Properties of the low-lying negative parity states in 45Sc

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PROPERTIES OF THE LOW-LYING NEGATIVE PARITY STATES IN ^{45}Sc

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Résumé. — Les décroissances des états de parité négative d'énergie d'excitation inférieure à 2 107 keV dans le noyau ^{45}Sc ont été étudiées par la réaction ^{42}Ca(α, pγ)^{45}Sc à une énergie de bombardement de 10,5 MeV. Les protons ont été détectés dans un compteur annulaire de silicium, à un angle moyen de 171° par rapport à l'axe de faisceau. Des spectres de rayonnements γ ont été mesurés aux angles 105° $\geqslant \theta \geqslant$ 0° au moyen d'un détecteur Ge(Li). Les spins et les vies moyennes des niveaux ainsi que les rapports d'embranchement et les mélanges multipolaires des transitions γ ont été déduits des mesures de corrélations angulaires proton-γ. Les éléments de matrice réduits des transitions électromagnétiques ont été obtenus pour un certain nombre de transitions. Des calculs basés sur le modèle à couplage fort ont été effectués. Ces résultats sont comparés à l'expérience.

Abstract. — The electromagnetic decays of the negative parity states in ^{45}Sc up to an excitation energy of 2 107 keV have been investigated via the ^{42}Ca(α, pγ)^{45}Sc reaction at a bombarding energy of 10.5 MeV. Reaction produced protons were detected in an annular silicon detector at an average angle of 171°. Gamma-ray spectra were measured with a Ge(Li) detector at angles 105° $\geqslant \theta \geqslant$ 0°. Spins and lifetimes of the levels as well as branching and mixing ratios of their decay γ-rays have been obtained from proton-gamma angular correlation measurements. Reduced electromagnetic transition matrix elements have been extracted for a number of observed transitions. Calculations based on the strong coupling model have been performed. The results are compared with experiment.

1. **Introduction.** — The low-lying negative parity states in the ^{45}Sc nucleus have been the subject of several theoretical investigations. Both the spherical shell model of McCullen, Bayman and Zamick [1] who considered 5 particles coupled in the $1f_{7/2}$ shell, and the strong-coupling deformed rotator model of Malik and Scholz [2] have been used in order to explain the negative parity level scheme. However insufficient experimental data were available to allow a very detailed test of these models.

The energy levels and their decay properties have been investigated by many authors. When this work was begun the information available on the ^{45}Sc nucleus had been obtained from the following experiments : Coulomb excitation [3-10], beta-decay [9], [11, 12], radiative proton capture [13-16], inelastic proton scattering [10], [17-21], one or two particle transfer reactions [22-25] and the (α, pγ) reaction [26, 27]. The low-lying negative parity states from $I^\pi = 1/2^-$ to $15/2^-$ have been extensively discussed in all these papers. However, many ambiguities concerning spin assignments existed and the electromagnetic properties had scarcely been investigated. During the course of the present work, Metzger [28], using the nuclear resonance fluorescence technique, deduced lifetimes for some excited states in disagreement with previous values measured by the Doppler shift attenuation method. Finally, some high-spin states have recently been populated in heavy-ion induced fusion evaporation reactions [29].

In order to get more information on the negative parity states up to 2 107 keV, lifetimes, decay modes and spin values were measured using the ^{42}Ca(α, pγ) ^{45}Sc reaction. The experimental procedure and data analysis will be presented in section 2. The results of the present work are given in section 3. In the last section, the level scheme and the electromagnetic properties will be compared to the results of a new calculation in the framework of the strong coupling model.

Positive parity states were also populated in this reaction; their properties will be presented and discussed in a separate paper (M. Toulemonde *et al.*, to be published).

2. **Experimental procedure and data analysis.** — 2.1 EXPERIMENTAL PROCEDURE. — The excited states of ^{45}Sc were populated by the ^{42}Ca(α, pγ)^{45}Sc reac-

tion at a bombarding energy of 10.5 MeV. The doubly ionized ^4He particle beam, provided by the 5.5 MV Van de Graaf accelerator of Strasbourg, had an intensity of about 150 nA. The target, positioned at 45° to the beam axis, consisted of a 150 μg/cm² metallic calcium film (enriched to > 92 % in ^{42}Ca) evaporated on a 500 μg/cm² metallic Ba backing in order to stop the recoiling ^{45}Sc ions. This backing was deposited on a thick tantalum foil which stopped the beam. To prevent the target from oxidation, it was covered with a 100 μg/cm² gold layer.

Protons from the reaction were detected in a 150 mm² annular silicon counter placed at 180° with respect to the beam direction and 3.5 cm from the target. To eliminate the backscattered α-particles, the detector was covered with an 25 mg/cm² Al foil. Under these conditions, the energy resolution of the particle detection system was approximately 170 keV.

