Experimental study of ^{26}Al through the 1n pick-up reaction ^{27}Al(d, t)

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The ^{27}Al(d,t) reaction has been studied to extract spectroscopic information for the odd-odd nucleus ^{26}Al. The excited states of ^{26}Al up to 5.50 MeV have been analyzed using the local, zero range distorted wave Born approximation. A new set of optical model potential parameters was extracted from the measured elastic scattering angular distribution. The spectroscopic factors calculated for these states are found to be in good agreement with previously reported values for the same; they are also in agreement with those obtained from shell model predictions.

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I. INTRODUCTION

Transfer reactions are powerful tools to study the structure of nuclei. Determination of excitation energy, spin, parity, branching ratio, spectroscopic factor, and lifetime of various states is the main focus to reveal the structure of all product nuclei in general, and some nuclei of special interest in particular. There are evidences that short-lived nuclei were present in the early solar system [1] and ^{26}Al is the first cosmic radioactivity detected through its characteristic γ rays in the interstellar medium. Since its lifetime ($\sim 10^6$ y) is much shorter as compared to the time for galactic evolution ($\sim 10^{10}$ y), the detection of ^{26}Al at the present time indicates that nucleosynthesis is currently active in our galaxy and it is known that massive stars are the main sources for the origin of ^{26}Al [2,3]. It is, therefore, necessary to understand the formation and destruction of ^{26}Al in our galaxy in order to understand its evolution. So, from astrophysics as well as basic nuclear physics points of view, the nucleus ^{26}Al has evoked lot of interest—as the decay of ^{26}Al may be used as an isotopic chronometer for galaxies [4]; moreover it is also used to probe the standard model [5,6].

In previous years many of the states of ^{26}Al have been studied using different reaction channels, like ^{28}Si(p,^{3}He) [7], ^{28}Si(d,α) and ^{24}Mg(^{3}He,p) [8], ^{27}Al(p,d) [9,10], ^{27}Al(^{3}He, α) [11,12]. In addition, an attempt has been made in the past to study the ^{27}Al(d,t) reaction up to 2.08 MeV excitation energy using off-line measurements of captured tritium activity in stacked ^{27}Al foils [13]; however, no direct measurement of the ^{27}Al(d,t) reaction has so far been available, to the best of our knowledge, in the literature. The spins, parities, and branching ratios for different excited states of ^{26}Al have been compiled by Endt [14] and studied by Endt *et al*. [15,16]. Attempts have also been made to understand the structures of the excited states of ^{26}Al theoretically in terms of the shell model; comparison of spectroscopic factors up to 4.699 MeV have been made with a $0d_{5/2}$-$1s_{1/2}$ shell model scheme [9]. Furthermore, from the calculation of spectroscopic factors for several excited states of ^{26}Al, it was shown that C^2S values for the low-lying states are in good agreement with shell-model predictions [11]. Relative spectroscopic factors for several excited states of ^{26}Al have also been extracted and compared [10,12].

Since the spectroscopic factor is a fundamental property of the structure of any particular nucleus, it should not vary with bombarding energy or with the reactions chosen; but it is well known that the extracted values of the spectroscopic factors do not come out to be the same for all reaction channels, which could be due to the choice of the potential parameters [17–20]. So, the investigation of the spectroscopic factors of different excited states of ^{26}Al using different reaction channels is the primary motive of the present study; it would be interesting to know how the spectroscopic factors for different excited states of ^{26}Al vary for different reaction channels. In the present paper, the structure of ^{26}Al has been investigated using the single nucleon transfer reaction ^{27}Al(d,t) at 25 MeV bombarding energy. The spectroscopic factors for 14 excited states of ^{26}Al have been extracted using zero-range distorted wave Born approximation (DWBA) calculations and compared with earlier reported values obtained using other single neutron pick up reactions. Relative spectroscopic factors (calculated using the value of the ground state spectroscopic factor to be one) extracted from the present data have also been compared with those reported earlier for other pick-up reactions. Shell-model results have been taken from [9] and [11] to compare with the present results.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Variable Energy Cyclotron Centre, Kolkata, using a 25 MeV deuteron beam from the K130 Cyclotron on a self-supported ^{27}Al (thickness ~ 90 μg/cm^2) target. The angular distributions of various transfer channels were measured using a three-element telescope, consisting of a single-sided 55 μm thick Si(ΔE) strip detector (16 vertical strips of 3 mm width) and a double-sided 1030 μm thick Si(E) strip detector (16 strips, width 3 mm, both sides mutually orthogonal to each other). These were backed

