Energy dependence of fusion cross sections

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Observed enhancements of fusion cross sections at low energies are explained as caused by an underestimate of beam energy due to an overestimate of the stopping energy loss.

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It was claimed recently [1,2] that the experimental and theoretical Coulomb penetration factors for very low energies, of the order of magnitude 5–20 keV, are in disagreement with each other for different light projectiles and targets, in such a way that some of the experimental cross sections, although very small, are higher than predicted from the usual penetration factors. Knowledge of these factors is necessary to obtain information about the cross sections of a number of reactions of astrophysical interest. The penetration factor, together with the de Broglie factor E^{-1}, contains the main energy dependence of the cross sections. The astrophysically relevant energies of relative motion of ions are generally small compared to most experimental ones and the cross sections are often obtained by extrapolation. Therefore, these discrepancies must be resolved before the use of such experimental cross sections in astrophysics can be justified.

A correction factor for electronic screening was introduced [3] as a possible explanation for the observed discrepancy.

To simplify the discussion we shall in the following consider one definite nuclear reaction:

$$d + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p. \tag{1}$$

If deuterons, as most often is the case, are the beam and the target a gas of atomic ^{3}He, the effect may be ascribed to the two electrons of He which in an adiabatic approach will distribute themselves for each nuclear distance in such a way as to minimize the electronic energy. When this is added to the Coulomb repulsion of the nuclei a new, lower barrier, as a function of the distance between the nuclei is obtained. The maximal lowering comes when the nuclear distance is near zero where it is given by the energy difference between a Li^+ ion and a He atom, i.e., 120 eV. The lowering of the Coulomb barrier is equivalent to an energy gain for the incident particles of 120 eV.

The 120 eV represents an upper limit of the effect in at least two ways: The adiabatic energy gain for larger distances between the nuclei must be smaller, and the average energy gain will be smaller if the nonadiabatic probability of the electrons being in an excited state is taken into account.

The experiments, on the other hand, call for a larger penetration, i.e., a larger energy gain than that given by the adiabatic approximation, and that could never be due to electronic rearrangement. Time-dependent Hartree-Fock calculations confirm this statement [4]. We shall here propose another possible explanation, also mainly of electronic origin, for the observed effect. The energy of the projectiles, which take part in the measured nuclear reaction, is not that of the original incoming beam; they have lost energy in collisions with atoms of the target gas before they reach the region to which the detectors are sensitive. This energy loss was estimated from experiments concerning stopping of ions, supplemented by stopping theory [5,6]. Since reliable experimental results mainly concern higher energies, the numbers for the relevant energies ($\leqslant$10 keV) have been obtained from extrapolation by means of the theory assuming velocity proportionality in this extrapolation to low energies. In Ref. [2] the energy loss of 10 keV deuterons (Lab. Syst.) between the entrance of the gas chamber and the region where the detector is placed (a distance of 10.5 cm) is estimated to be 210 eV (Lab. Syst.) (in a ^{3}He gas at $p = 0.20$ Torr). The energy of the original incident beam was given with 0.05% precision.

In the ${}^3\mathrm{He}+d$ c.m. system the incoming energy and energy loss estimate are 6 keV and 126 eV, respectively.

An energy gain in the relative motion of the nuclei, ΔE, leads to an enhancement of the Coulomb barrier penetration by a factor

$$f(E) = \exp[\pi\eta\Delta E/E] \tag{2}$$

(this was also the factor which, for $\Delta E = 120$ eV, was used above, giving too little enhancement: 1.26).

Here η is the Sommerfeld parameter, given by the charges of the colliding ions divided by their relative velocity, in units where E is in keV, masses in amu:

$$\pi\eta = 15.65 Z_1 Z_2 [\mu/E]^{1/2}. \tag{3}$$

The observed enhancement is approximately 1.57. Remarkably, this is just the number which would be seen if the stopping energy loss were completely neglected, i.e., if ΔE were replaced by $120+126$ eV.

New, and presumably overlooked, experimental results on low energy electronic stopping of proton and deuteron projectiles in helium gas [7] indicate that the ionization cross sections and therefore also the energy loss, at low bombard-

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ing energies are considerably smaller than that given by the above-mentioned extrapolation method. This is related to the fact that the cross section for the relevant process, i.e., ionization of target and projectile, which process is dominant at energies of 30 to 100 keV, falls off rapidly with lowering of the projectile energy, according to semiclassical ionization theory [8] approximately as E^4, cf. Eq. (3.13) of the said reference. Therefore, at some lower energy value, another process will dominate in the energy loss mechanism, namely the transfer of an electron between the target and the positive ion projectile. The cross section for this process also falls off rapidly with lowering of the bombarding energy; in the relevant region, however, only as E, cf. considerations in Ref. [9], see, e.g., Eq. (4.9.51). The deviation of the classical trajectory from a straight line with constant velocity also leads to a decrease of the cross section at lower energies [8]. However, for the suggested mechanism this effect is of minor importance.

A quantitative determination of these effects, based on the coupled channels formalism, has been given by Grande and Schiwietz [10]. These calculations, which agree with the experimental values of Golser and Semrad [7], show that for d-^{3}He collisions with center-of-mass energies of 6 keV, the mean energy loss is less than 30% of that given by the extrapolation procedure mentioned above. The numbers revised along these lines bring the theoretical values for the Coulomb penetration factors into the range of the experimental errors, cf. the data given in Ref. [1] on the d-^{3}He process, i.e., Fig. 5.22 in that reference.

The considerations given above will be followed up by detailed calculations of stopping energy loss along the lines already sketched. The authors feel, moreover, that the preliminary numbers given here encourage further explanation along these lines. The meaning of this Rapid Communication, while waiting for the results of lengthy calculations, is to suggest, e.g., to astrophysicists, that the present discrepancies between theory, with *inclusion* of an electron screening factor, and experiment may well be explained within the frame of usual atomic collision theory, thus posing no serious problem for nuclear astrophysics.

In conclusion we should like to quote Lindhard "It seems probable that the measurement of d-^{3}He fusion primarily can be used to estimate *low energy stopping* of d in He" [11].

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