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- Screening in Nuclear Reactions Strong and Weak Screening
- Relativistic Electron-Positron Plasmas
- Comparison of Relativistic and Classical Screening
- Screening With Relativistic Plasmas
- Results BBN White Dwarfs: Type Ia Stellar Interiors PP SNe X-Ray Burst Other Regimes Other Regimes Other Effects o the Relativistic Plasma

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Relativistic Electron-Positron Plasma Screening In Astrophysical Environments Enhancements to Weak and Intermediate Screening

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Review: Nuclear Screening



Assume constant electron background. Salpeter approximation assumes constant energy shift.



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Review: Nuclear Screening

$$V(r) = \frac{Z_1 Z_2 e^2}{r} + \tilde{U}(r)$$
$$\Gamma_{12} \propto \int_0^\infty E^{1/2} e^{-E/kT} \times \frac{\sigma(E - U_0) dE}{r}$$

Assume constant electron background. Salpeter approximation assumes constant energy shift.



Approximate turning-point (fm) vs particle energy in screened and unscreened case.(C+C)

Energy shift changes classical turning point in a Coulomb potential.

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Review: Strong and Weak Screening Regimes

Weak Screening

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Salpeter Approximation Shift in energy changes classical turning point.

$$\begin{split} E_C \ll kT \\ V(r)_{scr} &\rightarrow V_0(r) e^{-r/\lambda_D} \\ \Gamma_{scr} &\rightarrow e^{-U_0/kt} \Gamma_0 \\ \lambda_D &= \left(\frac{T}{4\pi e^2 n \sum_i (Z_i + Z_i^2) Y_i}\right)^{1/2} \end{split}$$

- Debye-Huckel Screening: Poisson Equation to first order.
- NOTE: Corrections to the ion-sphere model may result in potential shifts ~ a few percent.

Strong Screening

$$\begin{split} & E_C \gtrsim kT \\ & U_0 \propto \left[(Z_1 + Z_2)^{5/3} - Z_1^{5/3} - Z_2^{5/3} \right] \\ & \times \frac{\rho}{M_{12}}T \end{split}$$

lons approach a lattice-like configuration.



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Relativistic Electron-Positron Plasmas

Relativistic Plasmas

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Screening of reaction rates using e^-e^+ plasmas.

Schwinger-Dyson equation for photon propagator.

 $\left|\frac{\pi^2}{\lambda_{\rm D}^2} = e^2 \frac{\partial}{\partial \mu} \int_0^\infty dp p^2 \left[\frac{1}{e^{(E-\mu)/T} + 1} - \frac{1}{e^{(E+\mu)/T} + 1}\right] \overset{\bullet}{\searrow}$ Screening potential at close range $V_{C}^{
m scr}(r\ll\lambda_{D})\sim V_{C}^{
m bare}-rac{Z_{1}Z_{2}e^{2}}{\lambda_{D}}=V_{C}^{
m bare}-E_{0}$ High Temperature Limit

$$E_0(T \gtrsim m_e) = \frac{Z_1 Z_2 e^3}{\pi} \left[\mu^2 + \frac{\pi^2}{3} T^2 \right]^{1/2}$$
$$\sigma(E) \rightarrow \sigma(E + E_0)$$

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Energy shift could be important for low-lying resonances. $Z_1 = 2, Z_2 = 4$

1.2 1.4 1.6 1.8

• e^+e^- plasma

0.2 0.4 0.6 0.8

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E₀ (keV)

T→0.5-1 MeV

Electron number density

modified by pair production

Relativistic Plasmas

10⁹ = 0 MeV 10⁸ 2 MeV 10 չը (fm) 10 10 10 10-1 T (MeV) ³⁰ ²⁵ ²⁰ ¹⁵ ¹⁰

T=1 MeV, μ =0

[Famiano, Balantekin, & Kajino (2016)]



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Comparison of classical and relativistic Debye lengths. Assume C+C plasma. Classical Debye Length:

$$\lambda_D = \left(\frac{T}{4\pi e^2 n\xi}\right)^{1/2}$$

$$\xi = \sum_i \left(Z_i^2 + Z_i\right) Y_i$$

Relativistic Effects

Example: Neutral ¹²C Plasma



Approximate Screening Regimes

- Strong screening: ions "locked" into a lattice.
- Wigner-Seitz spheres.
- Ion-sphere approximation.

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Relativistic Effects

Example: Neutral ¹²C Plasma



Where might relativistic screening be appropriate? How the intermediate screening region is handled can be quite important.

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Relativistic Effects

Example: Neutral ¹²C Plasma



For WD ignition we will need quantum plasma physics.

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Note the ⁷Be \rightarrow ¹⁰C branch.

Could a resonance here be

significant?

[Broggini et al. (2012), Hammache et al. (2013)]

Results for BBN





- Very small effects
- Low Z
- More massive nuclei not produced until $T \lesssim 0.5$ MeV

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Resonances in ⁷Be+³He



T=1 MeV

- Resonances \lesssim 500 keV ruled out [Hammache et al. (2013)].
- TRRs including resonances are small in this regime.
- Shifts in resonances indicated above.
- Possible effect for sub-threshold resonances.

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Astrophysical Sites Where Plasma Screening Could Be Important



- r-Process screening effects
- x-Ray burst frequency changes
- x-Ray burst light curve changes
- More work to follow



exp(log L):t*3.15e7

x-Ray bursts light curves [PRELIMINARY].

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- Explored relativistic plasma effects in BBN.
- Continuing to work on dynamics in:
 - r-Process
 - WD
 - x-Ray bursts
 - Massive stellar cores
- One really has to be careful in the intermediate screening region.

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Clayton, D.D., *Principles of Stellar Evolution and Nucleosynthesis*, The University of Chicago Press 1968

Broggini et al., JCAP 06, 30 (2012)

Famiano, M.A., Balantekin, B., & Kajino, T., Phys. Rev. C 93, 045804 (2016)

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Hammache, F. et al., Phys. Rev. D 88, 062802 (2013)