Solar Fusion III: New data and theory for H-burning stars

A small presentation of the big decadal review.

Yago Herrera [1,2] Aldo Serenelli [1,2] (on behalf of 50 authors)

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Cerdanyola del Vallès, Barcelona, Spain.

[2] Institut d'Estudis Espacials de Catalunya (IEEC),
Barcelona, Spain.

2024 ChETEC-INFRA General Assembly
Strasbourg, France
May 2024

The Solar Fusion review series

A bit of history...

- SF I: "Solar Fusion Cross Sections"
  (Adelberger et al, 1998, Reviews of Modern Physics 70(4), 1265)
  Solar Neutrino Problem $\longrightarrow$ need for accurate nuclear rates.

- SF II: "Solar fusion cross sections II: the pp-chain and CNO cycles"
  (Adelberger et al, 2011, Reviews of Modern Physics 83(1), 195)
  Updates to CN reactions, Solar Composition Problem.

- SF III: "Solar Fusion III: New data and theory for H-burning stars"
  More updates, new neutrino measurements, expanding the scope.

July 2022 Workshop: Solar Fusion Cross Sections III (INT-22-82W)

David Brower Center and UC Berkeley, Berkeley, CA, USA

Submitted to RevModPhys (May 14th, 2024).
Available e-print: `https://arxiv.org/abs/2405.06470`

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SF III Overview

Purpose

- Review and summarize developments in the past decade on:
  - Solar neutrino detections and open questions.
  - Nuclear reactions rates in the Sun and other H-burning stars (incl. pp-chain + all CNO + Ne-Na cycles).
  - Electron screening of nuclear reactions.
  - Radiative opacities. New!
  - Experimental facilities (nuclear reactions, neutrino obs., opacity).
- Identify challenges and recommendations for future work.

Solar neutrinos: Open questions

Precise ν fluxes measurement could help test/constrain:

- ✓ Nuclear reactions (pp, pep, hep, CNO, ...)
- ✓ SSM aspects (Z_{ini}, T_{core}, elements mixing, core metal abundances, opacity, ...)
- ✓ Neutrino physics (matter interaction, flavor oscillations). New physics (non-standard interactions?, sterile neutrinos?)

Solar Composition Problem

Solar atmosphere 3D RHD models
$\rightarrow$ 2 possible sets of elements abundances:

- High Z (Magg et al. 2022)
- Low Z (Asplund et al. 2021)
  !! Tension with helioseismic probes
  (depend on both composition + opacity)

⋆ Break degeneracy with CNO ν-fluxes
⊘ Uncertainties from:

- Mainly detector (Borexino)
- But also nuclear rates (S_{114}, S_{34}, S_{17})

Gallium Anomaly

$^{71}\text{Ga} + \nu_e \rightarrow e^- + {}^{71}\text{Ge}$ under-produced

- ?? Sterile neutrinos $\rightarrow$ conflict with limits on Solar ν (L constrain)
- ?? Corrections to cross-sections:
  ^{71}Ge e^- capture constrains on ^{71}Ga absorption of ν from $^{37}\text{Ar}/^{51}\text{Cr}$ $\rightarrow$ Solar ν ?

The ^{8}B neutrino spectrum

Need higher precision $\rightarrow$ Search for *hep* ν

– ^{8}B uncertainty (Longfellow et al., 2023),
– difference with Winter et al., (2006),
– *hep* spectrum (scale).

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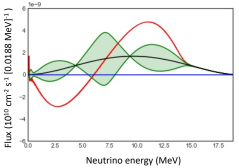

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Solar neutrinos: Experimental program

★ **Super-/Hyper-Kamiokande** *(Japan, 1996–)*

- 50 kton / 250 kton water detectors
- Highest precision measurement of e^- ES from Solar ν (SuperK)
- Sensitive searches for day/night distortions (SuperK). Higher sensitivity (HyperK)
- HyperK: Impact on ^{8}B ν spectrum (high energy), *hep* ν search.

