Low-lying levels in ^{45}Sc

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The low-lying levels of ^{45}Sc up to 1662 keV excitation energy were investigated by measuring thick target yields and angular anisotropies of the deexcited gamma rays with a high resolution 57 cm^3 Ge(Li) detector using 2–4 MeV protons. The ambiguity in the branching ratios for the 939, 1409, and 1662 keV levels has been resolved. The existence of weak gamma-ray transitions of 166 and 708 keV energies has been supported. The reaction mechanism for this range of proton energies in ^{45}Sc has been established. The ambiguity in the mode of excitation for 543 and 974 keV levels has been resolved. The reliable values of $B(E\lambda)$ for 377, 543, 720, and 974 keV levels excited with protons have been measured by considering the contribution of compound nucleus formation. The ambiguity in the J^π values for 974 and 1409 keV levels has been resolved by the χ^2-fit method. The 708 keV gamma ray has been assigned a new δ value. The results have been discussed in view of the various nuclear models.

I. INTRODUCTION

The low lying states in the ^{45}Sc nucleus have been the subject of several theoretical[1–9] and experimental investigations.[10] Rust *et al.*[1] have described the low-lying odd parity levels of ^{45}Sc as being due to the coupling of the odd $1f_{7/2}$ proton to the first excited (2^+) state of the even-even ^{44}Ca core. The shell model calculations have been performed to explain low-lying levels of ^{45}Sc by assuming the $(1f_{7/2})^5$ configurations[2–4] and the full f-p shell configuration.[5,6] The low-lying odd parity states have been explained by Buitendag *et al.*[7] as arising from intermediate coupling of a single proton in the $1f$-$2p$ major nuclear shell to the ^{44}Ca core (0^+ or 2_1^+ state) and by Malik and Scholz[8] as being due to the strong coupling symmetric rotor motion[9] including the Coriolis coupling between the bands. The low-lying positive parity states, however, have been suggested as either being due to the coupling of a $1d_{3/2}$ proton hole to the ^{44}Ca core[7] or to the excitation of $d_{3/2}$ and $s_{1/2}$ hole states in the nuclear core.[8]

For ^{45}Sc, the nuclear structure data available up to 1983 have been summarized in Nuclear Data Sheets.[10] Information on the low-lying levels of ^{45}Sc has been obtained via beta decay, radiative proton capture, inelastic proton and neutron scattering, one- or two-particle transfer reactions, $(\alpha,\mathrm{p}\gamma)$ reactions, resonance fluorscence, and Coulomb excitations. Of particular importance to the present study are the experiments on proton and neutron inelastic scattering,[1,7,11–16] radiative capture,[17,18] $(\alpha,\mathrm{p}\gamma)$ reactions,[19,20] and Coulomb excitations.[7,14,16,21,22]

Patil and Kulkarni[22] recently excited 377, 543, 720, 974, 1068, 1237, 1409, and 1662 keV levels with 2.5–3.5 MeV protons and, assuming them to be Coulomb excited, assigned J^π as $\frac{5}{2}^-$ or $\frac{7}{2}^-$ to the 974 keV level. They found the 543 keV level to follow the $E3$ excitation curve, while the other levels were due to $E2$ excitation. Also, Patil and Kulkarni did not comment on the earlier observed[13–16] levels at 939, 1303, and 1433 keV energies with the inelastic scattering of protons of the same energy range. The recent experimental measurements[7,11,12] and the theoretical investigations of Cole[6] do not support these new assignments. Besides, no other measurements exist for the excitation of ^{45}Sc levels through Coulomb excitation with the protons. In view of the inclusion of the work of Patil and Kulkarni in the latest Nuclear Data Sheet,[10] and the above contradictions, it was thought essential to reinvestigate the ^{45}Sc nucleus, with the low-energy protons (2–3.7 MeV), using the improved electronics and a Ge(Li) detector of better resolution.

II. REACTION MECHANISM

Knowledge of the reaction mechanism is essential for the accuracy and quality of spectroscopic information extracted from it. For the inelastic scattering of low-energy protons, the total cross section may be described as

$$\sigma_{\mathrm{p,p'}}=\sigma_{\mathrm{direct}}+\sigma_{\mathrm{compound}}+\sigma_{\mathrm{Coulomb}}\ . \tag{1}$$

