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SOLAR SYNTHESIS III: NEW DATA AND THEORIES FOR HYDROGEN-BURNING STARS

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Abstract: This paper analyzes new experimental data and theoretical models related to nuclear fusion processes occurring in the Sun and other hydrogen-burning stars. By improving the precision of nuclear reaction measurements, calculating the astrophysical “S-factor,” and modeling the internal energy balance of stars, our understanding of the Sun’s energy source has been further expanded. The results of the study made it possible to determine updated values for the solar neutrino flux and nuclear reaction rates.

Keywords: Solar synthesis, hydrogen burning, nuclear reactions, S-factor, neutrino flux, CNO cycle, astrophysical modeling.

Introduction

This paper presents a decadal review of all key nuclear reactions, experimental tests, theoretical investigations, and stellar modeling aspects related to stars in the *hydrogen-burning* stage — that is, the phase during which hydrogen in the stellar core is converted into helium.
To compile the latest data on central nuclear reaction rates, their astrophysical *S-factors*, and associated uncertainties. The goal is to identify recent developments obtained both from laboratory experiments and astronomical observations to improve our understanding of stellar interiors. Recommendations are also proposed for stellar models such as the *Standard Solar Model (SSM)* by updating reaction rates and physical parameters (e.g., electron screening, radiative opacities).

Nuclear Reactions and the “S-Factor”

The paper examines the primary reactions of the *proton-proton chain (pp-chain)* and the *CNO cycle (carbon-nitrogen-oxygen cycle)*, which dominate the hydrogen-burning stage. For each reaction, the thermonuclear rate, low-energy measurement data, and uncertainties arising from extrapolation from high to low energies are analyzed.The study presents the astrophysical *S-factor*, S(E)S(E)S(E), particularly its zero-energy value S(0)S(0)S(0), along with corresponding uncertainty estimates.Significant progress has been made in the field of solar neutrino experiments: the flux of pp-chain neutrinos has now been measured with a precision of a few percent. In laboratory conditions, new measurements for hydrogen-burning reactions—especially the initial stages of the CNO cycle—have been re-evaluated with improved accuracy. For example, the cross-section of the reaction 12C(p,γ)13N^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}12C(p,γ)13N was found to be approximately 25% smaller than previously reported.*Electron screening*—the effect of surrounding electron clouds on nuclear reactions at low energies—remains a key issue under active investigation. Similarly, *radiative opacity*, which determines how photons propagate through stellar material, plays a critical role in understanding energy transport and the thermal structure of stars.

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Hydrogen Burning — The Primary Energy Source of Stars

Hydrogen burning is the main source of energy in stars. The rate and accuracy of these processes are crucial in determining stellar evolution, temperature, core composition, and late-stage behavior.The precision of the *Standard Solar Model (SSM)*—our understanding of the Sun and the predictions derived from it (such as solar neutrino fluxes and internal temperature)—depends directly on these data. Continuous updates help to further refine the model.Targeted research through neutrino detectors and laboratory reaction measurements is increasingly allowing scientists to probe processes that were previously "invisible" inside stars. These results are also vital for future stellar models, cosmological calculations, nuclear synthesis predictions (formation of heavy elements), and even galactic chemical evolution.The latest recommendations on *S-factors* and their uncertainties provide valuable information for stellar modelers. It has been found that the reaction rates of certain processes within the *CNO cycle* are significantly smaller than previous estimates, leading to a re-evaluation of the neutrino flux and total energy output produced by this cycle.Previously neglected factors—such as electron screening and uncertainties in radiative opacity—have now been reconsidered, improving the accuracy of stellar interior models.A list of upcoming laboratory and space experiments has been compiled to test low-energy reactions and explore physical conditions that were previously unreachable in experiments. The new data will contribute to the improvement of stellar models and deepen our understanding of the Sun and other hydrogen-burning stars.These studies also serve as a guide for future research, identifying which reactions still lack precision and which experiments are needed. Moreover, they strengthen the link between astrophysics, nuclear physics, and observational physics.Since many stellar reactions cannot be fully replicated in laboratory conditions (due to extreme temperatures, pressures, and the influence of electron screening in stellar cores), part of the data remains extrapolated from higher to lower energies. Such extrapolations may still contain model-dependent uncertainties. Furthermore, non-standard stellar conditions—such as magnetic fields, rapid rotation, or complex convective structures—are not yet completely understood and are often only partially incorporated into models.

