Neutron spectroscopic factors from transfer reactions

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In the present paper, we examine past measurements of ground state to ground state (d, p) and (p, d) transfers that were performed on targets with $Z = 3$–24. We describe a procedure that we utilized to extract a consistent set of spectroscopic factors. Most of the 80 spectroscopic factors that we extracted are in good agreement with large-basis shell model predictions. We evaluate the consistency of this method by comparing the spectroscopic factors obtained separately in (p, d) and (d, p) reactions. For nuclei for which Endt has compiled values, our results and those of Endt are strongly correlated. We apply our method to more reactions and more nuclei than Endt had, and our comparisons between spectroscopic factors obtained in (d, p) and (p, d) reactions display more consistency than the corresponding comparisons in Endt.

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I. INTRODUCTION

Mathematically, a spectroscopic factor is defined by a matrix element between the initial state in the entrance channel and the final state in the exit channels [1–5]. For an A(d, p)B 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. Measurements of spectroscopic factors therefore provide quantitative information about the single-particle structure of nuclei in the shell model.

In the past four decades, (d, p), (p, d), and other single-nucleon transfer reactions have been extensively used to extract spectroscopic information for single-nucleon orbits [1–6]. In practice, one extracts spectroscopic factors by taking the ratios of the experimental cross sections to the cross sections calculated within a reaction model. In our analysis, we employ a variant of the distorted-wave Born approximation (DWBA) theory [3–5] as our reaction model. For (p, d) and (d, p) transfer reactions, the effects from deuteron breakup can be significant at energies above 15 MeV per nucleon [7]. We take deuteron breakup into account by using the Johnson-Soper (JS) adiabatic approximation [8] to construct the deuteron potential. As this approach is not strictly DWBA, we label this as the JS adiabatic three-body model.

Many of the published spectroscopic factors are not consistent. For example, it is not unusual to find published spectroscopic factors for a particular nucleus that fluctuate by factors of 2–3 [7]. Similarly, one can find published values from different authors for the spectroscopic factor of a given reaction that agree within uncertainties, even though the data used to extract them are not in agreement. Some of the difficulties in the past extractions of spectroscopic factors have been associated with ambiguities in the optical model parametrizations used in the reaction models, different normalizations, or different assumptions used in the analysis [7,9]. To allow comparisons of the experimental spectroscopic factors with theoretical predictions over a broad range of nuclei, we have adopted a systematic and consistent approach involving minimal assumptions and have reanalyzed existing transfer reaction data. Aspects of this minimal approach can hopefully be extended to nuclei far from stability.

In a survey of 80 nuclei studied via the transfer (p, d) and (d, p) reactions [10], we extracted the ground state spectroscopic factors using the adiabatic three-body model. Most of the extracted SF values agree with the predicted SFs from large-basis shell model (LBSM) calculations within the experimental and theoretical uncertainties [10]. These spectroscopic factors that we obtained over a wide range of nuclei can provide important benchmarks for comparison with more advanced reaction models for single-nucleon transfer reaction mechanisms [11,12]. It is therefore important to know which sets of data are more reliable and should be included in future analyses where knowledge gaps may occur [12].

The data analyses presented in Ref. [10] were performed using transfer reaction measurements that have been performed over the past 40 years. One purpose of this paper is to set forward the criteria that we used in our data evaluation and the quality control measures that we applied to select the 235 reactions out of a larger set of 430 reactions that had been measured by many research groups (listed below in Table I). In addition, we explain the procedure we used to extract a consistent set of spectroscopic factors from (p, d) and (d, p) transfer reactions. As described in Ref. [10], the set of spectroscopic factors obtained agrees well with the modern shell model predictions and can be viewed as benchmarks for other analyses with different input or analysis criteria.

This paper is organized as follows. We begin in Sec. II with a brief description of the input parameters used in the JS three-body adiabatic reaction model. This is important because spectroscopic factors are usually extracted by dividing the measured differential cross sections by theoretical cross sections, which is predicted by a reaction model. We then explain in Sec. III how the data have been compiled and describe the uncertainties introduced in the process. We explain in Sec. IV the procedure for extracting the SFs. Problems with consistencies between measurements are discussed in Secs. V–VII. Section VIII deals with the internal consistency

of the approach. As the pickup (p, d) reaction is the inverse of the stripping (d, p) reaction, ground state SFs obtained separately by the (p, d) and (d, p) reactions should be the same within experimental uncertainties. We use this fact in Sec. VIII to assess the consistency of our method and to assign uncertainties to the extracted SFs. Section IX compares some of our SF values with those compiled by Endt [9]. Owing to recent interest in the neutron spectroscopic factor of ^{15}C, Sec. X discusses the challenges and problems of the reaction, ^{14}C$(d, p)^{15}$C. Recently, it has been observed in nucleon-knockout reactions that spectroscopic factors are suppressed with respect to the LBSM values with increasing nucleon separation energy [13,14]. Section XI discusses whether there is evidence for such a trend in the transfer reaction data we analyzed. Section XII summarizes our findings.

II. REACTION MODEL

For the JS three-body adiabatic model, we adopted parameters that have been widely used in the literature for neutron-transfer reactions. The transfer cross sections are calculated within the JS adiabatic approximation [8], which approximates the full many-body system by a three-body system consisting of a neutron, a proton, and an inert core. The core would be the target in a (d, p) reaction or the final nucleus in a (p, d) reaction. The phenomenological nucleon-nucleus optical model potentials (CH89) [15] are folded to construct the deuteron optical potential used in the DWBA integral. By using the folded potential instead of a phenomenological deuteron optical potential, one includes the main corrections to the transfer cross section from the breakup of the deuteron in the field of the target.

Even though the breakup effect is mainly important for energies above 15 MeV per nucleon, to be consistent, we constructed the deuteron potential using the JS adiabatic approximation at all incident energies. At low incident energies, the results obtained by using the JS approach are similar [7,40] to those obtained by using the global deuteron potential of Daehnick [16].) The potential binding of the transferred neutron to the inert core was chosen to be Woods-Saxon in shape with a fixed radius parameter of 1.25 fm and a diffuseness parameter of 0.65 fm [7]. The depths of the central potential wells are adjusted to reproduce the experimental binding energies. Consistent with the findings of Ref. [17], we find that the surface properties of the neutron bound state wave function are dominated by the central potential. Thus, we have neglected for simplicity the spin-orbit interaction in constructing the valence neutron wave function. (We studied this effect in Ref. [10]. In the light nuclei, studied here, the effect is of the order of 10% or less. Such effect may become important for heavier nuclei.) All calculations make the local energy approximation (LEA) for finite range effects [18] using the zero-range strength ($D_o^2 = 15006.25$ MeV^2 fm^3) and range ($\beta = 0.7457$ fm) parameters of the Reid soft-core $^3S_1$-$^3D_1$ neutron-proton interaction [19]. Nonlocality corrections with range parameters of 0.85 and 0.54 fm are included in the proton and deuteron channels, respectively [20]. The same set of input parameters is used for all the reactions analyzed here. We labeled our SF values as SF(JS) in our figures, to distinguish them from other SF values obtained when different input parameters or potentials are used. The transfer reaction calculations were carried out using a version of the code TWOFNR [21] which respects the detailed balance between (p, d) and (d, p) reactions that connect the same states. The code TWOFNR is chosen mainly for convenience, as it contains all the input options discussed below. With the same input parameters, we employed two other widely used reaction model codes, DWUCK5 and FRESCO [22], and found that they provide predictions that are basically the same as those provided by TWOFNR [11,12,40].

III. COMPILATION AND DIGITIZATION OF ANGULAR DISTRIBUTION DATA

For the present work, we mainly focus on the transfer reaction A(d, p)B and its inverse reaction B(p, d)A where the nucleus B is considered to be composed of the core A plus the valence neutron n. To avoid confusion, we adopt the convention that the extracted neutron spectroscopic factors always refer to nucleus B which would be the residue in a (d, p) reaction and the target in a (p, d) reaction. Table I contains 430 reactions that we examined.

Nearly all the angular distributions from the references listed in Table I have been digitized from the published figures. The few exceptions are those found in the Nuclear Science References (NSR) database of the National Nuclear Data Center (NNDC) [249]. The data from NSR are in tabulated form, and the sources of these data are from the Former Soviet Union or Japan, whose journals are not widely available in the United States. These non-U.S. and non-European data complement our search for data in *Physical Review, Physical Review Letters, Nuclear Physics,* and, occasionally, *Physics Letters* and *Journal of Physics G*. While we have made an effort to find nearly all the relevant experiments that published the absolute differential cross sections, we could have missed some reactions, especially if the incident energy was below 10 MeV and above 70 MeV. Except when noted, Table I does not include reactions with cross sections published in arbitrary units. The data and calculations are posted on a website [250]. Eventually, we hope all the digitized data used in this work will be adopted by the NSR.

By checking some of the data carefully and sometimes repeating the digitization several times, we estimated the uncertainties introduced by the digitization process to be less than 0.5° in determining the angles and less than 10% in extracting the differential cross sections. For illustration, we use the data for the reaction ^{14}N$(d, p)^{15}$N at $E_d = 12$ MeV [25,86]. This set of data was first published in tabulated form in Ref. [25]. The tabulated data are plotted as closed points in Fig. 1. Later the authors in Ref. [86] plotted the data in a figure, which we digitized. We compare our digitized data (open points) with the tabulated data (closed points) in Fig. 1. We see a difference of less than 10% between the two sets of data. Of course, the digitization errors also depend on the actual size of the graphs available in the original literature. As described later, generally, errors introduced by

TABLE I. Reactions studied in this work. Not all the spectroscopic factors extracted in the present work [SF(JS)] were used in computing the average SF for a specific nucleus. The extracted values not used are listed in the fifth column as SF(bad). Most of these include reactions at low beam energy ($E_{\text{beam}} < 10$ MeV). Values marked with * were obtained from data determined to be problematic. Last column gives abbreviated comments: BS (bad shape), BD (bad data), AU (arbitrary unit), No (normalization problem), NP (missing first peak), and QV (low Q values).

