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Systematics of ground state α-cluster spectroscopic strengths for odd-A sd-shell nuclei

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The systematics of the ground-state α-cluster spectroscopic strengths for odd-A nuclei from ^{21}Ne to ^{39}K deduced by finite-range distorted-wave Born-approximation calculations from the measurements of the (^{6}Li,d) reaction are presented. This analysis shows the new result that the α spectroscopic strength increases abruptly in the middle of the sd shell with a maximum for ^{29}Si and ^{31}P and a fall towards the end of the shell.

[NUCLEAR REACTIONS (^{6}Li,d) on odd-A $2s$-$1d$ shell targets, finite range DWBA analysis; deduced systematics of ground state α spectroscopic strengths.]

The study of α-cluster spectroscopic strengths of bound states in nuclei is less extensive than that of single-particle widths. However, the even-even nuclei in the sd and fp shell have received considerable attention and the experimental systematics of the ground state α-particle spectroscopic strengths for these nuclei measured in the (^{6}Li, d) reaction have been reported.[1] These systematics have not yet been theoretically understood on the basis of model calculations, particularly in the upper half of the sd shell. In the present work we report the experimental systematics of the ground state α-cluster spectroscopic strengths for odd-A sd-shell nuclei in the mass range $A = 21$ to 39. The new result, which is brought out by this investigation, is the abrupt rise of the strength at A_f (final nucleus mass number) $= 29$ where the value is largest for ^{29}Si and ^{31}P, and decreases towards the end of the sd shell.

The results were obtained from the measurements of absolute cross sections and angular distributions of the (^{6}Li, d) reactions using the University of Rochester MP tandem accelerator. Of the nine (^{6}Li, d) reactions used in the analysis for the present systematics, the reactions on the targets ^{27}Al, ^{29}Si, and ^{31}P with a 36 MeV ^{6}Li beam have been completed recently by us. The measurements on ^{35}Cl performed earlier[2] have now been analyzed and included in the present analysis. Though the measurements on the targets ^{17}O and ^{25}Mg have been reported previously[3,4] these have been concerned with the strengths of the excited states and not the ground states. Preliminary results of the measurements on the target ^{19}F and ^{23}Na have been reported[5,6] and the reaction ^{21}Ne(^{6}Li, d)^{25}Mg is reported in Ref. 7. In the present work the transitions from ground state to ground state in all nine (^{6}Li, d) reactions are analyzed in a consistent way with a view to obtain the systematics of the variation of the spectroscopic strength as a function of mass number.

The deuteron angular distributions to the ground states in all cases were calculated by the exact finite-range distorted-wave–Born-approximation calculations by the use of the code LOLA[8] with the assumption of cluster-transfer mechanism. The α-particle spectroscopic strengths S were obtained from the equation

$$\frac{d\sigma}{d\Omega}_{\text{expt}} = S\left(\frac{2J_f+1}{2J_i+1}\right)\frac{d\sigma}{d\Omega}_{\text{LOLA}},$$

where J_f and J_i represent spins of final and initial nuclei in the reaction. In studying the systematics over a wide range of nuclei, it is necessary for the consistency of the analysis to choose appropriately the optical-model potentials and bound-state parameters. For all the cases a single set of ^{6}Li and deuteron optical-model parameters proved sufficient to give good fits for the angular distribution by the use of the code LOLA. The ^{6}Li potential used was the one employed by Strohbusch *et al.*[9] and depends on A only through the $A^{1/3}$ dependence of the radii for the real and imaginary potentials. The deuteron potential[10] used had a mild Z and A dependence. The bound-state well had a radius of $1.3\,A_t^{1/3}$ fm and a diffuseness of 0.65 fm in all cases. The well depth was adjusted to reproduce the known binding energy of the α particle in the final nuclear state. The number of radial nodes was fixed by the oscillator conservation relation

$$2(N-1)+L=\sum_{i=1}^{4}[2(n_i-1)+l_i],$$

where n_i and l_i are the individual nucleon shell-model orbitals. For the transfer for four nucleons in the $2s$-$1d$ shell the above equation yields $2(N-1)+L=8$. For the ^{6}Li$=\alpha+d$ system the intercluster

TABLE I. Ground state α-cluster spectroscopic strengths in odd-A $2s$-$1d$ shell nuclei ($T_z = +\frac{1}{2}$), deduced from (^{6}Li, d) reactions (L transfer = 2).