A 80 cm³ Ge(Li) counter, mounted on a movable table at 6.5 cm from the target center, was used to measure the γ-ray yield at $\theta = 0°$, 35°, 55°, 90° and 105° to the beam direction. The energy resolution of this detector was 3.5 keV for the 1.33 MeV ^{60}Co γ-rays. The instrumental anisotropy of the arrangement was determined by measuring the angular correlation of the γ-transitions from the $I^\pi = 1/2^+$, 934.9 keV level in ^{45}Sc.

The proton-γ coincidences were collected in a dual parameter system as described elsewhere [30]. The γ-ray spectra were stored in 4 096 channels and the proton spectra in 118. As an example, the spectrum of γ-rays, at $\theta = 90°$, in coincidence with protons feeding the 377 and 543 keV levels is presented in figure 1. It should be pointed out that the difficulty in the analysis of the angular correlation measurements of Zuk *et al.* [26] is removed in the present case. Because of the small energy difference of the $I^\pi = 7/2^-$, ground state and the $I^\pi = 3/2^+$, first excited state (12.4 keV), the transitions desexciting a level to both these states could not be resolved in the NaI detector. As can be seen in figure 1, such transitions are easily analysed in the present experiment.

2.2 ANGULAR CORRELATION ANALYSIS. — Since the outgoing protons were detected at $\langle \theta_p \rangle = 171°$, magnetic substates $m = \pm 1/2$ were populated. Following the arguments given by Ball *et al.* [31] for a similar study of the $^{40}Ca(\alpha, p\gamma)^{43}Sc$ reaction, the contribution from the $m = \pm 3/2$ substrates, due to the finite size of the particle detector, can be neglected in this experiment. The experimental angular correlations for the strongest transitions in ^{45}Sc (an example is shown in the upper part of figure 2) were fitted to a series of Legendre polynomials. The coefficients of these polynomials are listed in table I while the branching ratios extracted from them are given in table II. For the very weak transitions, these values (or limits) were derived from the $\theta = 55°$ measurement. The allowed values of I and δ are based on a χ^2 analysis of the angular correlations [32]. An example of the χ^2 plot for two spin sequences for the 720.6 keV transition is shown in the lower part of

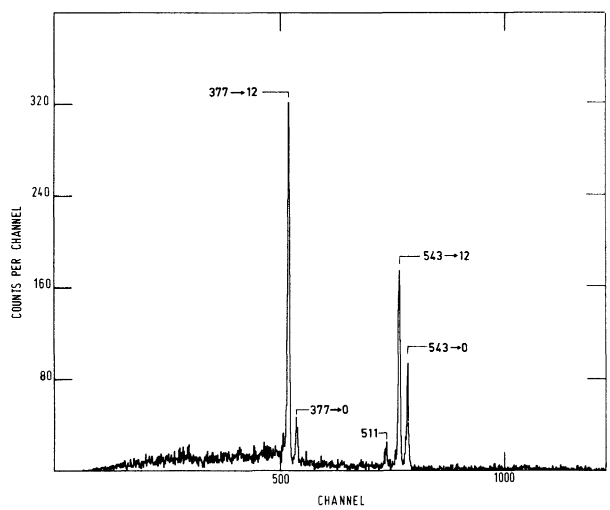

FIG. 1. — Coincidence Ge(Li) spectrum at $\theta = 90°$ resulting from the decay of the 377 and 543 keV levels in ^{45}Sc.

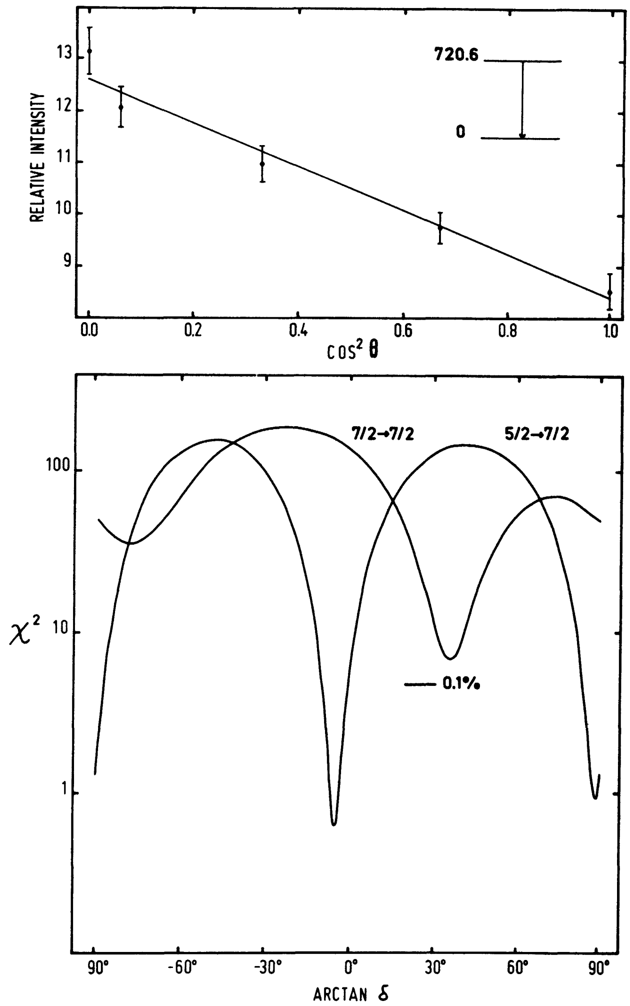

FIG. 2. — Measured angular correlation for the 720.6 keV γ-transition, along with the Legendre polynomial fit (upper part) and χ^2 plot for different spin sequences (lower part).

