Mem. S.A.It. Vol. 77, 907

Memorie della

Electron screening in metallic environments: a plasma of the poor man

C. Rolfs

Experimentalphysik III, Ruhr-Universitt Bochum, Germany

Abstract. Fusion reactions play a key role in stars for the understanding of their energy production, evolution and neutrino emission. An important aspect is hereby the effects of electron screening, which increase the fusion cross sections. The fusion reaction D(D,p)T was recently studied in deuterated metals and insulators, i.e. for 58 samples across the periodic table, where a dramatic increase was observed for all the metals. An explanation of the data is presented as well as important future applications are discussed.

Key words. Nuclear Astrophysics–Fusion reactions–Radioactive decay

For the astrophysically important class of charged-particle-induced fusion reactions, there is a repulsive Coulomb barrier in the entrance channel of height $E_c = Z_1 Z_2 e^2/r$, where Z_1 and Z_2 are the integral nuclear charges of the interacting particles, e is the unit of electric charge, and r is the radius. Due to the tunneling effect through the Coulomb barrier, the cross section $\sigma(E)$ of the fusion reaction drops nearly exponentially with decreasing energy E:

$$\sigma(E) = S(E)E^{-1}exp(-2\pi\eta), \quad (1)$$

where $\eta = 2\pi Z_1 Z_2 e^2/hv$ is the Sommerfeld parameter (h = Planck constant, v = relative velocity). The function S(E) defined by this equation contains all nuclear effects and is referred to as the nuclear or astrophysical S(E) factor. It is commonly used to extrapolate available data to the relevant thermal energies in stars and other astrophysical objects (Assenbaum et al 1987), i.e. E $\approx$ 0.01 E_c. In this extrapolation of the cross section using equation 1, it is assumed that the Coulomb potential of the target nucleus and projectile is that resulting from bare nuclei. However, for nuclear reactions studied in the laboratory, the target nuclei and the projectiles are usually in the form of neutral atoms or molecules and ions, respectively. The electron clouds surrounding the interacting nuclides act as a screening potential: the projectile effectively sees a reduced Coulomb barrier, both in height and radial extension. This, in turn, leads to a higher cross section for the screened nuclei, $\sigma_s(E)$, than would be the case for bare nuclei, $\sigma_b(E)$. There is, in fact, an enhancement factor (Assenbaum et al. 1987, Rolfs & Rodney 1988)

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) \sim exp(\pi\eta U_e/E) \geq 1, \quad (2)$$

where U_e is an electron-screening potential energy. This energy can be calculated, for example, from the difference in atomic binding energies between the compound atom and the pro-

Send offprint requests to: C. Rolfs

jectile plus target atoms of the entrance channel, or from the acceleration of the projectiles by the atomic electron cloud: e.g. for the D(D,p)T reaction one finds an acceleration of U_e = 2·13.6 eV = 27.2 eV due to the atomic electrons at the Bohr radius. For energy ratios E/$U_e \gg 1000$, shielding effects are negligible, and laboratory experiments can be regarded as essentially measuring the bare cross section: $\sigma(E) = \sigma_b$(E). However, for E/$U_e \ll$ 100, shielding effects begin to become important for understanding and extrapolating low-energy data. Relatively small enhancements arising from electron screening at E/$U_e \approx 100$ can cause significant errors in the extrapolation of cross sections to lower energies, if the curve of the cross section is forced to follow the trend of the enhanced cross sections, without correction for the screening. Note that for a stellar plasma, the value of the bare cross section σ_b(E) must be known because the screening in the plasma could be quite different from that in the laboratory nuclear-reaction studies, i.e. σ_p(E) = f_p(E) σ_b(E), where the plasma enhancement factor f_p(E) must be explicitly included for each situation. A good understanding of electron-screening effects in the laboratory is needed to arrive at reliable σ_b(E) data at low energies. An improved understanding of laboratory electron screening may also help eventually to improve the corresponding understanding of electron screening in stellar plasmas, such as in our sun.

Experimental studies of reactions involving light nuclides (see Strieder el al. 2001 and references therein) have shown the expected exponential enhancement of the cross section at low energies (equation 2). However, the observed enhancements were in some cases larger (up to about a factor 2) than could be accounted for from available atomic-physics models, i.e. the adiabatic limit U_{ad}. Recently, the electron screening in D(D,p)T has been studied for deuterated metals and insulators, i.e. 58 samples in total (Raiola et al. 2002, 2005). As compared to measurements performed with a gaseous D_2 target (U_e = 25±5 eV (Greife et al. 1995), U_{ad} = 27.2 eV), a large screening was observed in all metals (of order U_e = 300 eV, i.e. higher by one order of magnitude than U_{ad}), while a small (gaseous) screening was found for the insulators. An explanation of the surprisingly large screening in metals was suggested by the Debye plasma model applied to the quasi-free metallic electrons. The electron Debye radius around the deuterons in the lattice is given by

$$R_D = (\epsilon_o kT/e^2 n_{eff}\rho_a)^{1/2} = 69(T/n_{eff}\rho_a)^{1/2}, \quad (3)$$