The direct reaction contribution, i.e., σ_{direct}, is unimportant for the protons of $E_{\mathrm{p}}<5$ MeV.[23] The available empirical relation for the safe energy[24] for the Coulomb excitation of a nucleus with a projectile is applicable only for the heavy projectiles. In the present investigation, the reaction mechanism has been ascertained for the first time by comparison of the experimental results with detailed theoretical calculations of compound formation and Coulomb excitation for the given range of proton energies. The calculations for the compound nucleus contribution were made with a computer code CINDY written by Sheldon and Rogers.[25] All the possible channels through $(\mathrm{p,p'}\gamma)$, $(\mathrm{p,n}\gamma)$, $(\mathrm{p},\alpha\gamma)$, and (p,γ) reactions were assumed to be the competing channels, and the requisite transmission coefficients were evaluated from the optical model potential parameters derived by Perey[26] for protons, derived by Wilmore and Hodgson[27] for neutrons, and compiled by Perey and Perey[28] for the alphas. The level density relation chosen for this procedure was that of Gilbert and Cameron.[29]

III. EXPERIMENTAL PROCEDURE

The experiment was performed using proton beam from the Variable Energy Cyclotron at the Physics Department, Panjab University, Chandigarh. The typical beam current used in this experiment was 300 nA. A thick self-supporting target of Sc_2O_3 (99.99% pure) was positioned at 45° to the beam axis and the gamma rays were detected by a shielded 57 cm^3 Ge(Li) detector having a resolution of 1.9 ± 0.1 keV full width at half maximum (FWHM) for the 1332 keV ^{60}Co gamma ray and mounted on a movable table at 20 cm from the target and measured with a Nuclear Data-100 system (4096 channel analyzer) in a manner described elsewhere.[30,31] Since the target was sufficiently thick to absorb all the incident protons, it worked as a Faraday cup for the charge collection. The charge collected at a target was measured by an ORTEC digital current integrator. To suppress the electrons emitted from the target by the photoelectric effect, an electron suppressor was placed near the target towards the beam. The absolute detector efficiency curve was obtained using standard radioactive sources of ^{54}Mn, ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{152}Eu.

The singles spectra were taken at different proton energies (2–3.7 MeV) with the Ge(Li) detector at 55° with respect to the beam direction to avoid anisotropic effects. A typical singles gamma-ray spectrum recorded with 3.0 MeV protons and displaying the well-resolved peaks, each marked with the source of origin (background peaks are marked B), is shown in Fig. 1. The angular distributions were measured at five detector settings between 0° and 90° from the beam direction with 3.0 MeV protons.

IV. DATA ANALYSIS

The observed spectra were analyzed by means of the computer code SAMPO,[32] which calculated the different peak areas (N_γ), intensities (I_γ), and energies (E_γ). The observed gamma rays were assigned their origin by taking into account the background spectrum with the machine on. The branching ratios were measured at different proton energies. The existence of the gamma rays deexciting the particular level was established by drawing gamma-ray intensity as a function of proton energy curves for these gamma rays, and the level scheme was constructed with the average branching ratios.

The thick target yields per incident proton for the levels excited, corresponding to the compound nucleus and Coulomb excitation process, were obtained from the relationship

$$\frac{Y}{I} = \frac{N}{\rho} \int_E^0 \frac{\sigma(E)dE}{dE/dx} , \tag{2}$$

where N/ρ is the number of atoms per g of target, $\sigma(E)$ the relevant cross section for exciting a level with a projectile of energy E, and dE/dx the stopping power in

