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Perspective

Deep underground accelerators for studying near-threshold quantum effects in hot stellar plasmas

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Low energy particle accelerators, located at deep underground locations, have been developed over the last three decades, to perform nuclear reaction measurements at nearly cosmic ray free background conditions. They are a unique tool in our desire to study and interpret the origin of the elements in our universe, from the Big Bang to present times [1]. The important goal of underground accelerator studies is to pursue cross section measurements near the characteristic energy range of stars, the so-called Gamow Window

$$E_0 \pm \Delta E = 0.122 \cdot \left(Z_1^2 Z_2^2 \mu T_9^2\right)^{\frac{1}{3}} \pm 0.236 \cdot \left(Z_1^2 Z_2^2 \mu T_9^5\right)^{\frac{1}{6}} \,(\mathrm{MeV}), \quad (1)$$

which depends on the temperature of the stellar environment with T_9 being the temperature in Giga-Kelvin, the reduced mass μ and the atomic numbers Z_1 and Z_2 of the two interacting nuclei. The temperatures in stellar nucleosynthesis environments typically range from 0.01 to 1.0 GK for quiescent stellar hydrogen and helium burning with higher temperatures possible at the later phases of heavy ion burning. At explosive burning conditions, temperatures up to 10 GK can be reached in core collapse supernovae or accreting and merging neutron stars. This translates into center of mass Gamow energies of 10 to a few hundred keV, depending on temperature and the kind of interacting particles. While for neutron induced reactions the cross section typically increases with decreasing energy according to the $1/v$-law, for charged particle interaction the cross section drops rapidly due to the Coulomb and orbital momentum barrier. The cross section $\sigma(E_{\mathrm{cm}})$ for particle interaction at center of mass energy E_{cm} at temperatures corresponding to the energy kT of the Maxwell Boltzmann distribution determines the rate per particle pair of the nuclear reaction processes

$$N_{\mathrm{A}}\langle\sigma v\rangle = N_{\mathrm{A}} \cdot \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{-3/2} \int_0^{\infty} \sigma(E_{\mathrm{cm}}) \cdot E \cdot \mathrm{e}^{\left(-\frac{E_{\mathrm{cm}}}{kT}\right)} \mathrm{d}E. \quad (1)$$

A reaction rate determines the energy production from a specific reaction in stellar burning and can dictate the timescale of the associated nucleosynthesis process; the slowest reactions typically determine the overall timescale of nucleosynthesis processes, and they are the most important to study, but also the most difficult to measure.

Stellar reaction processes are typically sorted into proton capture and fusion reactions on light nuclei, that govern the regime of stellar hydrogen burning in main sequence stars, of alpha capture reactions that determine stellar reactions in red giant stars, also providing a strong neutron flux through (α, n) reactions, and finally fusion reactions between light isotopes up to mass 16 which dominate late stellar burning conditions. Fusion reactions between ^{12}C and ^{16}O determine the later phases of heavy ion burning, and the emitted proton and alpha particles are captured facilitating the build-up of heavier nuclei.

Because of the Coulomb barrier, cross section measurements of these reactions at their respective stellar energies remain a nearly-unsurmountable challenge and have been only successful in a few cases of fusion reactions with low Z particles. This is not only because the cross sections are typically in the sub-femto-barn range, but also because cosmic radiation generates a continuous background rate in the detector material that often becomes many orders of magnitude higher than the event rate of the reaction. Stellar nucleosynthesis simulations therefore rely primarily on the extrapolation of laboratory data at higher energies using, for example, sophisticated R-matrix models to include as many as the feasible reaction contributions that may emerge at energies near the vicinity of the particle thresholds.

The physics of the particle threshold is generally unknown! Traditional nuclear structure experiments using transfer reactions studied the excitation range of a nucleus up to the threshold because the unknown effects emerging at the threshold introduced large uncertainties in the interpretation of the spectroscopy results [2], as experiments at low energy accelerators demonstrated [3,4]. On the other hand, these direct cross section studies of charge particle nuclear reaction are limited by the Coulomb barrier from exploring the effects that dictate the reaction features at very low energies. Reaction model calculations on the other side still suffer from the lack of theoretical understanding of the threshold

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effects and the big uncertainties of the actual model parameters making the predictions unreliable.

The reaction cross section near the threshold is governed by a number of quantum effects associated with the nuclear transition probability; this includes the emergence of new quantum structures such as nuclear clustering through coupling of the wave functions of bound states with the continuum [5]. Another important issue is the tailing of sub-threshold states into the unbound region causing direct interference between bound and unbound states or with non-resonant direct reaction components affecting the cross section [6]. Furthermore near threshold resonance configurations may also be due to potential driven effects since the emergence of structures may not be correlated with quantum-physical compound configurations but with dynamical processes associated with the fusion of two particles [7]. Finally the shape and expansion of the nuclear potential may affect the very low energy tunnel probability for charged particles. In short, one does not fully understand the energy range in the vicinity of the particle thresholds. Our lack of understanding of the reaction features in that energy range has introduced a number of uncertainties in our interpretation of low energy reaction events.

