Nuclear Astrophysics in Rare Isotope Facilities

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Nuclear reactions in stars are difficult to measure directly in the laboratory at the small astrophysical energies. In recent years indirect methods with rare isotopes have been developed and applied to extract low-energy astrophysical cross sections [1].

A. Elastic scattering and (p, p′) reactions

Elastic proton scattering has been one of the major sources of information on the matter distribution of unstable nuclei in radioactive beam facilities. The extended matter distribution of light-halo nuclei (^{8}He, ^{11}Li, ^{11}Be, etc.) was clearly identified in elastic scattering experiments [2, 3]. Information on the matter distribution of many nuclei important for the nucleosynthesis in inhomogeneous Big Bang and in r-process scenarios could also be obtained. In (p, p') scattering one obtains information on the excited states of the nuclei [4].

B. Transfer reactions

Transfer reactions $A(a,b)B$ are effective when a momentum matching exists between the transferred particle and the internal particles in the nucleus. Thus, beam energies should be in the range of a few 10-100 MeV per nucleon [5]. Low energy reactions of astrophysical interest can be extracted directly from breakup reactions $A+a \longrightarrow b+c+B$ by means of the Trojan Horse technique [6]. If the Fermi momentum of the particle x inside $a=(b+x)$ compensates for the initial projectile velocity v_a, the low energy reaction $A+x=B+c$ is induced at very low (even vanishing) relative energy between A and x. Very successful results using this technique have been reported [7].

The Asymptotic Normalization Coefficient (ANC) technique relies on fact that the amplitude for the radiative capture cross section $b+x \longrightarrow a+\gamma$ is given by $M = \left\langle I^a_{bx}(\mathbf{r_{bx}})|\mathcal{O}(\mathbf{r_{bx}})|\psi_i^{(+)}(\mathbf{r_{bx}})\right\rangle$, where $I^a_{bx} = \langle\phi_a(\xi_b,\ \xi_x,\ \mathbf{r_{bx}})|\phi_x(\xi_x)\phi_b(\xi_b)\rangle$ is the integration over the internal coordinates ξ_b, and ξ_x, of b and x, respectively. For low energies, the overlap integral I^a_{bx} is dominated by contributions from large r_{bx}. Thus, what matters for the calculation of the matrix element M is the asymptotic value of $I^a_{bx} \sim C^a_{bx}\ W_{-\eta_a,1/2}(2\kappa_{bx}r_{bx})/r_{bx}$, where C^a_{bx} is the ANC and W is the Whittaker function. This method has been used with great success for many reactions of astrophysical interest [8, 9], with the advantage of avoiding the treatment of the screening problem [7].

C. Coulomb Excitation and Dissociation

Coulomb excitation in radioactive beam facilities has been very successful to extract

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information on electromagnetic properties of nuclear transitions of astrophysical interest [10]. A reliable extraction of useful nuclear properties from Coulomb excitation experiments at intermediate and high energies requires a proper treatment of special relativity [11].

The (differential, or angle integrated) Coulomb breakup cross section for $a + A \longrightarrow b + c + A$ is directly proportional to the photo-nuclear cross section $\sigma^{\pi\lambda}_{\gamma+a \rightarrow b+c}(\omega)$ for the multipolarity $\pi\lambda$ and photon energy ω. Time reversal allows one to deduce the radiative capture cross section $b + c \longrightarrow a + \gamma$ from $\sigma^{\pi\lambda}_{\gamma+a \rightarrow b+c}(\omega)$ [12]. The method has been used successfully in a number of reactions of interest for astrophysics [13, 14].

The contribution of the nuclear breakup has been examined by several authors (see, e.g. [15]). ^{8}B has a small proton separation energy (≈ 140 keV). For such loosely-bound systems it had been shown that multiple-step, or higher-order effects, are important [16].

D. Charge exchange reactions

Charge exchange reactions induced in (p, n) reactions are often used to obtain values of Gamow-Teller matrix elements, $B(GT)$, which cannot be extracted from beta-decay experiments. This approach relies on the similarity in spin-isospin space of charge-exchange reactions and β-decay operators. As a result of this similarity, the cross section σ(p, n) at small momentum transfer q is closely proportional to $B(GT)$ for strong transitions: $\frac{d\sigma}{dq}(q=0) = KN_D|J_{\sigma\tau}|^2 B(\alpha)$, where K is a kinematical factor, N_D is a distortion factor (accounting for initial and final state interactions), $J_{\sigma\tau}$ is the Fourier transform of the effective nucleon-nucleon interaction, and $B(\alpha = F, GT)$ is the reduced transition probability for non-spin-flip, $B(F) = (2J_i+1)^{-1}|\langle f|| \sum_k \tau_k^{(\pm)} ||i\rangle|^2$, and spin-flip, $B(GT) = (2J_i+1)^{-1}|\langle f|| \sum_k \sigma_k \tau_k^{(\pm)} ||i\rangle|^2$, transitions.