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{6}Li	^{6}Li$(p,d)^{5}$Li	33.6	[23]		1.12	1.12	3	
^{7}Li	^{6}Li$(d,p)^{7}$Li	4.5	[24]	1.59			2	
^{7}Li	^{6}Li$(d,p)^{7}$Li	4.75	[24]	1.81			2	
^{7}Li	^{6}Li$(d,p)^{7}$Li	5	[24]	1.90*			2	BS
^{7}Li	^{6}Li$(d,p)^{7}$Li	5.25	[24]	1.78			3	
^{7}Li	^{6}Li$(d,p)^{7}$Li	5.5	[24]	1.70			3	
^{7}Li	^{6}Li$(d,p)^{7}$Li	12	[25]		1.85	1.85	2	
^{7}Li	^{7}Li$(p,d)^{6}$Li	30.3	[26]	0.34*			3	BS
^{7}Li	^{7}Li$(p,d)^{6}$Li	33.6	[23]	0.86*			3	BS
^{8}Li	^{7}Li$(d,p)^{8}$Li	12	[25]		0.62	0.62	3	
^{9}Li	^{8}Li$(d,p)^{9}$Li	10.7	[246]	0.56			2	BS
^{9}Li	^{8}Li$(d,p)^{9}$Li	19.1	[27]		0.98	0.98	5	
^{9}Be	^{9}Be$(p,d)^{8}$Be	5	[28]	0.43			7	
^{9}Be	^{9}Be$(p,d)^{8}$Be	6	[28]	0.47			4	
^{9}Be	^{9}Be$(p,d)^{8}$Be	7	[28]	0.45			3	
^{9}Be	^{9}Be$(p,d)^{8}$Be	8	[28]	0.51			3	
^{9}Be	^{9}Be$(p,d)^{8}$Be	9	[28]	0.53			2	
^{9}Be	^{9}Be$(p,d)^{8}$Be	10	[28]		0.46		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	11	[28]		0.46		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	14.3	[29]		0.41		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	15	[30]		0.42		3	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	17	[31]		0.51		3	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	21	[31]		0.50		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	25	[31]		0.43		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	26.2	[29]	0.35*			1	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	29.1	[31]		0.48		2	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	33.6	[23]		0.44		1	BS
^{9}Be	^{9}Be$(p,d)^{8}$Be	46	[32]		0.49	0.45	1	BS
^{10}Be	^{9}Be$(d,p)^{10}$B	4.5	[24]	2.44			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	4.75	[24]	2.11			3	
^{10}Be	^{9}Be$(d,p)^{10}$B	5	[24]	2.14			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	5.25	[24]	2.06			3	
^{10}Be	^{9}Be$(d,p)^{10}$B	5.5	[24]	2.01			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	5.75	[24]	1.83			3	
^{10}Be	^{9}Be$(d,p)^{10}$B	6	[24]	2.01			3	
^{10}Be	^{9}Be$(d,p)^{10}$B	6.5	[33]	1.55			5	
^{10}Be	^{9}Be$(d,p)^{10}$B	7	[33]	1.48			4	
^{10}Be	^{9}Be$(d,p)^{10}$B	7.5	[33]	1.07			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	8	[33]	1.05			1	
^{10}Be	^{9}Be$(d,p)^{10}$B	8.5	[33]	1.11			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	9	[33]	1.10			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	9.5	[33]	1.03			2	
^{10}Be	^{9}Be$(d,p)^{10}$B	10	[33]	1.10*			2	NP
^{10}Be	^{9}Be$(d,p)^{10}$B	10.5	[33]	1.18*			2	NP
^{10}Be	^{9}Be$(d,p)^{10}$B	11	[33]	1.17*			2	BD
^{10}Be	^{9}Be$(d,p)^{10}$B	11.8	[25]		1.49		3	BD
^{10}Be	^{9}Be$(d,p)^{10}$B	11.8	[34]		1.42		2	
^{10}Be	^{9}Be$(d,p)^{10}$B	12.5	[35]		1.72		4	NP
^{10}Be	^{9}Be$(d,p)^{10}$B	15	[36]		1.75		4	
^{10}Be	^{9}Be$(d,p)^{10}$B	15.3	[37]		1.40	1.58	4	NP
^{10}Be	^{9}Be$(d,p)^{10}$B	17.3	[38]	0.99*			3	BS
^{10}Be	^{9}Be$(d,p)^{10}$B	28	[39]	2.26*			2	BS
^{10}Be	^{10}Be$(p,d)^{9}$B	49.8	[40]	2.96*			10	BD

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{11}Be	^{10}Be$(d,p)^{11}$Be	12	[30]		0.44		3	
^{11}Be	^{10}Be$(d,p)^{11}$Be	25	[41]		0.53	0.49	3	
^{11}Be	^{11}Be$(p,d)^{10}$Be	35.3	[42]		0.57	0.57	2	
^{10}B	^{10}B$(p,d)^{9}$B	33.6	[43]		0.57		3	
^{10}B	^{10}B$(p,d)^{9}$B	49.5	[44]		0.43	0.50	3	
^{11}B	^{10}B$(d,p)^{11}$B	4.5	[24]	1.11			2	
^{11}B	^{10}B$(d,p)^{11}$B	4.75	[24]	1.06			3	
^{11}B	^{10}B$(d,p)^{11}$B	5	[24]	0.92			2	
^{11}B	^{10}B$(d,p)^{11}$B	5.25	[24]	0.85			2	
^{11}B	^{10}B$(d,p)^{11}$B	5.5	[24]	0.81			2	
^{11}B	^{10}B$(d,p)^{11}$B	8.2	[45]	5.05			3	AU
^{11}B	^{10}B$(d,p)^{11}$B	10.1	[46]	1.00*			4	BD
^{11}B	^{10}B$(d,p)^{11}$B	12	[25]		1.25		2	BS
^{11}B	^{10}B$(d,p)^{11}$B	13.5	[47]		1.68		5	
^{11}B	^{10}B$(d,p)^{11}$B	15.5	[45]	1.50*			6	AU
^{11}B	^{10}B$(d,p)^{11}$B	21.5	[45]	0.32*			9	AU
^{11}B	^{10}B$(d,p)^{11}$B	28	[39]		1.52	1.55	2	
^{11}B	^{10}B$(d,p)^{11}$B	28	[45]	0.06*			2	AU
^{11}B	^{11}B$(p,d)^{10}$B	19	[48]	3.16*			3	BD
^{11}B	^{11}B$(p,d)^{10}$B	33.6	[43]		1.29	1.29	3	
^{11}B	^{11}B$(p,d)^{10}$B	44.1	[40]	1.05*			2	BD
^{12}B	^{11}B$(d,p)^{12}$B	11.8	[49]		0.44		5	
^{12}B	^{11}B$(d,p)^{12}$B	12	[50]		0.47	0.45	3	
^{12}B	^{11}B$(d,p)^{12}$B	12	[25]	0.35*			1	BS
^{12}C	^{12}C$(p,d)^{11}$C	19.3	[51]					QV
^{12}C	^{12}C$(p,d)^{11}$C	19.5	[51]					QV
^{12}C	^{12}C$(p,d)^{11}$C	20	[51]					QV
^{12}C	^{12}C$(p,d)^{11}$C	30.3	[52]		2.68		3	
^{12}C	^{12}C$(p,d)^{11}$C	39.8	[53]	5.50*			4	No
^{12}C	^{12}C$(p,d)^{11}$C	61	[54]		3.36		6	
^{12}C	^{12}C$(p,d)^{11}$C	65	[55]		3.07	3.12	3	
^{12}C	^{12}C$(p,d)^{11}$C	65	[56]	3.03*			1	BS
^{13}C	^{12}C$(d,p)^{13}$C	4	[57]	0.64			3	
^{13}C	^{12}C$(d,p)^{13}$C	4.5	[57]	0.67			2	
^{13}C	^{12}C$(d,p)^{13}$C	4.5	[58]	0.59			2	
^{13}C	^{12}C$(d,p)^{13}$C	4.5	[59]	0.43			2	
^{13}C	^{12}C$(d,p)^{13}$C	7.15	[60]	0.88			4	
^{13}C	^{12}C$(d,p)^{13}$C	8.9	[61]	0.92			6	
^{13}C	^{12}C$(d,p)^{13}$C	10.2	[62]		0.85		3	
^{13}C	^{12}C$(d,p)^{13}$C	11.8	[34]		0.82		3	
^{13}C	^{12}C$(d,p)^{13}$C	11.8	[49]	0.60*			2	BD
^{13}C	^{12}C$(d,p)^{13}$C	12	[63]		0.71		2	
^{13}C	^{12}C$(d,p)^{13}$C	12	[25]		0.87		3	
^{13}C	^{12}C$(d,p)^{13}$C	12.4	[62]		0.78		4	
^{13}C	^{12}C$(d,p)^{13}$C	14.7	[62]		0.72		3	
^{13}C	^{12}C$(d,p)^{13}$C	14.8	[64]		0.77		1	
^{13}C	^{12}C$(d,p)^{13}$C	15	[65]		0.68		2	
^{13}C	^{12}C$(d,p)^{13}$C	16.6	[66]		0.59		2	
^{13}C	^{12}C$(d,p)^{13}$C	19.6	[66]		0.61		2	
^{13}C	^{12}C$(d,p)^{13}$C	25.9	[67]		0.66		6	
^{13}C	^{12}C$(d,p)^{13}$C	30	[68]		0.62	0.73	2	BS
^{13}C	^{12}C$(d,p)^{13}$C	51	[40]					BD
^{13}C	^{12}C$(d,p)^{13}$C	56	[69]	0.99*			1	NP
^{13}C	^{13}C$(p,d)^{12}$C	35	[70]		0.79		2	BS
^{13}C	^{13}C$(p,d)^{12}$C	41.3	[71]		0.86		1	BS
^{13}C	^{13}C$(p,d)^{12}$C	48.3	[40]		0.9		5	BS
^{13}C	^{13}C$(p,d)^{12}$C	55	[72]		0.67	0.81	3	BS

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{13}C	^{13}C$(p,d)^{12}$C	65	[56]	1.61*			3	NP
^{14}C	^{13}C$(d,p)^{14}$C	12	[25]		1.94		5	
^{14}C	^{13}C$(d,p)^{14}$C	13	[73]		1.61	1.82	3	NP
^{14}C	^{13}C$(d,p)^{14}$C	56	[69]	2.34*			2	NP
^{14}C	^{14}C$(p,d)^{13}$C	14.5	[74]	0.88*			4	NP
^{14}C	^{14}C$(p,d)^{13}$C	18.5	[48]		1.87		3	
^{14}C	^{14}C$(p,d)^{13}$C	27	[75]		1.02		4	
^{14}C	^{14}C$(p,d)^{13}$C	35	[76]		1.66	1.50	5	
^{15}C	^{14}C$(d,p)^{15}$C	2	[77]	1.07			2	
^{15}C	^{14}C$(d,p)^{15}$C	2.6	[77]	0.66			1	
^{15}C	^{14}C$(d,p)^{15}$C	3	[77]	0.73			2	
^{15}C	^{14}C$(d,p)^{15}$C	3.4	[77]	0.78			2	
^{15}C	^{14}C$(d,p)^{15}$C	14	[78]		1.12	1.12	1	
^{15}C	^{14}C$(d,p)^{15}$C	16	[79]	1.15*			1	NP
^{15}C	^{14}C$(d,p)^{15}$C	17	[75]	0.42*			1	BS
^{14}N	^{14}N$(p,d)^{13}$N	14.5	[74]		0.68		5	
^{14}N	^{14}N$(p,d)^{13}$N	18.5	[80]		0.76		3	
^{14}N	^{14}N$(p,d)^{13}$N	21	[81]	0.60*			2	NP
^{14}N	^{14}N$(p,d)^{13}$N	30.3	[82]		1.00	0.77	2	
^{14}N	^{14}N$(p,d)^{13}$N	65	[55]	0.48*			2	NP
^{15}N	^{14}N$(d,p)^{15}$N	10	[83]					BD
^{15}N	^{14}N$(d,p)^{15}$N	10.03	[84]		1.66		2	
^{15}N	^{14}N$(d,p)^{15}$N	11.65	[84]					NP
^{15}N	^{14}N$(d,p)^{15}$N	12	[25]		1.12		3	
^{15}N	^{14}N$(d,p)^{15}$N	14.8	[85]		1.58		5	
^{15}N	^{14}N$(d,p)^{15}$N	31	[86]		1.18	1.39	3	
^{15}N	^{14}N$(d,p)^{15}$N	52	[86]	1.94*				BD
^{15}N	^{15}N$(p,d)^{14}$N	18.6	[80]		1.76		4	
^{15}N	^{15}N$(p,d)^{14}$N	39.8	[87]		1.43	1.65	2	
^{16}N	^{15}N$(d,p)^{16}$N	14.8	[85]		0.42	0.42	4	
^{16}O	^{16}O$(p,d)^{15}$O	18.5	[48]	1.74*			4	BS
^{16}O	^{16}O$(p,d)^{15}$O	19	[48]	2.33*			5	BS
^{16}O	^{16}O$(p,d)^{15}$O	20	[48]		2.32		4	
^{16}O	^{16}O$(p,d)^{15}$O	21.27	[88]	1.69*			5	
^{16}O	^{16}O$(p,d)^{15}$O	25.52	[88]		2.82		4	
^{16}O	^{16}O$(p,d)^{15}$O	30.3	[52]		2.31		4	
^{16}O	^{16}O$(p,d)^{15}$O	31.82	[88]		2.29		2	
^{16}O	^{16}O$(p,d)^{15}$O	38.63	[88]		2.09		4	
^{16}O	^{16}O$(p,d)^{15}$O	39.8	[53]		2.59		2	
^{16}O	^{16}O$(p,d)^{15}$O	45.34	[88]		2.70		4	
^{16}O	^{16}O$(p,d)^{15}$O	65	[55]	2.32*		2.46	1	NP
^{16}O	^{16}O$(p,d)^{15}$O	65	[56]	2.75*			1	NP
^{17}O	^{16}O$(d,p)^{17}$O	1.3	[57]					
^{17}O	^{16}O$(d,p)^{17}$O	2.279	[89]					
^{17}O	^{16}O$(d,p)^{17}$O	2.582	[89]	1.54			1	
^{17}O	^{16}O$(d,p)^{17}$O	2.864	[89]	1.54			1	
^{17}O	^{16}O$(d,p)^{17}$O	3.155	[89]	1.56			1	
^{17}O	^{16}O$(d,p)^{17}$O	3.49	[62]	2.57			2	
^{17}O	^{16}O$(d,p)^{17}$O	4	[57]	2.39			4	
^{17}O	^{16}O$(d,p)^{17}$O	4.11	[62]	2.11			2	
^{17}O	^{16}O$(d,p)^{17}$O	6	[90]	1.24			6	
^{17}O	^{16}O$(d,p)^{17}$O	6.26	[91]	1.39			5	
^{17}O	^{16}O$(d,p)^{17}$O	7.5	[90]	1.26			6	
^{17}O	^{16}O$(d,p)^{17}$O	7.85	[90]	1.22			6	
^{17}O	^{16}O$(d,p)^{17}$O	8	[92]	1.40			1	
^{17}O	^{16}O$(d,p)^{17}$O	8.2	[90]	1.11			6	
^{17}O	^{16}O$(d,p)^{17}$O	8.55	[90]	0.96			6	