TABLE I

Results of least squares Legendre polynomial fits to the proton-γ angular correlations

E_i (keV)	E_f (keV)	A_2/A_0 (^{a})	A_4/A_0 (^{a})
377	0	0.36 ± 0.03	
	12	0.24 ± 0.11	
721	0	− 0.30 ± 0.03	
	12	− 0.17 ± 0.28	
1 069	377	0.20 ± 0.04	
	721	− 0.13 ± 0.07	
1 237	0	0.45 ± 0.04	− 0.18 ± 0.04
1 409	0	0.47 ± 0.04	
1 557	1 069	0.11 ± 0.06	
1 662	0	− 0.98 ± 0.04	0.09 ± 0.03
	1 237	− 0.14 ± 0.06	
2 092	0	− 0.05 ± 0.04	
	1 069	− 0.37 ± 0.18	
2 107	1 237	0.40 ± 0.05	− 0.22 ± 0.06

(^{a}) These values have not been corrected for the finite solid angle attenuation factors $Q_2 = 0.92$ and $Q_4 = 0.78$ for the Ge(Li) detector.

figure 2. Spin values were discarded if the corresponding χ^2_{min} was not within the 0.1 % confidence limit. Signs of δ are given according to the phase convention of Rose and Brink [33]. The errors associated with δ were obtained at a χ^2 value corresponding to one standard deviation from χ^2_{min}. In addition possible spin sequences and mixing ratios were rejected on the basis of unacceptable transition strengths [34].

2.3 LIFETIME ANALYSIS. — As a check on possible gain shifts in the Ge(Li) system and in order to get the energy calibration, ^{56}Co γ-rays coincident in the Ge(Li) counter and in a 5 × 5 cm NaI(Tl) crystal, shielded from the beam, were simultaneously recorded. Peak positions measured at the different angles were determined from first moment calculations. Each coincident γ spectrum was calibrated and calibration errors were quadratically added to the errors found in the center of gravity determination. The full Doppler shifts were computed from the kinematics. The average recoil velocity of the ^{45}Sc ions was $\langle \beta \rangle = \langle v/c \rangle \simeq 0.9$ %. The experimental attenuation factors $F(\tau)$ and the unshifted γ-ray energies were computed from least-squares fits to the experimental points versus cos θ (Fig. 3). The resulting values are given in table II.

The attenuation factor $F(\tau)$ was computed as a

TABLE II

Excitation energies, branching ratios and lifetimes

Initial level (keV)	Final level (keV)	Branching ratios (%) this work	$F(\tau)$ (%) this work	τ(fs) (α, pγ) this work	(p, p′ γ) ref. [21]	(p, γ) ref. [15]	(γ, γ) ref. [28]	(C.E.) (^{a})
376.8 ± 0.3	0	8.6 ± 0.5	≤ 9	> 6 000	> 1 600			65 000 ± 5 000
	12.4	91.4 ± 0.5						
720.6 ± 0.5	0	96.5 ± 0.5	75 ± 2	360^{+110}_{-80}	220 ± 60		320 ± 30	
	12.4	3.5 ± 0.5	86 ± 9					
	other	< 2						
1 068.6 ± 1.0	376.8	76 ± 2	66 ± 3	500^{+180}_{-120}				
	720.6	24 ± 2	66 ± 10					
	other	< 10						
1 237.5 ± 0.5	0	100	18 ± 2	$3\,400^{+1400}_{-900}$	1 100 ± 200		2 630 ± 200	3 100 ± 600
	other	< 10						
1 409.5 ± 0.5	0	87 ± 4	60 ± 2	620^{+180}_{-120}	600 ± 300	≤ 172	400 ± 30	
	720.6	13 ± 4						
	other	< 10						
1 557.1 ± 1.0	1 068.6	100	72 ± 4	400^{+180}_{-110}				
	other (^{b})	< 8						
1 662.0 ± 0.5	0	79 ± 3	85 ± 2	200^{+70}_{-50}	110 ± 30		151 ± 13	
	1 237.5	21 ± 3						
	other	< 5						
2 092.3 ± 1.0	0	83 ± 2	100 ± 1	< 50		12 ± 3	8 ± 1	
	376.8	7 ± 2						
	1 068.6	10 ± 2	105 ± 7					
	other (^{c})	< 10						
2 106.8 ± 0.6	1 237.5	100	2 ± 2	> 8 000				
	other	< 15						

(^{a}) The lifetime values have been calculated using the weighted average of the B(E2) values obtained Coulomb excitation experiments [3-10]; only the pure E2-γ transitions have been considered.

