प्रस्तावित सुविधा

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नाभिकीय खगोल भौतिकी हेतु भूमिगत सुविधा

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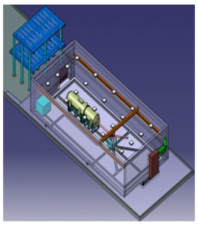

प्रस्तावित 5 MV डीसी त्वरक प्रयोगशाला की योजना

सारांश

एक भूमिगत नाभिकीय खगोल भौतिकी सुविधा का निर्माण 10 वर्षों की समय सीमा के भीतर प्रस्तावित है, जिसका कम से कम 1.5 किलोमीटर हिस्सा चट्टान के भीतर होगा। यह नाभिकीय खगोल भौतिकी की अपेक्षा के अनुरूप निम्न अनुप्रस्थ काट नाभिकीय अभिक्रियाओं के मापन हेतु आवश्यक स्तर तक ब्रह्मांडीय पृष्ठभूमि को कम करने में सहायक होगा। रु. 300 करोड़ की लागत से प्रथम 7 वर्षों के दौरान एक ईसीआईआर आधारित 5 MV डीसी त्वरक का निर्माण करने का प्रस्ताव है, जिसके बाद अगले 3 वर्षों के भीतर प्रायोगिक सुविधाओं का विकास किया जाएगा। यह सुविधा हीलियम और कार्बन दहन अभिक्रियाओं के लिए समर्पित होगी जिसका तापमान हाइड्रोजन दहन के दौरान होने वाली अभिक्रियाओं की तुलना में उच्च होती है।

Proposed Facility

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An Underground Facility for Nuclear Astrophysics

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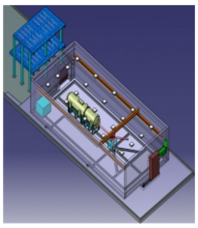

Schematic of the proposed 5 MV DC accelerator laboratory

ABSTRACT

An underground nuclear astrophysics facility has been proposed to be built in a time frame of 10 years, with a rock overburden of at least 1.5 km. This will help reduce the cosmic background to a level essential for the measurement of low cross section nuclear reactions of nuclear astrophysics interest. An ECIR based single ended 5 MV DC accelerator is proposed to be built in first 7 years, followed by the development of experimental facilities within next 3 years, with an outlay of Rs. 300 crore. This facility will be devoted to Helium and Carbon burning reactions that take place at higher temperatures than those occurring during the hydrogen-burning processes.

KEYWORDS: *ECR, Cosmic, Carbon burning, Hydrogen-burning.*

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Background

For more than two decades LUNA (Laboratory for Underground Nuclear Astrophysics) in Gran Sasso, Italy [1-3] has been the only underground laboratory in the world. Over the years many plans have been discussed on different continents for additional laboratories dedicated to the study of nuclear reactions of astrophysical interest at very low energies under almost background free conditions. Only now some of these projects (like Jinping Underground facility for nuclear astrophysics (JUNA) in China [4], Compact Accelerator System for Performing Astrophysical Research (CASPAR) in USA [5] and Felsenkeller shallow underground facility at Germany [6] became or will soon become reality. To keep pace with the international communities, we propose a low energy underground accelerator for nuclear astrophysics, the first of its kind in India.

Motivation

Accurate knowledge of thermonuclear reaction rates is a key issue in nuclear astrophysics since it is important for understanding the energy generation, neutrino production and the synthesis of the elements in stars. Cross-section measurements are mainly hampered by the very low counting rate and cosmic background. An underground location is extremely advantageous for such studies, as demonstrated by the experiments in LUNA and recently in JUNA. It has been found that the rock overburden of about 1400 m (3800 m water equivalent) reduces the muon component of the cosmic background by a factor of 106; the neutron component by a factor of 103; and the gamma component by a factor of 10 with respect to a laboratory on the Earth's surface. As a result, the gamma background above 3 MeV in an HPGe detector placed underground is reduced by a factor of ~2500 with respect to the same detector placed over-ground. In addition, going underground enhances the effect of passive shielding particularly for lower energy gammas where the background is dominated by environmental radioactivity.

