The Trojan Horse Method: an Indirect Technique in Nuclear Astrophysics

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To obtain the astrophysical factor at astrophysical energies different indirect techniques are being used to overcome the presence of the Coulomb barrier. The Trojan Horse (TH) method is a powerful indirect technique which allows one to determine the astrophysical factor for rearrangement reactions. The TH method, first suggested by Baur [1], involves obtaining the cross section of the binary $x + A \to b + B$ process at astrophysical energies by measuring the two-body to three-body ($2 \to 3$) process $a + A \to y + b + B$, in the quasi-free (QF) kinematics regime, where particle $a = (xy)$ is accelerated at energies above the Coulomb barrier. After penetrating through the Coulomb barrier, nucleus a undergoes breakup leaving particle x to interact with target A while projectile y flies away. From the measured $a + A \to y + b + B$ cross section, the energy dependence of the binary sub-process, $x + A \to b + B$, is determined. The main advantage of the TH method is that the extracted cross section of the binary sub-process does not contain the Coulomb barrier factor. Consequently the TH cross section can be used to determine the energy dependence of the astrophysical factor, $S(E)$, of the binary process, $x + A \to b + B$, down to zero relative kinetic energy of the particles x and A without distortion due to electron screening. The absolute value of $S(E)$ must be found by normalization to direct measurements at higher energies. At low energies where electron screening becomes important, comparison of the astrophysical factor determined from the TH method to the direct result provides a determination of the screening potential. Even though the TH method has been applied successfully to many direct and resonant processes [2], there are still reservations about the reliability of the method due to two potential modifications of the yield from off-shell effects and initial and final state interactions in the TH $a + A \to y + b + B$ reaction. In the TH reaction, particle x in the binary sub-process $x + A \to b + B$ is virtual (off-energy-shell). In the standard analysis, the virtual nature of x is neglected and the plane wave approximation is used. We addressed, for the first time, the reliability of these assumptions. It has been explained why the reaction cross sections with virtual particles are not affected by the barrier factor. We have also explained why the energy dependence of the cross section of the direct binary reaction $x + A \to b + B$ with the virtual particle x and plane wave approximation in the initial state is similar to the energy dependence of the astrophysical factor for this reaction. We demonstrated how to take into account the Coulomb interaction in the initial state of the TH reaction $a + A \to y + b + B$ when extracting the astrophysical factor for the binary reaction $x + A \to b + B$. Our results justify the application of the TH as indirect technique in nuclear astrophysics.

[1] G. Baur, Phys. Lett. **178B**, 135 (1986).
[2] C. Spitaleri *et al.*, Phys. Rev. C **69**, 055806 (2004).