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学位論文題目	Theoretical study of screening effects by bound electrons on low energy nuclear reactions (低エネルギー核反応に対する標的核束縛電子による遮蔽効果の理論的研究)
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論 文 内 容 要 旨

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. The result shows that at the low incident energy Ec.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, $^3He^+$+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. It is remarkable that our calculations give systematically a larger screening energy than that in the conventional calculations.

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.

[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)

論文審査の結果の要旨

本論文は，実験室で行われた超低エネルギー核反応における標的核の束縛電子による遮蔽効果について論じたものである。

先ず，理論的枠組みとして，散乱の初期に対応する遠方の古典領域と標的核と入射核が近づいたトンネル領域における，電子の波動関数の量子力学的な時間発展と原子核間の相対運動を一貫して記述できる半古典的平均場トンネル理論を開発した。

ついで，その定式化に基づいて，$^3He^+$+d反応やD+d反応をはじめ幾つかの系に対して数値解析を行い，(1) 遮蔽ポテンシャルは，トンネル領域において空間的に強く変化し，これまでの全ての解析で仮定されていたような，ポテンシャル障壁の距離によらない定数分だけの低下では表現できない，(2) 遮蔽効果の大きさを定量的に正しく評価するためには，今回の計算のようにトンネル領域をあらわに取り扱うなど，古典領域のみを扱い，古典的転回点での電子の波動関数から遮蔽効果の大きさを評価する従来の計算法を越えた解析が必要である，(3) 今回の新しい評価法では，従来の方法より大きな遮蔽効果が得られる，(4) 遮蔽ポテンシャルの強い空間変動および従来の取り扱いを超える大きな遮蔽効果は，系の対称性やトンネル領域に至る前の電子の遷移などにより，古典的転回点で電子の断熱配位に混じりがある場合に特に顕著に現れる，(5) これまでは，融合後の原子と標的核原子における電子の束縛エネルギーの差が理論的に可能な遮蔽エネルギーの最大値（断熱極限での遮蔽エネルギー）と信じられていたが，系の対称性などによりその値を超える遮蔽効果が起こり得る。しかし，現在報告されているような断熱極限の数倍におよぶ大きな遮蔽効果は期待できない，ことなどを明らかにした。

論文では，更に，2準位結合チャネル計算を通して，半古典的平均場トンネル理論の有効性が示され，また，トンネル領域での有効ポテンシャルが強い空間依存性を示すことが示されている。

半古典的平均場トンネル理論の開発を含め，これら全ての結論は，本研究で初めて明らかにされたものであり，超低エネルギー核反応，元素生成反応，環境下での量子トンネル効果の研究において，極めて重要な知見である。

本論文は，木村 幸恵が自立して研究活動を行うに必要な高度な研究能力と学識を有している事を示している。従って，木村 幸恵提出の博士論文は，博士（理学）の学位論文として合格と認める。