Relativistic Electron-Positron Plasma Screening In Astrophysical Environments

Enhancements to Weak and Intermediate Screening

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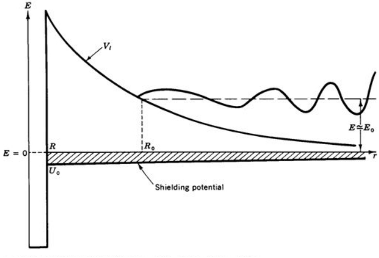
Outline

Review: Nuclear Screening

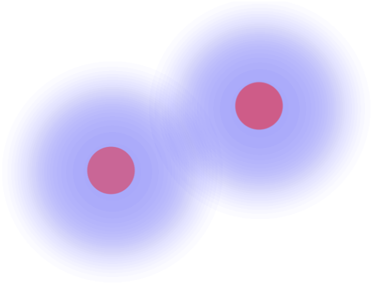
$$V(r) = \frac{Z_1 Z_2 e^2}{r} + \tilde{U}(r)$$

$$\Gamma_{12} \propto \int_0^\infty E^{1/2} e^{-E/kT} \sigma(E - U_0) dE$$

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



[Clayton (1968)]



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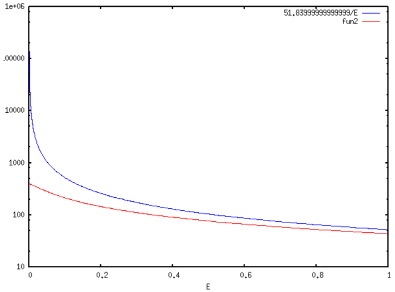


Approximate turning-point (fm) vs particle energy in screened and unscreened case.(C+C)

Energy shift changes classical turning point in a Coulomb potential.

Review: Strong and Weak Screening Regimes

Weak Screening

Salpeter Approximation
Shift in energy changes classical turning point.

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

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

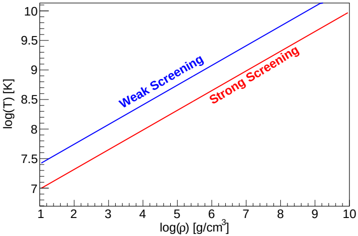
$$\langle \sigma v \rangle_{scr} = f \langle \sigma v \rangle_0 = e^{-U_0/T} \langle \sigma v \rangle_0$$
$$f = \exp\left[\frac{Z_1 Z_2 e^2}{\lambda_D T}\right]$$

Strong Screening

Ion-Sphere

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

Ions approach a lattice-like configuration.

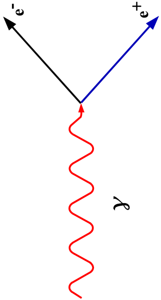


Relativistic Plasmas

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

Schwinger-Dyson equation for photon propagator.

$$\frac{\pi^2}{\lambda_D^2} = e^2 \frac{\partial}{\partial\mu}\int_0^\infty dpp^2\left[\frac{1}{e^{(E-\mu)/T}+1} - \frac{1}{e^{(E+\mu)/T}+1}\right]$$



Screening potential at close range

$$V_C^{\mathrm{scr}}(r \ll \lambda_D) \sim V_C^{\mathrm{bare}} - \frac{Z_1Z_2e^2}{\lambda_D} = V_C^{\mathrm{bare}} - E_0$$

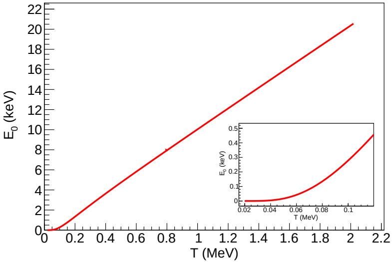
High Temperature Limit

$$E_0(T \gtrsim m_e) = \frac{Z_1Z_2e^3}{\pi}\left[\mu^2 + \frac{\pi^2}{3}T^2\right]^{1/2}$$

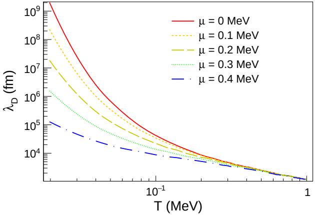
$$\sigma(E) \to \sigma(E+E_0)$$

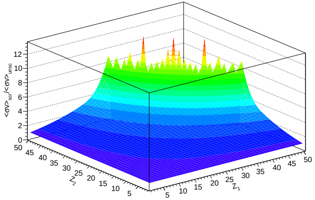
Relativistic Plasmas

- e^+e^- plasma
- T→0.5-1 MeV
- Electron number density modified by pair production



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



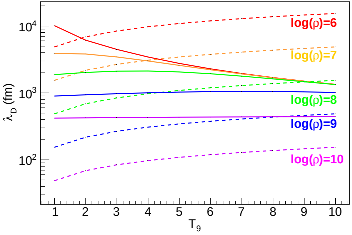


T=1 MeV, μ=0

[Famiano, Balantekin, & Kajino (2016)]