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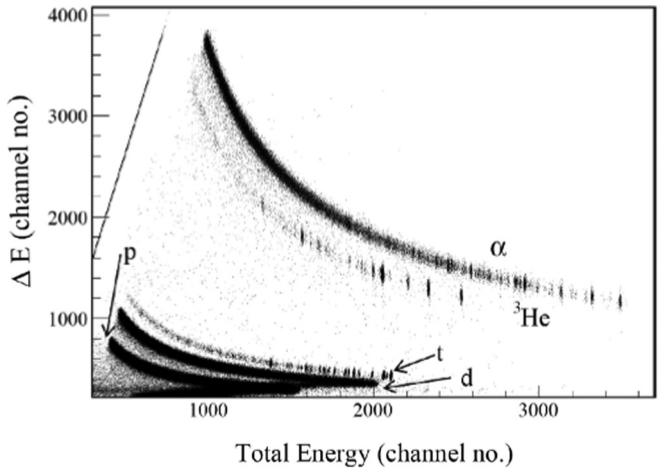

FIG. 1. Typical two dimensional Si(E)-Si(ΔE) spectrum of light charged particles obtained at $\theta_{\rm lab} = 37^\circ$ for d(25 MeV) + ^{27}Al reaction.

by four CsI(Tl) detectors, each of thickness 6 cm. A horizontal slit of width 6 mm was placed in front of the telescope. The solid angle subtended by each strip was 0.47 msr.

The inclusive angular distributions of the ejectiles were measured in the angular range of 16° to 40° in steps of 0.9°. Different ridges seen in Fig. 1 correspond to different outgoing particles produced in the reactions ^{27}Al(d,t), ^{27}Al(d, ^{3}He), and ^{27}Al(d, α). A typical excitation energy spectrum of ^{26}Al, obtained from the tritium ridge, which was populated via the reaction channel ^{27}Al(d,t), is shown in Fig. 2. Well-separated peaks corresponding to different populated states of ^{26}Al are clearly visible in the excitation energy spectrum. Calibration of detectors was done with seven states of ^{26}Al (0, 228, 417, 1058, 2070, 2365, and 2545 keV) from the ^{3}H spectrum. The error in cross section data was taken to be the total error including systematic as well as statistical errors. The systematic error included the uncertainties in the target thickness measurement, the Faraday cup reading and the solid angle measurement. In measuring excitation energies, energy loss corrections due to the target thickness and the dead layers in Si detectors were taken into consideration. Some of the data were presented at the FUSION14 conference [21].

III. EXTRACTION OF OPTICAL MODEL POTENTIAL PARAMETERS

The elastic scattering cross sections of 25 MeV deuteron were measured in the angular range of 16° to 40° in steps of 0.9° using the combination of Si strip and CsI(Tl) detectors of the detector telescope described earlier. The elastic angular distribution data were fitted using the optical model search code ECIS94 [22]. The parametric Woods-Saxon (WS) form was used for both real and imaginary potentials in the optical model analysis. We extracted three sets of optical model potential parameters for the entrance channel which were consistent in the description of the measured elastic angular distribution. The parameter set A (given in Table I) was obtained from the search initiated with volume real, surface imaginary, and spin-orbit potential parameters taken from [23]. For other sets (sets B and C), we used the optical model potential parameters given in [24] as the initial parameters for the searches. All the parameters were varied to arrive at the minimum χ^2 per degree of freedom, χ^2/N_f. The best fit potential parameters corresponding to minimum χ^2/N_f are listed in Table I. Initially, we fitted the data for elastic scattering of 23 MeV deuterons from an ^{27}Al target [25]. The best fit potential parameters for the 23 MeV (set C in Table I) elastic scattering data were subsequently used as the starting parameter set for fitting 25 MeV elastic scattering data of the

