Quenching of neutron spectroscopic factors of radioactive carbon isotopes with knockout reactions within a wide energy range*

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Abstract: The quenching factors of one-neutron spectroscopic factors, which are ratios of theoretical to experimental one-neutron removal cross sections, are studied for the carbon isotopes $^{15-19}$C, with ^{12}C and ^{9}Be targets within incident energies from around 50 to 900 MeV/nucleon. The resulting values of quenching factors do not show strong energy dependence within such an energy range. The average values of the these quenching factors agree well with the systematics in [J.A. Tostevin and A. Gade, Phys. Rev. C, 90 057602 (2014)], which was established for a large set of radioactive nuclei with different masses below 305 MeV/nucleon.

Keywords: spectroscopic factors, knockout reactions, eikonal model, one-neutron removal

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1 Introduction

Spectroscopic factors (SFs) are important quantities that are traditionally thought of as a link between studies of nuclear reactions and nuclear structures [1]. Experimentally, SFs are mainly extracted from transfer reactions and nucleon knockout or one nucleon removal reactions. It has been found that the proton SFs of some stable nuclei, such as ^{16}O and ^{40}Ca, extracted from (e,e′p) and (d,^{3}He) reactions, are smaller than shell model predictions by about 40%–50% [2]. This is known as the quenching of the SFs. The quenching factors (QFs) of the SFs have been related to nucleon-nucleon correlations that have not been dealt with properly within the nuclear shell model [3]. Because of this, the quenching of SFs has been studied intensively in recent years [4–12]. Results of systematic studies of knockout reactions with nuclei at different regions of the nuclear chart show that the quenching factors depend on the binding energies of the removed nucleons: they are close to unity for removal of weakly-bound nucleons and are much smaller than unity for removal of deeply-bound ones. This is best shown when the QFs are plotted as a function of the neutron-proton asymmetries, which are defined as the differences between the single neutron and proton binding energies, see, e.g., in Ref. [12]. However, systematic studies of transfer reactions suggest that there is no clear evidence for such dependence on the neutron-proton asymmetries [7, 10]. The reason for the discrepancy in these two systematic studies is still an open question.

Most measurements of the knockout reactions are performed at relatively low energies (below about 300 MeV/nucleon) and are analyzed with the eikonal model [12–19]. It is interesting to study the quenching factors of the SFs extracted from knockout reactions within a wider energy range to see if they have any dependence on incident energy. For this reason, we study the one-neutron removal reactions of the radioactive carbon isotopes $^{15-19}$C with a ^{9}Be and a ^{12}C target at incident energies from around 50 to about 900 MeV/nucleon. The eikonal model for one-neutron removal cross sections was used, which takes into account both the diffraction dissociation and stripping mechanisms for the one-neutron removal processes. Our results show that these QFs do not have evident energy dependence within this range of incident energies.

In this paper, we give the details and the results of our eikonal model calculations for the one-neutron removal cross sections in Section 2. The summary and conclusions of this work are given in Section 3.

2 Theoretical analyses

For inclusive one-neutron removal cross sections, all excited states of the core nucleus are included in the ex-

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perimental data, see, e.g. Ref. [20]. For this reason, theoretically, the total one-neutron removal cross section, $\sigma_{\text{-1n}}$, should be calculated as the sum of the one-nucleon removal cross sections associated with each of the bound state of the core nucleus [14]:

$$\sigma^{\text{th}}_{\text{-1n}}=\sum_{n\ell j}\left[\frac{A}{A-1}\right]^{N}C^2S(J^{\pi},n\ell j)\sigma_{\text{sp}}(n\ell j,S_N^{\text{eff}}), \qquad (1)$$

where C^2S are the shell model spectroscopic factors which depend on the spin-parties of the core states, J^{π}, and the quantum numbers of the single particle states of the removed nucleon, $n\ell j$. The factors $[A/(A-1)]^N$ are for the centre-of-mass corrections to the shell model SFs, where N is the number of the oscillator quanta associated with the major shell of the removed particle and A is the mass number of the composite nucleus [13, 21]. σ_{sp} are the single particle cross sections calculated assuming the SFs being unity, which includes the contributions from both diffraction dissociation or elastic breakup ($\sigma_{\text{sp}}^{\text{els}}$) and stripping or inelastic breakup ($\sigma_{\text{sp}}^{\text{inel}}$) mechanisms, where the target nucleus remains in its ground state or is left in its excited states, respectively: $\sigma_{\text{sp}}=\sigma_{\text{sp}}^{\text{els}}+\sigma_{\text{sp}}^{\text{inel}}$. In the eikonal model, they are expressed as [22]:

