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1.103 Continuum Stripping Reactions as an Indirect Method for Studying Astrophysically Interesting Nuclear Reactions

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For stellar evolution, nucleosynthesis and the solar neutrino problem certain nuclear reaction cross sections at rather low bombarding energies (corresponding to temperatures in the stellar interior) have to be known. Since reliable, purely theoretical calculations are usually very difficult, one has to rely on direct experimental measurements of such reactions in the laboratory. This method meets, however, with great experimental difficulties and very great efforts have gone into such experiments. These great difficulties are directly related to the low cross sections which occur in nuclear reactions well below the Coulomb barrier.

We propose an indirect method to overcome the low reaction rates of sub-barrier reactions, the stripping into the continuum*. We explain this by means of an example (other types of reactions can be dealt with in a similar manner). We consider the reaction

$$p + {}^{18}O \rightarrow \alpha + {}^{15}N \qquad (1)$$

which is relevant for the CNO cycle. The total cross section, which connects the channels c and c', is given in terms of the S-matrix $S^{J^\pi}_{c\ell s;c'\ell's'}$ by[3)]

$$\sigma(c\rightarrow c') = \frac{\pi}{k^2(2s+1)} \sum_{J^\pi \ell\ell'} (2J+1) \left| S^{J^\pi}_{c\ell s;c'\ell's'} \right|^2 . \qquad (2)$$

The total spin and parity are given by J^π, s and s' denote the channel spins, ℓ and ℓ' the orbital angular momenta. For the low energies of interest, $\ell=0$ is expected to be most important, but, as one already knows from angular distributions, $\ell=1$ will also play a role, at least for $E_p > 70$ keV (Ref. 2).

Instead of studying reaction (1) directly, we propose to study the stripping reaction into the continuum

$$(b+p) + {}^{18}O \rightarrow \alpha + {}^{15}N + b \qquad (3)$$

where a = (b+p) is a projectile (e.g. a=d, ^3He, α,...) with sufficient incident energy to overcome the Coulomb barrier. Thus, the (p,α)-reaction on the ^{18}O target is no more hindered by the Coulomb barrier, and the cross section for reaction (3) at (p+^{18}O)-relative energies at stellar conditions does not suffer from the very small cross section due to the barrier penetration. However, the problem is now to link, by means of theoretical nuclear reaction calculations, the cross sections for reac-

* See also G. Baur, B. Hoffmann, F. Rösel, D. Trautmann and R. Shyam, Proc. Workshop on Coincident Particle Emission from Continuum States in Nuclei, Bad Honnef, June 4-7, 1984, p. 538, ed. by. H. Machner and P. Jahn (World Scientific Publ. Comp., Singapore).

tion (3) to the astrophysically relevant cross section (2). We want to discuss now such a procedure and the assumption under which it is supposed to be valid.

Using a surface approximation for a direct nuclear process (3), it has been shown[3-6] that the cross section for (3) can be expressed in terms of the S-matrix-elements relevant for eq. (2). Such a surface approximation, appropriate for strongly absorbing projectiles a and ejectiles b, could be overcome in the work of Austern and Vincent[7] and Kasano and Ichimura[8] for inclusive breakup reactions. In this more generally valid formulation, the direct and simple connection to the S-matrix for process (1) is no longer there, however, it has been shown by numerical calculations[8] that the surface approximation is, under typical cases investigated, quite reliable.

Using the surface approximation, we can write the triple differential cross section for process (3) as

$$\frac{d^3\sigma}{d\Omega_b d\Omega_\alpha dE_b} = \sum_{sm_s s'm_s'} \Big| \sum_{\substack{\ell\ell' J^\pi M \\ m_\ell m_\ell'}} T_{\ell' m_\ell'}(\vartheta_b) \langle \ell' m_\ell' s' m_s' | JM \rangle S^{J^\pi}_{c'\ell' s'; c\ell s} \langle \ell m_\ell s m_s | JM \rangle Y_{\ell m_\ell}(\hat{k}_\alpha) \Big|^2 , \qquad (4)$$

where we have averaged over initial and summed over final spin values. The quantities $T_{\ell m_\ell}(\vartheta_b)$ can be calculated in a DWBA model (see Refs. 5,6) where as input optical model parameters are needed as well as the vertex constant for $(b+p)\rightarrow b+p$. As in eq. (2), the S-matrix elements needed for reaction (1) enter, although they are weighted in a different manner involving the factor $T_{\ell m_\ell}(\vartheta_b)$. This factor depends on the projectile-ejectile combination, the incident energy and final momentum of particle b. A complication will be that higher angular momentum values, which may not be important in the sum of eq. (2), will appreciably contribute to the sum in eq. (4). It is hoped that by suitable projectile-ejectile combinations and choice of bombarding energies, as well as by coincidence measurements, which are sensitive to the ℓ-value, it will eventually be possible to determine from eq. (4), using $T_{\ell m}$ as a theoretical input, the cross section, eq. (2). This quantity is usually available only by means of extrapolation of direct measurements of reactions (1) down to the astrophysically relevant energies; this procedure can be especially suspect in the case of low energy or subthreshold resonances. Such effects could be detected fairly unambiguously by continuum stripping measurements. The measurement of polarization observables would further help to determine the reaction mechanism (see Ref. 9).

We conclude that the present method can determine low energy cross sections relevant for astrophysics. However, one will have to rely on a reaction theoretical input. Judging from the overall agreement of such theories with experiment (for a review see Ref. 6) this should be possible.

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