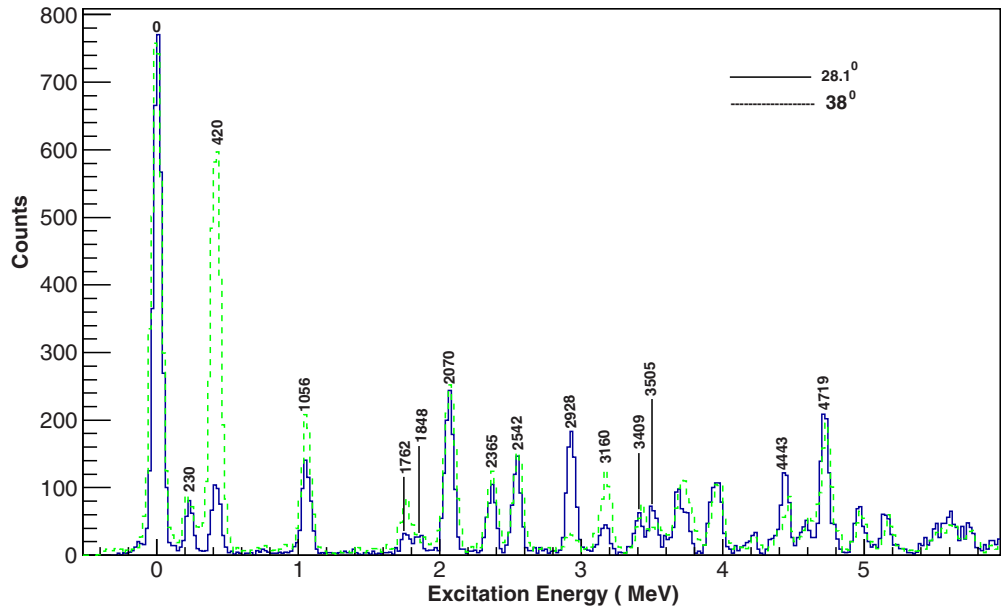

FIG. 2. (Color online) Typical excitation energy spectrum of ^{26}Al obtained in the reaction d(25 MeV) + ^{27}Al at $\theta_{\rm lab} \approx 28^\circ$ (solid line) and at $\theta_{\rm lab} \approx 38^\circ$ (dashed line).

TABLE I. The best fit potential parameters used in DWUCK4 code for the ^{27}Al(d,t) reaction.

Reactions	Set	V MeV	R_o fm	a_0 fm	W_v MeV	W_s MeV	R_I fm	a_I fm	V_{ls} MeV	R_{ls} fm	a_{ls} fm	R_c fm
$d + ^{27}$Al	A	89.209	1.061	0.701		2.250	1.360	0.850	9.00	1.061	0.801	1.25
	B	90.301	1.055	0.675		2.407	1.400	0.850	9.00	1.055	0.780	1.25
	C	88.095	1.055	0.780		3.524	1.300	0.650	9.00	1.055	0.780	1.25
$t + ^{26}$Al	[a]A1	161.91	1.200	0.720	39.99		1.40	0.840	2.50	1.20	0.720	1.30
	[b]B1	172.0	1.140	0.710	17.52		1.670	0.780				1.30
[c]$n + ^{26}$Al			1.200	0.650								1.30

[a]Parameters extracted from the relation given in Perey and Perey [26].
[b]Parameters taken from ^{28}Si(d,t) [27].
[c]Well depth adjusted to get the required separation energy for the transferred particle.

present experiment. The final parameter values are given as set B in Table I. The optical model fits to the elastic scattering data are displayed in Fig. 3 for both sets (A and B) of potential parameters. Between the two sets, the values of χ^2 are almost same, but the total reaction cross sections differ by ∼10%. We used two sets of optical model parameters for the $t + ^{26}$Al exit channel. The first set (A1 in Table I) for tritium was obtained from the relation given in Perey and Perey [26] and the second set (B1 in Table I) was taken from [27] for the ^{28}Si(d,t) reaction.

IV. DWBA ANALYSIS

The zero-range distorted wave Born approximation calculations were performed for the observed excited states up to 5.50 MeV in ^{26}Al produced through the ^{27}Al(d,t) reaction using the computer code DWUCK4 [28]. The value of the transferred angular momentum was calculated with the relation as prescribed in [29]. The measured as well as fitted angular distributions for the ground and different excited states are shown in Figs. 4 to 10. To extract spectroscopic factors using zero range DWBA, we used the following relation between experimental and theoretical cross sections as used in [30]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = \frac{3.33C^2S}{2J+1}\left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA}, \qquad (1)$$

where $(\frac{d\sigma}{d\Omega})_{\rm exp}$ is the experimental differential cross section and $(\frac{d\sigma}{d\Omega})_{\rm DWBA}$ is the cross section predicted by the DWUCK4 code, J $(J = l \pm \frac{1}{2})$ is the total angular momentum of the orbital from where the neutron is picked up, C^2 is the isospin Clebsch-Gordon coefficient, and S is the spectroscopic factor.