R_D in units of m, the temperature T of the quasi-free electrons in units of K, n_{eff} the number of these electrons per metallic atom, and the atomic density ρ_a in units of atoms/m^3. With the Coulomb energy of the Debye electron cloud and a deuteron projectile at R_D set equal to $U_e \equiv U_D$, one obtains

$$U_D = 2.09 \cdot 10^{-11}(n_{eff}\rho_a/T)^{1/2}, \quad (4)$$

U_D in units of eV. For T = 293 K, $\rho_a = 6 \cdot 10^{28}$ m^{-3}, and n_{eff} = 1 one obtains a radius R_D, which is about a factor 10 smaller than the Bohr radius of a hydrogen atom; as a consequence, one obtains U_D = 300 eV, the order of magnitude of the observed U_e values. A comparison of the calculated and observed U_e values led to n_{eff} values, which were for most metals of the order of one. The acceleration mechanism of the incident ions leading to the high observed U_e values is thus the Debye electron cloud at the rather small radius R_D. The n_{eff} values were compared also with those derived from the Hall coefficient: they agreed within experimental uncertainties for all metals with known Hall coefficient. Another critical test of the Debye model was the predicted temperature dependence, $U_D \propto T^{-1/2}$, i.e. a decrease of U_D with increasing temperature, which was experimentally verified for T = 260 to 670 K. Furthermore, the Debye energy U_D should scale with the nuclear charge Z_t of the target atoms, $U_D \propto Z_t$: the prediction was verified (Cruz et al. 2005, Zahnow et al. 1997 & Kettner et al. 2006) in ^7Li(p,α)α and ^{6}Li(p,α)^{3}He (Z_t = 3), ^{9}Be(p,α)^{6}Li and ^{9}Be(p,D)^{8}Be (Z_t = 4), ^{50}V(p,n)^{50}Cr (Z_t= 23), and ^{176}Lu(p,n)^{176}Hf (Z_t= 71), always for pure metals and alloys. The data demonstrated that

the enhanced electron screening occurs across the periodic table and is not restricted to reactions among light nuclides studied so far. The two reactions with neutrons in the exit channel demonstrated furhermore that the electron screening is an effect in the entrance channel of the reaction and not influenced by the ejectiles of the exit channel, i.e. by the charged particles of the exit channel studied so far. The results for ^{7}Li(p,α)α and ^{6}Li(p,α)^{3}He demonstrated an isotopic independence of the effects of electron screening, as expected. Finally, the Debye model predicts a dependence on the nuclear charge of the ion, $U_D \propto Z_i$; the prediction was verified in the D(^{3}He,p)^{4}He studies in metals ($Z_i = 2$): taking a typical value of $U_e = 300$ eV for the D+D fusion reaction in metals at T = 293 K, one expects for D(^{3}He,p)^{4}He the Debye value to be $U_D = Z_i U_e(D + D) = 600$ eV, consistent with observation ($U_e = 680 \pm 60$ eV). It should be noted that the Debye model is used to calculate the effects of electron screening on fusion reactions in a stellar plasma, $f_p(E)$. Using a metallic plasma the Debye model was tested (in the reports just discussed) successfully with respect to all parameters entering the model. One may thus call metals *a plasma of the poor man*. An improved theory is highly desirable to explain why the simple Debye model appears to work so well. Without such a theory, one may consider the Debye model as a parametrisation of the data, with an excellent predictive power.

There is another important prediction of the Debye model concerning radioactive decay of nuclides in a metallic environment. In general, for the α-decay and β^+-decay one expects a shorter halflife due to the acceleration mechanism of the Debye electrons for these positively charged particles similar as for the protons, deuterons or ^{3}He in the fusion reactions, while for the β^--decay and e-capture process one predicts a longer halflife.

For example, if the α-decay ^{210}Po $\rightarrow \alpha +$ ^{206}Pb with $E_\alpha = 5.30$ MeV and $T_{1/2} = 138$ days occurs in a metal cooled to T = 4 K, one arrives at $U_D = Z_\alpha Z_t U_e(D + D)(293/4)^{1/2} = 2 \cdot 82 \cdot 300$ eV$\cdot$8.5 = 420 keV, where we used again a typical value of $U_e = 300$ eV for the D+D fusion reaction in metals at T = 293 K and assumed the relation $U_D \propto T^{-1/2}$ to be valid also below T = 260 K. The enhancement factor then gives $f_{lab} = 265$, and thus the halflife is shortened to 0.5 days. For the biologically dangerous transuranic waste ^{226}Ra $\rightarrow \alpha +$ ^{222}Rn ($E_\alpha = 4.78$ MeV, $T_{1/2} = 1600$ years) an analogous calculation leads to $T_{1/2} = 1.3$ years. Experiments are in progress to test these predictions.

If they should also be verified, one may have a solution to remove the transuranic waste (involving all an α-decay) of used-up rods of fission reactors in a time period of a few years. Finally, a reduced halflife of α-emitters such as ^{238}U and ^{232}Th in a metallic environment may have important corrections in their use as cosmo-chronometers (Rolfs & Rodney 1988) (i.e. the age of the elements) as well as in understanding the flux of geo-neutrinos using the Kamland detector (Araki et al. 2005) (i.e. the energy source of the earth).

References

Araki, T. et al. 2005, Nature, 436, 499
Assenbaum, H.J. et al. 2002, Z.Phys., A327, 461
Cruz, J. et al. 2005, Phys.Lett., B624, 181
Greife, U. et al. 1995, Z.Phys., A351, 107
Kettner, K.U. et al. Eur.Phys.J., in press
Raiola, F. et al. 2002, Eur.Phys.J., A13, 377
Raiola, F. et al. 2004, Eur.Phys.J., A19, 283
Raiola, F. et al. 2005, Eur.Phys.J., A31, 1141
Rolfs, C. & Rodney, W.S. 1988, Cauldrons in the Cosmos (University of Chicago Press)
Strieder, F. et al. 2001, Naturwissenschaften, 88, 461
Zahnow, D. et al. 1997, Z.Phys., A359, 211