(^{b}) The branching ratio for the transition to the 543.3 keV ($5/2^+$) level is less than 20 %.

(^{c}) The branching ratio for the transition to the 1 303.5 keV ($3/2^+$, $5/2^+$) level is less than 25 %.

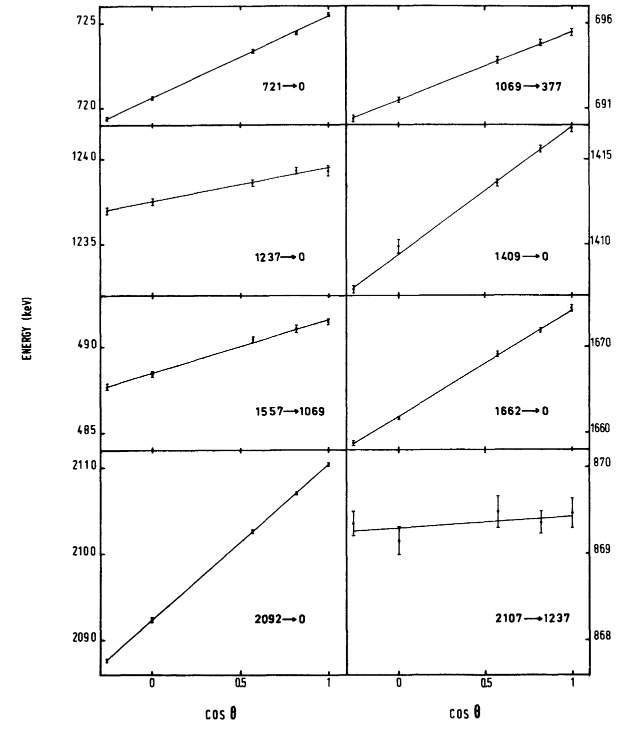

FIG. 3. — Attenuated Doppler shifts for some γ-transitions desexciting negative parity states. The solid lines are least squares fits to the measured energies.

function of τ with the stopping theory of Lindhard, Scharff and Schiott [35] including the Blaugrund approximation [36]. Recently Broude *et al.* [37] and Haas *et al.* [38] have shown that lifetime values deduced from the Doppler-shift attenuation method (DSAM) can vary depending on the slowing-down environment. However the values obtained with calcium or barium as the slowing down material agree with those obtained in an independent way, namely the recoil distance method (RDM). ^{40}Ca being a contaminant of the present target, the attenuated Doppler shifts for the γ-rays desexciting the 1 159 keV level in ^{43}Sc, populated via the $^{40}Ca(\alpha, p\gamma)$ reaction, were analysed. An experimental attenuation factor $F(\tau) = 0.12 \pm 0.04$ leads to the following lifetime $\tau = 5.4^{+2.8}_{-1.2}$ps without any correction to the stopping power. A value $\tau = 6.4 \pm 1.5$ ps has been determined previously by RDM [39]. The agreement indicates a correct phenomenological treatment of the stopping power for ^{45}Sc ions recoiling in calcium and barium. Therefore, no correction factors f_n and f_e were applied to the nucleon and electronic stopping powers. Limits assigned to the mean lives were obtained assuming 20 % uncertainty in the stopping powers. The present lifetime values as well as previous results are presented in table II.

3. **Results.** — A summary of the experimental results obtained in the present work and a comparison with previous data are given in tables II and III. The over-all agreement between the present lifetime values and those obtained in the resonance fluorescence experiments is good. It should be pointed out that our reported lifetime values for the 1 237 and 1 409 keV levels are in disagreement with the values determined via the (p, p′ γ) and (p, γ) reactions respectively. This difference may come from the treatment of the stopping power in the case of recoiling ions with lower velocities ($\langle \beta \rangle \simeq 0.4\,\%$ for the first reaction, $\langle \beta \rangle \simeq 0.1\,\%$ for the second one). Furthermore since the 1 237 keV transition is pure E2, additional lifetime information is directly available from Coulomb excitation experiments [3-10]; the weighted average of the reported reduced E2 transition probabilities, $B(E2)\uparrow = 138 \pm 28\ e^2\ fm^4$, corresponds to a lifetime $\tau = 3\,100 \pm 600$ fs, in agreement with the present determined value. As pointed out earlier, calcium and barium seem to be slowing down materials providing correct lifetime values using the Doppler shift attenuation method; this leads to a greater confidence in the experimental transition probabilities determined in the present work.

TABLE III

Spin and multipole mixing ratio values derived from the present angular correlation measurements. Lifetime and other arguments limiting I^π and δ values are included (see text).