Target nuclide	J_i^π	Final nuclide	J_f^π	Possible L transfer	$\frac{d\sigma}{d\Omega}_{\mathrm{LOLA}}$ (μb/sr) ($L = 2$) at 11.5°	$\frac{d\sigma}{d\Omega}_{\mathrm{expt}}$ (μb/sr) ($L = 2$) at 11.5°	$S(^6\mathrm{Li}, d)$ for $L = 2$
^{17}O	$\frac{5}{2}^+$	^{21}Ne	$\frac{3}{2}^+$	2,4	37.0	42.6	0.34 ± 0.11
^{19}F	$\frac{1}{2}^+$	^{23}Na	$\frac{3}{2}^+$	2	18.6	4.0	0.02 ± 0.01
^{21}Ne	$\frac{3}{2}^+$	^{25}Mg	$\frac{5}{2}^+$	2,4	16.3	12.4	0.10 ± 0.03
^{23}Na	$\frac{3}{2}^+$	^{27}Al	$\frac{5}{2}^+$	2,4	10.8	2.5	0.03 ± 0.01
^{25}Mg	$\frac{5}{2}^+$	^{29}Si	$\frac{1}{2}^+$	2	8.0	8.8	0.66 ± 0.13
^{27}Al	$\frac{5}{2}^+$	^{31}P	$\frac{1}{2}^+$	2	6.6	7.2	0.65 ± 0.13
^{29}Si	$\frac{1}{2}^+$	^{33}S	$\frac{3}{2}^+$	2	5.4	16.1	0.30 ± 0.06
^{31}P	$\frac{1}{2}^+$	^{35}Cl	$\frac{3}{2}^+$	2	4.2	12.0	0.29 ± 0.06
^{35}Cl	$\frac{3}{2}^+$	^{39}K	$\frac{3}{2}^+$	2,0	2.7	2.5	0.18 ± 0.09

wave function given in Ref. 11 was used with the α-d system in a relative 2S state.

The α-cluster spectroscopic strengths extracted by the above analysis for $L = 2$ transfer between the ground states in the nine cases studied (which are all $T_z = +\frac{1}{2}$ nuclei) are given in Table I. The values of the L transfer allowed by the angular momentum selection rule are shown in the fifth column of the table. In five cases only one L value (= 2) is allowed because the spin of either the target or the final nucleus is $\frac{1}{2}^+$. In the case of ^{21}Ne → ^{25}Mg the experimental angular distribution shows[7] only $L = 2$ contribution. In the transitions[3,6] ^{17}O → ^{21}Ne and ^{23}Na → ^{27}Al, the predominant contribution is from $L = 2$ and a least-squares fit procedure, using $L = 2$ and $L = 4$ pure shapes, is employed[3,6] to analyze the angular distribution data to obtain the contributions of $L = 2$ and 4, respectively.