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{17}O	^{16}O$(d,p)^{17}$O	9	[62]	0.98			3	
^{17}O	^{16}O$(d,p)^{17}$O	9.3	[93]	0.88			3	
^{17}O	^{16}O$(d,p)^{17}$O	10	[90]		1.04		3	
^{17}O	^{16}O$(d,p)^{17}$O	10.2	[62]		0.78		2	BD
^{17}O	^{16}O$(d,p)^{17}$O	11	[90]		0.88		2	
^{17}O	^{16}O$(d,p)^{17}$O	11.8	[34]	0.62*			3	BS
^{17}O	^{16}O$(d,p)^{17}$O	12	[94]	0.47*			4	BD
^{17}O	^{16}O$(d,p)^{17}$O	12.4	[62]		1.03		3	
^{17}O	^{16}O$(d,p)^{17}$O	13.3	[93]		1.13		5	
^{17}O	^{16}O$(d,p)^{17}$O	14.8	[62]		0.98		2	
^{17}O	^{16}O$(d,p)^{17}$O	15	[95]		1.02		3	
^{17}O	^{16}O$(d,p)^{17}$O	19	[62]	0.81*			1	BS
^{17}O	^{16}O$(d,p)^{17}$O	25.4	[96]		0.89		3	
^{17}O	^{16}O$(d,p)^{17}$O	26.3	[97]	1.37*			6	
^{17}O	^{16}O$(d,p)^{17}$O	36	[96]		0.87		4	
^{17}O	^{16}O$(d,p)^{17}$O	63.2	[96]		1.07	0.99	3	
^{17}O	^{17}O$(p,d)^{16}$O	8.62	[98]	1.10*			4	
^{17}O	^{17}O$(p,d)^{16}$O	9.56	[98]	1.01*			2	BS
^{17}O	^{17}O$(p,d)^{16}$O	10.5	[98]		0.78		4	
^{17}O	^{17}O$(p,d)^{16}$O	11.16	[98]	0.70*			2	BS
^{17}O	^{17}O$(p,d)^{16}$O	11.44	[98]		0.74		4	
^{17}O	^{17}O$(p,d)^{16}$O	31	[99]		0.99	0.81	2	
^{18}O	^{17}O$(d,p)^{18}$O	18	[100]		1.80	1.80	3	
^{18}O	^{18}O$(p,d)^{17}$O	17.6	[48]		1.72		4	
^{18}O	^{18}O$(p,d)^{17}$O	18.2	[101]		1.43	1.60	3	
^{18}O	^{18}O$(p,d)^{17}$O	20	[102]	0.79*			2	BS
^{18}O	^{18}O$(p,d)^{17}$O	24.4	[102]	1.50*			2	BS
^{18}O	^{18}O$(p,d)^{17}$O	29.8	[102]	1.40*			3	BS
^{18}O	^{18}O$(p,d)^{17}$O	37.5	[102]	0.97*			1	NP
^{18}O	^{18}O$(p,d)^{17}$O	43.6	[102]	1.01*			2	BD
^{19}O	^{18}O$(d,p)^{19}$O	10	[103]	0.63*			1	NP
^{19}O	^{18}O$(d,p)^{19}$O	14.8	[104]		0.47		4	
^{19}O	^{18}O$(d,p)^{19}$O	15	[105]		0.38	0.43	3	
^{19}F	^{19}F$(p,d)^{18}$F	18.5	[80]		1.62		4	
^{19}F	^{19}F$(p,d)^{18}$F	19.3	[106]		1.58	1.60	3	
^{20}F	^{19}F$(d,p)^{20}$F	12	[107]		0.013	0.013	3	
^{20}F	^{19}F$(d,p)^{20}$F	16	[108]					BD
^{21}Ne	^{20}Ne$(d,p)^{21}$Ne	11	[109]		0.044		2	
^{21}Ne	^{20}Ne$(d,p)^{21}$Ne	16.4	[110]		0.031	0.035	5	
^{21}Ne	^{21}Ne$(p,d)^{20}$Ne	20	[111]		0.030	0.030	8	BS
^{22}Ne	^{21}Ne$(d,p)^{22}$Ne	10.2	[111]					BD
^{22}Ne	^{22}Ne$(p,d)^{21}$Ne	18.2	[112]		0.26		4	
^{22}Ne	^{22}Ne$(p,d)^{21}$Ne	20	[113]		0.20	0.24	2	
^{23}Ne	^{22}Ne$(d,p)^{23}$Ne	12.1	[110]		0.24		6	
^{23}Ne	^{22}Ne$(d,p)^{23}$Ne	12.1	[112]		0.24	0.24	6	
^{24}Na	^{23}Na$(d,p)^{24}$Na	7.83	[114]		0.59	0.59	2	
^{24}Mg	^{24}Mg$(p,d)^{23}$Mg	27.3	[115]		0.39		4	
^{24}Mg	^{24}Mg$(p,d)^{23}$Mg	33.6	[116]	0.34*			2	BD
^{24}Mg	^{24}Mg$(p,d)^{23}$Mg	49.2	[117]		0.44	0.41	3	
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	5	[118]	0.75			6	
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	6	[118]	0.50			3	
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	10	[119]		0.28		3	
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	12	[120]		0.33		3	BS
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	14	[121]		0.27		3	
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	15	[121]	0.28*		0.29	1	BS
^{25}Mg	^{24}Mg$(d,p)^{25}$Mg	56	[69]	0.49*			6	NP
^{26}Mg	^{25}Mg$(d,p)^{26}$Mg	8	[122]	2.97			7	

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{26}Mg	^{25}Mg(d, p)^{26}Mg	12	[123]		2.01	2.01	8	
^{26}Mg	^{25}Mg(d, p)^{26}Mg	13	[124]	2.62*			7	BD
^{26}Mg	^{26}Mg(p, d)^{25}Mg	20	[125]		2.01		2	
^{26}Mg	^{26}Mg(p, d)^{25}Mg	23.95	[126]		3.06		4	
^{26}Mg	^{26}Mg(p, d)^{25}Mg	35	[127]		2.97	2.80	3	BS
^{27}Mg	^{26}Mg(d, p)^{27}Mg	5.07	[128]	1.03			1	
^{27}Mg	^{26}Mg(d, p)^{27}Mg	12	[129]		0.45	0.45	2	
^{27}Al	^{27}Al(p, d)^{26}Al	20	[130]		1.51		3	
^{27}Al	^{27}Al(p, d)^{26}Al	35	[131]		1.32	1.40	4	
^{28}Al	^{27}Al(d, p)^{28}Al	6	[132]	0.43			3	
^{28}Al	^{27}Al(d, p)^{28}Al	12	[133]		0.60		3	
^{28}Al	^{27}Al(d, p)^{28}Al	23	[134]		0.82	0.66	1	
^{28}Si	^{28}Si(p, d)^{27}Si	27.6	[135]	15.44*			6	
^{28}Si	^{28}Si(p, d)^{27}Si	33.6	[116]		4.40	4.40	4	
^{29}Si	^{28}Si(d, p)^{29}Si	5	[136]	0.73			1	
^{29}Si	^{28}Si(d, p)^{29}Si	5.8	[137]	0.41			2	
^{29}Si	^{28}Si(d, p)^{29}Si	9	[92]	0.39			2	
^{29}Si	^{28}Si(d, p)^{29}Si	10	[138]		0.56		2	
^{29}Si	^{28}Si(d, p)^{29}Si	17.85	[139]		0.36		2	
^{29}Si	^{28}Si(d, p)^{29}Si	18	[140]		0.24	0.42	1	
^{29}Si	^{29}Si(p, d)^{28}Si	27.3	[141]	1.32*			2	NP
^{30}Si	^{29}Si(d, p)^{30}Si	10	[142]		0.93		1	BS
^{30}Si	^{29}Si(d, p)^{30}Si	12.3	[143]					NP
^{30}Si	^{29}Si(d, p)^{30}Si	16	[144]		0.64	0.79	1	
^{30}Si	^{30}Si(p, d)^{29}Si	27	[145]		0.87		3	
^{30}Si	^{30}Si(p, d)^{29}Si	27.3	[141]	0.87*		0.87	1	NP
^{31}Si	^{30}Si(d, p)^{31}Si	7	[146]	0.58			5	
^{31}Si	^{30}Si(d, p)^{31}Si	10	[146]		0.55		4	
^{31}Si	^{30}Si(d, p)^{31}Si	10	[147]		0.55		2	
^{31}Si	^{30}Si(d, p)^{31}Si	12.3	[143]		0.71		2	
^{31}Si	^{30}Si(d, p)^{31}Si	12.3	[148]		0.47		6	
^{31}Si	^{30}Si(d, p)^{31}Si	17	[143]		0.54	0.54	2	
^{32}P	^{31}P(d, p)^{32}P	10	[149]		0.68		2	
^{32}P	^{31}P(d, p)^{32}P	20	[150]		0.48	0.58	2	
^{32}S	^{32}S(p, d)^{31}S	24.5	[151]	3.40*			1	NP
^{32}S	^{32}S(p, d)^{31}S	33.6	[116]		1.51	1.51	2	NP
^{33}S	^{32}S(d, p)^{33}S	18	[140]		0.70	0.70	4	
^{34}S	^{33}S(d, p)^{34}S	12	[152]		1.85		4	
^{34}S	^{33}S(d, p)^{34}S	12	[153]		1.23	1.58	3	
^{34}S	^{34}S(p, d)^{33}S	24.5	[151]		1.08	1.08	3	
^{34}S	^{34}S(p, d)^{33}S	35	[154]	3.30*			8	BS
^{35}S	^{34}S(d, p)^{35}S	10	[155]		0.30	0.30	5	
^{35}S	^{34}S(d, p)^{35}S	11.8	[156]		0.30		2	BS
^{37}S	^{36}S(d, p)^{37}S	12.3	[157]		0.88		4	
^{37}S	^{36}S(d, p)^{37}S	25	[158]		0.89	0.88	1	
^{35}Cl	^{35}Cl(p, d)^{34}Cl	40	[159]		0.35	0.35	4	
^{36}Cl	^{35}Cl(d, p)^{36}Cl	7	[160]	0.43			3	
^{36}Cl	^{35}Cl(d, p)^{36}Cl	12.3	[161]		0.68	0.68	1	
^{37}Cl	^{37}Cl(p, d)^{36}Cl	19	[130]	30.10*				AU
^{37}Cl	^{37}Cl(p, d)^{36}Cl	35	[162]		1.58		2	
^{37}Cl	^{37}Cl(p, d)^{36}Cl	40	[159]		0.66	0.97	4	
^{38}Cl	^{37}Cl(d, p)^{38}Cl	7.5	[163]	1.06*			3	BS
^{38}Cl	^{37}Cl(d, p)^{38}Cl	12	[164]		1.81	1.81	3	
^{36}Ar	^{36}Ar(p, d)^{35}Ar	27.5	[165]		4.32		5	
^{36}Ar	^{36}Ar(p, d)^{35}Ar	33.6	[116]		2.53	3.34	6	
^{37}Ar	^{36}Ar(d, p)^{37}Ar	9.162	[166]	0.29			6	

