Neutron Spectroscopic Factors

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Spectroscopic factors are fundamental quantities in nuclear physics. They have been extensively used in understanding the single particle properties of nuclear structures and astrophysical network calculations. Neutron spectroscopic factors of 88 ground state and 565 excited states for Z=3-28 stable nuclei from (d,p) and (p,d) transfer reactions are extracted using a systematic approach with minimum assumptions. This extensive set of data suggests that the extracted spectroscopic factors are in good agreement with the predictions of the large-basis shell-model predictions. The (p,d) neutron transfer reaction measurements have been extended to exotic nuclei of proton-rich ^{34}Ar and neutron-rich ^{46}Ar. The experimental results show little reduction of the ground state neutron spectroscopic factor of the proton-rich nucleus ^{34}Ar compared to that of ^{46}Ar. The results suggest that correlations, which generally reduce such spectroscopic factors, do not depend strongly on the neutron-proton asymmetry of the nucleus in this isotopic region as was reported in knockout reactions. The present results are consistent with results from systematic studies of transfer reactions and the dispersive-optical model analysis, but are inconsistent with the trends observed in knockout reaction measurements.

1. Introduction

Transfer reaction is a powerful probe to study the single-particle structure in a nucleus. The degree of single-particle nature is governed by the nucleon-nucleon (N-N) correlations which modify the nuclear wave functions from the independent particle mean-field model. These correlations manifest themselves indirectly through the reduction in the occupancy of a single-particle state which is quantified by the spectroscopic factor.

Mathematically, spectroscopic factor is defined by a matrix element between the initial state in the entrance channel and the final state in the exit channels [1,2]. For an A(d,p)B one-nucleon transfer reaction, for example, this matrix element evaluates the degree to which the wave function of the final nucleus B can be described by the initial nucleus A plus a neutron in a specific single-particle orbit. For the one-step transfer reaction in the distorted-wave Born approximation (DWBA), the experimental spectroscopic factor is the ratio of the experimental cross sections to the cross sections calculated within a reaction model. The overlap integral between the wave functions of one state in nucleus A and another state in nucleus B for transfer between these states gives the theoretical counterpart [1,2]. Measurements of spectroscopic factors therefore provide quantitative information about the single-particle structure of nuclei, and connect the experimental results to theoretical nuclear structure in the shell model calculations.

In the past half-century, transfer reaction has been used as an experimental tool to obtain abundant spectroscopic information for stable nuclei. With the recent revived interest in transfer reactions stemming from the availability of radioactive beams with high luminosity, it is essential to review and understand the existing theoretical reaction models of transfer reactions, and develop a systematic framework to study the structures from stable to exotic nuclei. In this proceeding, the methodology to extract consistent spectroscopic factors systematically using published angular distributions of (p,d) and (d,p) transfer reactions is introduced in Section 2.

Based on this framework, a survey of deduced ground-state and excited-state spectroscopic factors of Z=3-28 stable nuclei is described in Section 3, which provides checks for the descriptions of nucleon correlations in the current nuclear structure calculations. Section 4 presents the extension of transfer reaction measurements to the exotic Ar isotopes and discusses the asymmetry dependence of nucleon correlations based on the relative spectroscopic factor.

2. Extraction of spectroscopic factors from transfer reactions

Transfer reactions provide most of the spectroscopic factor information for stable nuclei in the past half century. However, it is not unusual to find published spectroscopic factors for a particular nucleus that fluctuate by a factor of two as shown in the top panel of Fig. 1. In this case, ^{41}Ca should be a well-understood nucleus as composed of a neutron outside the closed ^{40}Ca core and the ground state neutron spectroscopic factor should be one. Instead, many different spectroscopic factors values were extracted from ^{40}Ca(d,p)^{41}Ca reactions.

Many of the difficulties in the past extractions of spectroscopic factors have been associated with ambiguities in choosing the optical model parameterizations which are used in the DWBA model to construct the distorted waves of incoming and outgoing reaction channels. In addition, geometries of the bound-state radial wave functions of the transferred particle are strongly correlated to the magnitudes of the spectroscopic factors [1,2]. They are not determined a priori and vary from analysis to analysis. These inconsistencies in spectroscopic factor extractions hinder the use of transfer reactions from studying evolution of nuclear structures, such as the shell evolution along the isotopic or isotonic chains. Therefore it is crucial to develop a systematic approach to extract

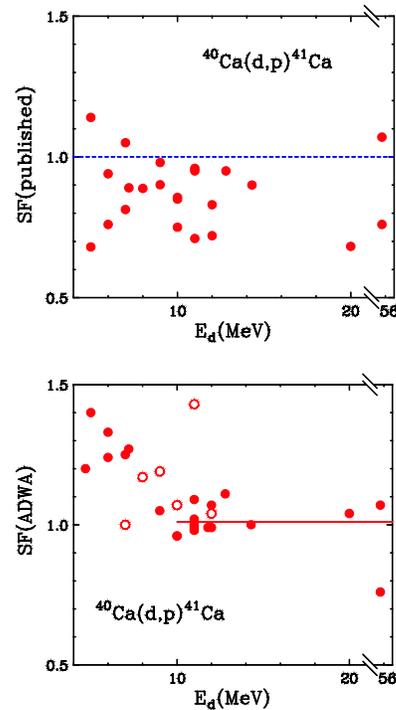reliable relative spectroscopic factors from transfer reactions.

