Indirect Methods in Nuclear Astrophysics

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In calculations of nucleosynthesis either in stellar burning or in the big bang one needs nuclear cross sections at energies far below the Coulomb barrier at 10 to several 100 keV, which are very difficult, if not impossible, to measure. One often has to rely on extrapolations of the astrophysical S-factor. An alternative are indirect methods to determine such cross sections, the most important ones are Coulomb dissociation and particular transfer reactions, the so-called Trojan Horse method.

Radiative capture processes (p,γ) are important in stellar nucleosynthesis and can be well described as a 1-step process proceeding mainly by E1-transitions. Coulomb dissociation is the inverse process, where the virtual photons are provided by the electric field of a heavy nucleus [1]. In the inverse process, however, multipolarities contribute with different weight, e.g. E2 being much stronger, and also higher order and nuclear contributions have to be known in order to extract the S-factor. We have investigated this problem in two ways:

We have explicitely calculated higher order (up to 3-steps), different multipolarities and nuclear contributions for ^8B breakup scattered on ^{208}Pb for different projectile energies [2] in preparation for a GSI-experiment. We showed that at a bombarding energy of 250 MeV the disturbing effects are well under control. A second method is a dynamic description of Coulomb breakup by solving the time-dependent Schrödinger equation [3]. This method includes all orders but is restricted to simple single-particle models of the nucleus. This method has been applied to the breakup of ^7Li at 42 MeV, where the dynamic effects are found to be important [4].

A more general indirect method are transfer reactions to the continuum. $A + (b + x) \to C + c + b$, where the subprocess $A + x \to C + c$ can be investigated at low energies because of the Fermi motion in $a = 3Db + x$. This method was proposed qualitatively by Baur [5] and called the Trojan Horse method. We have recently formulated it in more detail in the framework of DWBA, and investigated the plane wave limit, where the resulting 3-body cross section can be factorized [6], but where the 2-body cross section is modified because of the off-shell nature.

The method has been applied to two cases. The important threshold behavior of the $^{12}C(\alpha,\gamma)^{16}O$ reaction can be investigated by studying the $\alpha -^{12}C$ elastic scattering at very low energies. In the THM this has been done by investigating the $^6Li(^{12}C,\alpha^{12}C)d$ reaction, where $^6Li = 3D\alpha + d$ is the Trojan Horse. $\alpha -^{12}C$ cross sections have been obtained in the energy region of 1.6-3.2 MeV in good agreement with direct measurements [7]. However, a close analysis shows that elastic scattering is, in fact, complicated in the THM because of the presence of Coulomb scattering.=20

We have also applied the THM to nuclear reactions, namely to the astrohysical $d(^6Li,\alpha)\alpha$ reaction studied as the $^6Li(^6Li,\alpha\alpha)\alpha$ breakup process [8]. We were able to extract the S-factor down to energies of 10 keV, comparable to direct measurements. An advantage of the THM is that it is free from electron screening effects, for which the direct measurements have to be corrected empirically. Thus the method may also be useful to understand the screening effect.

References

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