Low-Lying Excited States in In^{115} and In^{117}

V. R. PANDHARIPANDE, K. G. PRASAD, R. M. SINGRU, AND R. P. SHARMA
Tata Institute of Fundamental Research, Bombay, India
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The low-lying levels in In^{115} and In^{117} have been studied by gamma-gamma and beta-gamma directional correlation and life-time measurements. The gamma-gamma directional correlation of the 1306–274-keV cascade in In^{117} was found to be $W(\theta)=1+(0.271\pm0.013)P_2(\cos\theta)+(0.026\pm0.042)P_4(\cos\theta)$. The measurement of the beta-gamma directional correlation between the beta transition from Cd^{115} to the 598-keV level in In^{115} and the following gamma transition of energy 261 keV gave a P_2 coefficient $A_2(W)=-0.16\pm0.02$. Based on these measurements it is shown that the levels at 598 and 588 keV in In^{115} and In^{117}, respectively, have spin and parity $\frac{3}{2}^-$. The half-life of the 747-keV level in In^{117} was found to be 4.9 ± 0.2 nsec.

I. INTRODUCTION

THE energy levels of odd-mass indium isotopes have been of great interest in the recent years and considerable data[1–8] about these isotopes have been collected. In the neighboring even-even tin isotopes the first phonon energy is about 1250 keV. Therefore in the odd-mass indium isotopes the lowest collective levels which may arise owing to the coupling of the proton hole with the first phonon vibration of the even-even core are expected to occur in the energy region of 1.2 MeV. Such collective levels in In^{115} have been examined by Silverberg[9] and their existence has been indicated in our earlier work.[4] The levels in the lower energy region in these isotopes may be predominantly single-particle levels. The ground state in these isotopes has the spin and the parity assignment as $\frac{9}{2}^+$ and a configuration $g_{9/2}^{-1}$. The first excited state is known to be a $p_{1/2}$ isomeric state. The experimental data on the other low-lying energy levels in most of the cases are rather incomplete and the spin and the parity assignments to these levels are mainly based on the log *ft* values of the beta-transitions to these levels.

Burson *et al.*[1] have indicated that the second excited state in In^{113} at 645 keV is $\frac{3}{2}^-$ and de-excites by a 255-keV $(M1+E2)$ transition to the $p_{1/2}$ isomeric state at 390 keV. An excited state in In^{115} at 598 keV has been shown to be $\frac{5}{2}^-$ by Varma *et al.*[2] Recent work by Hans *et al.*[5] where they have carried out gamma-gamma directional correlation measurement for 230–262-keV cascade further confirms a $\frac{5}{2}^-$ assignment to this state. In the case of In^{115} it is also indicated by Tandon *et al.*[3] that a level at 829 keV has a half-life of 5.5 nsec and that it has a positive parity. In our earlier investigations[6] on In^{117} it has been shown that an assignment of $\frac{1}{2}^-$ or $\frac{3}{2}^-$ to the 588-keV second excited state is possible. Directional correlation measurements made by Mancuso *et al.*[8] indicate an assignment $\frac{3}{2}^-$ to this state.

The study of the above indium isotopes is further expected to give direct information about the role of neutron-proton residual interaction in nuclear structure. Recently, Silverberg[10] has treated the effect of short range neutron-proton interaction in a quasiparticle approximation on the single-particle level spacings. He has examined the variation in the energy difference between the levels $1g_{9/2}$ and $2p_{1/2}$ occurring in the odd-mass indium isotopes $(A=109-119)$.

The present work was initiated to study the systematics of the low-lying energy levels of odd-mass indium isotopes. For an accurate determination of the energies of the various low-lying gamma transitions in In^{115} and In^{117}, their singles gamma spectra have been studied on a lithium-drifted germanium detector. Further the beta-gamma directional correlation measurements have been carried out in In^{115} and the gamma-gamma directional correlation and lifetime measurements are carried out

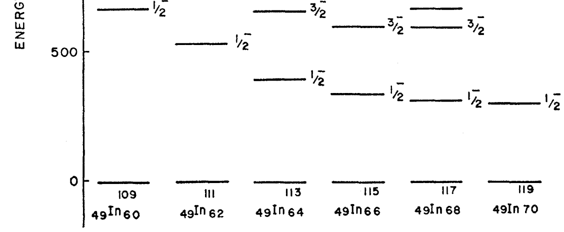

FIG. 1. Energy levels of odd-mass indium isotopes. The levels above 1 MeV are not shown here.