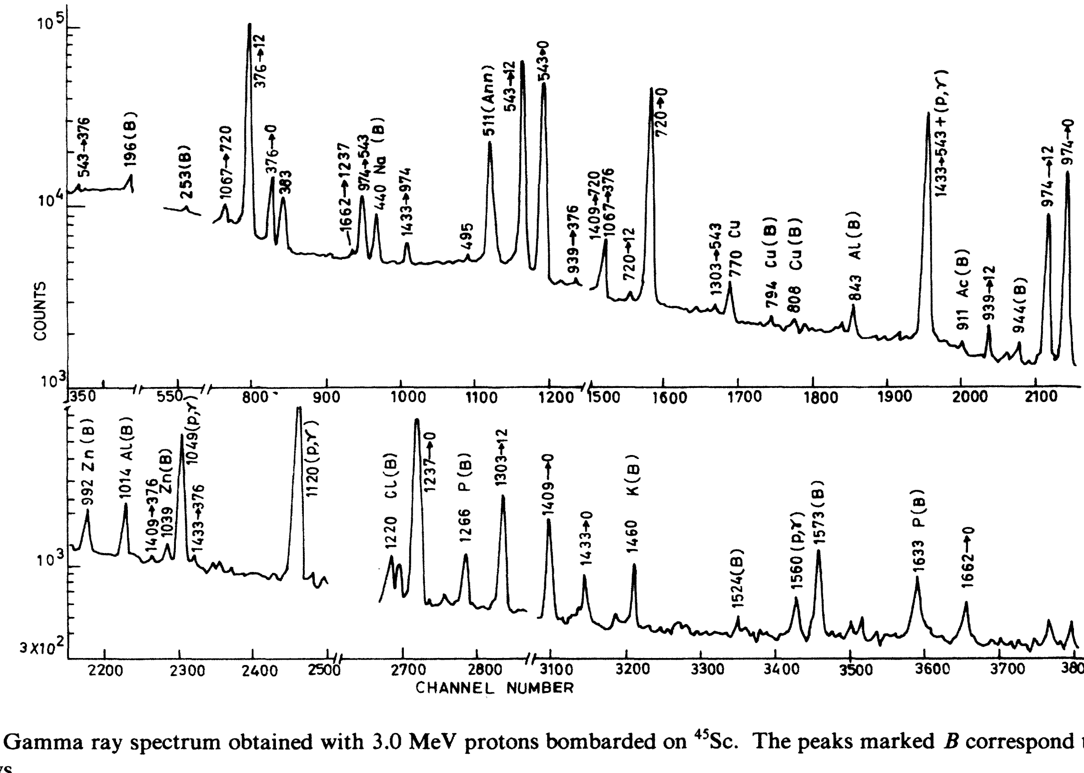

FIG. 1. Gamma ray spectrum obtained with 3.0 MeV protons bombarded on ^{45}Sc. The peaks marked B correspond to background gamma rays.

TABLE I. Comparison of branching ratios in ^{45}Sc.

Level (keV) J^{π}	E_{γ} (keV)	Present work	Ref. 22	Ref. 7	Ref. 13	Ref. 16	Ref. 15	Ref. 19
376.68±2.25	376.7	8.7±1.0	8±1	9	9	8	10.0±1.1	8.6±0.5
$\frac{3}{2}^-$	364.3	91.3±1.0	92±1	91	91	92	90.0±1.1	91.4±0.5
543.08±0.17	543.1	41.3±0.5	42±1	41	40	42	41	
$\frac{5}{2}^+$	530.7	58.2±0.4	58±1	59	60	58	56	
	166.4	0.4±0.2				0.3	0.7	
720.48±0.14	720.5	99.3±0.5	100	100	100	100	100	96.5±0.5
$\frac{5}{2}^-$	708.3	0.7±0.3						3.5±0.5
938.68±0.15	926.7	82.4±1.0		72		100	71±10	
$\frac{1}{2}^+$	563.0	17.6±1.2		28			29±10	
974.44±0.10	974.4	57.6±1.3	60±1	55	57	58	57.9±2.0	
$\frac{7}{2}^+$	962.1	30.8±1.6	25±1	33	32	32	32.2±2.0	
	431.2	11.6±1.2	15±1	12	11	10	9.9±1.0	
1067.73±0.30	691.1	78.2±0.8	68±1	68		80	82.4±2.0	76±2
$\frac{3}{2}^-$	347.4	21.8±1.0	32±1	32		20	17.6±2.0	24±2
1237.14±0.21	1237.1	100	100	100	100	100	100	100
$\frac{11}{2}^-$								
1409.20±0.20	1409.2	89.4±0.4	100	85	99	91	87.7±2.1	87±4
$\frac{7}{2}^-$	1032.6	4.0±0.4		6	1		3.8±1.3	
	689.0	6.6±1.0		9		9	8.5±1.6	13±4
1662.15±0.25	1662.2	76.10±1.8	70±1	80	75	83	70±5	79±3
	942						8.9±4.1	
$\frac{9}{2}^-$	425.0	24.90±2.0	30±1	20	25	17	13.1±3.2	21±3
	253						8.0±4.0	