$$\sigma_{\text{sp}}^{\text{els}}=\left\langle\phi_{n\ell j}\left||S_{\text{v}}|^2|S_{\text{c}}|^2\right|\phi_{n\ell j}\right\rangle-\left|\langle\phi_{n\ell j}|S_{\text{v}}S_{\text{c}}|\phi_{n\ell j}\rangle\right|^2, \quad (2)$$

and

$$\sigma_{\text{sp}}^{\text{inel}}=\frac{\pi}{k^2}\left\langle\phi_{n\ell j}\left|\left(1-|S_{\text{v}}|^2\right)|S_{\text{c}}|^2\right|\phi_{n\ell j}\right\rangle, \qquad (3)$$

where $|\phi_{n\ell j}\rangle$ is the single-particle wave function of the removed neutron, and S_{c} and S_{v} are the scattering matrices of the core nucleus and the valence neutron respectively with the target nucleus. In the eikonal model they are functions of the impact parameters:

$$S_{\text{c,v}}(b)=\exp\left[\frac{\text{i}}{k_{\text{NN}}}\int_0^{\infty}\text{d}qq\rho_{\text{c,v}}(q)\rho_{\text{t}}(q)f_{\text{NN}}(q)J_0(qb)\right], \qquad (4)$$

in which $J_0(qb)$ is the Bessel function of the first kind, and $\rho_{\text{c,v}}(q)$ and $\rho_{\text{t}}(q)$ are the Fourier transformations of the nuclear density distributions of the core nucleus and the valence nucleon, and the target nuclei, respectively. At forward angles, the nucleon-nucleon scattering amplitude, $f_{\text{NN}}(q)$, can be parametrized with the nucleon-nucleon total cross sections, σ_{NN}, the ratio of the real to the imaginary part of f_{NN}, α_{NN}, and the slope parameter of the NN elastic differential cross sections, β_{NN} [22]:

$$f_{\text{NN}}(q)=\frac{k_{\text{NN}}}{4\pi}\sigma_{\text{NN}}(i+\alpha_{\text{NN}})\exp(-\beta_{\text{NN}}q^2). \qquad (5)$$

There have been different parametrizations of the NN scattering amplitudes. The widely used ones are that of Ray [23], which covers the energy range from 100 to 2200 MeV/nucleon and Lenzi et al. [24], which covers the energy range from 30 to 342.5 MeV/nucleon. Recently Horiuchi et al. combined these two parametrizations and arrived at a new set of parameters which covers an energy range from 30 to 1000 MeV/nucleon [25]. A calculation of the total reaction cross sections of the ^{12}C+^{12}C system at various energies with these three sets of parameters is shown in Fig.1 together with the experimental data. Clearly, the parameters of Horiuchi et al. give the best overall agreement with the experimental data. For this reason, we use the parameters of Horiuchi et al. throughout this work. All our calculations are made with the computer code MOMDIS [22].

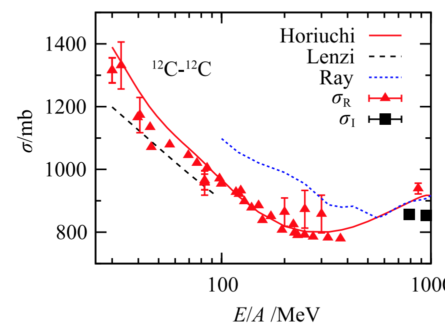

Fig. 1. (color online) Comparisons of the reaction cross sections of ^{12}C on a ^{12}C target at various incident energies between theoretical and experimental results. The experimental data are taken from Refs. [26–33] for total reaction cross sections (triangles) and Ref. [34] for interaction cross sections (squares). The solid, dashed and dotted curves are theoretical results with the parameters (in Eq. (5)) of Horiuchi et al. [25], Lenzi et al. [24] and Ray [23], respectively.