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{37}Ar	^{36}Ar(d, p)^{37}Ar	10.02	[167]		0.34		5	
^{37}Ar	^{36}Ar(d, p)^{37}Ar	18	[140]		0.37	0.36	5	
^{38}Ar	^{38}Ar(p, d)^{37}Ar	26	[168]		2.47	2.47	6	
^{39}Ar	^{38}Ar(d, p)^{39}Ar	10.064	[169]		0.87		3	
^{39}Ar	^{38}Ar(d, p)^{39}Ar	11.6	[170]		0.77	0.81	4	
^{40}Ar	^{40}Ar(p, d)^{39}Ar	27.5	[165]		1.08	1.08	5	
^{40}Ar	^{40}Ar(p, d)^{39}Ar	35	[171]	2.25*			4	BS
^{41}Ar	^{40}Ar(d, p)^{41}Ar	11.6	[170]		0.57		2	BS
^{41}Ar	^{40}Ar(d, p)^{41}Ar	14.83	[172]		0.54	0.55	3	
^{39}K	^{39}K(p, d)^{38}K	35	[173]		2.12		4	BS
^{40}K	^{39}K(d, p)^{40}K	12	[164]		1.71	1.71	5	
^{41}K	^{41}K(p, d)^{40}K	15	[174]		0.91	0.91	3	
^{42}K	^{41}K(d, p)^{42}K	10	[175]		0.91		1	
^{42}K	^{41}K(d, p)^{42}K	12	[176]		0.71	0.81	1	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	27.3	[177]		3.49		3	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	30	[178]		4.43		4	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	33.6	[116]		5.50		3	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	40	[179]		3.86		3	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	65	[180]		4.4	4.35	5	
^{40}Ca	^{40}Ca(p, d)^{39}Ca	65	[56]	5.00*			3	NP
^{41}Ca	^{40}Ca(d, p)^{41}Ca	4.13	[181]	1.36			1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	4.69	[181]	1.20			1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	5	[182]	1.62			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	5	[183]	1.40			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	6	[182]	1.33			1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	6	[184]	1.24			2	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	7	[185]	1.25			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	7	[186]	1.00			1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	7.2	[185]	1.27			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	8	[186]	1.17			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	9	[183]	1.05			5	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	9	[186]	1.19			3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	10	[187]		0.96		3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	10	[188]		0.96		1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	10	[186]	1.07*				BD
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[189]		1.00		3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[190]					NP
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[183]		0.99		4	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[191]		1.09		4	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[186]	1.43*			3	BD
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[192]		0.98		3	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11	[193]		1.02		2	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	11.8	[34]		0.99		1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	12	[190]		0.99		2	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	12	[194]		1.07		2	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	12	[186]	1.04*			3	BS
^{41}Ca	^{40}Ca(d, p)^{41}Ca	12.8	[195]		1.11		1	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	14.3	[196]		1.00		5	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	20	[197]		1.04	1.01	2	
^{41}Ca	^{40}Ca(d, p)^{41}Ca	56	[69]	0.76*			4	BS
^{41}Ca	^{40}Ca(d, p)^{41}Ca	56	[198]	1.07*			3	BS
^{42}Ca	^{41}Ca(d, p)^{42}Ca	11	[191]		1.92		2	
^{42}Ca	^{41}Ca(d, p)^{42}Ca	12	[194]		1.78		5	
^{42}Ca	^{41}Ca(d, p)^{42}Ca	12	[199]		1.81	1.82	3	
^{42}Ca	^{42}Ca(p, d)^{41}Ca	26.5	[200]		2.18		4	
^{42}Ca	^{42}Ca(p, d)^{41}Ca	40	[179]		2.00	2.12	2	
^{43}Ca	^{42}Ca(d, p)^{43}Ca	7	[185]	0.85			3	

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{43}Ca	^{42}Ca$(d, p)^{43}$Ca	7.2	[185]	0.93			3	
^{43}Ca	^{42}Ca$(d, p)^{43}$Ca	7.2	[201]	0.84			3	
^{43}Ca	^{42}Ca$(d, p)^{43}$Ca	10	[187]		0.66		2	
^{43}Ca	^{42}Ca$(d, p)^{43}$Ca	10	[188]		0.59	0.63	2	
^{43}Ca	^{43}Ca$(p, d)^{42}$Ca	40	[202]		0.63	0.63	3	0.64
^{44}Ca	^{43}Ca$(d, p)^{44}$Ca	8.5	[203]	5.14		5.14	3	
^{44}Ca	^{44}Ca$(p, d)^{43}$Ca	17.5	[204]		2.84		2	
^{44}Ca	^{44}Ca$(p, d)^{43}$Ca	26.5	[200]		5.34		4	
^{44}Ca	^{44}Ca$(p, d)^{43}$Ca	40	[179]		3.23	3.93	5	
^{45}Ca	^{44}Ca$(d, p)^{45}$Ca	7	[185]	0.55			3	
^{45}Ca	^{44}Ca$(d, p)^{45}$Ca	7	[205]	0.62			2	
^{45}Ca	^{44}Ca$(d, p)^{45}$Ca	7.2	[185]	0.54			2	
^{45}Ca	^{44}Ca$(d, p)^{45}$Ca	10	[187]		0.37		2	
^{45}Ca	^{44}Ca$(d, p)^{45}$Ca	10	[188]		0.37	0.37	2	
^{47}Ca	^{46}Ca$(d, p)^{47}$Ca	7	[185]	0.35			3	
^{47}Ca	^{46}Ca$(d, p)^{47}$Ca	7.2	[185]	0.29			3	
^{47}Ca	^{46}Ca$(d, p)^{47}$Ca	10	[187]		0.26		2	
^{47}Ca	^{46}Ca$(d, p)^{47}$Ca	10	[206]		0.26	0.26	4	
^{48}Ca	^{48}Ca$(p, d)^{47}$Ca	17.5	[204]		8.82		5	
^{48}Ca	^{48}Ca$(p, d)^{47}$Ca	18	[207]		5.51		4	
^{48}Ca	^{48}Ca$(p, d)^{47}$Ca	40	[179]		7.35	7.35	3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	4.5	[208]	0.77			4	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	5	[208]	0.76			3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	5.5	[208]	0.73			3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	7	[185]	0.81			3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	7	[208]	0.89			4	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	7	[209]	1.50			4	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	7.2	[185]	0.87			3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	10	[187]	0.79*			1	NP
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	10	[188]		0.63		2	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	11.9	[210]	0.61*			2	NP
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	13	[211]		0.77		3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	16	[211]		0.68		3	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	19.3	[211]		0.64	0.69	1	
^{49}Ca	^{48}Ca$(d, p)^{49}$Ca	56	[212]	0.66*			3	BS
^{45}Sc	^{45}Sc$(p, d)^{44}$Sc	17.5	[213]		0.30	0.30	3	BS
^{46}Sc	^{45}Sc$(d, p)^{46}$Sc	7	[214]	0.39			2	
^{46}Sc	^{45}Sc$(d, p)^{46}$Sc	12	[215]		0.51	0.51	3	
^{46}Ti	^{46}Ti$(p, d)^{45}$Ti	17.5	[216]		2.60		3	
^{46}Ti	^{46}Ti$(p, d)^{45}$Ti	26	[217]		2.29	2.42	4	
^{46}Ti	^{46}Ti$(p, d)^{45}$Ti	34.78	[218]	1.28*			3	
^{47}Ti	^{46}Ti$(d, p)^{47}$Ti	7	[219]		0.030		4	BS
^{47}Ti	^{46}Ti$(d, p)^{47}$Ti	7	[220]		0.020	0.025	4	BS
^{47}Ti	^{46}Ti$(d, p)^{47}$Ti	10	[221]	0.01*			4	BD
^{47}Ti	^{46}Ti$(d, p)^{47}$Ti	10	[220]	0.01*			4	BD
^{48}Ti	^{47}Ti$(d, p)^{48}$Ti	13.6	[222]		0.14	0.14	1	BS
^{48}Ti	^{48}Ti$(p, d)^{47}$Ti	24.8	[218]	0.10*			4	BD
^{48}Ti	^{48}Ti$(p, d)^{47}$Ti	29.82	[218]	0.12*			3	BD
^{48}Ti	^{48}Ti$(p, d)^{47}$Ti	35.15	[218]		0.11		3	
^{48}Ti	^{48}Ti$(p, d)^{47}$Ti	39.97	[218]		0.11		3	
^{48}Ti	^{48}Ti$(p, d)^{47}$Ti	45.05	[218]		0.097	0.11	3	
^{49}Ti	^{48}Ti$(d, p)^{49}$Ti	6	[223]	0.30			4	
^{49}Ti	^{48}Ti$(d, p)^{49}$Ti	21.4	[224]		0.23	0.23	3	
^{49}Ti	^{49}Ti$(p, d)^{48}$Ti	17.5	[216]		0.25		4	
^{49}Ti	^{49}Ti$(p, d)^{48}$Ti	20.9	[151]		0.27	0.26	4	
^{50}Ti	^{49}Ti$(d, p)^{50}$Ti	13.6	[222]		6.23		4	
^{50}Ti	^{49}Ti$(d, p)^{50}$Ti	21.4	[224]		8.00	7.12	4	

TABLE I. (*Continued*.)

Isotope	Reaction	E(MeV)	Ref.	SF(bad)	SF	⟨SF⟩	pt	Remark
^{50}Ti	^{50}Ti$(p,d)^{49}$Ti	17.5	[209]		5.98		4	
^{50}Ti	^{50}Ti$(p,d)^{49}$Ti	45.05	[218]		4.86	5.50	3	
^{51}Ti	^{50}Ti$(d,p)^{51}$Ti	6	[225]	0.53*			3	
^{51}Ti	^{50}Ti$(d,p)^{51}$Ti	21.4	[224]		1.25	1.25	5	
^{51}V	^{50}V$(d,p)^{51}$V	7.5	[226]		1.58	1.58	3	
^{51}V	^{51}V$(p,d)^{50}$V	18.5	[227]		1.33		3	BS
^{51}V	^{51}V$(p,d)^{50}$V	51.9	[228]		0.75	1.10	2	BS
^{50}Cr	^{50}Cr$(p,d)^{49}$Cr	17.5	[229]	0.11*			5	BS
^{50}Cr	^{50}Cr$(p,d)^{49}$Cr	55	[230]		0.11	0.11	3	BS
^{51}Cr	^{50}Cr$(d,p)^{51}$Cr	6.6	[231]	0.62			2	
^{51}Cr	^{50}Cr$(d,p)^{51}$Cr	7.5	[232]	0.67			2	
^{51}Cr	^{50}Cr$(d,p)^{51}$Cr	10	[233]	2.83*			3	AU
^{51}Cr	^{50}Cr$(d,p)^{51}$Cr	12	[234]		0.30	0.30	3	
^{52}Cr	^{52}Cr$(p,d)^{51}$Cr	17.5	[229]		6.55		6	
^{52}Cr	^{52}Cr$(p,d)^{51}$Cr	18.5	[227]		5.87	6.24	5	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	5.41	[235]	0.67			3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	5.72	[235]	0.57			4	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	6	[236]	0.46			4	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	6.02	[235]	0.53			2	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	6.33	[235]	0.49			3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	7.5	[237]	0.54			3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	9.14	[238]	0.36			3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	10	[221]		0.43		2	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	10	[239]		0.42		2	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	10	[240]		0.39		1	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	10	[241]		0.33		1	BD
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	10.15	[238]		0.37		3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	11.18	[238]		0.36		3	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	12	[242]		0.42		4	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	20	[247]		0.35		1	
^{53}Cr	^{52}Cr$(d,p)^{53}$Cr	22	[243]		0.36	0.39	2	
^{53}Cr	^{53}Cr$(p,d)^{52}$Cr	16.6	[151]		0.37	0.37	2	
^{54}Cr	^{53}Cr$(d,p)^{54}$Cr	12	[248]		0.71	0.71	2	
^{55}Cr	^{54}Cr$(d,p)^{55}$Cr	8	[244]		0.63	0.63	2	
^{55}Cr	^{54}Cr$(d,p)^{55}$Cr	10	[245]		0.42*		2	NP
^{55}Cr	^{54}Cr$(d,p)^{55}$Cr	10	[241]	0.87*			3	BD

digitization are relatively small compared to the uncertainties in the absolute cross section measurements.