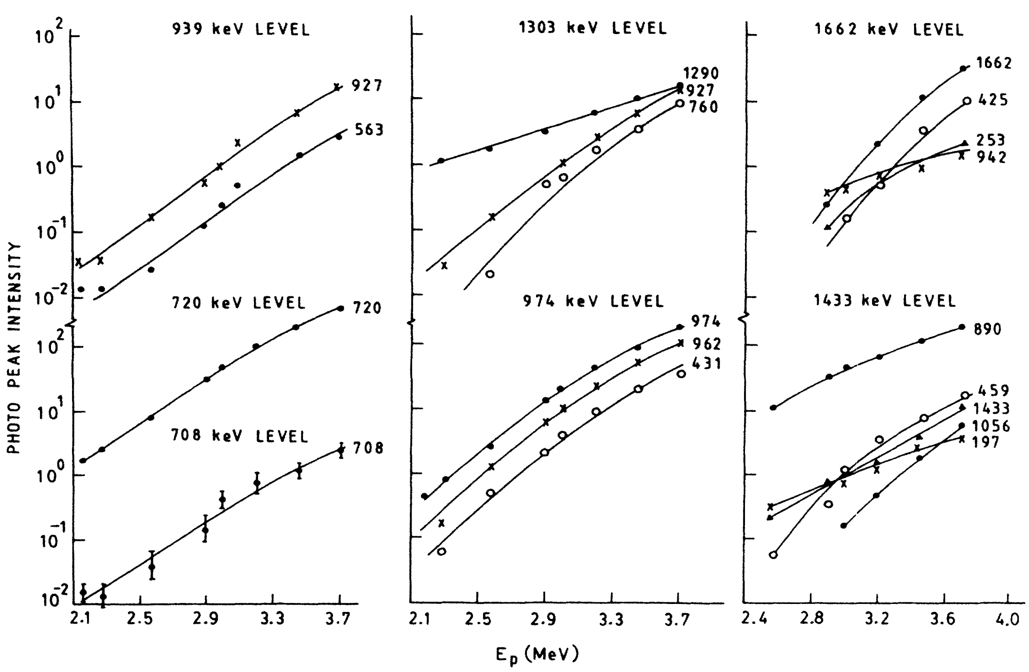

FIG. 2. Curves for gamma ray intensity as a function of proton energy.

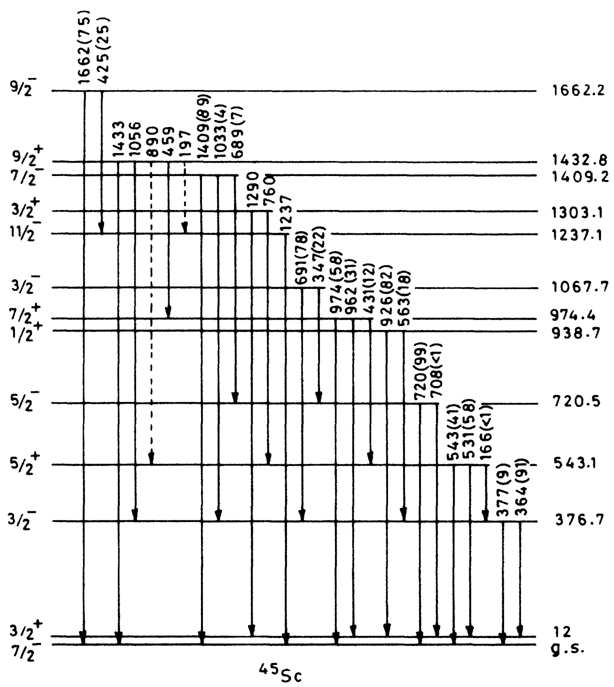

FIG. 3. Level scheme of ^{45}Sc.

MeV g^{-1} cm^2. The cross section corresponding to the compound nucleus formation $\sigma_c(E)$ was calculated with the computer code CINDY. The net yield for Coulomb excitation was obtained by the subtraction of the compound nucleus thick target yield from the experimental yield. Since the direct reaction contribution was negligible for the experimental range of proton energies, the net yield was definitely due to the Coulomb excitation mechanism and therefore was compared to the theoretical thick-target yield for $E\lambda$ excitation using the Coulomb excitation theory of Alder *et al.*[33] for deducing the $B(E\lambda)$ value.

The theory of the compound nucleus was used for the analysis of angular distribution data at 3 MeV protons, at which energy the main contribution comes from this reaction mechanism in this case. The theoretical values of A_2 and A_4 for various values of $\tan^{-1}\delta$ ranging from $-90°$ to $+90°$ were obtained for each possible spin up to $I_i \pm 2$ with computer code CINDY. These values were compared with the experimental angular distribution data using the χ^2-fits method.[30] The criterion of a 0.1% confidence limit was used to exclude the unacceptable spins. The mixing ration (δ) was measured from the minima of the χ^2 curve, and its error was measured from the values of δ corresponding to $\chi^2_{\min} \pm \chi^2_{\min}/n$. The phase convention of Krane and Steffan[34] was used for mixing ratios.

V. RESULTS AND DISCUSSIONS

The level energies and branching ratios (Table I) observed in the present work are in good agreement with the results of previous work.[10] The decay of the 1555 keV level could not be uniquely identified in the present work, as the 488 keV gamma ray was only weakly discernible. The ambiguity in branching ratios for the 720, 939, and 1662 keV levels has been resolved by plotting the gamma-ray intensity versus proton energy curves (Fig. 2), and the existence of weak gamma transitions of 166 and 708 keV