The above relation, valid for one-step processes, was proven to work rather well for (p,n) reactions (with a few exceptions). For heavy ion reactions the formula might not work so well. This has been investigated in refs. [17, 18]. In ref. [17] it was shown that multistep processes involving the physical exchange of a proton and a neutron can still play an important role up to bombarding energies of 100 MeV/nucleon. Ref. [18] uses the isospin terms of the effective interaction to show that deviations from the above formula is common under many circumstances. As shown in ref. [19], for important GT transitions whose strength are a small fraction of the sum rule the direct relationship between σ(p, n) and $B(GT)$ values also fails to exist. Similar discrepancies have been observed [20] for reactions on some odd-A nuclei including ^{13}C, ^{15}N, ^{35}Cl, and ^{39}K and for charge-exchange induced by heavy ions [21].

But charge-exchange reactions such as (p,n), (^{3}He,t) and heavy-ion reactions (A,A$\pm$1) provide information on the $B(F)$ and $B(GT)$ values needed for astrophysical purposes. This is one of the major research areas in radioactive beam facilities and has been used successfully [22].

E. Knock-out reactions

Single-nucleon knockout reactions with heavy ions, at intermediate energies and in inverse kinematics, have become a specific and quantitative tool for studying single-particle occupancies and correlation effects in the nuclear shell model [23, 24]. The experiments observe reactions in which fast, mass A, projectiles collide peripherally with a light nuclear target producing residues with mass $(A-1)$ [24]. The final state of the target and that of the struck nucleon are not observed, but instead the energy of the final state of the residue can be identified by measuring coincidences with decay gamma-rays emitted in flight.

New experimental approaches based on knockout reactions have been developed and shown to reduce the uncertainties in astrophysical rapid proton capture (rp) process calculations due to nuclear data. This approach utilizes neutron removal from a radioactive ion beam to populate the nuclear states of interest. In the first case studied [25], ^{33}Ar, excited states were measured with uncertainties of several keV. The 2 orders of magnitude improvement in the uncertainty of the level energies resulted in a 3 orders of magnitude improvement in the uncertainty of the calculated ^{32}Cl(p,γ)^{33}Ar rate that is critical to the modeling of the rp process.

F. Theoretical efforts

Recent works [26, 27] are paving the way toward a microscopic understanding of the many-body continuum. A basic theoretical question is to what extent we know the form of the effective interactions for threshold states. It is hopeless that these methods can be accurate in describing high-lying states in the continuum. In particular, it is not worthwhile to pursue this approach to describe direct nuclear reactions.

A less ambitious goal can be achieved in the coming years by using the Resonating Group Method (RGM) or the Generator Coordinate Method (GCM) [28]. These is a set of coupled integro-differential equations of the form
$\sum_{\alpha'} \int d^3r' \left[H^{AB}_{\alpha\alpha'}(\mathbf{r},\mathbf{r}') - EN^{AB}_{\alpha\alpha'}(\mathbf{r},\mathbf{r}')\right] g_{\alpha'}(\mathbf{r}') = 0,$
where $H^{AB}_{\alpha\alpha'}(\mathbf{r},\mathbf{r}') = \langle\Psi_A(\alpha,\mathbf{r})|H|\Psi_B(\alpha',\mathbf{r}')\rangle$ and $N^{AB}_{\alpha\alpha'}(\mathbf{r},\mathbf{r}') = \langle\Psi_A(\alpha,\mathbf{r})|\Psi_B(\alpha',\mathbf{r}')\rangle$. In these equations H is the Hamiltonian for the system of two nuclei (A and B) with the energy E, $\Psi_{A,B}$ is the wavefunction of nucleus A (and B), and $g_\alpha(\mathbf{r})$ is a function to be found by numerical solution of the above equation, which describes the relative motion of A and B in channel α. Full antisymmetrization between nucleons of A and B is implicit.

A simpler method was adopted in ref. [29, 30], where an excellent agreement was found with the momentum distributions in knockout reactions of the type ^{8}B+$A \longrightarrow$ ^{7}Be+X obtained in experiments at MSU and GSI facilities. The astrophysical S-factor for the reaction ^{7}Be(p, γ)^{8}B was also calculated and excellent agreement was found with the experimental data in both direct and indirect measurements [29, 30].

Field theories adopt a completely independent approach for nuclear physics calculations in which the concept of nuclear potentials is not used. The basic method of field theories is to start with a Lagrangian for the fields. From this Lagrangian one can "read" the Feynman diagrams and make practical calculations, after taking care of well-known complications such as regularization and renormalization. In nuclear astrophysics, this theory has been applied to $np \rightarrow d\gamma$ for big-bang nucleosynthesis [31, 32]; νd reactions for supernovae physics [34] and the solar pp fusion process [35]. EFT has also been used to deduce observables in reactions with halo nuclei and loosely bound states, with promising applications to astrophysics [36, 37, 38].

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