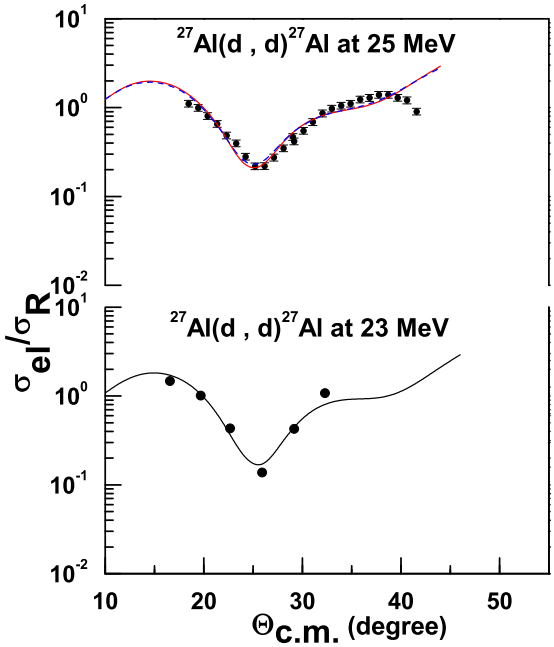

FIG. 3. (Color online) Angular distributions of elastically scattered deuteron from ^{27}Al at $E_{\rm lab}$ = 25 MeV and 23 MeV. The filled circles represent experimental data, solid and dash-dash lines represent optical model fits for sets A and B, respectively.

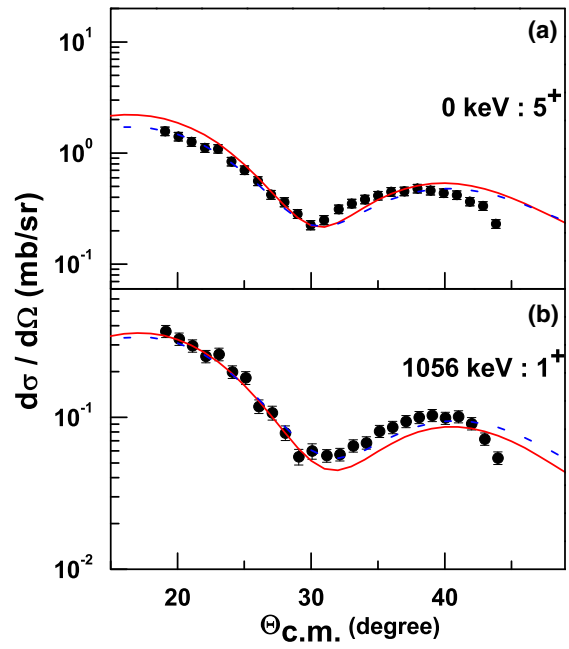

FIG. 4. (Color online) Angular distributions for the ground and 1056 keV states. Filled circles are the present experimental data. Solid and dashed-dashed lines are theoretical predictions from DWUCK4 code for pick up from $0d_{5/2}$ including finite range and non local corrections with sets A-A1 and A-B1, respectively.

TABLE II. Extracted values of spectroscopic factors for different states of ^{26}Al for the reaction ^{27}Al(d,t).

[a]Ex (keV)	J^π	l	[b]Ex (keV)	C^2S
0	5^+	2	0 ± 4	0.73 ± 0.21
228.3	0^+	2	230 ± 4	0.09 ± 0.03
416.8	3^+	2	420 ± 4	0.32 ± 0.07
		0	420 ± 4	0.07 ± 0.03
1057.7	1^+	2	1056 ± 4	0.17 ± 0.05
1759.0	2^+	2	1762 ± 6	0.038 ± 0.006
1850.6	1^+	2	1848 ± 8	0.019 ± 0.004
2068.8	2^+	2	2070 ± 4	0.26 ± 0.06
2365.1	3^+	2	2365 ± 4	0.13 ± 0.02
2545.3	3^+	2	2542 ± 4	0.16 ± 0.03
3159.8	2^+	2	3160 ± 5	0.06 ± 0.01
3402.6	5^+	2	3409 ± 8	0.06 ± 0.01
3507.6	6^+	4	3505 ± 5	0.06 ± 0.03
4430.7	2^-	1	4443 ± 6	0.23 ± 0.04
4705.3	4^+	2	4719 ± 4	0.27 ± 0.08

[a]Values taken from the NNDC [31].
[b]Present work. The uncertainty in excitation energy includes energy loss uncertainty in target thickness, detector dead layer correction and fitting error in excitation energy.