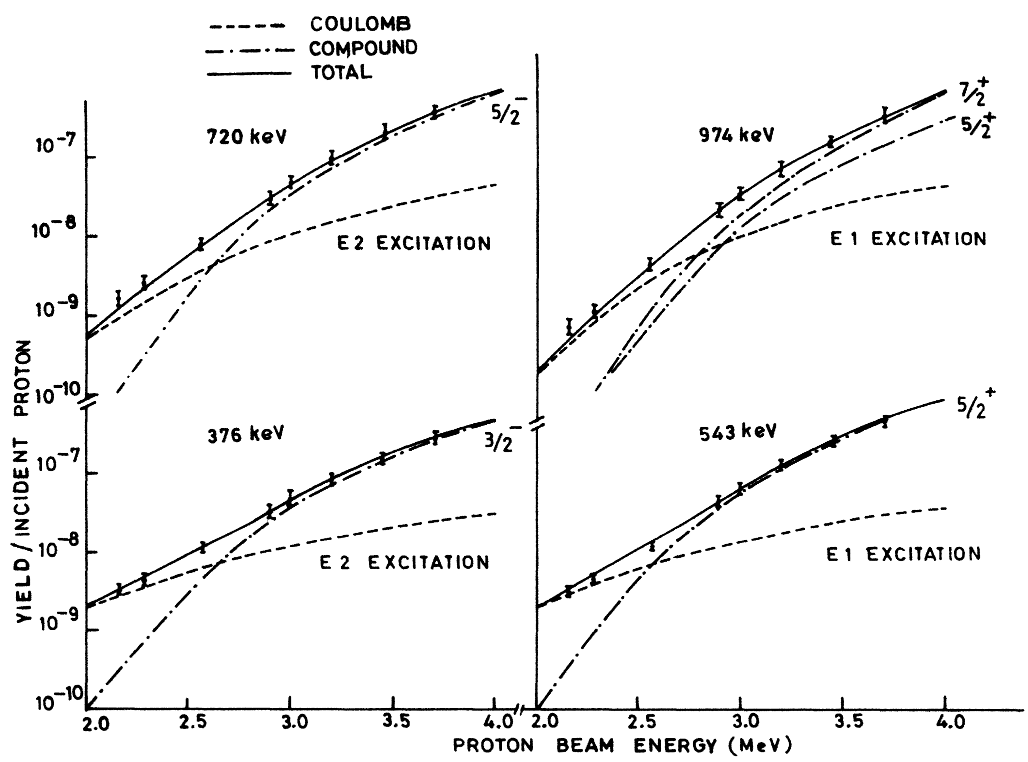

FIG. 4. Excitation functions for $E1$ and $E2$ excitations.

TABLE II. Comparison of $B(E\lambda)$ values with the previous data of ^{45}Sc.

Level energy (keV)	J^{π}	Experimental values of $B(E2)\uparrow$ (e^2cm$^4\times10^{-50}$) Present work	Patil (Ref. 22)	Buitendag (Ref. 7)	Chevallier (Ref. 19)	Blasi (Ref. 16)	Eastham (Ref. 14)	Theory (Ref. 7)
377	$\frac{3}{2}^-$	0.66±0.06	0.70±0.06	0.72±0.05	0.72±0.04	0.68±0.05	0.85±0.06	1.63
720	$\frac{5}{2}^-$	1.40±0.14	0.65±0.05	0.81±0.06	0.67±0.10	0.55±0.05	0.97±0.07	0.65
		Experimental values of $B(E1)\uparrow$ (e^2cm$^2\times10^{-30}$)						
		Present work	Patil (Ref. 22)	Toulemonde (Ref. 20)				
543	$\frac{5}{2}^+$	1.4±0.2	$E3$	1.77±0.73				
974	$\frac{7}{2}^+$	7.5±0.8	$E2$	1.39±0.33				

energies has been supported through the present observations. The level scheme thus constructed is shown in Fig. 3.

The compound nucleus contribution is found to be $\leq 5\%$ with the protons for energies ≤ 2.0 MeV for the 377, 543, 720, and 974 keV levels, which are found to have the most significant contribution of Coulomb excitation for our experimental range of proton energies. The net Coulomb yield (the yield corresponding to the Coulomb excitation mechanism) is found to follow the $E2$ curve for the 377 and 720 keV levels and the $E1$ curve for the 543 and 974 keV levels (Fig. 4). The levels at 1067 keV and above are excited only with the protons of energies greater than 2.4 MeV, at which energy the compound contribution is about 50%. Therefore, no $B(E\lambda)$ has been measured for these levels. Typical angular distribution χ^2 curves for the 974 and 1409 keV gamma rays are shown in Fig. 5. The results are presented and compared with the previous data in Tables I–III, and discussed below.

A. The 377 keV state

The comparison of the compound nucleus yield with the experimental yield shows that the former is about 5% at $E_p=2$ MeV and rises to about 50% at $E_p=2.65$ MeV. The net Coulomb yield is found to follow the $E2$ excitation curve with $B(E2)\uparrow=(0.66\pm0.06)$ e^2cm$^4\times10^{-50}$, which is in close agreement with the earlier values.[7,16,19,21,22] On the basis of the present observations, the agreement with the value of $B(E2)$ by Patil and Kulkarni[22] seems fortuitous. The angular distribution data analysis based on the χ^2-fit method supports $J^{\pi}=\frac{3}{2}^-$ for this level and gives a mixing ratio (δ) for the 364 keV gamma transition of $-1.24^{+1.04}_{-1.51}$. The lifetime calculated from the observed $B(E2)\uparrow$ and δ values is 71±10 ps, in agreement with the adopted value.[10]

B. The 543 keV state

Patil and Kulkarni have quoted this level as being the $E3$ Coulomb excited state, while Toulemonde *et al.*[20] ear-

TABLE III. Comparison of δ values with the previously reported data on ^{45}Sc.