The nucleon density distributions of the core nuclei, namely, $^{14-18}$C, required in Eq. (4) for the core-target S-matrix are obtained with Hartree-Fock calculations based on the SkX parametrization [35]. This parameter set has been extensively used in folding model calculations [36–38]. The same Hartree-Fock calculation was made for the nucleon density distribution of the ^{9}Be target, which has a root-mean-square (rms) radius of 2.272 fm. For the ^{12}C target, a two-parameter Fermi density with $\rho_0=0.194$ fm^{-3}, $c=2.214$ fm and $a=0.425$ fm was used [39, 40]. These parameters correspond to a rms radius of ^{12}C of 2.331 fm, which reproduces the experimental value of 2.33 ± 0.01 fm [41] very well.

Spectroscopic factors and level energies are required to calculate the inclusive one-neutron removal cross sections with Eq. (1). Results of two sets of shell model calculations were used for this purpose: one is given by Simpson and Tostevin [14], the other is by Yuan et al. [42]. Both shell model calculations were made with the computer code OXBASH [43], but the Hamiltonian WBP [44] was used in the former and YSOX [42] was used for the latter.

Table 1. Bound states of the core nuclei, E_x and J^π, and their associate single-particle states, $n\ell j$, of the valence nucleon and single-particle spectroscopic factors (C^2S) as results of shell model calculations used in one neutron removal cross section calculations of the carbon isotopes studied in this work. Numbers 1 and 2 in the subscripts stand for results by Simpson and Tostevin [14] and by Yuan [42], respectively.

reaction	E_{x1}/MeV	${J^\pi}_1$	$(n\ell j)_1$	C^2S_1	E_{x2}/MeV	${J^\pi}_2$	$(n\ell j)_2$	C^2S_2
(^{15}C, ^{14}C)	0.0	0^+	$1s_{1/2}$	0.978	0.0	0^+	$1s_{1/2}$	0.964
	6.094	1^-	$0p_{3/2}$	1.180	5.622	0^-	$0p_{1/2}$	0.425
	6.903	0^-	$0p_{1/2}$	0.459	6.177	1^-	$0p_{3/2}$	1.141
	7.012	2^+	$0d_{5/2}$	0.020	7.563	2^-	$0p_{3/2}$	0.0061
					7.868	2^+	$0d_{5/2}$	0.0143
(^{16}C, ^{15}C)	0.0	$\frac{1}{2}^+$	$1s_{1/2}$	0.601	0.0	$\frac{1}{2}^+$	$1s_{1/2}$	0.733
	0.74	$\frac{5}{2}^+$	$0d_{5/2}$	1.232	0.783	$\frac{5}{2}^+$	$0d_{5/2}$	1.134
(^{17}C, ^{16}C)	0.0	0^+	$0d_{3/2}$	0.035	0.0	0^+	$0d_{3/2}$	0.032
	1.766	2^+	$0d_{5/2}$	1.445	2.19	2^+	$0d_{5/2}$	1.364
			$1s_{1/2}$	0.163			$1s_{1/2}$	0.149
	4.1	2^+	$0d_{5/2}$	0.770	4.587	2^+	$0d_{5/2}$	0.107
			$1s_{1/2}$	0.225			$1s_{1/2}$	0.279
					4.844	4^+	$0d_{5/2}$	0.334
(^{18}C, ^{17}C)	0.0	$\frac{3}{2}^+$	$0d_{3/2}$	0.103	0.0	$\frac{3}{2}^+$	$0d_{3/2}$	0.089
	0.032	$\frac{5}{2}^+$	$0d_{5/2}$	2.800	0.006	$\frac{1}{2}^+$	$1s_{1/2}$	0.786
	0.295	$\frac{1}{2}^+$	$1s_{1/2}$	0.654	0.078	$\frac{5}{2}^+$	$0d_{5/2}$	2.72
(^{19}C, ^{18}C)	0.0	0+	$1s_{1/2}$	0.580	0.0	0^+	$1s_{1/2}$	0.512
	2.144	2^+	$0d_{5/2}$	0.470	2.050	2^+	$0d_{5/2}$	0.576
	3.639	2^+	$0d_{5/2}$	0.104	3.330	2^+	$0d_{5/2}$	0.112
	3.988	0^+	$1s_{1/2}$	0.319	3.423	0^+	$1s_{1/2}$	0.385
	4.915	3^+	$0d_{5/2}$	1.523	4.659	3^+	$0d_{5/2}$	1.670
	4.975	2^+	$0d_{5/2}$	0.922	4.754	2^+	$0d_{5/2}$	0.805

