Combined Method to Extract Spectroscopic Information

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SF was introduced by the shell model formalism and is typically related to the shell occupancy of a state $n$ in one nucleus relative to a state $m$ in a nearby nucleus. Today, phenomenological SFs are extensively used in a variety of topics, from nuclear reactions to astrophysics or applied physics, yet the procedure for their extraction from the data has remained essentially the same for decades. For more than forty years since the dawn of nuclear physics, direct transfer reactions, such as $(d,p)$, $(d,t)$, $(^3\text{He},d)$, $(^3\text{He},\alpha)$, have been the central tool to determine SFs. Extracting SFs with good precision from data is very important to test the validity of today's many body theories. For conventional nuclei there are many experiments available providing SFs, which are often lower than those predicted by shell model. Electron-induced knockout or electron scattering is supposed to provide a better accuracy in extracting SFs than transfer. However, for exotic nuclei near or on the driplines transfer reactions are a unique tool and, hence, can have a large impact in the programs of the new generation rare isotope laboratories. Given the experimental difficulties faced with measurements on the driplines, it is crucial to have a reliable method for analyzing and extracting useful information from each single data set.

Usually, transfer angular distributions are analyzed within the framework of the distorted-wave Born approximation (DWBA). The SF determined by normalizing the calculated DWBA differential cross section to the experimental one is compared with the SF predicted by shell model. Even when error bars in the experimental cross section are low, the uncertainty of the extracted SF resulting from the normalization of the DWBA cross section is often large, regardless of whether it agrees with the shell model prediction. The reasons for this inaccuracy are typically: i) optical potentials ambiguity, ii) the inadequacy of the DWBA reaction theory, or iii) the dependence on the single-particle potential parameters. This work will critically review the standard procedure of extracting SFs from transfer reactions focusing on the third point; the modified method eliminates the dependence of the extracted SFs on the single-particle potentials, the main advantage of the method. We discuss a modified approach to spectroscopy from transfer reaction which includes the asymptotic normalization coefficient (ANC) in the analysis using equation $C^2 = Sb^2$. Here, $C$ is the ANC, $S$ is the spectroscopic factor and $b$ is the single-particle ANC, i.e. the amplitude of the tail of the single-particle wave function of the nucleon bound state wave function. Introduction of the information about the ANC allows us to fix the contribution to the DWBA amplitude from the external region. Hence, the spectroscopic factor is determined from the contribution of the nuclear interior. This modified method requires two independent experiments. The goal of the first experiment is to determine the ANC. Sub-Coulomb transfer reactions or transfer reactions induced by heavy ions at energies above the Coulomb barrier. To demonstrate this method we analyzed $(d,p)$ on targets $^{208}\text{Pb}$, $^{12}\text{C}$, $^{7}\text{Li}$ and $^{84}\text{Se}$. To determine the spectroscopic factor we calculate the $b$ dependence of the function $R(b) = \frac{d\sigma^{\text{DW}}}{d\Omega} / b^2$, where $d\sigma^{\text{DW}}/d\Omega$ is the reduced DWBA differential
cross section. From solution of the equation \( R(b) = R^{\exp} \), \( R^{\exp} = \frac{d\sigma^{\exp}}{d\Omega} / C^2 \), where \( d\sigma^{\exp}/d\Omega \) is the experimental differential cross section, we can determine the single-particle ANC \( b \), and then the spectroscopic factor. As example we demonstrate the \( R(b) \) function for the \(^{208}\text{Pb}(d,p)^{209}\text{Pb} \) reaction. The solid line shows the experimental \( R^{\exp} \), and the strip indicates the experimental uncertainty. Experimental data are taken from [1] and ANC \( C^2 = 2.15 \pm 0.16 \text{ fm}^{-1} \) extracted from the sub-Coulomb transfer reaction \(^{208}\text{Pb}(d,p)^{209}\text{Pb} \) [2]. The dashed-dotted line is the theoretical \( R(b) \) function. The dotted line shows the \( R(b) \) function for \(^{208}\text{Pb}(d,p)^{209}\text{Pb} \) at 1.46 MeV. Solution of equation \( R(b) = R^{\exp} \) gives the \( b = 1.82^{+1.28}_{-0.72} \text{ fm}^{-1} \), and the spectroscopic factor \( S = 0.74^{+1.46}_{-0.44} \). As we see, due to the small contribution of the nuclear interior and large experimental uncertainty, the uncertainty of the extracted spectroscopic factor is quite large. The method here presented has the potential of reducing the uncertainty in the overlap function considerably. Results for \(^{208}\text{Pb}(d,p)^{209}\text{Pb} \) were used to illustrate the method. We also demonstrate that this method can rule out inadequate choices of optical potentials. Considering specific future experiments, we have performed exploratory calculations for \(^{84}\text{Se}(d,p)^{85}\text{Se} \). This method will become useful for a broad variety of transfer experiments in the field of rare isotopes. The same method can equally be used for transfer to excited states. These same ideas can be extended to other reactions, in particular breakup reactions which also have an impact on Astrophysics. Finally, it would be helpful if the state-of-the-art reaction codes would incorporate the formalism discussed.