E_γ	Transition	Present work	Patil (Ref. 22)	Toulemonde (Ref. 20)	Chevallier (Ref. 19)	Eastham (Ref. 14)
377	$\frac{3}{2}^-\to\frac{7}{2}^-$				−0.01±0.08	
364	$\frac{3}{2}^-\to\frac{3}{2}^+$	$-1.24^{+1.04}_{-1.51}$			0.01±0.02	−0.14 or ∞
543	$\frac{5}{2}^+\to\frac{7}{2}^-$	$1.25^{+1.22}_{-0.70}$		$0.035^{+0.050}_{-0.062}$		
531	$\frac{5}{2}^+\to\frac{3}{2}^+$	$-0.75^{+0.43}_{-0.57}$		$0.55^{+0.18}_{-0.11}$		
720	$\frac{5}{2}^-\to\frac{7}{2}^-$	$1.0^{+0.32}_{-0.42}$	0.18±0.03		−0.078±0.055	0.09 or ∞
708	$\frac{5}{2}^-\to\frac{3}{2}^+$	$1.25^{+1.35}_{-0.47}$				
974	$\frac{7}{2}^+\to\frac{7}{2}^-$	$-0.32^{+0.06}_{-0.11}$	−0.17±0.02	$-0.09^{+0.12}_{-0.17}$		
432	$\frac{7}{2}^+\to\frac{5}{2}^+$	$-0.75^{+0.37}_{-0.85}$		$0.24^{+0.16}_{-0.12}$		
1237	$\frac{11}{2}^-\to\frac{7}{2}^-$	$-0.10^{+0.05}_{-0.04}$	∞		0.02±0.02	$E2$
1409	$\frac{7}{2}^-\to\frac{7}{2}^-$	$-0.06^{+0.05}_{-0.04}$ or $-3.27^{+0.30}_{-0.80}$	−2.62±0.62		0.9±0.4	

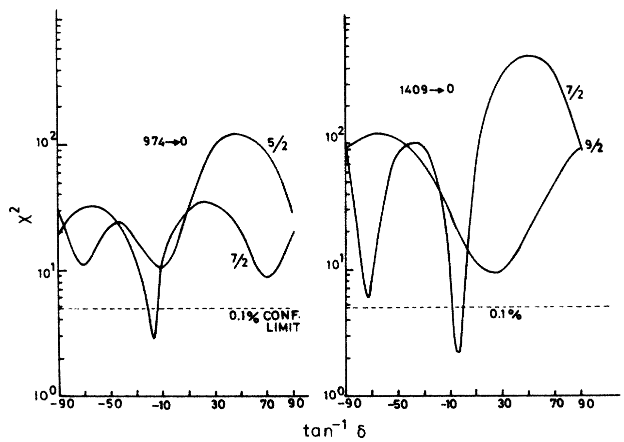

FIG. 5. Values of χ^2 as a function of mixing ratio for 974 and 1409 keV gamma rays.

lier established it as $E1$ excited. In our case, the net yield responsible for Coulomb excitation is clearly found to follow the $E1$ excitation curve (Fig. 4), with $B(E1)\uparrow = (1.4 \pm 0.2)\ e^2\text{cm}^2 \times 10^{-30}$, which is in excellent agreement with the earlier value.[20] The angular distribution analysis supports $J^\pi = \frac{5}{2}^+$ and gives δ for the 543 and 531 keV transitions as $1.25^{+1.22}_{-0.70}$ and $0.75^{+0.43}_{-0.57}$, respectively. It suggests a lifetime of $\tau < 8.2$ ps, in agreement with the adopted value.[10]