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[10] L. Silverberg, Nucl. Phys. **60**, 483 (1964).

in In^{117}. The spin assignments to the 598-keV level in In^{115} and 588-keV level in In^{117} are based on the present measurements. These results are compared with the other neighboring odd-mass isotopes of indium (Fig. 1) and the possible nature of the low-lying energy levels has been discussed.

II. EXPERIMENTAL PROCEDURE

A. Source Preparation

The enriched samples of Cd^{114} (98%) and Cd^{116} (97.2%) in the form of CdO were obtained from the Oak Ridge National Laboratory and were irradiated in the Canada India Reactor at Trombay for periods of 48 and 6 h, respectively, with a flux of 10^{13} neutrons/cm²/sec. The sources of Cd^{115} and Cd^{117} were chemically purified for any contamination of Zn, Ag, Mn, etc. The chemical procedure followed has been described earlier.[6] The possible contribution to these activities due to other Cd isotopes is expected to be much less than 1% of the total activity produced. The sources for the gamma-gamma angular-correlation measurement were in liquid form while the beta sources were deposited on a thin Mylar film (500 $\mu g/cm^2$).

B. Singles Gamma Spectra

The singles gamma spectra of Cd^{115} and Cd^{117} were studied on a lithium-drifted germanium detector with a full width at half-maximum of 9 keV for the 662-keV transition in Ba^{137}. The spectra were recorded on a 512-channel analyzer. In order to scan the low-energy region the calibration was sufficiently expanded and the observations were started within 10 min of the indium separation from the source. These spectra are given in the Figs. 2 and 3.

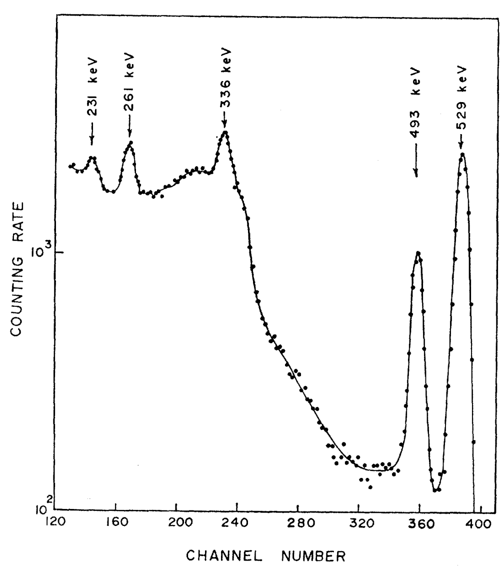

FIG. 2. Cd^{115} gamma-ray spectrum.

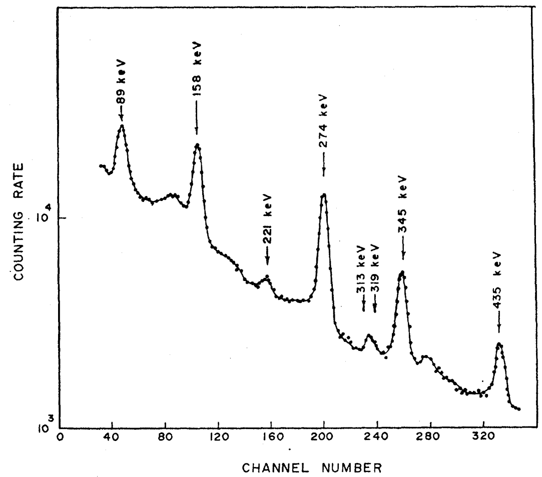

FIG. 3. Cd^{117} gamma-ray spectrum in the energy range 70–450 keV.

C. Directional-Correlation Measurements

The gamma-gamma directional-correlation measurements for the 1306–274-keV cascade in In^{117} (Fig. 6b) have been carried out by using three detectors. The detectors were 2 in. diam × 2 in. thick NaI(Tl) crystals coupled to RCA 6810A photomultipliers. The arrangement of the detectors is shown in Fig. 4. The two detectors B and C were kept fixed at right angles to each other while the third one, A, was movable and could be placed at any desired position. As shown in Fig. 4, the detector A, in position 1, was placed in such a way that the detector B was at 90° and the detector C was at 180° with respect to A. In position 2, both B and C were at an angle of 135° with respect to A, while in the third position C and B were at 90° and 180°, respectively.