E_i (keV)	E_f (keV)	I_i^π	I_f^π	δ
377	0	3/2⁻	7/2⁻	-0.01 ± 0.08
	12	3/2⁻	3/2⁺	0.01 ± 0.02
721	0	5/2⁻	7/2⁻	-0.088 ± 0.055
1 069	377	3/2⁻	3/2⁻	0.11 ± 0.05
	721	3/2⁻	5/2⁻	-0.04 ± 0.13
1 237	0	11/2⁻	7/2⁻	0.02 ± 0.02
1 409	0	5/2⁻	7/2⁻	0.9 ± 0.4
		7/2⁻	7/2⁻	$-0.05^{+0.09}_{-0.13}$
1 557	1 069	1/2⁻	3/2⁻	unconstrained
1 662	0	9/2⁻	7/2⁻	0.47 ± 0.05
	1 237	9/2⁻	11/2⁻	0.03 ± 0.13
2 092	0	5/2⁻	7/2⁻	0.05 ± 0.06
	1 069	5/2⁻	3/2⁻	0.05 ± 0.20
2 107	1 237	15/2⁻	11/2⁻	0.02 ± 0.05

Another general remark concerns the dipole to quadrupole mixing ratios δ. The wide allowed range for δ resulting from a previous experiment [26], is now considerably narrowed and can lead to much more accurate values for the $B(E2)\downarrow$ reduced transition probabilities. Furthermore unambiguous spin assignments have been made for most of the negative parity states up to 2 107 keV.

In this section, some observed states of ^{45}Sc will be discussed individually. Since no new information was obtained for the $3/2^-$, 376.8 keV, the $11/2^-$, 1 237.5 keV and the $15/2^-$, 2 106.8 keV levels, except lifetimes (or limits), they will not be discussed individually here. The present angular correlation and lifetime results confirm the spin and parity assignments made in reference [22] for the first level, in references [26, 27] for the second level and in reference [27] for the latter one.

3.1 720.6 keV LEVEL. — This level decays by a 96.5 % branch to the $7/2^-$ ground state and a 3.5 % branch not reported previously to the $3/2^+$, 12.4 keV state. This level has been seen in the (^{3}He, d) reaction [22] where the deuteron angular distribution was fitted with $l_p = 3$ implying $I^\pi = 5/2^-, 7/2^-$. The angular correlation of the 721 keV transition leads to a definite $I^\pi = 5/2^-$ assignment (Fig. 2) in agreement with Eastham and Phillips [10]. In order to reproduce acceptable E2 transition strengths, δ values > 15 and < -60 were rejected and the value given in table III adopted. Taking into account the weighted average value $B(E2) \uparrow = 67 \pm 10$ e^2 fm^4 deduced from Coulomb excitation experiments [3-10] and the branching ratio and lifetime values, we calculate an absolute value for the mixing ratio $|\delta| = 0.084 \pm 0.007$ in excellent agreement with the present one.

3.2 1 068.6 keV LEVEL. — In both stripping and pick up reactions [22, 23] this state is populated by an $l_p = 1$ transition, allowing $I^\pi = 1/2^-$ and $3/2^-$. The level decays by a 76% branch to the $3/2^-$, 376.8 keV level and a 24% branch to the $5/2^-$, 720.6 keV level; this last branch was not reported by Zuk *et al.* [26] who could not resolve the 1 068.6 → 720.6 keV and 376.8 → 12.4 keV transitions due to the use of an NaI detector. In the present case, the simultaneous analysis of the two reported transitions rules out $I = 1/2$ and yields a definite $I^\pi = 3/2^-$ to the level. This confirms the proposed $I = 3/2$ value of Rust *et al.* [21] based on the analysis of the ^{45}Sc(p, p′) reaction in terms of Hauser-Feshbach theory.

3.3 1 409.5 keV LEVEL. — This level was found to decay by a 87 % branch to the $7/2^-$ ground state and by a 13 % branch to the $5/2^-$, 720.6 keV level, in agreement with the results of Blasi *et al.* [9] using the ^{45}Sc(p, p′ γ) reaction. The last branch was not observed in other experiments. A very weak branch to the $3/2^-$, 376.8 keV level has been reported by Chasman *et al.* [18] and Rust *et al.* [21]. This weak transition could not be observed in the present experiment.

The negative parity for this level results from the assigned $L_{np} = 0 + 2$ orbital angular momentum to the transferred neutron-proton pair in the ^{43}Ca(^{3}He, p) reaction [24]. The angular correlation for the 1 409.5 keV transition can be fitted at the 0.1 % confidence level by $I = 5/2$, 7/2 and 9/2. The present data alone are not sufficient to distinguish between the different spin sequences. The assignment $9/2^-$ has been proposed by Blasi *et al.* [9]. In that case, the mixing ratio for the ground state transition would be $\delta = -0.44 \pm 0.07$. However, taking into account the lifetime value given in table II and considering the weak branch to the $3/2^-$, 376.8 keV level, the $9/2^-$ possibility can be ruled out on the basis of unrealistic M3 enhancement. Moreover, Rust *et al.* [21] analysing the experimental proton angular distribution in terms of the Hauser-Feshbach theory, assigned a probable 7/2 spin to this level.

3.4 1 557.1 keV LEVEL. — Only a branch to the $3/2^-$, 1 068.6 keV state has been observed in the present work. In view of the limits set on other possible branches, it is in disagreement with the results of Chasman *et al.* [18] but does not contradict the γ-decay proposed by Schulte *et al.* [14] for this level.