C. The 720 keV state

In our present results this level decays by a 708 keV gamma transition to the 12 keV state with a branching ratio of 0.7 ± 0.3 %. This transition was earlier observed by Chevallier *et al.*[19] via the ^{42}Ca(α,pγ) reaction. Dang *et al.*[15] quoted the observed 708 keV gamma ray as being due to the ^{45}Sc(p,nγ)^{45}Ti reaction. We confined E_p to being less than 3.71 MeV, which cannot excite the 744 keV level of ^{45}Ti. Also $I_\gamma(720)/I_\gamma(708)$ is found to be constant (Fig. 2). Thus the observed 708 keV gamma ray in our case is definitely from the 720 keV state. The present work does not support the 720→377 transition suggested by Erlandsson.[17]. The net Coulomb yield is found to follow the $E2$ excitation curve with $B(E2)\uparrow = (1.40 \pm 0.14)\ e^2\text{cm}^4 \times 10^{-50}$, which is in agreement with the earlier values.[7,14] The angular distribution supports $J^\pi = \frac{5}{2}^-$ and gives δ values for the 720 and 708 keV transitions of $1.00^{+0.32}_{-0.42}$ and $1.25^{+1.36}_{-0.47}$, respectively. It gives the lifetime $\tau = 11 \pm 4$ ps, which is not far from the adopted value[10] of 30.1 ps.

D. The 939 keV state

This level, according to our measurements, decays to the 12 and 377 keV states with branching ratios of 82.4 ± 1.0 % and 17.6 ± 1.2 %, respectively, in excellent agreement with the work of Schulte *et al.*[18] who have also not suggested any contributions from the 1303 keV level to the 927 keV gamma transition. The present results do not support the earlier investigations[1,14,16,17] where the 563 keV transition was not observed. The disagreement with the values of the branching ratios by Buitendag *et al.*[7] and Dang *et al.*[15] is because of their assumption of the existence of the 1303→376 (927 keV) transition which contributes to the intensity of the 927 keV transition from the 938 keV level. In the present work I_γ (927)/I_γ (563) is found to be constant with energy, and the total experimental yield is in excellent agreement with the compound theoretical yield. Therefore, the whole of the intensity of the 927 keV gamma ray is assumed to come from the 939 keV level. This is in agreement with the work of Eastham and Phillips.[14] In our case, the 927 and 563 keV gamma rays are isotropic and provide strong support for the $J^\pi = \frac{1}{2}^+$ hypothesis.

E. The 974 keV state

Patil and Kulkarni[22] have suggested this level as being due to $E2$ excitation with $J^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$, which has not been supported by recent investigations.[10] In the present work, the net Coulomb yield is clearly found to follow the $E1$ excitation curve with $B(E1)\uparrow = (7.5 \pm 0.8)\ e^2\text{cm}^2 \times 10^{-30}$, in agreement with the conclusion of Toulemonde *et al.*[20] about the $E1$ nature of the transition. The value of $B(E1)\uparrow$ is, however, higher than obtained by them. The angular distribution data suggest $J^\pi = \frac{7}{2}^+$ and give δ values for 974 and 432 keV transitions of $-0.32^{+0.06}_{-0.11}$ and $0.75^{+0.37}_{-0.85}$, respectively. This value of J^π has also been confirmed with the procedure of comparing the experimental yield with the total thick target yield calculated for $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$ (Fig. 4). The $B(E1)\uparrow$ and δ values suggest a lifetime of $\tau \simeq 0.47 \pm 0.06$ ps for this level, which is not in agreement with the adopted value of 5.1 ps, but interestingly is in agreement with the recent results of Elankov *et al.*[12]

F. The 1068 keV state

The branching ratios from this level are in excellent agreement with the earlier measurements,[15,16,19] but in lesser agreement with recent work.[7,22] This level has not been suggested by Chasman *et al.*[13] and only the 1068→377 keV transition was observed by Erlandsson.[17]

G. The 1237 keV state

This level decays to the ground state only. The χ^2 analysis of the angular distribution data suggests $J^\pi = \frac{11}{2}^-$. The ground state transition is found to be either a pure $E2$ or a mixed transition with a mixing ratio (δ) of $-0.10^{+0.05}_{-0.04}$.

H. The 1303 keV state

As discussed earlier, the contribution to the 927 keV transition is mainly from the 939 keV state. We, therefore suggest only two (1290 and 760 keV) transitions from this level, supporting earlier workers.[1,16,18] Surprisingly, Patil and Kulkarni[22] and Chevallier *et al.*[19] did not observe this level. Eastham and Phillips[14] observed only the 1290 keV transition. In the present work $I_\gamma(1290)/I_\gamma(760)$ varies with beam energy. The higher contribution of the 1290 keV transition at low beam energies may be due to the contribution via the (p,γ) reaction.

I. The 1409 keV state

According to the present measurements, this level decays to the ground, 377, and 720 keV states with branching ratios of 82.4±0.4%, 4.0±0.4%, and 6.6±1.0%, respectively, in excellent agreement with the values of Dang *et al.*[15] The observed weak transition of the 1033 keV gamma ray was not detected by Dang *et al.*, perhaps because of the poor resolution of their detectors. Our χ^2 analysis assigns $J^\pi = \frac{7}{2}^-$, in agreement with recent work,[10] and does not support the value $\frac{9}{2}^-$ assigned by Blasi *et al.*[16] The mixing ratio for the 1409 keV transition has two possible values—$0.06^{+0.05}_{-0.04}$ and $-3.27^{+0.30}_{-0.80}$.