The neutron single-particle wave functions associated with each bound state of the core nucleus in Eqs. (2) and (3) are obtained by using the separation energy procedure with Woods-Saxon (WS) potentials, namely, the depths of the WS potentials are adjusted to reproduce the effective binding energies of the valence neutrons in the projectile nuclei, $S_N^{\rm eff}=S_n+E^*_{n\ell j}$, where S_n is the neutron binding energy in the ground state of the projectiles, and $E^*_{n\ell j}$ is the level energy of the core nuclei, given by the shell model calculations previously mentioned. The radius and diffuseness parameters of these WS potentials are fixed to be $r_0=1.25$ fm and $a_0=0.7$ fm, which are taken to be the same as in Ref. [14]. The results of these two sets of shell model calculations are listed in Table 1.

With the parameters described above, the inclusive one-neutron removal cross sections for the $^{15-19}$C isotopes with carbon and beryllium targets at various energies are calculated. The results are listed in Table 2 together with the corresponding experimental data (the experimental cross sections measured at 700 MeV/nucleon are corrected ones with the average correction factors shown in Table 1 of Ref.[45]). Generally, theoretical cross sections calculated with shell model spectroscopic factors overestimate the experimental ones. Quenching factors of the SFs [46], which are ratios of the experimental to the theoretical cross sections $R_s=\sigma^{\rm exp}/\sigma^{\rm th}$, are also shown in Table 2 with these two sets of shell model SFs. It should be noted that the QFs are averaged values with single-particle SFs associated with *all* bound states of the core nuclei. This is different from the QFs extracted in transfer reactions, which are ratios of the shell model SFs to the experimental ones extracted from selective single particle states. This may be the reason for the systematic discrepancies found in the quenching factors obtained from transfer and inclusive nucleon removal reactions. A study of QFs in transfer reactions taking into account all bound excited states of the residue nuclei is being made.

The results of Table 2 can be more clearly seen in Fig. 2, where the quenching factors of SFs at different incident energies are plotted for each of the carbon isotopes. The following conclusions can be drawn from these results. 1) The quenching factors of SFs do not show strong dependence on the incident energies of the carbon isotopes, except for ^{15}C. However, from a global point of view in Fig. 2, we see that there are rather big uncertainties in the experimental cross sections, especially for ^{17}C and ^{19}C. The same may exist for the (^{15}C,^{14}C) reactions. Therefore, more precise measurements for these nuclei are needed. 2) Results obtained using the two sets of shell model calculations coincide with each other except for the (^{17}C,^{16}C) reaction. It has been shown by Suzuki et al. that the WBP interaction used in shell model calculations in Ref. [14] does not reproduce the energy levels of ^{17}C sufficiently well [52]. The corresponding theoretical SFs used in this case may also be problematic. This may be the reason for the differences in R_s values obtained with WBP and YSOX as shown in Figs. 2 and 3. More detailed study of the structure of ^{17}C is needed to clarify this case [1)].

We define the average values of the quenching factors in Table 2 and their uncertainties for each nucleus as:

$$\overline{R_s}=\frac{\sum\left(\frac{R_s^i}{\Delta R_s^{i\,2}}\right)}{\sum\left(\frac{1}{\Delta R_s^{i\,2}}\right)},\ \text{and}\ \overline{\Delta R_s}^2=\frac{1}{\sum\left(\frac{1}{\Delta R_s^{i\,2}}\right)},$$

where the sums are over the incident energies and ΔR_s^i are the errors of the R_s values given in Table 2, which were obtained with the experimental errors. The results are shown in Fig. 3 as a function of the effective asymmetry of the neutron proton Fermi surfaces [13], which were taken to be the same as those in Ref. [14]. These averaged R_s values are consistent with the systematics over a wide range of projectiles, asymmetries and separation energies as shown in Ref. [13].