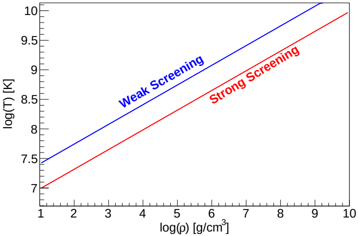
Relativistic Effects

Example: Neutral ^{12}C Plasma



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

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



Approximate Screening Regimes

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

Relativistic Effects

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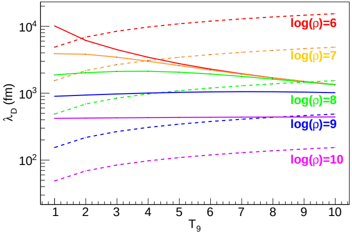

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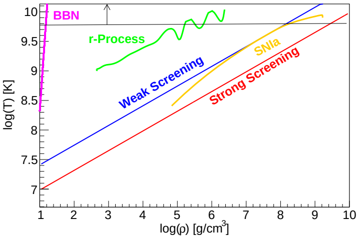

Where might relativistic screening be appropriate?

How the intermediate screening region is handled can be quite important.

Relativistic Effects

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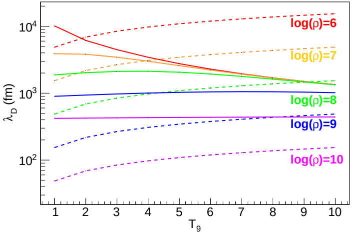

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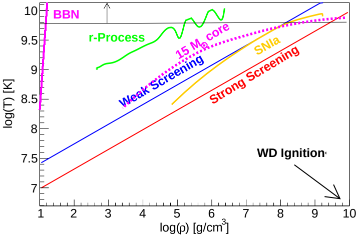

For WD ignition we will need quantum plasma physics.

Relativistic Effects

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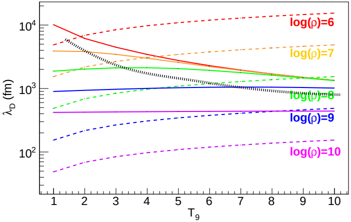

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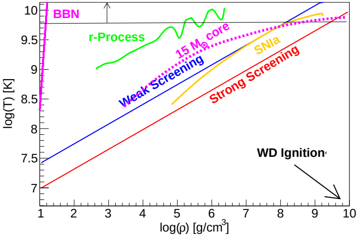

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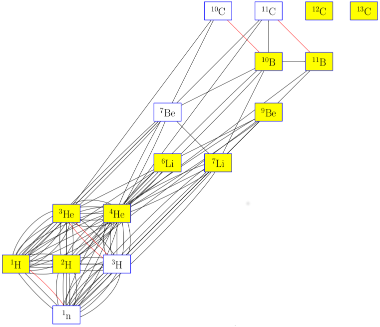
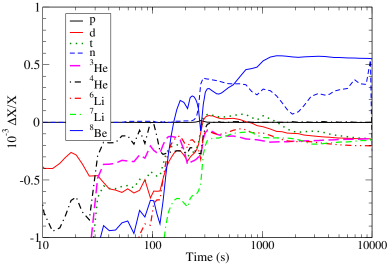
Results for BBN



Note the ^{7}Be→^{10}C branch.

Could a resonance here be significant?

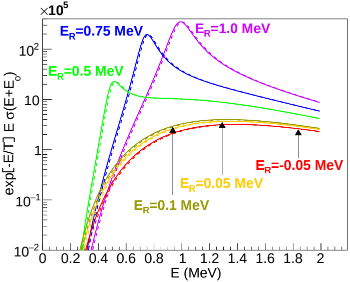
[Broggini et al. (2012), Hammache et al. (2013)]

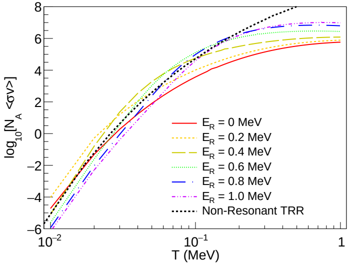


$$\frac{\Delta X}{X} \equiv \frac{X_{scr} - X_{bare}}{X_{bare}}$$

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

Resonances in ^{7}Be+^{3}He

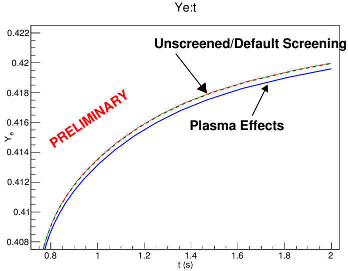




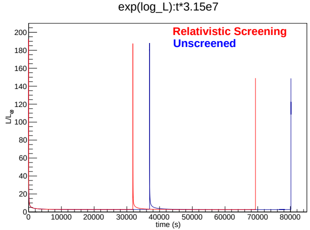
T=1 MeV

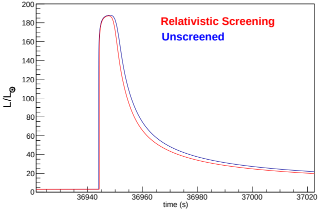
- Resonances $\lesssim$500 keV ruled out [Hammache et al. (2013)].
- TRRs including resonances are small in this regime.
- Shifts in resonances indicated above.
- Possible effect for sub-threshold resonances.

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





x-Ray bursts light curves [PRELIMINARY].

Conclusions

- 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)

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