IV. EXTRACTION OF SPECTROSCOPIC FACTORS

For nearly all the nuclei we studied, we used the ground state ℓ values determined from the angular distributions and the j^π values of the valence neutron ground states found in the isotope tables [251]. In general, the experimental angular distributions at larger angles are more sensitive to details of the optical potential, the effects of inelastic couplings and other higher order effects are not well reproduced by most reaction models. Furthermore, discrepancies between the shapes from calculations and experiments are much worse at the cross section minimum, which could give these points an unduly large weight in a least-squares minimization procedure. Thus, we follow the procedures used by many groups in the past 40 years that the spectroscopic factor is extracted by fitting the reaction model predictions to the angular distribution data at the first peak, with emphasis on the maximum. The accuracy in absolute cross section measurements near the peak is most important. When possible, we take the mean of as many points near the maximum as we can to extract the spectroscopic factors. We will use the angular distributions of ^{14}N$(d,p)^{15}$N shown in Fig. 1 to illustrate the procedure we adopted to extract the spectroscopic factors.

In Fig. 1, the first three data points with $\theta_{\text{c.m.}} < 25^\circ$ were used to determine the ratios of the measured and calculated differential cross sections. The mean of these three ratios was adopted as the spectroscopic factor. For example, for the two sets of data plotted in Fig. 1, the spectroscopic factors are 1.1 for tabulated data [25] and and 1.2 for digitized data [86]. The difference in the spectroscopic factors represents the uncertainties introduced by digitization. The theoretical angular distributions, obtained from TWOFNR were multiplied

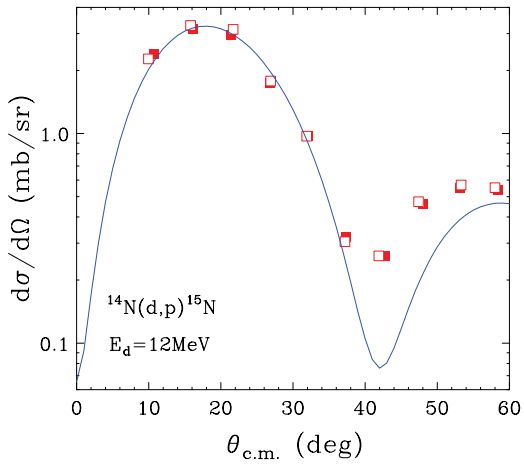

FIG. 1. (Color online) Comparison of tabulated data (closed points) [25] and digitized data (open points) [86] from the same measurement of the angular distributions of the protons obtained in the ^{14}N(d, p)^{15}N reaction at incident deuteron energy of 12 MeV. The curve is the predicted angular distributions from the code TWOFNR as described in the text, multiplied by 1.1, which is the spectroscopic factor.

by the spectroscopic factor 1.1 and plotted as the solid curve in the figure.

In cases when a "first peak" is not obvious or the angular distributions of the forward angles are nearly flat, e.g., in the reaction of ^{44}Ca(p, d)^{43}Ca at $E_p = 40$ MeV [179] as shown in Fig. 2, we find that fitting the shoulder gives more consistent results. In general, the agreement of the measured shape of the angular distributions in the vicinity of the first peak or the shoulder to the shape predicted by the transfer model gives some indication of the quality of the spectroscopic information that can be extracted by comparing the model to data. When there are more than one set of data that can be used to determine a given spectroscopic factor, we use the number of measured data points (labeled as pt in Table I) from a given measurement

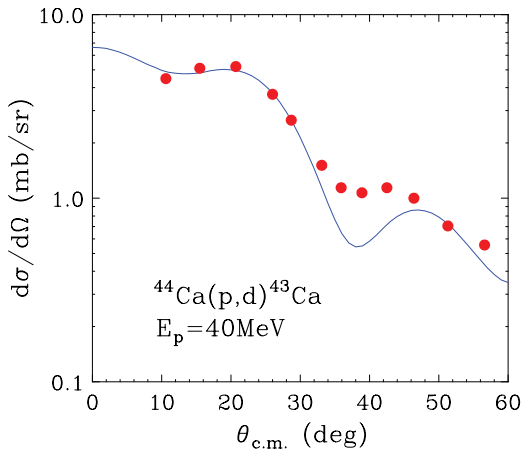

FIG. 2. (Color online) Angular distributions of the deuteron obtained in the ^{44}Ca(p, d) ^{43}Ca reaction at incident proton energy of 40 MeV [179]. The curve is the predicted angular distributions from the code TWOFNR as described in the text, multiplied by the spectroscopic factor.

that lie in the peak or shoulder region where data and theory are in good agreement to assign a relative weight to the SF extracted from that measurement. Various SFs extracted from different measurements were combined in a weighted average to compute the mean spectroscopic factors presented here.

V. EVALUATION OF ANGULAR DISTRIBUTION MEASUREMENTS

Even though most papers state the uncertainties of their cross section measurements to be 10–20%, the actual disagreements between experiments are often larger than the quoted uncertainties. An example is illustrated in the ^{11}B(d, p)^{12}B reaction. In the conventional literature, we find two measurements: one at the deuteron incident energy of 11.8 MeV [49] and another at 12 MeV [25]. Since the incident deuteron energy is nearly the same, one would expect the angular distributions from the two data sets plotted in Fig. 3 to be the same within experimental error. Reference [25] (open circles) stated that the accuracy of the absolute cross section measurements is 15%, while Ref. [49] (closed circles) quoted an error of 6%, which is smaller than the symbols in Fig. 3 Not only do the cross sections differ sometimes by a factor of 2, but also the shapes of the distributions (especially the first peak) are not the same. In this case, the shape of the angular distributions in Ref. [49] agrees with the calculation (solid curve) better than that measured in Ref. [25]. Fortunately, for this reaction, we are able to find another measurement in the NNDC database [50] (open diamonds). Near the peak at forward angles, this latter angular distribution agrees with Ref. [49], so we disregard the measurements of Ref. [25]. Data in Ref. [49] were measured nearly 40 years after the data in Ref. [25], and one may attribute the difference to the availability of better beam quality and detection systems for the measurements. However, when another reaction, ^{12}C(d, p)^{13}C at E_d = 11.8 MeV from Ref. [49] (closed circles) is compared to

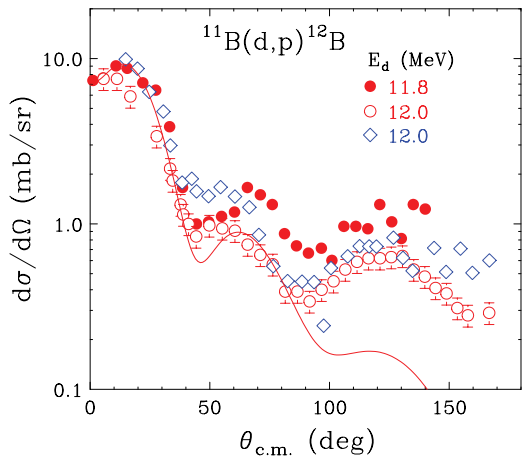

FIG. 3. (Color online) Comparisons of the angular distributions of the proton measured in the ^{11}B(d, p)^{12}B reactions in three different experiments. Open circles, closed circles, and open diamonds represent data from Refs. [25,49,50], respectively. The curve is the predicted angular distributions from the code TWOFNR multiplied by the spectroscopic factor.

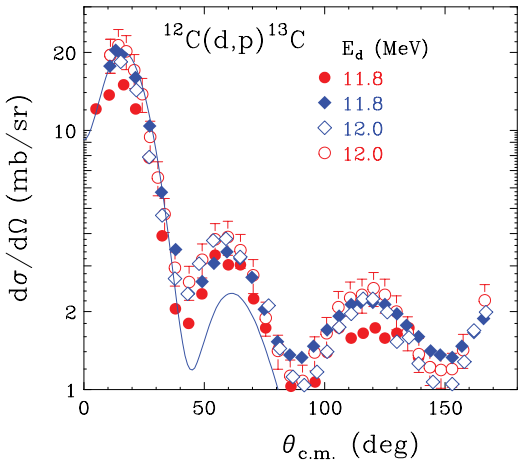

FIG. 4. (Color online) Comparison of the angular distributions of the proton measured in the ^{12}C(d, p)^{13}C reactions in four different experiments: Ref. [25] (open circles), Ref. [49] (closed circles), Ref. [63] (open diamonds), and Ref. [34] (closed diamonds). The curve is the predicted angular distributions from the code TWOFNR multiplied by the spectroscopic factor.

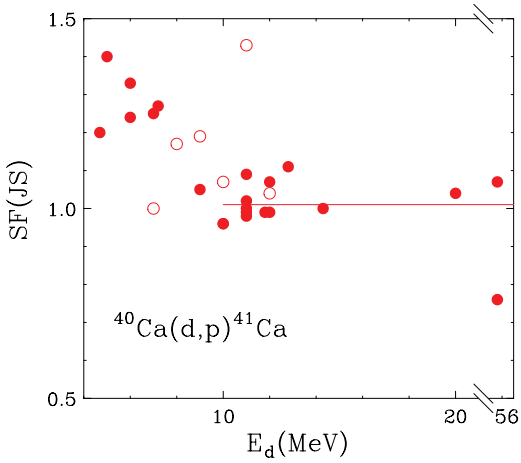

FIG. 5. (Color online) Comparison of spectroscopic factors, SF(JS), obtained from Ref. [186] (open circles) and from other measurements (closed circles). The increase of spectroscopic factors observed at E_d<10 MeV has been observed before [22,25] and attributed to the resonance structures in the elastic scattering of the deuterons [253]. Solid line is the mean SF(JS) between 10 and 56 MeV.

three other published angular distributions in Fig. 4 at E_d = 11.8 MeV (closed diamonds) [34], 12 MeV (open circles) [25], and 12 MeV (open diamonds) [63], the cross sections in the first peak measured in Ref. [49] is consistently low. No uncertainties in the measurements are given in Ref. [34] and Ref. [63], but it is clear that data in Ref. [49] do not agree with the other measurements, especially in the most forward angle region. Thus we disregard the SF values derived from Ref. [49] in our compilation of ^{12}C(d, p)^{13}C reactions. The authors of Ref. [49] cannot explain the discrepancies described here [252]. In general, data taken by the same group with the same setup sometimes have similar systematic errors that lead to rejection of the entire data set. When independent measurements are available for comparison, however, cross comparisons to other data can allow one to be more selective. The existence of confirming data allowed us to keep the ^{11}B(d, p)^{12}B data and discard the ^{12}C(d, p)^{13}C data even though both sets of data come from Ref. [49].

Cross comparisons of angular distributions sometimes help establish common systematic problems when one set of measurements was performed by the same group with the same setup. An example is illustrated in the ^{40}Ca(d, p)^{41}Ca reactions in Ref. [186], where the ground state angular distributions of ^{41}Ca at E_d = 7, 8, 9, 10, 11, and 12 MeV have been measured. Figure 5 shows the extracted spectroscopic factors [labeled as SF(JS)] as a function of incident deuteron energy for all the ^{40}Ca(d, p)^{41}Ca reactions. For clarity in presentation, no error bars are plotted. Except for the point at E_d = 7 and 12 MeV, the extracted spectroscopic factors from Ref. [186] (open circles) are consistently larger than the those extracted from other experiments that probed the same reaction at the same energy. Detailed comparisons of the angular distribution data show essentially the same effect, that the differential cross sections measured in Ref. [186] are systematically higher than the other measurements made by different groups [34,183,187–196]. Clearly, there must be some problems in the determination of the absolute cross sections in Ref. [186]. As it is not possible to find the cause of this discrepancy after so many years, we disregard the SF values determined in Ref. [186] in our review of the data.

Similarly, we disregard the data in Ref. [33] for the ^{9}Be(d, p)^{10}Be reaction, as most of the data in Ref. [33] are low when compared with the available data from other measurements. There are other examples. All the SF values that were not used are listed in column 5 of Table I. In general, a brief comment follows in the last column of Table I if the data set is considered to be problematic.

The disagreements among data sets generally exceed the quoted uncertainties of the experiments. Indeed, we have found that the most important aspect of data quality control is to have as many independent measurements as possible. Comparisons of different measurements help identify problematic measurements. The large number of measurements compiled in Table I improved the quality of the spectroscopic factors extracted in the present work.