Fig. 1: (Top) Fluctuations in the published ground-state spectroscopic factors of ^{41}Ca extracted from ^{40}Ca(d,p)^{41}Ca reactions. The (blue) dashed line is the shell model prediction. (Bottom) Ground-state spectroscopic factors of ^{41}Ca extracted from the same data sets using the systematic approach described in this work. The (red) solid line is the averaged value of spectroscopic factors for $E_d>10$ MeV.

A consistent three-body analysis of neutron transfer reaction data involving minimal assumptions has been developed for (p,d) and (d,p) transfer reactions [5,6]. The methodology uses Adiabatic Distorted-wave approximation (ADWA), an extension of DWBA theory with the Johnson-Soper (JS) adiabatic approximation to the neutron, proton, and target three-body system [4] taking into account the deuteron break up. To avoid the ambiguity in optical potentials

obtained from individual best fits to elastic scattering data, CH89 global nucleon-nucleus optical potentials [7] are used and these neutron and proton potentials are folded to obtain the deuteron optical potential. Non locality corrections with range parameters of 0.85 fm and 0.54 fm for the proton and deuteron channels, respectively are assumed [8]. The deuteron finite range corrections are calculated using the local energy approximation and the strength ($D_o^2=150006.25$ fm^3) and range ($\beta=0.7457$ fm) parameters of the Reid soft-core $^3S_1$-$^3D_1$ neutron-proton interaction [9]. For simplicity, a central neutron potential of Woods-Saxon shape with fixed radius ($r_o=1.25$ fm) and diffuseness ($a_o=0.65$ fm) parameters is assumed and the depth of potential is adjusted to reproduce the experimental binding energy. We use the University of Surrey version of TWOFNR [10], a direct reaction model code, to calculate the angular distributions [3,5,6].

We analyze the data sets of ^{40}Ca(d,p)^{41}Ca of Figure 1 using the systematic ADWA analysis approach. The bottom panel shows the new spectroscopic factors of ^{41}Ca. Between 10 to 56 MeV, we find that the mean spectroscopic factor is, 1.01 ± 0.06 shown by the solid line. The increase of spectroscopic factors at $E_d<10$ MeV is attributed to the resonance structures in the elastic scattering of the deuterons [11] and contributions from compound nucleus. These are not taken into account in the present reaction model.

3. Survey of spectroscopic factors from transfer reactions for stable nuclei

Eighty-eight ground-state and 565 excited-state neutron spectroscopic factors have been extracted by systematically analyzing more than 2000 measured (d,p) and (p,d) angular distributions. The systematic analysis as discussed in Section 2 adopts global optical-model potential CH89 and radius of transferred neutron orbital rms of $r_o=1.25$ fm. In this section,

the extracted spectroscopic factor values are compared to the LB-SM for ground-state and excited-state in sd- and fp-shell nuclei respectively. As the spectroscopic factors were not used in the derivation of the effective potential, they provide an independent evaluation of the effective interactions used in the shell models.
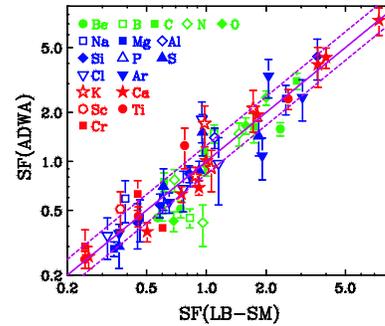

Fig. 2: Comparison of experimental spectroscopic factors to predictions from the large basis shell model predictions.

Figure 2 compares the experimentally extracted ground-state SF's for nuclei with predictions from the large basis shell model (LB-SM) predictions. The residual interaction within the LB-SM [13] involves the mixing of several different orbital in the shell model bases which are close to the Fermi energy. Using Oxbash code with the PPN, SPSDPF, SDPN, SD, and FPPN model space and the corresponding CKPPN, WBP, WPN, W, and FPBPPN interactions [13, 14] as input, the ground state neutron spectroscopic factors for 74 nuclei have been calculated with uncertainties of about 10-20%[12]. The success of the LB-SM calculation suggests that the correlations between nucleons in orbits near the Fermi energy are the most important ones to consider [12].

The excited-state SF values are of particular interest because they are used in astrophysical network calculations. Based on the same methodology, we have extracted 565 neutron spectroscopic factors of sd- and fp-shell nuclei. We are able to compare 125 of the