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Felsenkeller 5 MV underground accelerator: Towards the Holy Grail of Nuclear Astrophysics ^{12}C(α,γ)^{16}O

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Abstract. Low-background experiments with stable ion beams are an important tool for putting the model of stellar hydrogen, helium, and carbon burning on a solid experimental foundation. The pioneering work in this regard has been done by the LUNA collaboration at Gran Sasso, using a 0.4 MV accelerator. The present contribution reviews the status of the project for a higher-energy underground accelerator in Felsenkeller, Germany. Results from γ-ray, neutron, and muon background measurements in the Felsenkeller underground site in Dresden, Germany, show that the background conditions are satisfactory.
Two tunnels of the Felsenkeller site have recently been refurbished for the installation of a 5 MV high-current Pelletron accelerator. Civil construction work has completed in March 2018. The accelerator will provide intense, 50 μA, beams of ^{1}H^{+}, ^{4}He^{+}, and ^{12}C^{+} ions, enabling research on astrophysically relevant nuclear reactions with unprecedented sensitivity.

1 Introduction

Experimental nuclear astrophysics aims to understand the origin of the chemical elements by laboratory experiments [1].

One particularly challenging case is the ^{12}C(α,γ)^{16}O reaction. Its rate affects the carbon to oxygen abundance ratio at the end of stellar helium burning and, hence, the abundances of a host of other nuclides that are produced during subsequent burning stages [2]. There are no direct cross section data in the astrophysically relevant energy range, so the present knowledge of its rate depends on indirect approaches and R-matrix fits of a complicated excitation function, resulting in different central values and widely different error estimates [3–6].

A second key aspect of nuclear astrophysics are the nuclear reactions of solar hydrogen burning. After the discovery of solar neutrino oscillations [7], the focus has shifted to precision studies of our sun. Neutrino fluxes are presently better known than the related nuclear reactions of the proton-proton (pp) chain. Recently, they have been used to determine the cross sections of two pp-chain nuclear reactions: ^{3}He(α,γ)^{7}Be [8] and ^{7}Be(p,γ)^{8}B [9].

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The most precise technique hitherto developed to address stable-ion nuclear reactions such as these is underground nuclear astrophysics, which has been pioneered by the LUNA collaboration working deep underground in the Gran Sasso laboratory, Italy [10]. There, in recent years a number of nuclear reactions important for Big Bang nucleosynthesis [11, 12] and for stellar hydrogen burning [13–15, recent examples] have been studied using a 0.4 MV high-current accelerator.

The present contribution describes the progress of the higher-energy underground accelerator in Felsenkeller, Dresden, with a science program that is complementary to LUNA and also to the LUNA-MV project (F. Cavanna, these proceedings).