★ **Sudbury Neutrino Obs. and SNO+** *(Canada, 1999–)*

- 1 kton heavy water detector (SNO).
- ν_e flavor (charged current) + flavorless (neutral current) detections → Solar Neutrino Problem resolution
- SNO+: organic liquid scintillator (higher precision, low background ^{8}B ν measurements)

★ **Borexino** *(Italy, 2007–)*

- 100 ton fiducial organic LS
- Entire solar ν spectrum capability
- 1st detections of pp, pep, sub-MeV 7Be, CNO neutrinos, with few % uncert.

→ Probe Solar core composition
(points to High Z SSMs, with current uncert.)

★ **Jiangmen Underground Neutrino Obs. (JUNO)** *(China, under construction)*

- 20 kton LS, high energy resolution
- Expected capabilities: day/night effects, non-standard ν interactions effects on ^{8}B and ^{7}Be, precision constrains on Δm^2_{12}

★ **Deep Underground Neutrino Experiment (DUNE)** *(U.S., under construction)*

- 3 10-kton liquid Ar time projection chambers
- Expected capabilies: day/night effects, high-energy solar *nu* (GeV-scale optimized) via charged current, possibilities of expanding to include other solar ν.

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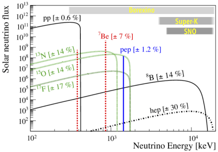

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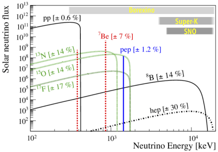

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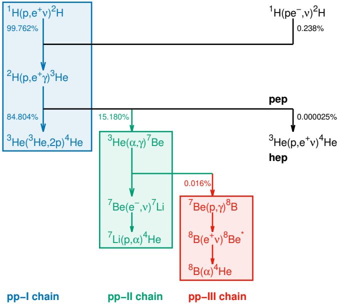
Nuclear reactions: *pp*-chain



Reactions, data and methods

$^1\mathrm{H}(p, e^+\nu)^2\mathrm{H}$	$\not\pi$EFT, χEFT, and lattice QCD calculations.
$^2\mathrm{H}(p, \gamma)^3\mathrm{He}$	Accelerators (LUNA), plasma inertial confinement fusion (OMEGA) + ab-initio calculations (Hyperspherical Harmonics) $\longrightarrow$ Bayesian analysis.
$^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$	No new experiments since SF II. Revised uncert. (+4%)
$^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$	Ab-initio models (FMD, NCSMC, halo EFT), R-matrix phenom. fit (BRICK), and several experiments (Madrid, ATOMKI, Notre Dame, LUNA, ...).
$^7\mathrm{Be}(e^-, \nu)^7\mathrm{Li}$	Few new studies. SF II recommendation holds.
(*pep*) $^1\mathrm{H}(pe^-, \nu)^2\mathrm{H}$	No new evaluations since SF II.
(*hep*) $^3\mathrm{He}(p, e^+\nu)^4\mathrm{He}$	Correlated HH, EFT* calculations, same as SF II. Further theoretical studies recommended.
$^7\mathrm{Be}(p, \gamma)^8\mathrm{B}$	Halo EFT, R-matrix model. Bayesian and χ^2 fits, with data from several experiments (Filippone, Hammache, Junghans, Buompane, ...) far from Gamow peak

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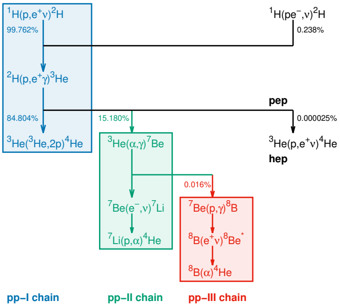

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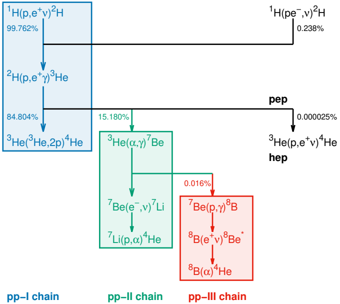

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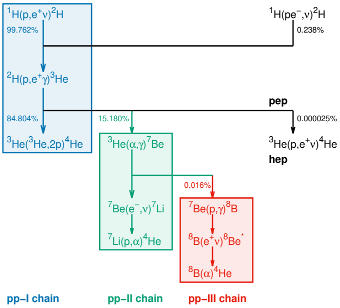