The astrophysical *S*-factor or simply *S*-factor $S(E) = \sigma(E) \cdot E \cdot e^{2\pi\eta}$ has been introduced, which represents the cross section $\sigma(E)$, corrected for an approximate Coulomb term $P_{\ell=0} = e^{2\pi\eta}$ of an s-wave particle at a certain energy E for the Sommerfeld parameter η. This means that the *S*-factor contains all information about the quantum mechanical components of the transition strength between the initial and the final nuclear configurations as well as the impact of the orbital momentum barrier for higher orbital momenta particle in the tunneling probability. This concept has served as a convenient tool for decades to extrapolate the reaction cross section towards the lowest energy range near the particle threshold of the compound nucleus.

However, several quantum processes can affect the *S*-factor at extremely low energies and introduce a level of uncertainty into the traditional extrapolation method, which is difficult to evaluate without reliable low energy reaction data. This not only affects the prediction of nuclear reaction and fusion processes in stars, but also for the development of fusion devices for energy production and other applications based on inertial or magnetic confinement techniques. A better understanding of these near threshold quantum phenomena is therefore desirable.

Theoretical studies suggest a number of these phenomena, emerging at very low energies. This includes the so-called electron screening effects, which translates into an effective reduction of the Coulomb barrier between two positively charged nuclei in the presence of electron clouds in the stellar plasma or the atomic electron shell in experiment. This effect causes an increase of the *S*-factor and therefore the reaction rate, in particular for high density burning conditions such as in white dwarf or neutron star environments. The screening effect appears to be substantially more complex than previously thought and its impact depends not only on the distribution of electrons surrounding the interacting nuclei, but also on the specific shape and structure of the latter [8], which has to be taken into consideration for a reliable extraction and extrapolation of the *S*-factor from experimental data.

The traditional approach of calculating Coulomb functions assuming spherical nuclei for the derivation of reaction rates is questionable, since interacting nuclei actually can be deformed or may also exhibit collective effects, such as nuclear incompressibility distorting the reaction cross section. This becomes critical in particular in the treatment of the *S*-factor for heavy ion fusion processes at stellar conditions. It, however, also raises the question to which extent the adopted Coulomb functions provide a reliable platform for the extrapolation of alpha induced reaction in a stellar helium burning environment. This will be of particular importance at very low energies, where the Coulomb functions need to be calculated with high numerical accuracy and even small disturbances may translate into exponentially enhanced effects in the low cross sections and *S*-factor predictions. Further deviations in the extrapolation of laboratory measured *S*-factors into the unknown energy range of stellar burning may be the aforementioned threshold effects due to the coupling of wave functions and potential modifications.

All these effects introduce substantial uncertainties which prevent a reliable prediction of reaction rates in low temperature fusion environments. There is indeed evidence that the presently used extrapolation methods for low energy cross section studies translate into reaction rates inconsistent with predictions based on other methods such as laser induced fusion experiments [9] or indirect techniques based on nuclear structure analysis. In addition to these experimental studies the extrapolated data are also leading to results in nucleosynthesis calculations that seem inconsistent with observations.

One example is the comparison of observational signatures such as the CNO neutrino flux from our sun [10] with the predicted flux based on the low energy measurements of the neutrino production rate by the ^{14}N(p,γ)^{15}O reaction [11]. This deviation could be caused by insufficiencies in the standard solar model but it could also be caused by quantum effects at very low energies or near the threshold that are not properly accounted for.

Another example is the question of the carbon oxygen ratio observed in white dwarfs, which is determined by the ^{12}C(α,γ)^{16}O reaction. The predictions based on the extrapolation of the ^{12}C(α,γ)^{16}O cross section [6], show significant deviations from observations made in white-dwarf seismology observations [12]. Again, these deviations could be caused by insufficiencies in the simulation of white dwarf material or the interpretation of the observations, but it could also be caused by unaccounted for quantum effects at very low energies.

The extrapolation of carbon and oxygen fusion processes remains unsolved, and the predictions range from large hindrance due to the incompressibility of nuclear matter to the emergence of strong cluster resonance features, causing a substantial enhancement in the rate. The so-called Trojan Horse Method (THM) [13] has been proposed as surrogate for the actual reaction study since as particle transfer mechanism it determines the nuclear transfer probability without the handicap of the Coulomb barrier in the capture of fusion cross section. However, the THM data need to be translated into reliable reaction data, which again requires a reliable low energy treatment of the aforementioned near threshold processes.