2 Background studies

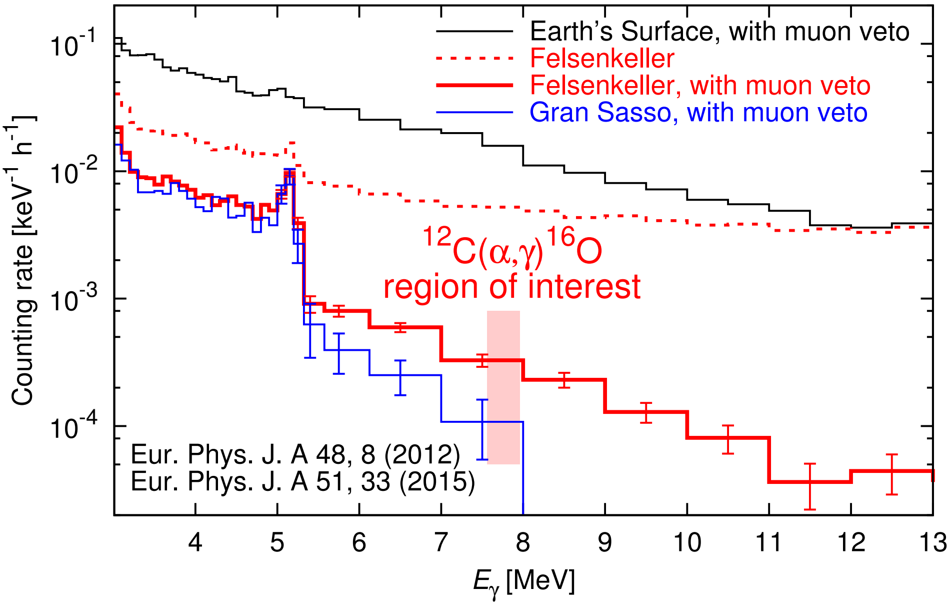

Figure 1. Background intercomparison using one and the same escape-suppressed HPGe detector, subsequently transported to different sites. The data [16, 17] show that using a muon veto, the Felsenkeller background is not far from the deep underground (Gran Sasso) case.

The Felsenkeller site is located 5 km from the city center of Dresden, Germany (population 500,000) and protected from cosmic rays by 45 m of hornblende monzonite rock. It consists of nine horizontal tunnels, two of which are used for the accelerator laboratory (see below). Detailed studies of the muon and neutron background have been carried out in the tunnels and will be described in forthcoming work.

The most important aspect for underground nuclear astrophysics, however, is the remaining high-energy background in a typical in-beam γ-ray detector. Detailed measurements at Felsenkeller [16, 17] have shown that the background in the crucial 7-8 MeV γ-energy range (affecting *inter alia* the ^{12}C$(\alpha,\gamma)^{16}$O reaction) is only a factor of 3 higher in Felsenkeller than deep underground at Gran Sasso (Figure 1).

3 Scientific program

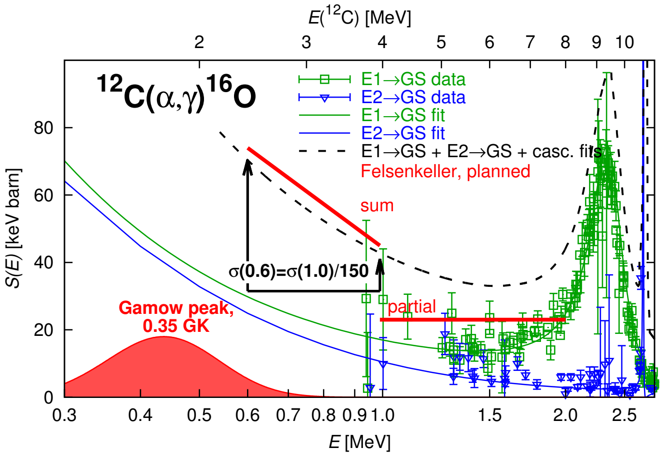

Figure 2. Excitation function of the $^{12}C(\alpha,\gamma)^{16}O$ reaction. Experimental data [18] and R-matrix fits for the dipole [18], quadrupole [4], and sum of all components [18] are plotted. The feasible energy range for direct total and partial cross section data at Felsenkeller, based on the measured background [16, 17] and assuming inverse kinematics, and the Gamow peak for 0.35 GK temperature are also shown.

The Felsenkeller scientific program draws on many years of experience in nuclear astrophysics experiments at the overground HZDR 3 MV Tandetron accelerator [19–24] and on a long-standing involvement in the LUNA collaboration [10, 11]. Complementary experiments studying the γ-widths of relevant levels [25, 26] have been performed at the local bremsstrahlung facility [27] and are underway at the local neutron time-of-flight facility [28].

For the in-house research by the two institutions HZDR and TU Dresden that together run the new Felsenkeller underground ion beam, two initial science cases have been selected: The $^{12}C(\alpha,\gamma)^{16}O$ reaction affecting helium burning and the $^{3}He(\alpha,\gamma)^{7}Be$ reaction affecting solar ^{7}Be and ^{8}B neutrinos.