Only in the case of ^{35}Cl → ^{39}K transition are $L = 0$ and 2 allowed. We obtain the $L = 2$ contribution from the experimental angular distribution data by a least-squares fitting procedure with pure $L = 0$ and 2 theoretical shapes. Since in this case the $L = 2$ contribution is small the error in obtaining the strength by this procedure increases the overall error. The sixth column shows the theoretically computed values of $(d\sigma/d\Omega)_{\mathrm{LOLA}}$ for $L = 2$ at 11.5° c.m., the angle at which the first maximum occurs in the angular distribution in all the cases. The aim in listing these values is to show that the calculated value of the cross sections $(d\sigma/d\Omega_{\mathrm{LOLA}}$ [which does not include the factor $(2J_f+1)/(2J_i+1)$] decreases smoothly as the mass number increases without any violent variations. The seventh column shows the values of $(d\sigma/d\Omega)$ obtained from experimental cross sections for $L = 2$, at 11.5° c.m. The last column gives the α spectroscopic strengths $S(^6\mathrm{Li}, d)$ derived from the present analysis normalized to unity for the case of $^{16}\mathrm{O}(^6\mathrm{Li}, d)^{20}\mathrm{Ne}_{\mathrm{g.s.}}$. The errors are estimated from the 20 to 30% error in absolute cross-section measurements in various reactions and the error arising in the determination of the $L = 2$ contribution where a mixture of L values is present. The value of the strength given here for ^{21}Ne → ^{25}Mg, which is one of the cases of relatively low strength, is as derived in the present systematic analysis and is higher than the value quoted in

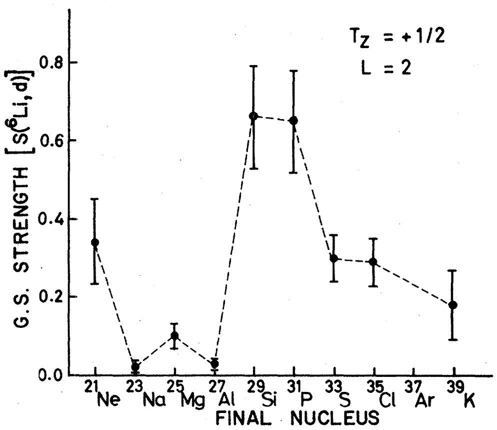

FIG. 1. Ground state α-cluster spectroscopic strengths for odd-A ($T_Z = +\frac{1}{2}$) sd shell nuclei deduced from (^{6}Li, d) reactions (L transfer = 2).

Ref. 7.

The α spectroscopic strengths are plotted in Fig. 1. The strengths are low and decreasing in the mass region $A_f = 21$ to 27 and rise sharply at $A_f = 29$ to a maximum and decrease again in the region $A_f = 33$ to 39. This variation with a maximum in the middle of the sd shell is a new result brought out by the present study of the systematics.

α spectroscopic strengths have been calculated by Draayer[12] for nuclei in the lower half of the sd shell where the SU(3) model provides a good description of the initial and final nuclear states. These predictions[12] for transitions to the ground states ($L = 2$) of ^{21}Ne, ^{23}Na, ^{25}Mg, and ^{27}Al are 0.74, 0.02, 0.03, and 0.14 which are to be compared with the experimental values 0.34, 0.02, 0.10, and 0.03, respectively. In the case of transitions to ^{29}Si simple SU(3) interpretations were not found to be applicable.[4] In the upper half of the sd shell for transitions to nuclei $A \geqslant 29$ there are no theoretical calculations at present to explain the increase observed for $A = 29$, 31 and the subsequent decrease in the region $A = 33$ to 39.

It is illustrated by Kurath and Towner[13] that many of the properties exhibited by α transfer are related to the properties of two-nucleon transfer and that in two-nucleon transfer orbitals with low l are much more important than those with high l. Based on these facts it may be probable that the increase of the ground state α-cluster strength observed in the experimental systematics in the middle of the sd shell for the nuclei $A = 29$, 31 is due to the effect of $s_{1/2}$ orbitals in comparison to $d_{5/2}$ and $d_{3/2}$ orbitals. The ground-state occupancies as calculated[14] from the single-nucleon transfer data for the $2s$-$1d$ shell nuclei, show increased $s_{1/2}$ occupancies in the middle of the $2s$-$1d$ shell for the nuclei $A = 29$, 31.

However, the complete theoretical understanding of the variation of α-cluster strength with mass number in $2s$-$1d$ shell should await detailed model calculations.

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