TABLE III. Comparison of $C^2S/C^2S_{\text{g.s.}}$ obtained from different reactions for different excited states of ^{26}Al.

[a,b]Ex (keV)	l	(d,t)[a]	(p,d)[9]	(p,d)[10]	$(^3\text{He},\alpha)$[11]	(d,t)[12,c]
0	2	1	1	1	1	1
230	2	0.12	0.15	0.14	0.14	0.15
420	2	0.44		0.05		
	0	0.09	0.18	0.15	0.12	0.12
1056	2	0.24	0.24	0.31	0.31	0.29
1762	2	0.05	0.07	0.02	0.02	
1848	2	0.03	0.05	0.016	0.02	
2070	2	0.35		0.52	0.50	
2365	2	0.18	0.28	0.23	0.26	
2542	2	0.22	0.28	0.30	0.30	
3160	2	0.08	0.12	0.10	0.10	
3409	2	0.09	0.19	0.09	0.08	
3505	4	0.08		0.04		
4443	1	0.32		0.02	0.02	
4719	2	0.37	1.00	0.71	0.86	

[a]Present work.
[b]The values of Ex for the present work are within ± 10 keV of the values reported earlier [9–12]. The state at 4443 keV is 4437 and 4430 keV in [11] and [10], respectively. The state at 4719 keV is reported as 4711 and 4705 keV in [11] and [10], respectively.
[c]Values of $C^2S/C^2S_{\text{g.s.}}$ for (d,t) reaction were taken from [13].

In general, the calculated angular distributions were found to reproduce the experimental data fairly well for states with excitation energies from 0.0 to 3.41 MeV except the state at 0.417 MeV. The deviations are comparatively low for lower excited states and gradually increase for higher excited states. A comparison of the $(^3\text{He}, \alpha)$ and (d,t) reaction on ^{27}Al, populating excited states of ^{26}Al up to 2.08 MeV, is available in [12].

The angular distributions for different excited states of ^{26}Al were analyzed with all the potential sets given in Table I. We used six combinations of the potential parameters, e.g., A-A1, B-A1, C-A1, A-B1, B-B1, and C-B1 to extract the spectroscopic factors and these six sets were also used to estimate the uncertainties in spectroscopic factors. The variations in the extracted spectroscopic factors among the potential combinations A-A1, B-A1, and C-A1, and those among the combinations A-B1, B-B1, and C-B1, were found to be less than 10%. To extract the spectroscopic factor of each state, two sets of average spectroscopic factors were computed; one set was obtained from the average of the spectroscopic factors for each state calculated with three combinations (A-A1, B-A1, and C-A1) of potential parameters and the other set obtained in the same way from the other three combinations (A-B1, B-B1, and C-B1) of potential parameters. Finally, the spectroscopic factor of each state was taken to be the mean of the corresponding average spectroscopic factors of the two sets. The extracted values of the spectroscopic factors for different excited states are given in Table II. The deviation between the mean spectroscopic factor and the individual spectroscopic factor for different excited states was found to be less than 20%. The deviations calculated from the two sets of average spectroscopic factors and the average errors in experimental data points were used to estimate the uncertainties in C^2S for different excited states of ^{26}Al.

A comparison of these spectroscopic factors with the previously reported values for the same obtained from other reactions is made in Table III. Keeping in mind the uncertainty in the absolute normalization between different reaction probes, the spectroscopic factors for different excited states of ^{26}Al relative to that of its ground state, $C^2S/C^2S_{\text{g.s.}}$ were used for comparison (see Table III).

We also attempted to extract C^2S using the finite range correction value of 0.845 and nonlocal parameters 0.54, 0.25, and 0.85 for deuteron, tritium and neutron, respectively. The fitted angular distributions for two states of ^{26}Al using these parameters are shown in Fig. 4; corresponding C^2S values were found to be reduced by 20–50% for the combination A-A1, and by 25–45% for the combination A-B1. Because of the large variation observed in C^2S values between the zero range and finite range calculations, we extracted spectroscopic factors for all excited states using zero range approximation only throughout the present paper.