In order to give an example of the science potential, the excitation function of the $^{12}C(\alpha,\gamma)^{16}O$ reaction is plotted in Figure 2. There are no significant data points below 1 MeV center-of-mass energy, yet in this range both the E1 and the E2 components of the cross section exhibit a steep rise to lower energies, due to two subthreshold resonances, one in each of the two channels. New data are clearly needed to constrain the fits, and actually with a summing detector it is possible to provide direct cross section values inside the stellar Gamow peak. This inverse-kinematics experiment will require intense ^{12}C beam, $\sim 50\,\mu$A.

In the $^{3}He(\alpha,\gamma)^{7}Be$ case, the main challenge lies in linking the ultra-low energy LUNA data [11] with a host of other experiments at much higher energy. Again, this can be accomplished at Felsenkeller, using $\sim 50\,\mu$A ^{4}He beam, in the center-of-mass energy range of 0.2-2 MeV.

In addition to this in-house research, a significant amount of beam time will be made available, free of charge, as a facility to national and international users based on scientific proposals to be evaluated by an independent scientific advisory committee.

4 Project status

The ion accelerator, a 5 MV Pelletron with double charging chains and a nitrogen gas stripper, has been furnished with an additional terminal ion source that will provide intense ^{1}H and ^{4}He beams in single-ended mode. This terminal ion source is in addition to the remaining multi-cathode cesium sputter ion source that will supply intense ^{12}C beams in tandem mode. Taken together, with these two modes it will be possible to address the most challenging cases of low-energy nuclear astrophysics.

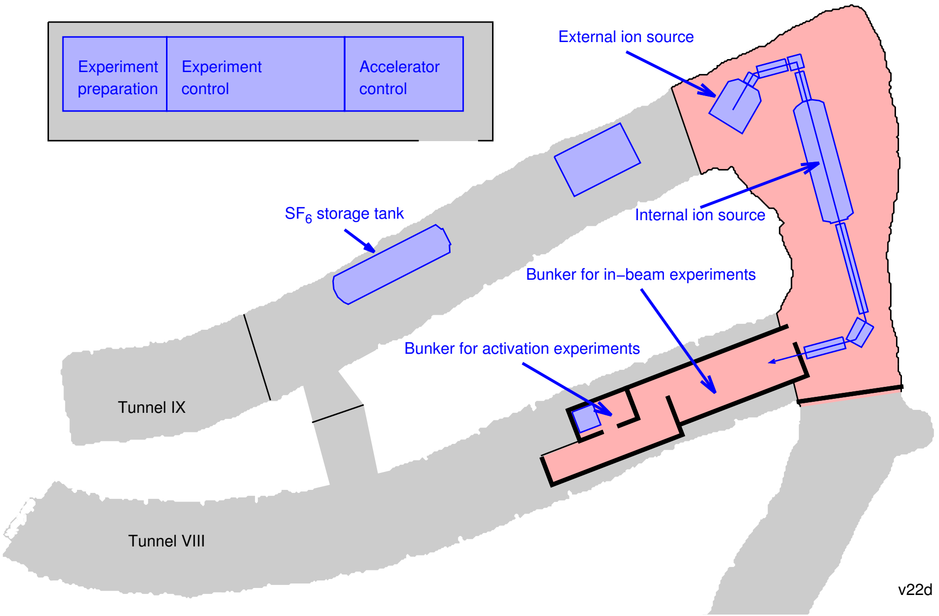

Figure 3. Sketch of the most important installations in Felsenkeller tunnels VIII and IX.

The original nine tunnels have been excavated in the 1850s to serve the former Felsenkeller brewery. Since 1982, tunnel IV hosts a low-activity γ-counting laboratory [29]. The new underground ion accelerator is hosted in tunnels VIII and IX (Figure 3).

As of the writing of this proceedings, the civil construction has completed. Most notably, a building has been erected inside the tunnels to house the accelerator and ion source, and two bunkers have been constructed from low-radioactivity concrete, one each for in-beam and activation experiments, respectively. A very large HPGe detector in a specially selected shield has been procured for the activity measurements. The ventilation and air conditioning system is already operating, and the accelerator and main electromagnets have been moved underground. The beam lines will be constructed in spring-summer 2018, with an aim to test both ion sources in the coming months.

It is hoped that first data from this new laboratory will be presented at the next CGS meeting.

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