Table 2. Results of experimental ($\sigma_{\text{-1n}}^{\text{exp}}$) and theoretical inclusive one-neutron removal cross sections for carbon isotopes at different incident energies, and the corresponding quenching factors of the neutron spectroscopic factors. Results with shell model calculations of Simpson and Tostevin [14], and Yuan [42] are represented as $\sigma_{\text{-1n}}^{\text{th1}}$ and R_{s1}, and $\sigma_{\text{-1n}}^{\text{th2}}$ and R_{s2}, respectively.

^{A}Z	target	energy/ (MeV/nucleon)	$\sigma_{\text{-1n}}^{\text{exp}}$/mb	$\sigma_{\text{-1n}}^{\text{th1}}$/mb	R_{s1}	$\sigma_{\text{-1n}}^{\text{th2}}$/mb	R_{s2}
^{15}C	C	54	137±16[20]	250.10	0.55±0.06	245.86	0.56±0.07
	C	62	159±15[20]	246.20	0.65±0.06	242.01	0.66±0.06
	Be	103	140.2±4.6[47]	195.52	0.72±0.02	192.00	0.73±0.02
	Be	700	148±23[45]	146.67	1.01±0.16	143.85	1.03±0.16
^{16}C	C	55	65±6[20]	112.40	0.58±0.05	118.92	0.55±0.05
	Be	62	77±9[20]	100.24	0.77±0.09	105.84	0.73±0.09
	C	83	65^{+15}_{-10}[20]	111.84	$0.58^{+0.13}_{-0.09}$	118.18	$0.55^{+0.13}_{-0.08}$
	Be	700	63±19[45]	77.21	0.82±0.25	80.90	0.78±0.23
^{17}C	C	49	84±9[20]	157.78	0.53±0.06	132.31	0.63±0.07
	Be	62	115±14[20]	140.21	0.82±0.10	117.89	0.98±0.12
	C	79	116±18[14]	156.71	0.74±0.11	131.60	0.88±0.14
	Be	700	72±19[45]	108.22	0.67±0.18	91.36	0.79±0.21
	C	904	129±22[20]	118.22	1.09±0.19	99.60	1.30±0.22
^{18}C	C	43	115±18[20]	180.98	0.64±0.10	188.66	0.61±0.10
	C	80	155±24[14]	179.70	0.86±0.13	186.94	0.83±0.13
	Be	700	80±14[45]	128.31	0.63±0.11	132.48	0.61±0.11
^{19}C	Be	57	264±80[48]	239.83	1.10±0.33	241.08	1.10±0.33
	Be	64	226±65[14]	237.87	0.95±0.27	239.41	0.94±0.27
	Be	88	105±17[49]	231.61	0.45±0.07	233.65	0.45±0.07
	C	243	163±12[50]	184.19	0.88±0,07	186.92	0.87±0.06
	Be	700	122±32[45]	171.12	0.72±0.19	173.89	0.70±0.18
	C	910	233±51[51]	192.15	1.21±0.27	194.48	1.20±0.26

1) C. X. Yuan, private communication.