This state is populated by an $l_p = 1$ transition in both stripping and pick up reactions [22, 23] which implies a spin assignment of $1/2^-$ or $3/2^-$. In the present experiment the angular correlations for the 489 keV transition is consistent with isotropy and thus with a 1/2 assignment but can also be fitted supposing a spin 3/2 for the initial state. Our data alone are not sufficient to give a definite spin assignment. However, according to Rust *et al.* [21], the experimental cross section for this level in the ^{45}Sc(p, p′) reaction gives clear evidence that the spin of the states is 1/2.

3.5 1 662.0 keV LEVEL. — This level appears to decay 79 % to the $7/2^-$ ground state and 21 % to the $11/2^-$, 1 237.5 keV level. The latter transition has not been reported by Sawa *et al.* [27] using the same reaction but at higher bombarding energies. The analysis of the γ-ray angular correlation for the 1 662.0 keV transition leads to $I = 5/2$ or 9/2. Realistic transition strengths for the present observed 1 662.0 → 1 237.5 keV transition are obtained only for a spin 9/2 assignment. In addition, positive parity can be rejected on the basis of unrealistic enhancement for an M2 component in the 1 662.0 keV transition. As a result, there is only one solution left : $I^\pi = 9/2^-$.

It should be pointed out that the present spin-parity assignment as well as the δ value for the 1 662.0 keV transition are in agreement with the quoted values of Sawa *et al.* [27] based on angular distributions and excitation functions.

3.6 2 092.3 keV LEVEL. — This level was observed in the ^{43}Ca(^{3}He, p) reaction with an $L_{np} = 0 + 2$ orbital angular momentum transfer [24]. It implies negative parity for the state. The present angular correlation measurement for the ground state transition can be fitted at the 0.1 % confidence level by $I = 7/2$ with $\delta = 0.51 \pm 0.10$, or $I = 5/2$ with $\delta = 0.05 \pm 0.06$ and $\delta = 5.7^{+2.4}_{-1.4}$, or $I = 3/2$ with $\delta = -0.19 \pm 0.12$. The angular correlation for the 2 092.3 → 1 068.6 keV ($3/2^-$) transition yields the following solutions : $I = 7/2$ with $\delta = 0.21^{+0.23}_{-0.17}$, or $I = 5/2$ with $\delta = 0.05 \pm 0.20$ and $\delta = 2.3^{+3.0}_{-1.0}$, or $I = 3/2$ with $\delta < 0.24$. On the basis of the lifetime results presented in table II, the $I^\pi = 3/2^-$ and $I^\pi = 7/2^-$ possibilities can be rejected because they would imply an enhanced M3 component in the first and second transition respectively.

Since the positive parity has already been excluded, we are left with an unique $5/2^-$ assignment for the spin and parity of this state; the larger δ values are not given in table III because they lead to E2 enhancements greater than 100 W.u.

4. **Discussion.** — Natural parity states for the ^{45}Sc nucleus have been calculated by McCullen, Bayman and Zamick [1] in the framework of the spherical shell model, considering 5 particles coupled in the $1f_{7/2}$ shell. The effective matrix elements of the residual interaction were estimated on the basis of the ^{42}Sc level scheme as it was known at that time. New calculations have been performed [29], [40] with improved values for the residual interactions. A rough agreement has been found between the energies of the lowest levels with $I \geqslant 7/2$ and the calculated values. The measured excitation energies for the $I = 3/2$, $5/2$, $1/2$ levels are definitely smaller than the calculated values and they appear difficult to reconcile with a pure $(1f_{7/2})^5$ configuration for any reasonable set of matrix elements for the residual interaction [29].

This situation is not surprising since the $3/2^-$ states at 377 and 1 069 keV as well as the $1/2^-$ state at 1 557 keV contain p-shell admixture in their wave functions as is shown in stripping reactions [22]. An extension of the shell model basis, to include the $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ subshells has been attempted recently by McGrory [41] but the calculations were limited to nuclei with $A \leqslant 44$. Figure 4 shows the experimentally established negative parity levels up to about 2.2 MeV of ^{43}Sc, ^{45}Sc and ^{47}Sc. The data on ^{43}Sc were obtained from reference [42], those on ^{45}Sc from the present work and those on ^{47}Sc from reference [43]. On the left side of the figure are the results of the shell model calculations [41] for $(fp)^3_{T=1/2}$ states. An improvement in the calculation of the excitation energies is observed as compared with the pure $(1f_{7/2})^3$ model. However, the complete low-lying odd-parity spectrum cannot be understood.

