Theoretical study of screening effects by bound electrons on low energy nuclear reactions

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Abstract

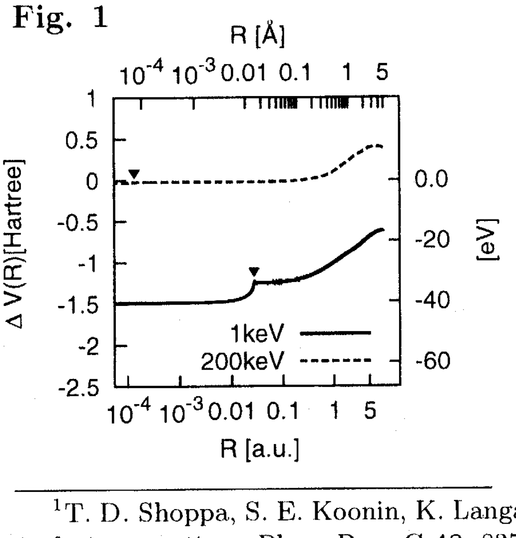
Nuclear reaction rates at astrophysical energies are interesting quantities for their own sake and also in connection with nucleosynthesis in stars. Experimental cross sections for all systems so far studied show increasing enhancement with decreasing bombarding energy over the values extrapolated from the data at high energies. Many attempts have been made to explain this phenomenon in terms of the screening effects by target electrons. A puzzling thing is that the observed enhancement in almost all existing data exceeds the value in the so-called adiabatic limit, which is thought to give the maximum screening energy.

There are searches for alternative explanations of this enhancement phenomenon. For example, the stopping power at extremely low energies is not well known. The projectile might capture electrons before reaching the target atom. Also, different values of the screening energy are obtained depending on the method of analysis.

However, it is interesting to study whether the screening effect by target electrons alone can cause a larger screening energy than the adiabatic limit. The aim of this thesis is to examine this possibility. In this connection one should note that the screening energy in the adiabatic limit used in literatures is not the true adiabatic limit which can never be exceeded, but is identified with the difference of the binding energies of the electrons in the target and the united atoms.

Our approach is the same as that in Ref.[1] in the sense that the time evolution of the relative motion between the projectile and the target nuclei and that of the electrons are followed self-consistently. The authors in Ref.[1] assumed that the screening effects can be represented by a constant shift of the Coulomb barrier. Accordingly, they solved the coupled equations only in the classical region and identified the screening energy with the potential shift at the external turning point. However, this prescription is valid only in the cases, where the electronic state is a single adiabatic state at the external point and the screening potential does not change during the tunneling process. Therefore, we explicitly study the tunneling region as well as the classically allowed region by applying a semiclassical mean field theory of quantum tunneling which we developed. We can thus examine also the spatial properties of the screening potential in the tunneling region. Fig. 1 shows the screening potential for the D+d reaction at the center-of-mass energies 1keV (solid line) and 200keV (dashed line) as a function of the separation distance between the nuclei. The filled triangles show the position of the external classical turning point. It should

Fig. 1



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[1] T. D. Shoppa, S. E. Koonin, K. Langanke and R. Seki, *One- and two-electron atomic screening in fusion reactions*, Phys. Rev. C **48**, 837 (1993)

be remarked that at the low incident energy $E_{\mathrm{c.m.}}$=1keV the screening potential exhibits a characteristic radial variation in sharp contrast to the assumption in all previous works that the screening effects can be well represented by a constant shift of the potential barrier in the tunneling region. The symmetry of the system plays an important role in this respect: the electron occupies the gerade and the ungerade configurations with an equal weight because of the symmetry. The change of the screening potential in the tunneling region is caused as a consequence that the contribution to the mean potential from the ungerade configuration, which has a higher electronic energy, quickly diminishes as the relative motion between the projectile and target penetrates into the tunneling region. This is clearly formulated in our semiclassical mean field theory. The same effects in the D+p, ^{3}He$^+$+d and ^{3}He+d reactions are shown in the thesis.

We quantify the screening effects by converting the enhancement of the tunneling probability into the screening energy. Fig. 2 shows the screening energy U_e as a function of the incident energy $E_{\mathrm{c.m.}}$ for the D+d reaction. The experimental value should be taken merely for a reference, because it is for a molecular D_2 target from Ref.[2] For comparison we plot also the screening energy obtained by the calculation only in the classically allowed region (dashed line with open squares). The thin dashed and solid lines refer to the sudden and *conventional* adiabatic limits, respectively. It is remarkable that our calculations (solid line with closed circles) give systematically a larger screening energy than that in the conventional calculations (open squares).

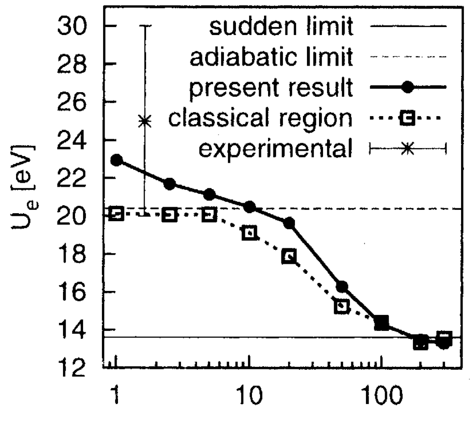

Fig. 2

In summary, using a semiclassical mean field theory, we show that the screening potential exhibits a characteristic radial variation in the tunneling region in sharp contrast to the assumption of the constant shift in all previous works. Also, we show that the explicit treatment of the tunneling region gives a larger screening energy than that in the conventional approach, which studies the time evolution only in the classical region and estimates the screening energy from the screening potential at the external classical turning point. This modification becomes important if the electronic state is not a single adiabatic state at the external turning point either by pre-tunneling transitions of the electronic state or by the symmetry of the system even if there is no essential change with the electronic state in the tunneling region.

The List of Publications

S. Kimura and N. Takigawa, *Fusion from an excited state*,
Phys. Rev. C **66**, 024603 (2002)

S. Kimura, N. Takigawa, M. Abe, and D.M. Brink, *Influence of tunneling on electron screening in low energy nuclear reactions in laboratories*,
to be published in Phys. Rev. C (2003), nucl-th/0211080

and 3 other papers

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[2] U. Greife, F. Gorris, M. Junker, C. Rolfs, and D. Zahnow, Z. Phys. A **351**, 107 (1995)