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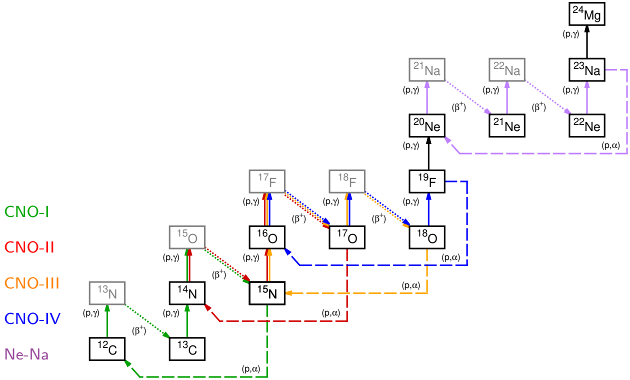

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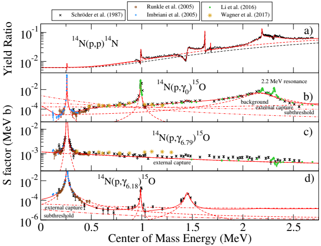
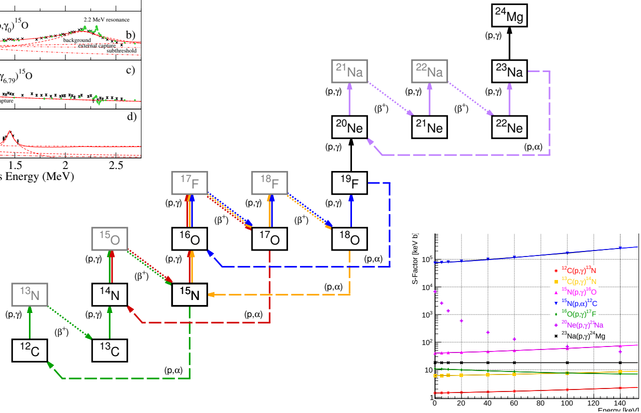


CNO-I
CNO-II
CNO-III
CNO-IV
Ne-Na



Nuclear reactions: S-factors final recommendations

Reaction	S_{ij}	$S(0)$ (MeV b)	$S'(0)$ (b)	$S''(0)$ (MeV^{-1} b)
$^{1}H(p, e^{+}\nu)^{2}H$	S_{11}	4.09×10^{-25}	4.5×10^{-24}	9.9×10^{-22}
$^{2}H(p, \gamma)^{3}He$	S_{12}	2.03×10^{-7}	see text	
$^{3}He(^{3}He, 2p)^{4}He$	S_{33}	5.21	-4.90	22.42
$^{3}He(\alpha, \gamma)^{7}Be$	S_{34}	5.61×10^{-4}	-3.03×10^{-4}	–
$^{3}He(p, e^{+}\nu)^{4}He$	S_{hep}	8.6×10^{-23}	–	–
$^{7}Be(p, \gamma)^{8}B$	S_{17}	2.05×10^{-5}	–	–
$^{14}N(p, \gamma)^{15}O$	$S_{1\,14}$	1.68×10^{-3}	–	–
$^{12}C(p, \gamma)^{13}N$	$S_{1\,12}$	1.44×10^{-3}	2.71×10^{-3}	3.74×10^{-2}
$^{13}C(p, \gamma)^{14}N$	$S_{1\,13}$	6.1×10^{-3}	1.04×10^{-2}	9.20×10^{-2}
$^{15}N(p, \gamma)^{16}O$	$S^{\gamma}_{1\,15}$	4.0×10^{-2}	1.07×10^{-1}	1.84
$^{15}N(p, \alpha)^{12}C$	$S^{\alpha}_{1\,15}$	73	3.37×10^{2}	1.32×10^{4}
$^{16}O(p, \gamma)^{17}F$	$S_{1\,16}$	1.09×10^{-2}	-4.9×10^{-2}	3.11×10^{-1}
$^{17}O(p, \gamma)^{18}F$	$S_{1\,17}$	4.7×10^{-3}	–	–
$^{18}O(p, \gamma)^{19}F$	$S_{1\,18}$	2.30×10^{-2}	–	–
$^{20}Ne(p, \gamma)^{21}Na$	$S_{1\,20}$	6.78	–	–
$^{21}Ne(p, \gamma)^{22}Na$	$S_{1\,21}$	$\approx 2.0 \times 10^{-2}$	–	–
$^{22}Ne(p, \gamma)^{23}Na$	$S_{1\,22}$	0.415	–	–
$^{23}Na(p, \gamma)^{24}Mg$	$S_{1\,23}$	1.80×10^{-2}	0	0