VI. TRANSFER REACTIONS AT HIGH AND LOW ENERGY

When the Q value, momentum transfer, or angular momentum transfer are not well matched or there are significant contributions from the compound nucleus, the shape of the experimental angular distributions may be poorly described by theory. We find better agreement for ground state transfers at incident energies of around 10–20 MeV and poorer agreement at very low or high (>50 MeV) beam energies. Figure 6 shows the angular distributions of protons emitted from the ^{40}Ca(d, p)^{41}Ca (g.s) reaction for E_d = 4.7–56 MeV. Only one angular distribution is shown at each incident energy. The agreement between data and prediction for the first peak improves with increasing energy. At very low incident energy, the shapes of the measurements and the calculated transfer cross sections do not agree. This phenomenon is also seen

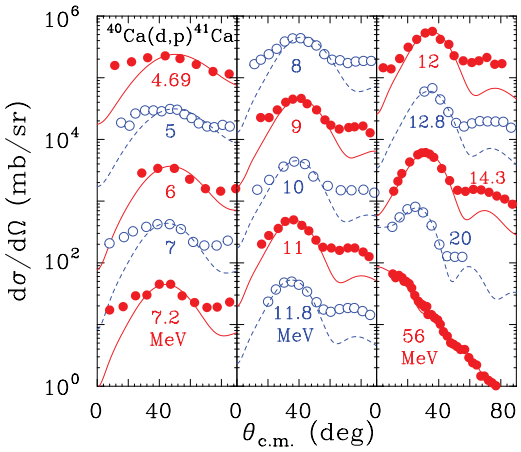

FIG. 6. (Color online) Angular distributions for ^{40}Ca(d, p)^{41}Ca reactions for beam energy of 4.69–56 MeV. Each distribution is displaced by factors of 10 from adjacent distributions. Overall normalization factor is 10 for the 7.2 MeV data. References are listed in Table I.

in other reactions. The spectroscopic factors as a function of incident energy are shown in Fig. 5 The increase of spectroscopic factors at $E_d < 10$ MeV has been observed before [7,25] and has been attributed to the resonance structures in the elastic scattering of the deuterons [253]. As explained in the last section, the open points based on the data from Ref. [186] are discarded. Between 10 and 56 MeV, we find that the mean spectroscopic factor, 1.01 ± 0.06 shown by the solid line in Fig. 5, describes the data at all energies within experimental errors.

In reactions with large negative Q values such as ^{12}C(p, d)^{11}C ($Q = -16.5$ MeV), the center-of-mass energy available in the exit channel is very small, even at ~20 MeV proton incident energy [42]. The validity of the calculated angular distribution is questionable at these energies, and we discard these data. For other reactions measured at low incident energy (<10 MeV), the data could be dominated by compound nucleus emissions or resonances in the low energy elastic scattering [253]. When possible, we exclude spectroscopic factors obtained with incident beam energies less than 10 MeV when computing the mean SF values. These "excluded" spectroscopic factors are listed in column 5 of Table I.

Even though we exclude data with incident energy lower than 10 MeV from the calculation of the mean SF, these low energy data are still valuable. In cases where very few measurements (sometimes only one) with incident energy greater than 10 MeV are available, they provide checks for consistency of the measurements. Examples are ^{49}Ti(p, d)^{48}Ti and ^{48}Ti(d, p)^{49}Ti reactions [151,216,223,224]. In the ^{43}Ca(d, p)^{44}Ca reaction, only data at 8.5 MeV [203] are available. Similarly, we only have data at 7.5 MeV for the ^{50}V(d, p)^{51}V reaction [226] and at 7.83 MeV for the ^{23}Na(d, p) ^{24}Na reaction [114]. We adopt these results despite their low incident energies.

At high energies, momentum transfer and angular momentum transfer are mismatched, so conditions may not be optimized to extract reliable spectroscopic factors. Furthermore, the global nucleon-nucleus potentials (CH89) [15] are fitted only to 65 MeV for protons and to 26 MeV for neutrons. Thus, we do not include data from reactions at incident energies greater than 65 MeV in this work. In examining data over a wide range of d or p incident energies, we find that the optimum beam energies for studying transfer reactions lie between 8 and 20 MeV per nucleon.

VII. NUCLEI WITH SMALL SPECTROSCOPIC FACTORS COMPARED WITH INDEPENDENT PARTICLE MODEL PREDICTIONS

For the ^{50}Cr(p, d)^{49}Cr reactions, there are two measurements at beam energies of 17.5 and 55 MeV [229,230]. In each case, the predicted and measured angular distributions are different, as shown in Fig. 7 with closed circles for 17.5 MeV data [229] and open circles for 55 MeV data [230]. From the magnitude of the measured cross sections, a spectroscopic factor value of 0.11 is derived. The extracted spectroscopic factor is very low, especially for an even-even nucleus. It is reasonable to speculate that there is considerable configuration mixing of the valence nucleus. When very low SF values compared with values predicted by the independent particle model [3–5] are obtained for ground state transitions, we find that sometimes the predicted shape of the angular distributions may not agree well with that of the data. This may indicate that one-step transfer amplitudes are not dominant and comparison of data to such calculations may be unreliable. Other examples are ^{20}F, ^{21}Ne, ^{22}Ne, ^{24}Mg, ^{35}Cl, ^{45}Sc, ^{47}Ti, ^{48}Ti, ^{50}Cr, and ^{51}V nuclei.

For the ^{46}Ti(d, p)^{47}Ti reaction [219–221], measurements at both $E_d = 7$ and 10 MeV are very different from the predicted cross sections, and they disagree with each other in shape and absolute cross sections. We did not extract spectroscopic factors for this nucleus.

VIII. COMPARISON OF SPECTROSCOPIC FACTORS OBTAINED FROM (p, d) AND (d, p) REACTIONS

The neutron pickup (p, d) and neutron stripping (d, p) are inverse reactions, both of which connect the ground states

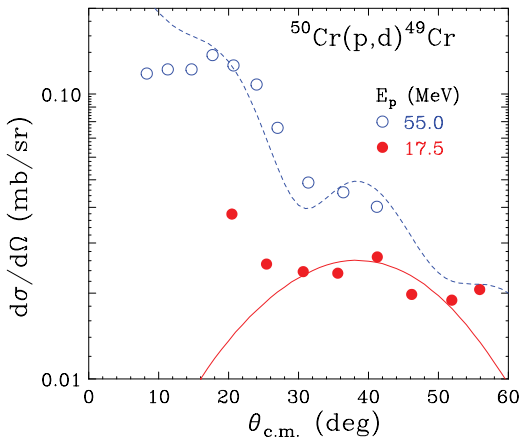

FIG. 7. (Color online) Comparison of angular distributions of the deuteron measured in the ^{50}Cr(p, d)^{49}Cr reactions in two different experiments: Ref. [229] (closed circles) and Ref. [230] (open circles).

TABLE II. Nuclei with spectroscopic factors obtained from both (p, d) and (d, p) reactions. N_{pd} and N_{dp} denote the number of (p, d) and (d, p) independent measurements included in the analysis.

B	$B(p, d)A$	N_{pd}	$A(d, p)B$	N_{dp}
^{11}Be	0.57	1	0.49	2
^{11}B	1.29	1	1.55	3
^{13}C	0.81	4	0.73	12
^{14}C	1.50	3	1.82	2
^{15}N	1.65	2	1.39	4
^{17}O	0.81	3	0.99	10
^{18}O	1.60	2	1.80	1
^{21}Ne	0.03	1	0.04	2
^{26}Mg	2.80	3	2.01	1
^{30}Si	0.87	1	0.79	2
^{42}Ca	2.12	2	1.82	3
^{43}Ca	0.63	1	0.63	2
^{44}Ca	3.93	3	5.14	1
^{48}Ti	0.11	3	0.14	1
^{49}Ti	0.26	2	0.23	1
^{50}Ti	5.50	2	7.12	2
^{51}V	1.10	2	1.58	1
^{53}Cr	0.37	1	0.39	8

of the nuclei in the entrance and exit channels. They should yield the same spectroscopic factors. From Table I, we select the nuclei, which have been studied reasonably well by both neutron pickup and stripping reactions to the ground states. The averaged SF values are listed in the second and fourth columns of Table II. The numbers of measurements contributing to the averages are listed next to the mean values in the third and fifth columns.

There are strong correlations between the spectroscopic factors determined from the (p, d) and (d, p) reactions, as shown in Fig. 8 The solid line corresponds to perfect agreement. These are independent values determined using the procedure outlined above. The scatter of the data points about the solid line can be used to determine an overall uncertainty for such analyses. As explained in Sec. V, the quoted experimental uncertainties are not always reliable. In the absence of a completely independent criterion that can be applied to each data set without comparison to others, we assume the uncertainty of each measurement to be the same, even though certain experiments may actually be more accurate than others. If we require the chi-square per degree of freedom of the scatter data shown in Fig. 8 to be unity, we can extract a random uncertainty of 20% for a given measurement. The obtained uncertainty of 20% is consistent with that of comparisons of analyses of systems that have a large number of measurements such as ^{12}C$(d, p)^{13}$C, ^{16}O$(p, d)^{15}$O, ^{16}O$(d, p)^{17}$O, ^{40}Ca$(d, p)^{41}$Ca, and other reactions. Examination of the large number of measurements in Table I suggests that the uncertainties in the extraction of the spectroscopic factors are largely limited by the disagreement among measurements. In Table II and Fig. 8, we have excluded measurements for ^{7}Li, ^{34}S, and ^{10}Be nuclei

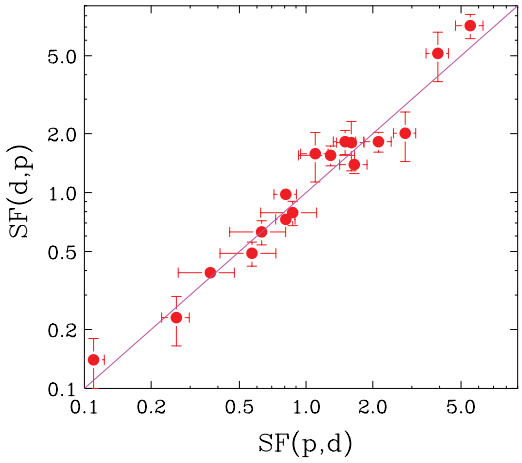

FIG. 8. (Color online) Comparison of spectroscopic factors obtained from (p, d) and (d, p) reactions as listed in Table II. Line indicates perfect agreement between the two values.

because of large errors associated with either the (p, d) or (d, p) measurements. If we include these three measurements, the estimated uncertainty in a given measurement increases to 28%.

Finally, we can compute the SF values and the associated uncertainties. These values are listed in Table III. We list the SF values that are obtained from the weighted average of independent measurements from both the (p, d) and (d, p) reactions in Table I. In these weighted averages, the low energy (<10 MeV) data and the inconsistent data (nominally marked with asterisks) that differ significantly from other sets of data are excluded. For values determined from only one measurement without the consistency checks provided by other independent measurements, an associated uncertainty of 28% is assigned. For values determined by more than one measurement (N), we take into account the distribution of the SFs around the mean. Figure 9 illustrates this procedure. The open stars in Fig. 9 represent the spectroscopic factors extracted from the good measurements of the calcium isotopes. However, the spread of the data is more than 20% for the ^{44}Ca and ^{48}Ca nuclei, even though three "good" measurements are found for each of these nuclei. For these nuclei, it is more realistic to assign the uncertainty using the standard deviations of the mean of the data points. Each of the associated uncertainties listed in Table III is determined by adopting either the standard deviation of the mean or an uncertainty of $20\%/\sqrt{N}$, depending on which of the two uncertainties is larger. For comparison, the mean SF values with the associated uncertainties are plotted as the solid stars with error bars in Fig. 9

IX. COMPARISON WITH ENDT'S "BEST VALUES"

In 1977, Endt compiled a list of the "best" SF values for the *sd*-shell nuclei [9]. For the neutron spectroscopic factors, Endt compiled the published SFs from (d, t), (p, d), $(^3$He,$\alpha)$, and (d, p) reactions. An uncertainty of 25% is assigned to the values. [(When only the (p, d) and (d, p)

TABLE III. Isotopes with the extracted spectroscopic factors [SF(JS)] and other information such as mass number A, charge number Z, and neutron number N for the nuclei. j^π, T, and S_n are the spin and parity, isospin, and neutron separation energy of the nuclei. For completeness, we list the rms radii of the neutron wave functions. Also listed are the Endt's compiled values when available. To compute the LBSM spectroscopic factors with OXBASH [254], we used the model space PPN, SPSDPF, SD, SDPF, FPPN and the corresponding interactions CKPPN, WBP, USD, SDPFNOW, FPBPPN.

