Underground nuclear astrophysics

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In stars, nuclear reactions take place in a narrow energy window called the Gamow peak. It is given by the product of two physical quantities: First, the Maxwell-Boltzmann energy distribution that is given by the temperature in the part of the star where nuclear burning occurs. Second, the cross section of the relevant nuclear fusion reactions. Since typical stellar temperatures are well below the repulsive Coulomb barrier energy, the energy dependence of the cross section is given by the quantum mechanical tunneling probability through this barrier and drops rapidly with decreasing energy. To give an example, for the Bethe-Weizsäcker cycle in the center of the Sun, the temperature is 1.4 keV, the Gamow peak energy is 28 keV, and the Coulomb barrier is at 2 MeV.

At such low, sub-Coulomb energies, experiments seeking to study nuclear burning face two obstacles: The cross sections of the reactions under study are very small, in the nanobarn to picobarn range, and strongly dependent on energy. These obstacles are overcome performing experiments with high-current ion accelerators in underground settings, where the background especially in γ-ray detectors is strongly suppressed.

Based on the pioneering work of the LUNA collaboration working at the Gran Sasso underground laboratory, Italy, new underground ion accelerator laboratories are now coming online in Germany, the United States, and China. As a result, in the coming years it can be expected that the nuclear reactions of hydrogen, helium, and carbon burning as well as those of Big Bang nucleosynthesis will be placed on firm experimental ground. This will pave the way for our Sun to be used as a calibrated laboratory for stellar and particle physics, and for new constraints on cosmology.

References

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