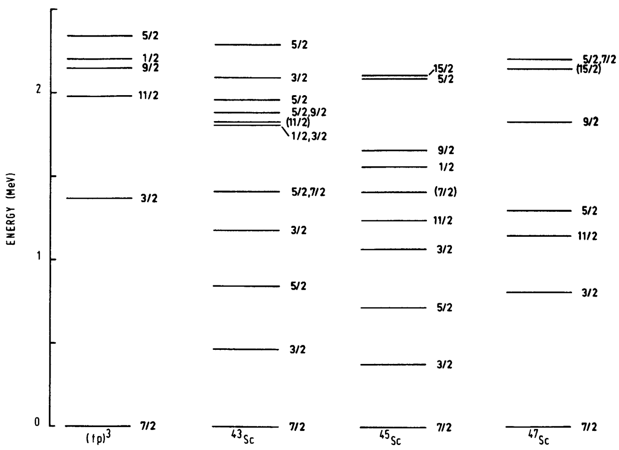

FIG. 4. — Low-lying negative parity levels of the nuclei ^{43}Sc, ^{45}Sc and ^{47}Sc as presently known. On the left side of the figure are the results of shell-model calculations [42] for $(fp)^3$ states.

In the case of the odd scandium isotopes, the $3/2^+$ states observed at very low excitation energy, strongly populated by $l_p = 2$ transitions in pick up reactions [44], are interpreted as proton holes in the $d_{3/2}$ shell. ^{43}Sc, ^{45}Sc and ^{47}Sc display $3/2^+$ levels at 151, 12 and 767 keV respectively. Such low-lying positive parity states suggest that configurations involving particle excitations of the ^{40}Ca core can be rather important for negative parity states as well. In the model of Johnstone [45] and Johnstone and Payne [46], the negative parity states of ^{43}Sc are assumed to arise from the mixture of pure $(fp)^3$ and 5p-2h (five particle-two hole) $K^\pi = 3/2^-$ rotational band states. An indication of the mixing of the two types of configurations is provided by the results of both the charge exchange reaction ^{43}Ca(^{3}He, t)^{43}Sc [47] and γ-ray spectroscopy in ^{43}Sc [48]. This model can account for the observed normal-parity level scheme. Although similar calculations, involving $(fp)^5$ and 7p-2h states have not yet been attempted for ^{45}Sc, we may compare the experimental and theoretical results of ^{43}Sc with the present results of ^{45}Sc. The strong similarity between the level schemes of these two nuclei suggest a $K^\pi = 3/2^-$ band in ^{45}Sc which comprise the levels at 377 keV ($3/2^-$), 721 keV ($5/2^-$), 1 409 keV ($7/2^-$) and probably the level at 1 662 keV ($9/2^-$) in addition to states arising chiefly from the $(fp)^5$ configuration. On the other hand the level scheme of ^{47}Sc differs appreciably from those of ^{43}Sc and ^{45}Sc. However, in that case the energy separation of the first $3/2^+$ core excited state and the ground state is larger than in the other two isotopes. Furthermore the agreement between the sequence of low-lying negative parity levels and the $(1f_{7/2})$ calculations performed by Brut [41] is quite good. This suggests that the contribution of the two hole states is less important than in ^{43}Sc and ^{45}Sc due to the neutron excess.

Another approach to the theoretical understanding of ^{45}Sc is provided by the strong coupling model of Bohr and Mottelson [49] which has been reasonably successfully applied to various nuclei in the $1f_{7/2}$ shell in spite of its great simplicity [2], [50, 51]. The calculations of Malik and Scholz [2] for the ^{45}Sc nucleus show a better agreement with the experimental data than the simple $(1f_{7/2})^5$ shell model. Unfortunately no transition probabilities have been calculated, therefore a detailed comparison with experiment is not possible. Calculations performed in the present study are based on the same model. The Nilsson Hamiltonian was used to describe the single particle motion. The lowest intrinsic state in ^{45}Sc is described with four neutrons coupled to $K = 0$ in the Nilsson orbitals No. 14 ($K = 1/2$) and No. 13 ($K = 3/2$) and the odd proton in the orbital No. 14 ($K = 1/2$). This unpaired proton was allowed to occupy any orbit in the $N = 3$ oscillator shell. The ground state band has therefore $K = 1/2$ but, due to the Coriolis coupling among different bands, the spin of the ground state differs from $1/2$. Details on the model as well as explicit relations for the matrix elements are given in reference [52]. The parameters C and D used in the Nilsson Hamiltonian are equal to -1.77 and -0.133 [51] consistant with the single particle energies as deduced from ^{41}Sc and ^{49}Sc. The value of the deformation parameter $\delta = 0.14$, close to the minimum of the total ground state energy, and the rotational constant $\hbar^2/2J = 90$ keV give the best fit between the calculated and observed spectrum. In figure 5 the experimental negative parity level scheme is compared to the calculated one. All levels are given in the theoretical spectrum up to 2.2 MeV and only states with $I > 13/2$ are reported at higher excitation energy. Electromagnetic properties were also calculated and the results of the calculations are given along with the experimental values in table IV. The free nucleon charge and gyromagnetic ratios were used, while a value of Z/A was adopted for the rotational gyromagnetic ratio. Values of -0.21 b and 5.36 n.m. are obtained for the electric quadrupole and magnetic dipole moments of the ground state which have to be compared to the experimental values [53] of -0.22 ± 0.01 b and $4.756\,33 \pm 0.000\,01$ n.m.