B	A	Z	N	j^π	T	S_n	rms	Endt	SF(JS)	LBSM	Model space	Interaction
^{6}Li	6	3	3	$\frac{1}{2}^-$	0	5.66	2.91		1.12 ± 0.32	0.68	PPN	CKPPN
^{7}Li	7	3	4	$\frac{1}{2}^-$	$\frac{1}{2}$	7.25	2.81		1.85 ± 0.37	0.63	PPN	CKPPN
^{8}Li	8	3	5	$\frac{1}{2}^-$	1	2.03	3.66		0.62 ± 0.18	1.09	PPN	CKPPN
^{9}Li	9	3	6	$\frac{1}{2}^-$	$\frac{3}{2}$	4.06	3.23		0.98 ± 0.28	0.81	PPN	CKPPN
^{9}Be	9	4	5	$\frac{3}{2}^-$	$\frac{1}{2}$	1.67	3.86		0.45 ± 0.03	0.57	PPN	CKPPN
^{10}Be	10	4	6	$\frac{3}{2}^-$	1	6.81	2.96		1.58 ± 0.15	2.36	PPN	CKPPN
^{11}Be	11	4	7	$\frac{1}{2}^+$	$\frac{3}{2}$	0.50	7.11		0.51 ± 0.06	0.74	SPSDPF	WBP
^{10}B	10	5	5	$\frac{3}{2}^-$	0	8.44	2.85		0.50 ± 0.07	0.60	PPN	CKPPN
^{11}B	11	5	6	$\frac{3}{2}^-$	$\frac{1}{2}$	11.45	2.73		1.48 ± 0.19	1.09	PPN	CKPPN
^{12}B	12	5	7	$\frac{1}{2}^-$	1	3.37	3.46		0.45 ± 0.06	0.83	PPN	CKPPN
^{12}C	12	6	6	$\frac{3}{2}^-$	0	18.72	2.53		3.12 ± 0.36	2.85	PPN	CKPPN
^{13}C	13	6	7	$\frac{1}{2}^-$	$\frac{1}{2}$	4.95	3.26		0.75 ± 0.10	0.61	PPN	CKPPN
^{14}C	14	6	8	$\frac{1}{2}^-$	1	8.18	3.00		1.63 ± 0.33	1.73	PPN	CKPPN
^{15}C	15	6	9	$\frac{1}{2}^+$	$\frac{3}{2}$	1.22	5.51		1.12 ± 0.32	0.98	SPSDPF	WBP
^{14}N	14	7	7	$\frac{1}{2}^-$	0	10.55	2.87		0.77 ± 0.12	0.69	PPN	CKPPN
^{15}N	15	7	8	$\frac{1}{2}^-$	$\frac{1}{2}$	10.83	2.89		1.48 ± 0.24	1.46	PPN	CKPPN
^{16}N	16	7	9	$\frac{3}{2}^+$	1	2.49	4.26		0.42 ± 0.12	0.96	SPSDPF	WBP
^{16}O	16	8	8	$\frac{1}{2}^-$	0	15.66	2.74		2.46 ± 0.26	2.00	PPN	CKPPN
^{17}O	17	8	9	$\frac{5}{2}^+$	$\frac{1}{2}$	4.14	3.48		0.94 ± 0.13	1.00	SD	USD
^{18}O	18	8	10	$\frac{5}{2}^+$	1	8.04	3.24		1.66 ± 0.19	1.58	SD	USD
^{19}O	19	8	11	$\frac{5}{2}^+$	$\frac{3}{2}$	3.95	3.57		0.43 ± 0.06	0.69	SD	USD
^{19}F	19	9	10	$\frac{1}{2}^+$	$\frac{1}{2}$	10.43	2.66		1.60 ± 0.23	0.56	SD	USD
^{20}F	20	9	11	$\frac{3}{2}^+$	1	6.60	3.39		~ 0.01	0.02	SD	USD
^{21}Ne	21	10	11	$\frac{3}{2}^+$	$\frac{1}{2}$	6.76	3.41	0.01	0.03 ± 0.01	0.03	SD	USD
^{22}Ne	22	10	12	$\frac{3}{2}^+$	1	10.36	3.27	0.19	0.24 ± 0.03	0.13	SD	USD
^{23}Ne	23	10	13	$\frac{5}{2}^+$	$\frac{3}{2}$	5.20	3.58	0.24	0.24 ± 0.03	0.32	SD	USD
^{24}Na	24	11	13	$\frac{1}{2}^+$	1	8.87	3.49	0.30	0.59 ± 0.17	0.39	SD	USD
^{24}Mg	24	12	12	$\frac{3}{2}^+$	0	16.53	3.13		0.41 ± 0.06	0.41	SD	USD
^{25}Mg	25	12	13	$\frac{5}{2}^+$	$\frac{1}{2}$	7.33	3.50	0.37	0.29 ± 0.03	0.34	SD	USD
^{26}Mg	26	12	14	$\frac{5}{2}^+$	1	11.09	3.35	1.80	2.43 ± 0.50	2.51	SD	USD
^{27}Mg	27	12	15	$\frac{1}{2}^+$	$\frac{3}{2}$	6.44	3.90	0.58	0.45 ± 0.13	0.46	SD	USD
^{27}Al	27	13	14	$\frac{5}{2}^+$	$\frac{1}{2}$	13.06	3.31	1.10	1.40 ± 0.20	1.10	SD	USD
^{28}Al	28	13	15	$\frac{1}{2}^+$	1	7.73	3.78	0.50	0.66 ± 0.10	0.60	SD	USD
^{28}Si	28	14	14	$\frac{5}{2}^+$	0	17.18	3.22		4.40 ± 1.24	3.62	SD	USD
^{29}Si	29	14	15	$\frac{1}{2}^+$	$\frac{1}{2}$	8.47	3.73	0.55	0.42 ± 0.13	0.45	SD	USD
^{30}Si	30	14	16	$\frac{1}{2}^+$	1	10.61	2.87	0.89	0.84 ± 0.10	0.82	SD	USD
^{31}Si	31	14	17	$\frac{3}{2}^+$	$\frac{3}{2}$	6.59	3.70	0.75	0.54 ± 0.07	0.58	SD	USD
^{32}P	32	15	17	$\frac{1}{2}^+$	1	7.94	3.64	0.80	0.58 ± 0.10	0.60	SD	USD
^{32}S	32	16	16	$\frac{1}{2}^+$	0	15.04	3.40		1.51 ± 0.43	0.96	SD	USD
^{33}S	33	16	17	$\frac{3}{2}^+$	$\frac{1}{2}$	8.64	3.63	0.70	0.70 ± 0.20	0.61	SD	USD
^{34}S	34	16	18	$\frac{3}{2}^+$	1	11.42	3.53	1.90	1.43 ± 0.35	1.83	SD	USD
^{35}S	35	16	19	$\frac{3}{2}^+$	$\frac{3}{2}$	6.99	3.77	0.38	0.30 ± 0.09	0.36	SD	USD

TABLE III. (*Continued*.)

B	A	Z	N	j^π	T	S_n	rms	Endt	SF(JS)	LBSM	Model space	Interaction
^{37}S	37	16	21	$\frac{7}{2}^-$	$\frac{5}{2}$	4.30	4.02		0.88 ± 0.12	0.92	SDPF	SDPFNOW
^{35}Cl	35	17	18	$\frac{3}{2}^+$	$\frac{1}{2}$	12.64	3.51		0.35 ± 0.10	0.32	SD	USD
^{36}Cl	36	17	19	$\frac{1}{2}^+$	1	8.58	3.70	1.20	0.68 ± 0.19	0.77	SD	USD
^{37}Cl	37	17	20	$\frac{1}{2}^+$	$\frac{3}{2}$	10.31	3.64	0.95	0.97 ± 0.43	1.15	SD	USD
^{38}Cl	38	17	21	$\frac{1}{2}^-$	2	6.11	3.94	0.78	1.81 ± 0.51	0.95	SDPF	SDPFNOW
^{36}Ar	36	18	18	$\frac{3}{2}^+$	0	15.26	3.45		3.34 ± 0.89	2.06	SD	USD
^{37}Ar	37	18	19	$\frac{3}{2}^+$	$\frac{1}{2}$	8.79	3.71	0.49	0.36 ± 0.05	0.36	SD	USD
^{38}Ar	38	18	20	$\frac{3}{2}^+$	1	11.84	3.60	2.50	2.47 ± 0.70	3.04	SD	USD
^{39}Ar	39	18	21	$\frac{7}{2}^-$	$\frac{3}{2}$	6.60	3.94	0.64	0.81 ± 0.11	0.83	SDPF	SDPFNOW
^{40}Ar	40	18	22	$\frac{7}{2}^-$	2	9.87	3.83	1.20	1.08 ± 0.31	1.91	SDPF	SDPFNOW
^{41}Ar	41	18	23	$\frac{7}{2}^-$	$\frac{5}{2}$	6.10	4.01	0.47	0.55 ± 0.08	0.65	SDPF	SDPFNOW
^{39}K	39	19	20	$\frac{3}{2}^+$	$\frac{1}{2}$	13.08	3.58	2.00	2.12 ± 0.60	1.72	SD	USD
^{40}K	40	19	21	$\frac{5}{2}^-$	1	7.80	3.90	0.94	1.71 ± 0.48	0.98	SDPF	SDPFNOW
^{41}K	41	19	22	$\frac{5}{2}^-$	$\frac{3}{2}$	10.10	3.84	0.56	0.91 ± 0.26	1.06	SDPF	SDPFNOW
^{42}K	42	19	23	$\frac{1}{2}^-$	2	7.53	3.96	0.34	0.81 ± 0.11	0.88	SDPF	SDPFNOW
^{40}Ca	40	20	20	$\frac{3}{2}^+$	0	15.64	3.81		4.35 ± 0.62	4.00	SD	USD
^{41}Ca	41	20	21	$\frac{7}{2}^-$	$\frac{1}{2}$	8.36	3.90	0.85	1.01 ± 0.06	1.00	FPPN	FPBPPN
^{42}Ca	42	20	22	$\frac{7}{2}^-$	1	11.48	3.82	1.60	1.93 ± 0.17	1.81	FPPN	FPBPPN
^{43}Ca	43	20	23	$\frac{7}{2}^-$	$\frac{3}{2}$	7.93	3.97	0.58	0.63 ± 0.07	0.75	FPPN	FPBPPN
^{44}Ca	44	20	24	$\frac{7}{2}^-$	2	11.13	3.87	3.10	3.93 ± 1.08	3.64	FPPN	FPBPPN
^{45}Ca	45	20	25	$\frac{7}{2}^-$	$\frac{5}{2}$	7.41	4.03		0.37 ± 0.05	0.50	FPPN	FPBPPN
^{47}Ca	47	20	27	$\frac{7}{2}^-$	$\frac{7}{2}$	7.28	4.08		0.26 ± 0.04	0.26	FPPN	FPBPPN
^{48}Ca	48	20	28	$\frac{7}{2}^-$	4	9.95	3.99		7.35 ± 1.42	7.38	FPPN	FPBPPN
^{49}Ca	49	20	29	$\frac{3}{2}^-$	$\frac{9}{2}$	5.15	4.59		0.69 ± 0.07	0.92	FPPN	FPBPPN
^{45}Sc	45	21	24	$\frac{3}{2}^-$	$\frac{3}{2}$	11.32	3.89	0.34	0.30 ± 0.08	0.35	FPPN	FPBPPN
^{46}Sc	46	21	25	$\frac{1}{2}^-$	2	8.76	4.00		0.51 ± 0.14	0.37	FPPN	FPBPPN
^{46}Ti	46	22	24	$\frac{7}{2}^-$	1	13.19	3.85		2.42 ± 0.34	2.58	FPPN	FPBPPN
^{47}Ti	47	22	25	$\frac{5}{2}^-$	$\frac{3}{2}$	8.88	4.01		0.03 ± 0.01			
^{48}Ti	48	22	26	$\frac{5}{2}^-$	2	11.63	3.94		0.11 ± 0.01			
^{49}Ti	49	22	27	$\frac{7}{2}^-$	$\frac{5}{2}$	8.14	4.08		0.25 ± 0.03			
^{50}Ti	50	22	28	$\frac{7}{2}^-$	3	10.94	4.00		6.36 ± 1.10			
^{51}Ti	51	22	29	$\frac{3}{2}^-$	$\frac{7}{2}$	6.37	4.46		1.25 ± 0.35			
^{51}V	51	23	28	$\frac{5}{2}^-$	$\frac{5}{2}$	11.05	4.01		1.28 ± 0.32			
^{50}Cr	50	24	26	$\frac{5}{2}^-$	1	13.00	3.94		0.11 ± 0.02			
^{51}Cr	51	24	27	$\frac{7}{2}^-$	$\frac{3}{2}$	9.26	4.08		0.30 ± 0.08			
^{52}Cr	52	24	28	$\frac{7}{2}^-$	2	12.04	4.00		6.24 ± 0.88			
^{53}Cr	53	24	29	$\frac{3}{2}^-$	$\frac{5}{2}$	7.94	4.34		0.39 ± 0.03			
^{54}Cr	54	24	30	$\frac{3}{2}^-$	3	9.72	4.22		0.71 ± 0.20			
^{55}Cr	55	24	31	$\frac{3}{2}^-$	$\frac{7}{2}$	6.24	4.53		0.63 ± 0.13			

