Theory of the Trojan Horse

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Nuclear astrophysical processes due to the presence of the Coulomb barrier have so small cross sections that it is very difficult or often impossible to measure in the lab conditions nuclear cross sections at stellar energies. That is why different indirect techniques are used to extract astrophysical information. There are three widely used indirect techniques: asymptotic normalization coefficient, Coulomb breakup reactions and Trojan Horse. The Trojan Horse method provides astrophysical information about nuclear reactions at stellar energies. In our work we consider the theory of the Trojan Horse. As any indirect technique, the Trojan Horse method has advantages and disadvantages. This method allows one to measure the astrophysical cross sections down to a few keV, however, the extracted astrophysical factor corresponds to a process where one of the entry particles is off-energy-shell. The question is how important are off-shell effects at astrophysically relevant energies. In standard calculations the off-shell effects are neglected. The purpose of this work is to provide an insight into the theory of the Trojan Horse, and specifically to develop a method allowing us to estimate the off-shell effects. Let us consider the breakup reaction $a + A \rightarrow b + c + C$, where $a = b + x$, and the subreaction of interest is $x + A \rightarrow b + B$. The reaction amplitude is given by

$$M = \langle \chi_{bB}^{(-)} \chi_{cC}^{(-)} \phi_b \phi_c | V_{bb} - U_{bb} + (V_{bb} - U_{bb}) G (V_{AA} - U_{AA}) | \phi_a \phi_A \chi_{AA}^{(+)} \rangle$$

This is the post-form of the exact amplitude. Here, $G$ is the total Green function, $\chi_{ij}^{(±)}$ is the distorted wave describing the relative motion of particles $i$ and $j$, $\phi_i$ is the bound-state wave function of nucleus $i$, $V_{ij} (U_{ij})$ is the interaction potential (optical potential) between particles $i$ and $j$. From this equation we need to single out the amplitude of the subreaction $x + A \rightarrow c + C$. The on-shell subreaction amplitude is given by

$$M_0 = \langle \chi_{cC}^{(-)} \phi_c | V_{cc} - U_{cc} + (V_{cc} - U_{cc}) G (V_{xA} - U_{xA}) | \phi_A \chi_{xA}^{(+)} \rangle$$

An important point is the presence of the scattering wave function $\chi_{xA}^{(+)}$ in the on-shell amplitude. This wave function is absent in Eq. (1) due to the off-shellity of the transferred particle $x$. We singled out the half-off-shell subreaction amplitude from (1) and compare it with the on-shell Eq. (2). The impact of the off-shell effects is estimated differently for resonance and direct $x + A \rightarrow c + C$ reactions. On the first stage we develop a model to estimate the off-shell effects for the direct subreaction assuming that it is described by the particle $t$ transfer, where $A = C + t$ and $c = x + t$. 

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