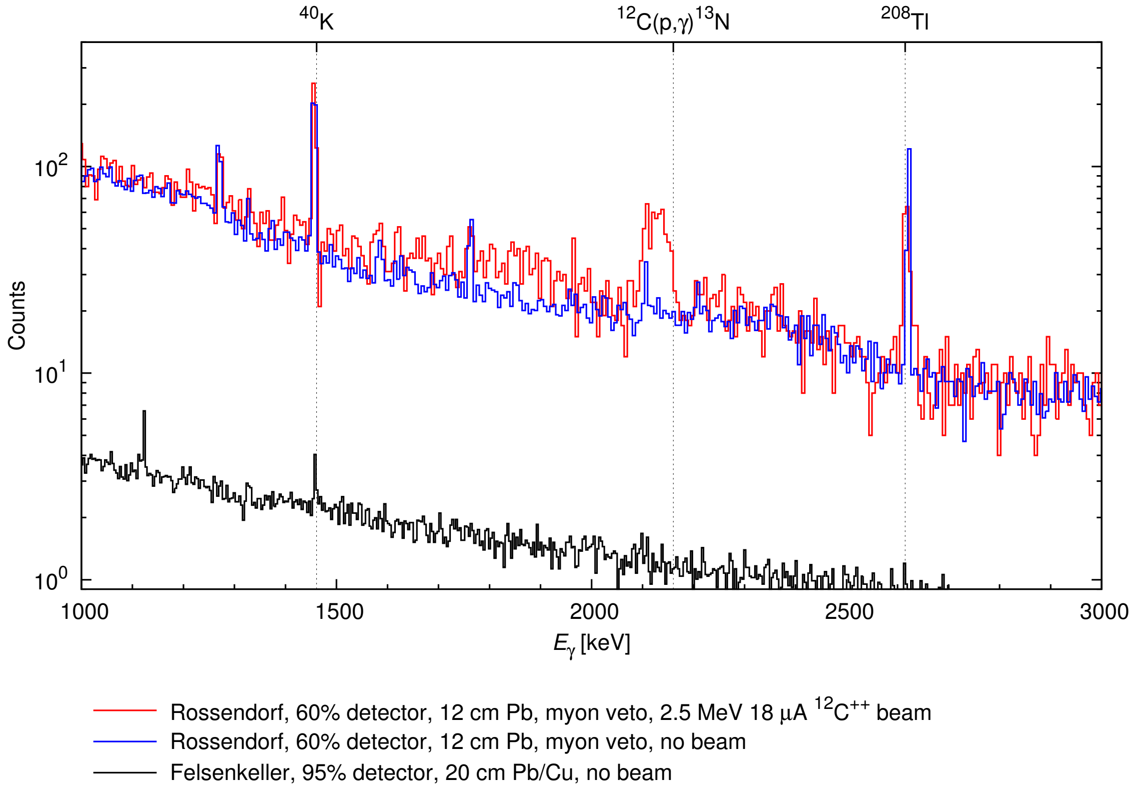

Figure 3: In-beam γ-ray spectrum obtained at the Earth's surface (Rossendorf) in an overnight run with intensive carbon beam on an implanted hydrogen target (red curve, [17]). Two other spectra are shown, rescaled for equal running time: no beam in the same setup (blue curve, [17]), and no beam underground (Felsenkeller, [13]).

projects such as LUNA-MV with their longer time horizons. In addition, the proximity of the laboratory to the TU Dresden campus will facilitate its use as an educational and outreach tool.

The accelerator will be used in part for in-house research by HZDR and TU Dresden, aiming for complementarity with the LUNA-MV project and science program. In addition, external users from any field of science will be highly welcome at Felsenkeller. Users are to be selected based on the recommendations of an independent group of outside advisers judging the scientific merits of the proposals.

The project (accelerator purchase, tunnel refurbishment) is fully funded. Existing preliminary plans for the tunnel renovation are currently being updated. An optimistic opening date of late 2015 is projected.

Acknowledgments

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