A. Spectroscopic factors for the ground, 230, 1056, 1762, and 1848 keV states

The angular distributions were analyzed for both sets of exit channel parameters in combination with set A. The spectroscopic factors for the ground, 230, 1056, 1762, and 1848 keV states were calculated with pick up from the $0d_{5/2}$ shell. The angular distributions for these states along with the respective theoretical predictions are shown in Fig. 5. The ground state spectroscopic factor was found to be less compared to that reported using other reactions [9,11]; however, it is in good agreement with the theoretically predicted value for the same (1.0 and 0.61, using two different model

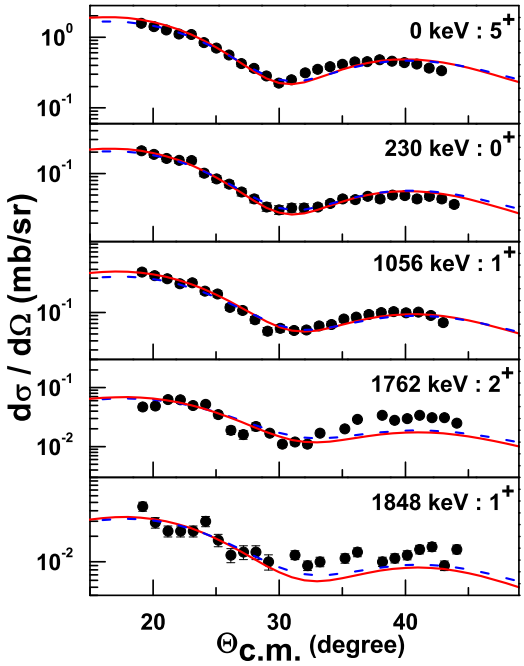

FIG. 5. (Color online) Comparison of experimental and theoretical angular distributions for the ground, 230, 1056, 1762, and 1848 keV states. Filled circles are the present experimental data. Solid and dashed-dashed lines are theoretical predictions from DWUCK4 code for pickup from $0d_{5/2}$ with set A-A1 and set A-B1, respectively.

configurations) [9]. For the 230 and 1056 keV states, the spectroscopic factors are found to be in good agreement with the values reported earlier [9,11]. In addition, the C^2S value obtained for the 1056 keV state is in very good agreement with the corresponding theoretical prediction (0.22) (see [9]). Spectroscopic factors for the states at 1762 keV and 1848 keV are also in good agreement with the previously extracted values as well as with the theoretically predicted values [9].

B. Spectroscopic factor for the 420 keV : 3^+ state

The angular distribution for the 420 keV state is shown in Fig. 6. For this state, the measured angular distribution is not in good agreement with the corresponding theoretical predictions. The spectroscopic factor for the 420 keV state was calculated for pickup from both $0d_{5/2}$ and $1s_{1/2}$ single particle orbits. The extracted spectroscopic factor for pickup from $1s_{1/2}$ orbital is found to be in good agreement with the values reported earlier (see Table III).

C. Spectroscopic factors for the 2070, 2365, 2542, 3160, and 3409 keV states

The 2070, 2365, 2542, 3160, and 3409 keV states were analyzed assuming pickup from the $0d_{5/2}$ single particle orbit; corresponding comparisons between the measured and fitted angular distributions are shown in Fig. 7. Around the excitation energy of 2070 keV, there are three states at 2068, 2069, and 2071 keV. These states could not be resolved in the present experiment. The analysis was performed assuming a single state at the average excitation energy of 2070 keV. A

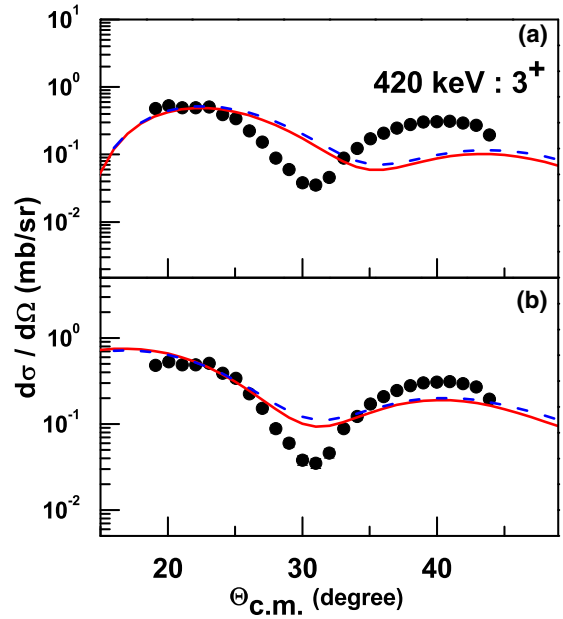

FIG. 6. (Color online) Same as Fig. 5 for the 420 keV state. The upper plot (a), represents calculation for pick up from $1s_{1/2}$ and lower plot (b), represents calculation for pick up from $0d_{5/2}$.