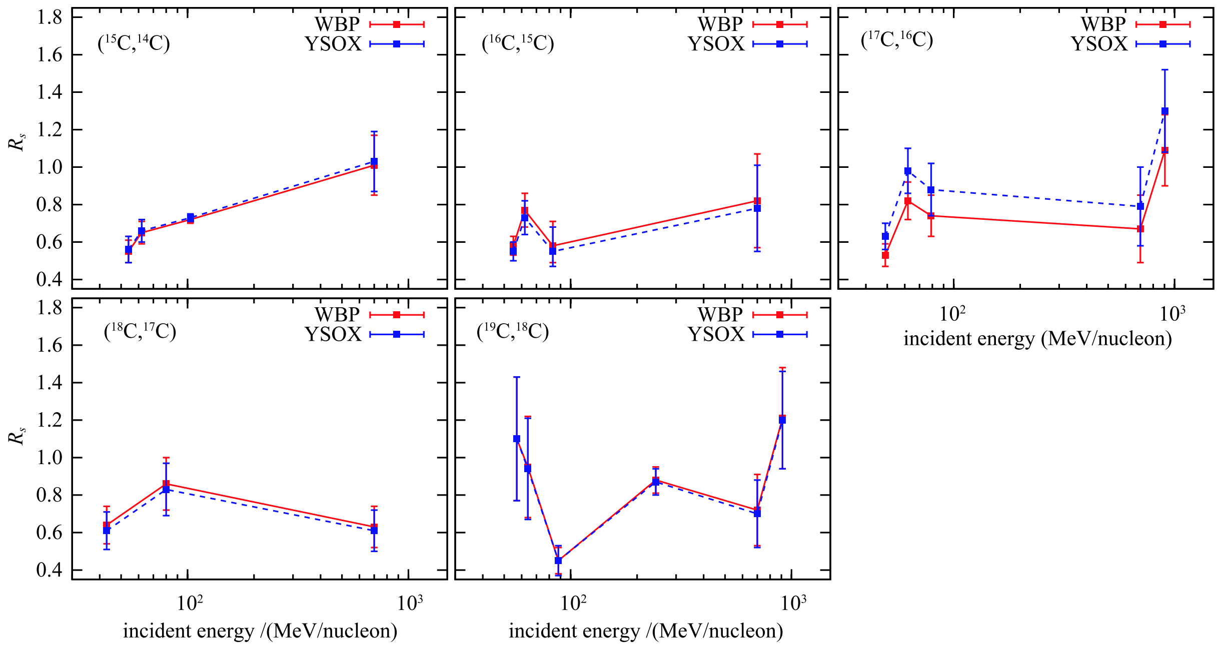

Fig. 2. (color online) Comparisons of quenching factors of the single neutron spectroscopic factors R_s of the radioactive carbon isotopes extracted from experimental data at various incident energies with shell model spectroscopic factors of Simpson and Tostevin [14] and Yuan [42]. The lines are to guide the eye.

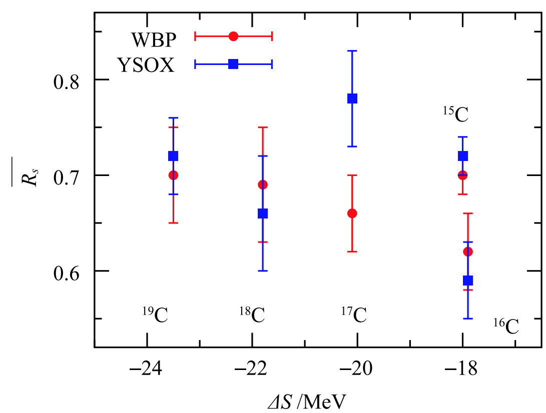

Fig. 3. (color online) Averaged value of quenching factors of single neutron spectroscopic factors $\bar{R}_s$ for radioactive carbon isotopes as a function of the effective asymmetry of the neutron proton Fermi surfaces $\Delta S = S_{1n} - S_{1p} + \bar{E}_f$, where S_{1n} and S_{1p} are the binding energies of single neutrons and protons in the ground states of the projectiles and $\bar{E}_f$ are averaged excitation energies of the core nuclei weighted with the corresponding one-neutron removal cross sections.

3 Summary and conclusions

In summary, inclusive one-neutron removal cross sections of the carbon isotopes $^{15-19}$C with carbon and beryllium targets have been analyzed with the eikonal model within an energy range from around 50 to 900 MeV/nucleon. Quenching factors of the one-neutron SFs are extracted with experimental data based on two sets of shell model calculations. No strong energy dependence was found in the QFs of these nuclei within the energy range studied in this work except for ^{15}C. However, given the large uncertainties of the existing experimental data, more measurements for the (^{15}C,^{14}C) reaction are needed to verify this energy dependence. The average values of these QFs are consistent with the systematics shown in Ref. [13]. Strong deviations of the QFs at different energies are found to exist in these nuclei especially for ^{17}C and ^{19}C, for which new measurements of the one-neutron removal cross sections are strongly suggested. The QFs extracted with two sets of shell model calculations agree well with each other except for ^{17}C, which may be related to the complex structure of ^{17}C and requires more theoretical work to understand this nucleus.

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