The proposal

We propose an underground nuclear astrophysics facility to be built in 10 years, with a rock overburden of at least 1.5 km. An ECR based single ended 5 MV DC accelerator is proposed to be built in first 7 years, followed by the development of experimental facilities within next 3 years, with a cost of Rs 300 Cr (excluding the tunnel cost).

Physics interest

The experimental programs using this facility are planned to be mainly devoted to Helium and Carbon burning reactions that take place at higher temperatures (i.e. higher energies) than those occurring during the hydrogen-burning processes. In particular, the 12C(α, γ)16O, 12C+12C and the (α, n) reactions on 13C and 22Ne are very important.

These key reactions of helium and carbon burning are responsible for the evolution of massive stars towards their final fate and the nucleosynthesis of most of the elements in the Universe. In particular, the 12C(α, γ)16O and 12C+12C reactions are the most ambitious goals of this project. During the He burning, the reaction 12C+α→ 16O+γ competes with the reaction 3α→ 12C+γ. These reaction rates will help determine the timescale of helium burning and the C/O ratio left at the end of the He burning. It also affects the white dwarf cooling timescale and the outcomes of both type Ia and core-collapse supernovae where 12C+12C is the trigger of C burning. The temperature at which C burning takes place depends on its rate: the larger the rate, the lower the C-burning temperature. Since the temperature controls the nucleosynthesis processes, reliable estimations of all the yields produced by C burning, for example the weak component of the s process which produces the elements between Fe and Sr, require precise knowledge of the 12C+12C rate. The 12C+12C rate also determines the lower stellar mass limit for C ignition. This limit separates the progenitors of white dwarfs, nova and type Ia supernovae, from those of core-collapse supernovae, neutron stars, and stellar mass black holes. This mass limit also controls the estimations of the expected numbers of these objects in a given stellar population, which are required to answer crucial questions such as: how many neutron stars are there in the Milky Way? How many double neutron stars are there in close binaries? And what is the expected merging rate?

Among the key processes for stellar nucleosynthesis, the sources of neutrons represent a longstanding and debated open problem [7,8]. Neutron-captures (the s or r processes) are known to be the most important mechanisms to produce the elements heavier than iron. The 13C(α,n)16O and 22Ne(α,n)25Mg reactions represent the most promising neutron sources as they operate from relatively low temperatures typical of He burning (100-300MK) and because 13C and 22Ne are relatively abundant nuclei in stellar interiors. The 13C(α,n)16O reaction operates in the He-burning

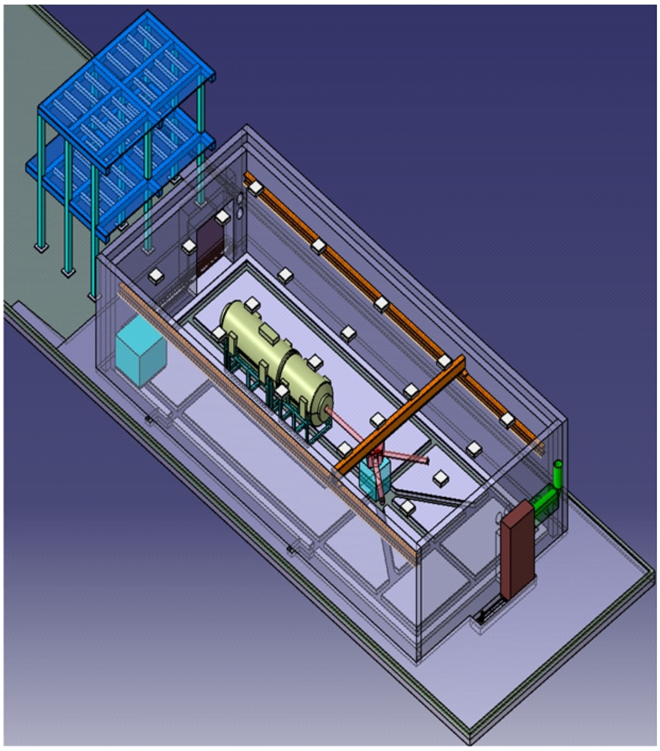

Fig.1: Schematic of the 5 MV accelerator laboratory.

shell of low-mass (less than 4 solar masses) AGB stars and it is the neutron source reaction that allows the creation of the bulk of the s-process elements such as Sr, Zr and the light rare earth elements in the Universe. The 22Ne(α,n)25Mg reaction operates in the He-burning shell of high-mass (more than 4 solar masses) AGB stars and during the core-He burning and the shell-C burning of massive stars (more than 10 solar masses). Experiments with the proposed underground accelerator facility will allow us to gain a full understanding of not only these two reactions but also many other important reactions through the direct measurement of their cross sections in the energy range of astrophysical interest.