A survey of both figure 5 and table IV leads to two statements. First of all, a definite improvement is obtained for the energy spectrum : up to 2.2 MeV excitation energy, the model accounts for all the negative parity levels. On the other hand, several calculated transition probabilities disagree with the experimental data. At this point, it should be reminded that for several other nuclei of the $1f_{7/2}$ shell, the present model successfully reproduced the electromagnetic properties for states having a predominant ground state configuration [51]. This fact appears also in the present investigation where the main contribution to the wave functions of the first $7/2^-$, $3/2^-$, $11/2^-$ and $1/2^-$ states corresponds to the unperturbed $K^\pi = 1/2^-$ ground state band. The difficulties encountered for reproducing transition probabilities for other levels may arise from the omission of other types of excitation. Thus, the model explicitly treats the excitations of the unpaired proton from the Nilsson orbital No. 14 to all the other orbitals of the (fp) shell

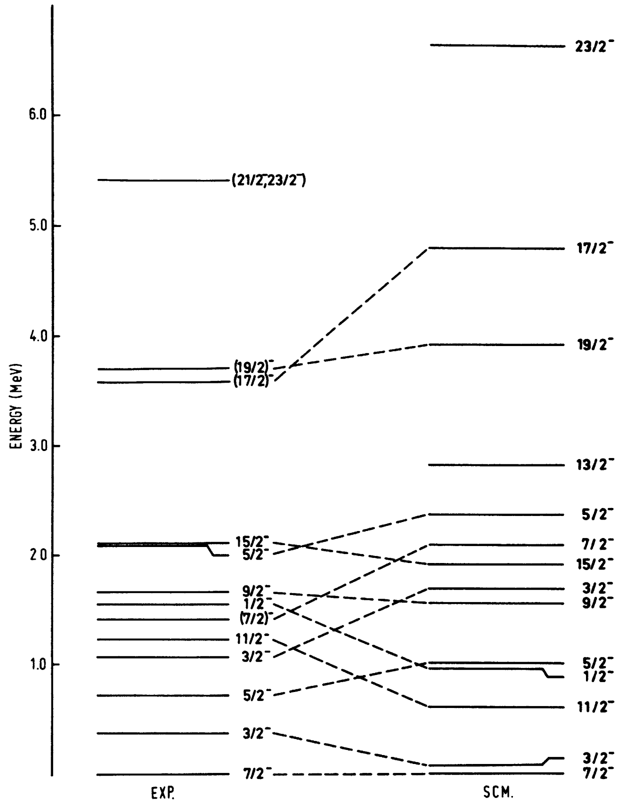

FIG. 5. — Comparison of the calculated negative parity energy levels in the framework of the strong coupling model (SCM) with experiment. The levels of angular momentum $I > 15/2$ are from reference [29].

TABLE IV

B(M1) and B(E2) reduced matrix elements for transitions between negative parity states in ^{45}Sc

E_i (keV)	E_f (keV)	I_i^π	I_f^π	B(M1) (μ_N^2) Exp.	B(M1) Th.	B(E2) (e^2 fm^4) Exp.	B(E2) Th.
377	0	$3/2^-$	$7/2^-$			144 ± 8	146
721	0	$5/2^-$	$7/2^-$	0.45 ± 0.05	0.87	89 ± 14	10
1 069	377	$3/2^-$	$3/2^-$	0.26 ± 0.09	0.25	93^{+171}_{-73}	10
	721		$5/2^-$	$0.65^{+0.27}_{-0.23}$	0.45	$< 3\,074$	55
1 237	0	$11/2^-$	$7/2^-$			104 ± 8	81
1 409	0	$7/2^-$	$7/2^-$	0.04 ± 0.01	0.13	> 12	0.32
	721		$5/2^-$	< 0.082	0.60	$< 2\,487$	24
1 557	1 069	$1/2^-$	$3/2^-$	< 1.69	3.4	$< 10^5$	21
1 662	0	$9/2^-$	$7/2^-$	0.05 ± 0.01	0.24	60^{+20}_{-16}	15
2 092	0	$5/2^-$	$7/2^-$	0.64^{+112}_{-9}	0.05	< 30	1.3
	377		$3/2^-$	< 0.145	0.04	< 708	1.5
	1 069		$3/2^-$	0.66 ± 0.25	0.87	< 735	14
2 107	1 237	$15/2^-$	$11/2^-$			< 206	81

but not the core excitations. Such excitations should be implicitly taken into account in a phenomenological way and this may explain the fair agreement obtained for the energy spectrum. However, the transition probabilities are much more sensitive to the details of the wave function. A better agreement for the electromagnetic properties may be obtained taking into account explicitly the 7p-2h component.

Note added in proof :

A value of (30 ± 3) ps has been measured for the mean life the 2 107 keV level by Bini, Blasi and Kutschera (private communication), resulting in a B(E2)↓ value of 55 ± 5 e^2 fm^4.

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