J. The 1433 keV state

All the earlier quoted gamma transitions were observed in the present work. The photopeak intensity versus proton energy curves for these gamma rays show the 197 and 890 keV gamma rays have comparatively high intensities at low beam energies. The former may be due to background (^{19}F contamination) and the latter due to the contribution of the transition from ^{45}Ti formed by the (p,γ) reaction on ^{45}Sc.

K. The 1662 keV state

Similar to the earlier case, all the deexcitation gamma rays from this level observed by Dang *et al.*[15] were seen in the spectrum. It seems that the 253 and 942 keV transitions arise from background as indicated in the photopeak intensity versus proton energy curves for these gamma rays. The gamma-ray transitions from this level have energies of 1662 and 425 keV with branching ratios of 75.10±1.8% and 24.90±2.0%, respectively, in excellent agreement with the observations of Chasman *et al.*[13] This level has a well-established value of J^π as $\frac{9}{2}^-$.

VI. MODEL DISCUSSION

The core excitation model of de-Shalit[35] reproduces the low lying levels of ^{45}Sc at 377, 720, 1237, 1409, and 1662 keV, as being due to the coupling of the odd $1f_{7/2}$ proton to the first excited 2^+ states of the even-even core of ^{44}Ca. This model supports the assignment of $J^\pi = \frac{7}{2}^-$ by us to the 1409 keV level. The $B(E2)$ values calculated by Rust *et al.*[1] using the core-excitation model are found to be in excellent agreement with recent observations[7,11,12] and also with our values.

Shell model calculations have been made by various workers.[2–6] Cole[6] performed shell model calculations for the level energies and other properties by using a Hamiltonian which was a modification of the Kuo-Brown interaction.[36] These and other calculations do not support the assignment of $J^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$ to the 974 keV level by Patil and Kulkarni,[22] but do support the assignment of $\frac{7}{2}^+$, as found in our measurements.

Buitendag *et al.*[7] made theoretical calculations based on the Thankappen-True version[37,38] of the excited core model by assuming the low-lying odd parity states of ^{45}Sc as arising from intermediate coupling of a single proton (p) in the $1f$-$2p$ major nuclear shell to the ^{44}Ca core nucleus in either its 0^+ ground state or 2^+ first excited state and explained the quintet at 377, 720, 1237, 1409, and 1662 keV which had also been explained earlier[1] by the core excitation model. Our values of the transition probabilities are also in general agreement with these calculations shown in Table II. The intermediate excited $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states at 1067 and 1555 keV were explained as being due to the coupling of a $2p_{3/2}$ proton to the 0^+ ground state and to the first 2^+ excited state of the ^{44}Ca core, respectively. The higher levels were explained by the coupling of the $1f_{7/2}$, $2p_{3/2}$, and $1f_{5/2}$ subshells with the allowed core states. The even parity states in ^{45}Sc were explained as being due to the coupling of a $1d_{3/2}$ proton hole to the two core states, although the level energies were not in agreement with the experimental values.

Malik and Scholz[8] have calculated the negative parity states of ^{45}Sc using the strong coupling asymmetric rotator model including the Coriolis coupling between the bands. The positive parity states were explained as arising from core excitation of the $2s$-$1d$ shell. The states at 12, 543, 974, and 1432 keV energies are the members of the $K = \frac{3}{2}^+$ rotational band and the 939 and 1303 keV states are those of the $K = \frac{1}{2}^+$ rotational band. According to Mauronzig,[39] these states obey the $J(J+1)$ rule. These calculations give better results than those for the $(1f_{7/2})$ shell configuration. The rotational band structure also supports our assignment of $J^\pi = \frac{7}{2}^+$ to the 974 keV level.

VII. CONCLUSION

Our study of the ^{45}Sc nucleus does not support the recent assignments of J^π and $B(E\lambda)$ values by Patil and Kulkarni.[22] This work establishes the reaction mechanism with 2 to 3.7 MeV protons and also removes the ambiguities in the values of branching ratios for quite a few levels. The transition probabilities for a few low-lying levels, i.e., 377, 543, 720, and 974 keV have been accurately measured through Coulomb excitation with protons.

All the odd parity low-lying levels are well accounted for by Buitendag *et al.*[7] as being due to the coupling between the $1f_{7/2}$ and $2p_{3/2}$ proton states and the 0^+ and 2^+ states of the ^{44}Ca core. The even parity states are well described by Malik and Scholz[8] as being due to the excitation of the $d_{3/2}$ and $s_{1/2}$ hole states in the nuclear core as the members of the $K = \frac{3}{2}^+$ and $\frac{1}{2}^+$ rotational bands.

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