Nuclear reactions: S-factors final recommendations

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^{7}Be$(p, \gamma)^8$B	S_{17}	2.05×10^{-5}	–	–
^{14}N$(p, \gamma)^{15}$O	$S_{1\,14}$	1.68×10^{-3}	–	–
^{12}C$(p, \gamma)^{13}$N	$S_{1\,12}$	1.44×10^{-3}	2.71×10^{-3}	3.74×10^{-2}
^{13}C$(p, \gamma)^{14}$N	$S_{1\,13}$	6.1×10^{-3}	1.04×10^{-2}	9.20×10^{-2}
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^{15}N$(p, \alpha)^{12}$C	$S^{\alpha}_{1\,15}$	73	3.37×10^2	1.32×10^4
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^{17}O$(p, \gamma)^{18}$F	$S_{1\,17}$	4.7×10^{-3}	–	–
^{18}O$(p, \gamma)^{19}$F	$S_{1\,18}$	2.30×10^{-2}	–	–
^{20}Ne$(p, \gamma)^{21}$Na	$S_{1\,20}$	6.78	–	–
^{21}Ne$(p, \gamma)^{22}$Na	$S_{1\,21}$	$\approx 2.0 \times 10^{-2}$	–	–
^{22}Ne$(p, \gamma)^{23}$Na	$S_{1\,22}$	0.415	–	–
^{23}Na$(p, \gamma)^{24}$Mg	$S_{1\,23}$	1.80×10^{-2}	0	0

B23 / SF III Solar Models (Y. Herrera, A. Serenelli) $\in$ WP8: Astronuclear Library

- SF III nuclear rates, High-/Low-Z compositions.
- Structure data: macrophysics, helioseismology, composition, ν-flows/distributions.
- Variations routine (Linear Solar Model) https://doi.org/10.5281/zenodo.10174170

Electron screening – Radiative opacities

Electron screening

Lab e^- environment $\neq$ Solar plasma

- Lab experiments
  - Bound e^- in target nucl. $\rightarrow$ Coulomb barrier reduction.
  - $\Rightarrow$ Lab cross-section are enhanced: $S^{\text{lab}}(E) \simeq S^{\text{bare}}(E) \exp\left(\frac{\pi\eta(E)U_e}{E}\right)$ (at low E)
  - Corrections can be obtained from fitting data, in some cases.
  - ! Things get complicated for E $\sim$ Solar core
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  - Weak screening approx ($Z_1Z_2 < 10$): $\frac{\sigma^{\text{bare}}(E)}{\sigma^{\odot}(E)} \sim \exp\left(\frac{\alpha Z_1 Z_2}{R_D kT}\right)$
  - ? Are corrections relevant? When?
- !! Little progress since Bahcall et al. (2002)

Radiative opacities

- Measure of radiative heat transfer inside stars $\rightarrow$ key role stellar structure and evolution modeling.
- RMO $\kappa_R(T, \rho, X_i)$: double weighted average of individual elements opacity, $\kappa_{\nu,i}$ $\longleftrightarrow$ Solar composition. (ν: photon freq.)
- Determining $\kappa_{\nu,i}$ in solar conditions is challenging (many photon-ion interactions)
- Different theoretical approaches $\rightarrow$ different opacity tables (OPAL, Opacity Project, OPLIB, ...).
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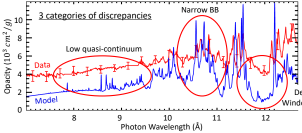

Experimental facilities

Underground facilities

- **Bellotti Ion Beam Facility (INFN-LNGS)**
  - New 3.5 MV Singletron
  - *p*, He, C beams (1, 0.5, 0.15 mA, respectively)
- **JUNA (CJPL)**
  - 400 kV accelerator
  - H^+ and He^+ beams (10 mA), He^{2+} beam (1 mA).
- **CASPAR**
  - 1 MV Van de Graff style JN accelerator (50–1100 kV op. range)
  - p, α beams (250 μA on target)
- **Felsenkeller**
  - 5 MV Pelletron-type accelerator
  - *p*, He, C beams ($\sim$ several tens of μA)