spectroscopic factor was subsequently extracted for this state with $l = 2$. The model calculation reproduced the present angular distribution quite well. The 2365 and 2542 keV states were analyzed using pickup from $0d_{5/2}$ single particle orbital only unlike the case of the 420 keV (3^+) state, where analyses were done for both $l = 2$ and $l = 0$ transfers. This is primarily due to the fact that the angular distributions for 2365 and

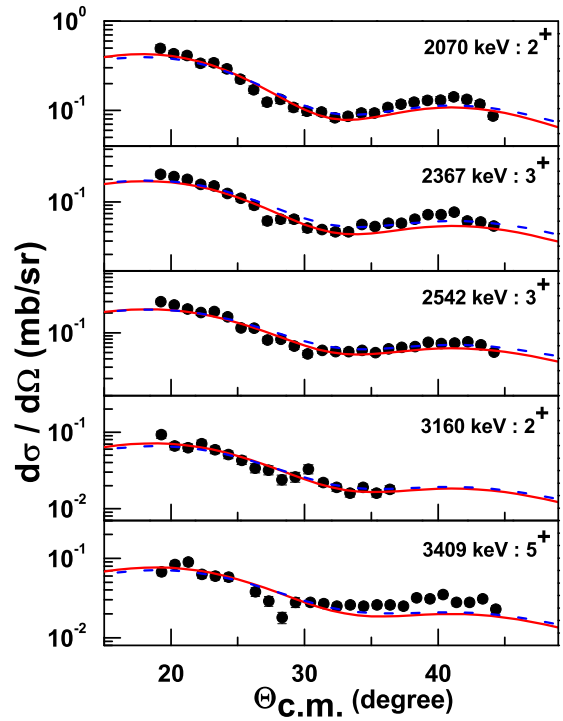

FIG. 7. (Color online) Same as Fig. 5 for the 2070, 2367, 2542, 3160, and 3409 keV states for pick up from $0d_{5/2}$.

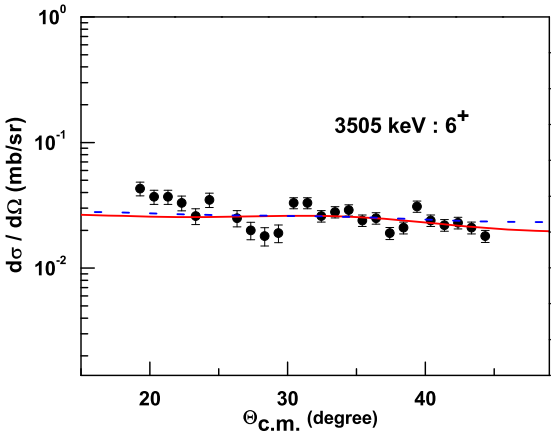

FIG. 8. (Color online) Same as Fig. 5 for the 3505 keV state for pick up from $0g_{9/2}$.

2542 keV states are found to be well reproduced by $l = 2$ transfers. The spectroscopic factors for 2365 keV and 2542 keV states were also found to be less in the present (d,t) reaction study compared to those obtained using other pick-up reaction probes; however, when the relative spectroscopic factors were considered, they were found to be in good agreement [10]. This points to the uncertainty in the normalization of different reaction data. The spectroscopic factor value for the 2542 keV state from this experiment (Table II) is large compared to its theoretically predicted value (0.03) [9]. The present value of the spectroscopic factor for 3160 keV state is comparable with its previously calculated value. The comparison of the DWBA predicted angular distribution with the data for 3409 keV state in ^{26}Al has resulted in a much smaller experimental spectroscopic factor value than that reported in Ref. [9]. However, it is in agreement with the experimentally extracted spectroscopic factor given in [11] as well as with the corresponding theoretical prediction given in [9].

D. Spectroscopic factor for the 3505 keV : 6^+ state

The angular distribution of the 6^+ state does not conform to either $l = 2$ or $l = 0$ one-step pick up from the s-d shell. One-step transfer requires a pick up from a $0g_{9/2}$ orbital corresponding to $l = 4$. This indicates a possible two-step mechanism for excitation of 6^+ state at 3505 keV (see [9]). In this paper, this state was analyzed assuming pickup from a $0g_{9/2}$ single particle orbital and the corresponding DWBA angular distribution is shown in Fig. 8. The spectroscopic factor for the state at 3505 keV was not reported in [9] and [11]; however, the relative spectroscopic factor given in [10] is in good agreement with the present result assuming pickup from the $0g_{9/2}$ orbital.