Plans

Fig.1 shows the schematic of the 5 MV accelerator laboratory. It requires a minimum underground space of about 80 m x 10 m. However, in addition to the facility for nuclear astrophysics, several other underground experimental facilities (e.g., dark matter searches, neutrino observatory, etc.) have also been proposed to be built within the same underground laboratory. So, a total space of about 150 m x 500 m that can accommodate all these facilities has been proposed.

Where do we stand today?

The research in the area of experimental Nuclear Astrophysics in our country is very nascent. With the commissioning of a 3 MV tandem accelerator FRENA (Facility for Research in Nuclear Astrophysics) at Saha Institute of Nuclear Physics, the planning of a few experiments has just begun. However, the number of experiments that can be pursued using FRENA is limited due to following reasons: 1) Cosmic background is too high as the accelerator is kept over-ground 2) Non-availability of inert beam 3) minimum energy is too high with respect to Gamow peaks of many reactions and 4) maximum energy is too low for inverse kinematics. To overcome some of these problems, a new single ended 5 MV over-ground accelerator with ECR based positive ion source has been proposed at Cotton University, Guwahati. But to solve the background problem an underground facility is essential. Already, the search for a suitable site for an underground

Plan of execution/Timeline

Years	Implementation/Delivery
Phase-I	150 MHz
1st – 3rd	Building of tunnels and caverns; design of laboratories, beam lines & experiments.
4th to 7th	Procurement and commissioning of a 5 MV machine.
Phase-II	
7th – 10th	Setting up of experimental facilities including beam lines, detector array, target assembly and data acquisition system including a few challenging experiments will be completed.

laboratory in India has been initiated for Indian Neutrino Observatory, Dark Matter search, etc., and hence this facility can also be placed in the same underground laboratory.

Summary

An underground accelerator facility for nuclear astrophysics studies has been proposed, with an estimated cost Rs 300 Cr, to be built within 10 years after the project is sanctioned. The depth of the underground lab will be a minimum of 1.5 km. The space required just for the nuclear astrophysics lab may be about 80 m x 10 m, however, an area of about 500 m x 150 m will be necessary to include all other underground labs in the same place. Some of the important reactions relevant to nuclear astrophysics that are planned to be measured using the proposed accelerator facility are 12C(α, γ)16O, 12C+12C, 13C(α,n)16O and 22Ne(α,n)25Mg.

References

[1] U. Greife, C. Arpesella, C. A. Barnes, F. Bartolucci, E. Bellotti, C. Broggini, P. Corvisiero, G. Fiorentini, A. Fubini, G. Gervino, et al., Nuclear Instruments and Methods in Physics Research A 350, 327 (1994).

[2] A. Formicola, G. Imbriani, M. Junker, D. Bemmerer, R. Bonetti, C. Broggini, C. Casella, P. Corvisiero, H. Costantini, G. Gervino, et al., Nuclear Instruments and Methods in Physics Research A 507, 609 (2003).

[3] Paolo Prati and on behalf of the LUNA Collaboration, Journal of Physics: Conference Series 1342, 012088 (2020).

[4] W. P. Liu et al., Few-Body Syst (2022) 63:43, https://doi.org/10.1007/s00601-022-01735-3

[5] https://caspar.nd.edu/

[6] D. Bemerer, Proc. Of Science, Vol-204, XIII Nuclei in the Cosmos (NIC-XIII) – Nuclear Reactions at Low Energies, 2015

[7] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Reviews of Modern Physics 29, 547 (1957).

[8] A. G. W. Cameron, Publications of the Astronomical Society of the Pacific 69, 201 (1957).8] E. Piasecki, L. Nowicki, in: Proc. Symposium, “Physics and Chemistry of Fission”, Jülich, 14-18 May 1979, IAEA, Vienna, vol. II, 1980, p. 193.