To remove all these uncertainties reliable cross section measurements at very low energies are necessary. Such data would allow a reliable interpretation of laser plasma experiments and the impact of screening, of the origins of the solar neutrino flux and the impact of threshold resonance features, the composition of white dwarf matter, light ion fusion and the possible emergence of clusters and many other yet unexplained nuclear physics features that may affect nuclear burning in gravitational or inertial and magnetic confined hot plasmas.

A direct measurement of charged particle reactions at very low energy range requires deep underground accelerator laboratories to reduce the cosmogenic background. Local passive and active shielding are necessary for reducing the radiogenic background at the underground site. Event identification methods need to be developed for removing beam induced background [14]. Presently there are three deep underground laboratories in operation worldwide, Laboratory Underground for Nuclear Astrophysics (LUNA) at the LNGS Gran Sasso Laboratory in Italy, Compact Accelerator System for Performing Astrophysical Research (CASPAR) at the Sanford Underground Research Facility (SURF) located at Homestake Mine in South Dakota, USA, and Jinping Underground Nuclear Astrophysics experimental facility (JUNA) at the China Jinping Underground Laboratory (CJPL) located in Jinping, China.

LUNA has been the pioneer in this field. LUNA has been initially a 50 kV platform serving as pilot project to measure fusion reactions between hydrogen and helium isotopes of the pp-chains at very low energies. It was followed by the installation a 400 kV Cockroft Walton accelerator to systematically measure many of the proton induced reactions of the CNO, NeNa and even MgAl cycles that characterize stellar core and shell hydrogen burning in stars [15]. For a reliable extrapolation one also needs to consider higher energy reaction components that tail into the low energy range. This requires not only to map the lower energy range, but also expand the studies towards higher energies beyond the 400 keV limit. This limit proved to be detrimental for an extended study of alpha induced reactions that govern the helium burning phases in red giant and AGB stars. For this reason the LUNA collaboration was successful in proposing and installing a new accelerator, a 3.5 MV Singletron, LUNA-MV to not only measure proton and alpha induced reactions over a broader energy range, but also to pursue low energy heavy ion fusion studies to address the uncertainties associated with nucleosynthesis from late stellar burning to the nature of type Ia supernovae [16]. With that machine coming on line in 2023, the LUNA collaboration is presently leading the field of experimental low energy reaction studies.

CASPAR is presently based on the use of a 1 MV Van de Graff accelerator and has focused primarily on the study of alpha capture reactions [17]. A new concept of a dual accelerator system, DIANA [18] for the study of reactions over a wide energy range has been developed. However, limited funding prevented its implementation. Nonetheless, its novel design features have informed several of the more recent developments and initiatives. The accessible energy range is between 150 keV and 1 MeV, which is suitable for the detailed study of alpha induced reactions in stellar helium burning in early star and red giant environments. The CASPAR program will also include the study of proton capture reactions on higher Z isotopes, to determine the endpoint of nova nucleosynthesis.

JUNA is the most recent development of an underground accelerator laboratory in the Jinping Mountains of Sichuan, China [19]. The large depth of the laboratory warrants excellent shielding from cosmic rays, and the marble rock material has only small radiogenic compounds [20]. JUNA operates a 400 kV open platform machine, but the use of an ECR source allows the development of α beams in 2^+ charge state. This helped in expanding the study of alpha capture reactions over a wider energy range than possible at the LUNA accelerator. JUNA operates since 2022 but has already performed important studies for the understanding of the origin of the radioactive ^{26}Al in our universe, to the break-out from the CNO cycle in first stars [21], and to the understanding of the ^{13}C(α,n)^{16}O neutron source for the s- and i-process. The JUNA team presently prepares plans for upgrading the laboratory by adding a second higher energy accelerator to study nuclear reactions of helium burning and heavy ion burning over a larger energy range. Such a development would greatly enhance the capability of JUNA in this very competitive field of underground accelerator physics.

The goal of deep underground accelerator is the study of sub-femto-barn nuclear reaction processes which may play a role in nuclear plasma burning. High precision measurements not only provide a better understanding of the quantum effects that influence nuclear capture and fusion processes near the threshold, but also reduce the nuclear physics uncertainties, which handicap a reliable interpretation and simulation of hot plasma environments and a confirmation of astrophysics model predictions when compared with the observed parameters such as the element or isotopic abundances.

While the study of near threshold effects in reaction processes using deep underground accelerators was focused on gravitational bound stellar environments, these measurements will also provide a better understanding for the nuclear physics aspects of the energy generation by fusion in new anthropogenic high temperature plasma environments based on inertial and magnetic confinement techniques.

Conflict of interest

The authors declare that they have no conflict of interest.

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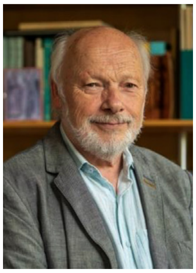

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