Reactions with Neutron-Deficient Nuclei

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Direct measurements relevant for nuclear physics and nuclear astrophysics involving unstable nuclei are difficult for two reasons: a) targets (or projectiles at appropriate energies for inverse kinematics) of unstable nuclei are not easily available, if at all, and b) charged-particle reactions at the very low energies relevant for stellar processes are very difficult to measure due to Coulomb repulsion, which leads to very low reaction cross sections. Hence, few direct measurements have been done on proton-rich nuclei to date. This problem has led to the development and use of indirect methods using reactions in radioactive facilities. The list of indirect techniques that are used today includes measurement of elastic scattering, reaction cross sections, Coulomb dissociation, nuclear breakup, transfer reactions, knock-out reactions, fragmentation reactions, and other indirect techniques. But even with the advent of rare isotope facilities worldwide, many pieces of valuable information still will require a dedicated facility such as EURISOL. Below I will discuss some of the open problems when using indirect techniques with reactions involving proton-rich nuclei.

REACTIONS WITH NEUTRON-DEFICIENT NUCLEI

Proton targets

Elastic proton scattering has been one of the major sources of information on the matter distribution of unstable nuclei in radioactive beam facilities. This is possible for proton-rich projectiles at intermediate and high energy collisions, 50 MeV/nucleon and beyond, because the reaction mechanism is well understood in terms of the *Glauber theory*. At lower energies, the reaction mechanism is more complicated, with a strong dependence on the details of the optical potential and on coupled-channels.

(p,p') reactions are excellent probes of the excited states of the projectile nucleus, despite the inherent need of a structure model to account for *coupled-channels* and *polarization effects*.

Quasi-free (p,2p) reactions are good probes of nuclear structure projectile energies of (200-1000 MeV/nucleon) when the projectile proton knocks out a bound nucleon. The energy spectra of the outgoing protons provide information on the energy of the struck nucleon in the nucleus. The shape of the angular correlations of the outgoing particles, or the recoil momentum of the nucleus, determines the *momentum distribution of the knocked-out proton*. In the last four decades quasi-free scattering experiments have been performed with this basic purpose, mostly for reactions on stable nuclear targets. The main theoretical problem with quasi-free scattering is a proper description of *multiple scattering* and *medium corrections* to the free scattering, whenever necessary. Very few experiments to date with quasi-free (p,2p) scattering has been done involving rare isotopes.

Transfer Reactions

Transfer reactions are well established tools to obtain spin, parities, energy, and spectroscopic factors of states in a nuclear system. For proton-rich nuclei, **(d,p) reactions** have appreciable cross sections and are particularly spectroscopic tools due to the simplicity of the deuteron. 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. Low energy *reactions of astrophysical interest* can be extracted directly from breakup reactions $A+a \rightarrow b+c+B$ by means of the **Trojan Horse technique**. 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. The main theoretical challenges are the proper treatment of *off-shell effects* and the normalization of the extracted astrophysical cross sections.

The **Asymptotic Normalization Coefficient** (ANC) technique relies on fact that the amplitude for the radiative capture cross section $b + x \rightarrow a + \gamma$ is given by $M=\langle I^a_{bx}(\mathbf{r}_{bx})|O(\mathbf{r}_{bx})|\psi_i(\mathbf{r}_{bx})\rangle$, 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. These coefficients can be extracted in transfer reactions when the *peripherality* of the reaction is dominant. It is not clear if the accuracy with which the peripherality condition in transfer reactions has been under control in previous experiments. As with other reaction types, a good knowledge of *effective interactions* among the nucleons and *clusters* is crucial for the extraction of the ANCs.

Coulomb and Nuclear Excitation and Dissociation

The (differential, or angle integrated) Coulomb breakup cross section for $a + A \rightarrow b + c + A$ 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 $b+c \rightarrow a+\gamma$ from $\sigma^{\pi\lambda}_{\gamma+a \rightarrow b+c}(\omega)$. The method has been used successfully in a number of reactions of interest for astrophysics.

One of the main obstacles for extracting the radiative capture cross section information is the contribution of the *nuclear breakup* and of *higher-order effects* from the **Coulomb breakup** contribution. There are still many open questions related to the apparent inability of a good agreement between theory and some experimental data.

Knockout Reactions

Single-nucleon knockout reactions with heavy ions, at intermediate energies (≥ 100 MeV/nucleon) and in inverse kinematics, have become a specific and quantitative tool for studying single-particle occupancies and correlation effects in the nuclear shell model. The experiments observe reactions in which fast, mass A, projectiles collide peripherally with a light nuclear target producing residues with mass (A − 1). 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. **Two-nucleon knockout reactions** are also useful to extract information on nucleon-nucleon corrections in nuclei. Either for one or two-nucleon knockout there is still much discussion on the role of the medium modifications of the nucleon-nucleon cross sections and the role of off-shell effects.

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. Not only (p,n), but (^{3}He,t) and heavy-ion reactions (A,A±1) also provide information on the Fermi, B(F), and Gamow-Teller, B(GT), transitions needed for astrophysical purposes.

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 thought to be closely proportional to B(GT) for strong transitions.This assumption, valid for one-step processes, was proven to work rather well for (p,n) reactions (with a few exceptions). For heavy ion reactions the proportionality might not work so well. Theoretical works support 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. In fact, deviations from the small momentum transfer assumption is common under several circumstances. For important GT transitions whose strength is 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 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.

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