reactions were studied, Endt assigned 50% uncertainties.] Endt's best values are listed in Table III. Figure 10 compares the spectroscopic factors determined by Endt and the present work [SF(JS)]. There are strong correlations between the two procedures, even though the values scatter around the dashed line, which indicates perfect agreement. From the consistency check with (p, d) and (d, p) reactions, we expect that our values should have smaller random uncertainties, because a systematic approach is used to extract the SF values directly from the measured angular distributions, while Endt's

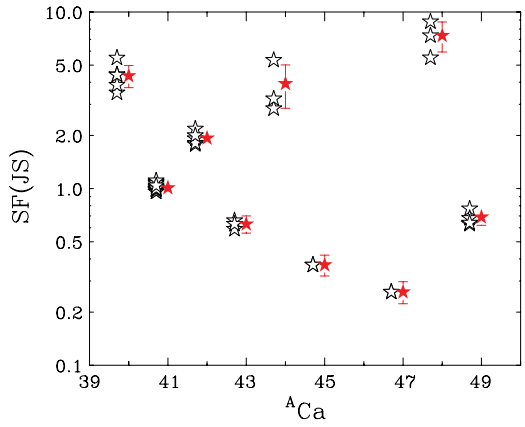

FIG. 9. (Color online) Spectroscopic factors obtained for Ca isotopes. Open stars represent individual measurements. The accompanying solid stars are the weighted averaged values with the associated uncertainties determined from the standard deviations or $20\%/\sqrt{N}$ of the mean SF values, whichever is larger.

compilation depended on the analysis by different authors and relied on the communication with the authors concerning the normalizations of the spectroscopic factors. We also have the advantage that many more measurements are included in Table I than those that were available for Endt's compilations.

X. ^{14}C(d, p)^{15}C REACTIONS

The ^{14}C(d, p)^{15}C reaction is important because ^{15}C has a loosely bound halo neutron. This reaction has been used to provide cross comparisons between the spectroscopic factors obtained from one-nucleon knockout and transfer reactions [254]. In addition, this reaction is a good candidate for extracting spectroscopic factors using the combined asymptotic normalization coefficient (ANC) method [255].

For the ^{14}C(d, p)^{15}C reaction, there are three measurements available, with E_d = 14 [78], 16 [79], and 17 MeV [75]. When data from these references are plotted in Fig. 11, they do not agree with each other within a factor of 2, even though the spectroscopic factors quoted in the original references are within 20% of each other (0.88 [78], 0.99 [79], 1.03 [75]). This underscores the importance of an analysis with a systematic and consistent approach as studied here.

Since we generally exclude data that do not measure the first forward angle peak, data taken at 16 (closed squares) and 17 MeV (open circles) [75,79] are discarded. The predicted angular distribution shape (solid curve) shows good agreement with data at 14 MeV [78] at angles less than 15°. Based on the criterion outlined above, we extracted the SF from this data set. However for such an important nucleus, a second independent measurement with data at forward angles would be desirable to determine the spectroscopic factor of the loosely bound neutron (S_n = 1.22 MeV).

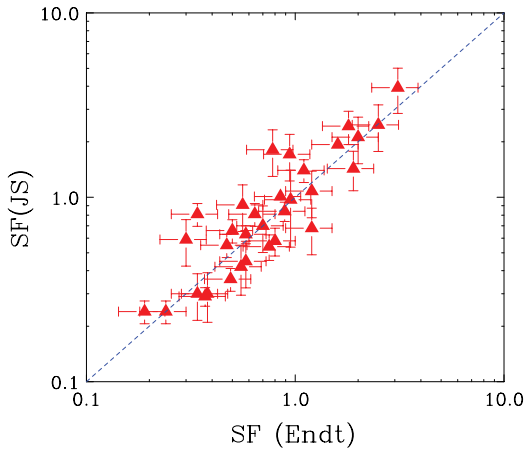

FIG. 10. (Color online) Comparison of SF(JS) and compiled values of Endt [9]. All values are listed in Table III. Line indicates perfect agreement between our values and Endt's compilation.

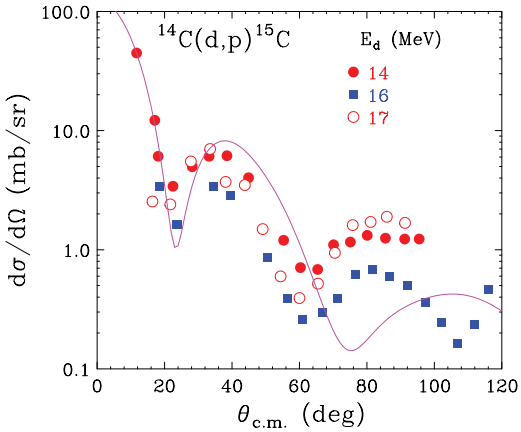

FIG. 11. (Color online) Comparison of the angular distributions of the proton measured in the ^{14}C(d, p) ^{15}C reactions in three different experiments with incident deuteron energy of 14 MeV [78] (closed circles), 16 MeV [79] (closed squares), and 17 MeV [75] (open circles). The curve represents the predicted angular distributions from the code TWOFNR as described in the text, multiplied by the spectroscopic factor of 1.1 which fits the data of Ref. [78], the only set of data with measurements at angles more forward than 15°.

XI. DEPENDENCE OF SPECTROSCOPIC FACTORS ON NEUTRON SEPARATION ENERGY

Recent measurements of spectroscopic factors from single-nucleon "knockout" reactions with radioactive and stable nuclei show increasing quenching of the spectroscopic factor values with nucleon separation energy [13,14]. The wide range of isotopes studied in this work and listed in Table III includes nuclei with neutron-separation energies ranging from 0.5 to 19 MeV. To examine any quenching trend, we computed the neutron spectroscopic factors using OXBASH, a large-basis shell model code [256,257]. The model spaces and interactions used in the calculations are listed in Table III. Using truncated model space, we were able to obtain more spectroscopic factors (^{37}S, ^{38}Cl, ^{39}Ar, ^{40}Ar, ^{41}Ar, ^{40}K, ^{41}K, and ^{42}K) than those published in Ref. [10]. Because of the amount of CPU time involved, we could not compute the SF values from OXBASH for every nucleus. Attempts are being made to extend OXBASH

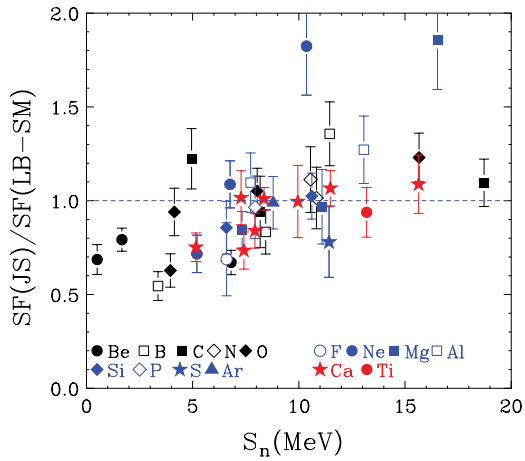

FIG. 12. (Color online) Ratios of SF(JS) values and the LBSM predicted SF values as a function of neutron separation energy (S_n). Open and closed symbols denote elements with odd and even Z, respectively. Only data with an overall uncertainties of less than 25% are included.

shell model calculations to Ti and Cr isotopes using high performance computing facilities [258].

Figure 12 shows the ratio of the experimental SF values to the LBSM values from OXBASH as a function of the neutron separation energy. Within the experimental uncertainties, we do not see the systematic quenching of the spectroscopic factors with increasing nucleon separation energy reported for measurements of nucleon knockout reactions induced by radioactive beams. Rather, there seems to be some indication that the trend is the opposite, i.e., the SF values are smaller than the predicted values for nuclei with small neutron separation energy. This trend persists in a smaller subset of the nuclei such as the Ca isotopes plotted as solid stars.

The structures of the neutron-rich nuclei with small neutron separation energy are of general interest. For loosely bound nuclei, knockout reactions with radioactive beams suggest no quenching. In our data set, there are seven nuclei with $S_n < 4$ MeV: ^{8}Li, ^{9}Be, ^{11}Be, ^{12}B, ^{15}C, ^{16}N, and ^{19}O. Except for ^{15}C, which was discussed in the previous section, the fits and quality of the data are comparable to those of the other data we have examined. However, the experimental SF values for these nuclei are consistently smaller than the LBSM predictions. (If we relax the criterion to $S_n < 5$ MeV, the conclusion is similar.) To be sure, we do not have many nuclei, and they are all light nuclei with $Z \leqslant 8$. Furthermore, the suppression ratios vary from 0.44 to 0.79 for the six nuclei we examined. Excluding ^{15}C, the average quenching factor is 0.6. The SF values (as a group) do not agree with the LBSM predictions. These results may indicate that the standard global potential [15] may not be appropriate to describe the scattering of these weakly bound nuclei with diffuse surfaces. Furthermore, target breakup may have to be explicitly taken into account when calculating transfer processes involving nuclei with very small neutron separation energies (<2 MeV). Further study with improved theoretical inputs is needed to understand these nuclei with loosely bound neutrons.

XII. SUMMARY

In summary, we have evaluated angular distribution measurements from past (p, d) and (d, p) transfer reactions using targets ranging from Li to Cr isotopes. Problems with past measurements are discussed and resolved mainly by comparing the data of several independent measurements. We observe problems with the consistencies between measurements. We expect such problems are not limited to the data studied here. The procedure developed to monitor the quality control of the data sets should be applicable to other analyses with a large number of data sets. Based on the analysis of the evaluated data and a reaction model with minimum assumptions, we develop a consistent approach to extract spectroscopic factors. Comparisons between spectroscopic factors obtained from (p, d) and (d, p) reactions suggest that most of the extracted values have uncertainties less than 20%. Thus our SF values have smaller random uncertainties than the values compiled by Endt. Furthermore, the method should be applicable to other stable beams and maybe rare isotope beam experiments. The present compilation of the neutron ground state spectroscopic factors of 80 nuclei provides important reference points for more sophisticated theoretical work on transfer reactions and development in nuclear structure model. For most nuclei, the agreement between data and LBSM predictions is within 20%. Even though most of the nuclei studied are close to the valley of stability, the nuclei range in neutron separation energy from 0.5 to 19 MeV. The present work does not support the observation that spectroscopic factors are suppressed with increasing neutron separation energy as found in nucleon knockout reactions.

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