E. Spectroscopic factor for the 4443 keV : 2^- state

In the case of the 4443 keV state, there may be mixing of two states; so we determined the centroid position and extracted the C^2S value. For this state (4443 keV : 2^-) the nature of the measured angular distribution was found to match with the corresponding DWBA prediction for pick up from $0p_{1/2}$ state

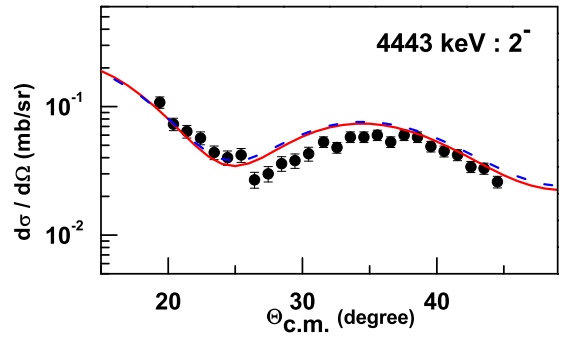

FIG. 9. (Color online) Same as Fig. 5 for the 4443 keV state for pick-up from $0p_{1/2}$.

(shown in Fig. 9). The spectroscopic factor extracted for this state in the present case (Table II) is found to be quite different from the value reported in [11]. The relative spectroscopic factor value obtained in the present as well as the previously reported values for this state are given in Table III.

F. Spectroscopic factor for the 4719 keV : 4^+ state

The 4719 keV excited state may also be due to the mixing of two states. So, for this state too we determined the centroid position and extracted the spectroscopic factor. The state was analyzed assuming $l = 2$ (shown in Fig. 10) and the spectroscopic factor is given in Table II. A relative spectroscopic factor for this state is given in Table III.

V. SUMMARY AND CONCLUSION

The reaction ^{27}Al$(d,t)^{26}$Al was studied using a deuteron beam at 25 MeV. The angular distributions of different excited states of ^{26}Al were studied with the zero range distorted wave Born approximation to extract the spectroscopic factors for these states. The optical model potential parameters were extracted from $d + ^{27}$Al elastic scattering data. For the 420 keV state, it is clear from Fig. 6 that the experimental angular distribution and the corresponding DWBA prediction are in good agreement for an $l = 2$ transfer, while it is not so for an $l = 0$ transfer. It was earlier indicated that this state was populated with pure $l = 0$ transfer [9,11]. However, from the

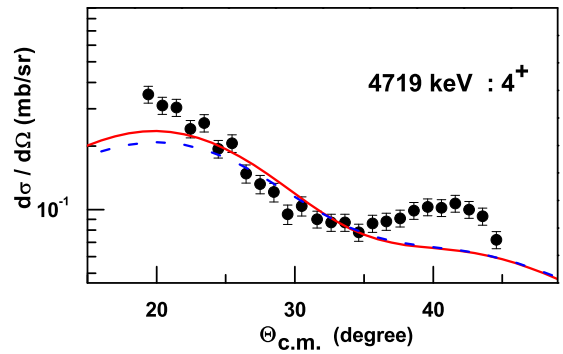

FIG. 10. (Color online) Same as Fig. 5 for the 4719 keV state for pickup from $0d_{5/2}$.

present study we conclude that it resembles more closely with an $l = 2$ transfer, rather than an $l = 0$ transfer. Interestingly, the spectroscopic factor obtained from the present study is comparable with its previously reported value for $l = 0$ transfer as well as the respective theoretical predictions [9].

The potential parameter dependence of spectroscopic factors was checked with two different sets of exit channel potential parameters. It was found that for the ^{27}Al(d,t) reaction at 25 MeV, the variation in spectroscopic factors was less than 10%. The estimated uncertainties in the extracted values of spectroscopic factors are within 30% except for the states at 420 keV ($l = 0$ case) and 3505 keV ($l = 4$ case). The present results also compare well with the previous measurements.

In conclusion, the reaction ^{27}Al(d,t) has been utilized for the first time for the study of ^{26}Al. The experimental and theoretical results for both the positive and negative parity states are in good agreement with each other. The extracted values of spectroscopic factors are found to be in good agreement with the respective shell model predictions wherever available, and with the experimental values reported earlier.

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