Plasma facilities

- **NIF / OMEGA**
  - Laser-induced implosion:
    30 kJ / 60 beams (OMEGA), 2 MJ / 192 beams (NIF)
  - T$\sim$1–20 keV, $\rho \sim 10^3$ g cm^{-1}
- **PANDORA**
  - Superconducting magnetic plasma trap (10^{13} e^--ion cm^{-3}, T$\sim$ 0.1 – 30 keV)
  - Non-intrusive monitoring of plasma properties.
  - 14 HPGe detectors for γ-ray spectroscopy
- **Sandia Z**
  - World's largest pulsed power accelerator (22 MJ / 100 ns discharge on cm-small targets)
  - Z-pinch X-ray most energetic source
    $\rightarrow$ Fe, O opacity measurements

Storage rings

- **CRYRING**
  - Storing and re-circulating radioactive ions
    $\rightarrow$ higher intensity and purity
  - Low density in-ring micro-droplet gas target
    $\rightarrow$ minimize beam energy loss and straggling

Final remarks

Summary of SF III

- The nuclear physics of the pp-chain remains a significant uncertainty in SSM predictions of the individual ν-fluxes (*pp*, *pep*, *hep*, ^{7}Be, ^{8}B, and CNO). The nuclear errors are comparable to, and in the case of the *hep* neutrinos greatly exceed, the "environmental" errors generated by other uncertainties in the SSM.
- The debate generated by the SCP has brought renewed attention to the complicated interplay between opacities and composition in the SSM. Given new experimental opportunities, here is the expectation of rapid progress in this field over the next decade.
- There has been only very limited progress on electron screening since SF II. Due to its importance, it merits additional attention in the coming decade.

Recommendations

- Experimental reactions need a single dataset spanning the entire energy range $\longleftarrow$ Underground facilities are capable.
  Theory efforts in pp-chain must continue and include precise ν spectra and laboratory data.
- Urgent need for precise S-factors measurements, reducing uncertainties to half of the SSMs environmental ones, so they are no longer a significant contribution to SSMs ν-flux uncertainties (e.g. CNO uncert. $\sim 8.4\%$ limits CNO-ν probing of solar core metallicity).
- New experimental methods could allow studying e^- screening in conditions $\sim$ Solar plasma (ring facilities). Theory efforts must improve.
- High priority should be granted to solving opacity discrepancies (models vs. exp.) for the Sun's principal metals, in order to break the degeneracy between solar composition and opacity in the SCP. Access to state-of-the-art, open-source opacity codes is in demand.
- Extending the use of current and next-generation dark matter detectors to solar neutrino detection. Some of the high-priority goals of solar neutrino physics might be achieved with a dual-purpose detector.
- Continuation of the *Solar Fusion* program in an open, international format, $\leq$ 10yr recurrence, Fostering connection between involved communities (nuclear, plasma, atomic, stellar, etc).

Thanks

Thank you on behalf of the SF III authors:

B. Acharya, M. Aliotta, A. B. Balantekin, D. Bemmerer, C. A. Bertulani, A. Best, C. R. Brune, R. Buompane, F. Cavanna, J. W. Chen, J. Colgan, A. Czarnecki, B. Davids, R. J. deBoer, F. Delahaye, R. Depalo, A. García, M. Gatu Johnson, D. Gazit, L. Gialanella, U. Greife, D. Guffanti, A. Guglielmetti, K. Hambleton, W. C. Haxton, Y. Herrera, M. Huang, C. Iliadis, K. Kravvaris, M. La Cognata, K. Langanke, L. E. Marcucci, T. Nagayama, K. M. Nollett, D. Odell, G. D. Orebi Gann, D. Piatti, M. Pinsonneault, L. Platter, R. G. H. Robertson, G. Rupak, A. Serenelli, M. Sferrazza, T. Szücs, X. Tang, A. Tumino, F. L. Villante, A. Walker-Loud, X. Zhang, K. Zuber