Indirect Methods in Nuclear Astrophysics ◇

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In many astrophysical scenarios, like stellar evolution and nucleosynthesis, nuclear reactions constitute a fundamental input to theoretical models. Their cross sections have to be determined with sufficient accuracy at rather low energies. These cross sections are ususally extremely small due to the Coulomb barrier in the initial channel and a direct experimental determination is often impossible. Besides theoretical model calculations there are various efforts to obtain information about the relevant ractions by applying indirect methods. Of course, the validity of these approaches, both theoretically and experimentally, has to be established.

In recent years the Coulomb dissociation method has been applied with much success to determine cross sections of radiative capture reactions $a(b,\gamma)c$ [1]. Here, one studies the breakup of nucleus c into fragments a and b in the scattering on a highly charged target. The cross section of this process is related via the detailed balance theorem to the cross section of the inverse photon dissociation reaction multiplied with virtual photon numbers which can easily be calculated theoretically. By a variation of projectile energy and scattering angle the contributions of different multipolarities can be separated and an extraction of the relevant astrophysical S-factor is rather straightforward. However at small projectile energies, the question arises whether this simple first order description of the process is sufficient. Final state effects, like the "post-acceleration" of the fragments in the Coulomb field of the target, can change their momenta and prevent a model independent analysis of the experiment.

In order to study these higher order effects we have developed a method for a fully dynamical calculation of the breakup process by solving the time-dependent Schrödinger equation [3]. As compared to other methods, like explicit higher order or coupled channels calculations, we obtain a clear concept of the process by a visualization of the time-dependent spatial distribution of the projectile wave function. We have applied our method to the Coulomb dissociation of 42 MeV ^{7}Li scattered ^{197}Au which corresponds to the conditions of a recent experiment [4]. The observed forward-backward asymmetry in the $\alpha - t$ fragment distribution could not be explained by first order theory, even if E2 contributions to the breakup were included. Howevr, the full dynamical calculation accounts essentially for the asymmetry in the angular correlation. This shows the importance of choosing suitable experimental conditions for a reliable application of the method.

A second approach for the study of a astrophysical nuclear reaction $A(x,c)C$ at small relative energies is the "trojan horse" method [2], which still has to become established as an indirect tool in nuclear astrophysics. Here, a spectator particle b is attached to nucleus x to form a projectile $a = (x + b)$ and a three-body type of reaction $A(a,bc)C$ is studied. In contrast to the two-body reaction, the projectile energy can be chosen to overcome the Coulomb barrier in the initial channel and the particle x is brought into the reaction zone to induce the reaction which one is interested in. From the experimentally determined three-body cross section we can extract information on the relevant two-body reaction although the connection is more complicated than in the Coulomb breakup method. In principle the "trojan horse" method can also be applied to radiative capture reactions.

In preparation for a study of the $^{12}C(\alpha,\gamma)^{16}O$ reaction with the "trojan horse" method, a recent experiment investigated the elastic αC scattering by means of the $^{12}C(^6Li,\alpha^{12}C)d$ reaction where the deuteron served as the spectator [5]. In the quasi-free (plane wave) approximation the cross section of this reaction can be written as a product of the three factors: the (off-shell) elastic αC scattering cross section, the ^{6}Li ground state momentum distribution and a kinematical factor. In Fig. 1 we show a calculated αC relative energy spectrum in a simulation of the experiment, which is in good agreement with the actually measured distribution. The 4^+ resonance at 3.2 MeV and the continuum at lower energies are clearly visible. This result indicates that the method is applicable and one can proceed to the more challenging case.

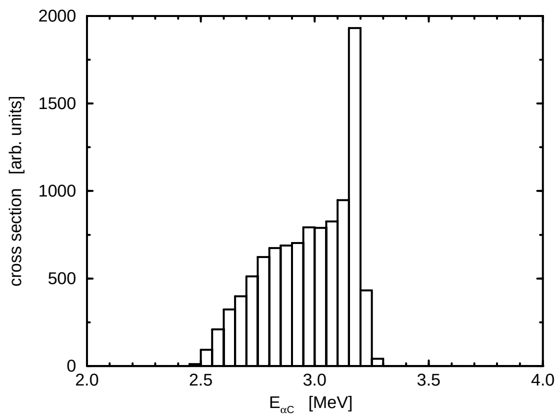

Fig. 1: Cross section of the $^{12}C(^6Li,\alpha^{12}C)d$ reaction as a function of the αC relative energy for 17.53 MeV ^{12}C projectiles, a deuteron momentum $p_d < 10$ MeV/c and an αC scattering angle of 120°.

References

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