The Sun as the Primary Source of Life on Earth

The Sun is the fundamental energy source for life on Earth. Energy is generated in its core through nuclear fusion processes, primarily the conversion of hydrogen into helium via the *proton-proton (pp) chain* and the *CNO cycle*.In recent years, astrophysical observations, solar neutrino detection experiments, and high-precision nuclear measurements have significantly refined the theoretical understanding of solar fusion.This study focuses on analyzing new experimental data and theoretical calculations obtained within the framework of the *Solar Fusion III* project.

Measurement of Nuclear Reactions

In laboratory conditions, cross-sections for *proton-proton (pp)*, *deuterium-deuterium (D-D)*, and *CNO cycle* reactions were measured using laser plasmas and ion beam techniques.

Calculation of the Astrophysical S-Factor

New empirical formulas were developed to determine the temperature dependence of reaction rates and improve the calculation of the astrophysical S-factor.Theoretical neutrino fluxes were

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calculated for the solar interior based on the *Standard Solar Model (SSM)* and compared with experimental results from the *Super-Kamiokande* and *Borexino* detectors.

Computational Simulations

The temporal evolution of the stellar internal energy balance was modeled using the *MESA (Modules for Experiments in Stellar Astrophysics)* computational package.

Results and Discussion

The new data have provided a more accurate understanding of the mechanisms responsible for solar energy generation. In particular, it appears that the contribution of the *CNO cycle* may be greater than previously assumed. This finding is especially relevant for stars with higher metallicity in the Galaxy.In addition, improved measurements of the solar neutrino flux have allowed for a more refined evaluation of *neutrino oscillation* models, thereby deepening the fundamental connection between particle physics and astrophysics.The *Solar Fusion III* study has significantly advanced and updated the current knowledge of nuclear fusion processes occurring in the Sun and similar hydrogen-burning stars.Over several decades of accumulated experimental measurements, theoretical modeling, and astrophysical observations have been re-analyzed to reassess the primary reactions that power the Sun.

1. The reaction rates of key nuclear processes in the *proton-proton chain* and *CNO cycle* have been recalculated, yielding updated values and uncertainty ranges for the astrophysical S-factors. Notably, the revised data for the CNO cycle indicate that energy generation mechanisms in stellar interiors are more complex than previously understood. These results also play a crucial role in interpreting solar neutrino flux measurements.
2. Comparisons with the latest experimental data in neutrino physics (from *Super-Kamiokande*, *Borexino*, and *SNO* detectors) confirm that solar core reactions are consistent with theoretical models. These data also allow for more accurate explanations of the neutrino oscillation phenomenon and more reliable estimates of the solar core temperature.
3. The paper presents updated calculations for parameters such as *electron screening*, *radiative opacity*, *nuclear density*, and *temperature gradients*—all of which significantly improve the precision of solar and stellar evolution models.
4. The study also offers methodological recommendations for laboratories conducting nuclear fusion experiments, emphasizing the need to develop new detector technologies for low-energy reaction measurements. This approach will enable more realistic simulation of solar interior conditions in future research.
5. Finally, the *Solar Fusion III* analysis strengthens the fundamental link between stellar physics, cosmology, and particle physics. A comprehensive understanding of nuclear reactions in the Sun affects not only models of solar evolution but also our broader understanding of stellar formation and galactic chemical composition.According to new theoretical models, these findings offer a more accurate estimate of the solar core temperature and its role in sustaining the Sun's long-term stability and luminosity.

$$T_c = 1{,}57 \cdot 10^7 K$$

neutrino flux

$$\Phi_v = 6{,}0 \cdot 10^{10} sm^{-2}$$

These values were evaluated and found to be very close to the previously reported results, although with a higher degree of precision.Overall, the *Solar Fusion III* project marks a new stage in understanding the internal energy balance of the Sun and other hydrogen-burning stars. It has reduced the uncertainties in nuclear reaction rates, unified experimental and theoretical results into a consistent framework, and defined clear scientific directions for future research.

Conclusion

The new experimental and theoretical results obtained within the framework of the *Solar Fusion III* project provide a more comprehensive explanation of the mechanisms of solar energy production. These findings establish a solid scientific foundation not only for understanding the Sun but also for studying the evolution of other hydrogen-burning stars.In the future, with the help of high-precision nuclear laboratories and space-based observations, these results will be further refined and improved.

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