The coincidence arrangement was set up in two channels so that the pulses from both counters B and C could be observed in coincidence with those in the counter A. This arrangement was of the usual fast-slow type and the coincidence circuit for the two channels was similar to that used by Simms.[11] The coincidence resolving time was $2\tau = 30$ nsec. The coincidence effi-

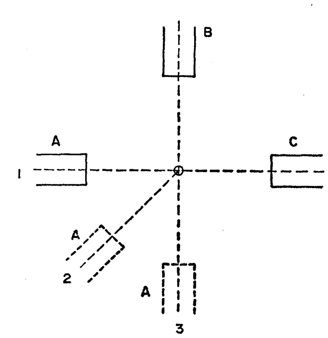

FIG. 4. Experimental arrangement of the detectors for the gamma-gamma directional-correlation measurements.

[11] P. C. Simms, Rev. Sci. Instr. 32, 894 (1961).

ciency was checked by using the annihilation radiation from a Na^{22} source. A comparison of the coincidence and singles spectra indicated that the coincidence efficiency remained constant above 30 keV and that it was almost 100%. Frequent checks were carried out for any shift of the photo peaks in all the three counters.

The three detectors were aligned in such a way that their axes of symmetry were in the same horizontal plane and passed through the center of the source. The source was at a distance of 5.5 cm from the detectors and was centered within an accuracy of 1%. The strength of the source was adjusted such that the true-to-chance-coincidence ratio was better than 20. The complete angular correlation arrangement was checked by measuring the gamma-gamma directional correlation of the 1170–1330-keV cascade occurring in the decay of Co^{60}.

In the present gamma-gamma directional correlation measurements of 1306–274-keV cascade the photopeak corresponding to the 274-keV gamma ray was accepted as the gate in the counter A. The coincidences with the 1306-keV gamma radiation were observed simultaneously at two angles in the counters B and C. The detectors B and C were covered with $\frac{1}{4}$ in. thick lead on all sides to prevent spurious conicidences due to Compton scattering. The beta absorbers were $\frac{3}{8}$ in. thick perspex disks placed on all the three detectors.

The coincidence counts were collected for an interval of 5 min in each of the three positions of the counter A (Fig. 4). The standard procedure of recording the coincidences in the sequence $\theta=90°$, 135°, 180°, 180°, 135°, 90°, etc., was followed. Thus, starting from position 1 the counter A was moved to position 3 in the order 1, 2, and 3 and then back to position 1 in the reverse order. The data collected from the three positions (1, 2, 3 or 3, 2, 1) of the counter A was treated as one set of observation. As explained above, in each set the 274–1306-keV coincidence counts at 90° were observed between the counters A and B (position 1) and between A and C (position 3). Simultaneously the coincidence counts at 180° were collected between A and C (position 1) and between A and B (position 3). The respective singles and coincidence counts corresponding to 90° and in 180° position 1 were added to their counter parts in position 3. Since in position 2 both the B and C counters were at 135° with respect to A, the data for the above cascade at this angle was obtained by adding the singles and coincidence counts of the two pairs of the detectors in this position. The coincidence counts at 90°, 135°, and 180° thus obtained in each set were normalized to the singles counting rate and the anisotropy at 135° (A_{135}) and at 180° (A_{180}) was calculated. Finally a properly weighted mean of A_{135} and A_{180} was found for all sets of observations. In the above method of cross adding of the counts in each set, it is not necessary to apply the decay correction. Such a correction is difficult to apply to the singles counting rates of short lived activities which decay to active daughter products. This particular difficulty can be minimized by using the above method of cross adding. In this method the uncertainties due to the shift in photopeaks and window widths as encountered in a fixed counter system, are also reduced to a minimum, because both the counters B and C are utilized in turn for the collection of data at all the three angles.

The beta-gamma directional correlation measurements in the decay of 53-h Cd^{115} were carried out by using two detectors. The experimental arrangement has already been described in our earlier work.[4] The beta detector was a 1 in. diam × 0.25-in. thick anthracene crystal and the source was placed in vacuum at a distance of 3.5 cm from the detector. The 261-keV gamma radiation was observed in coincidence with the betas in the energy interval 650–850 keV at the two angles 90° and 180°.

D. Lifetime Measurements

The half-life of the 747-keV excited state in In^{117} has been measured by using the modified Green-Bell[12] type 6BN6 time-to-pulse-height converter. The slope of the prompt curve as obtained by using the Co^{60} source was 0.4 nsec. The delayed coincidences between the betas of energy 1200±100 keV and the 435-keV gamma transition were recorded on a 512-channel analyzer. The data for this measurement and the prompt curve using a Co^{60} source were collected alternately under exactly similar conditions. The Cd^{117} and Co^{60} sources were alternated after every 20 min.

III. RESULTS AND ANALYSIS

A. Gamma-Gamma Directional Correlation

The gamma-gamma directional correlation function for the 1306–274-keV cascade in In^{117} was expressed in the form

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)+\cdots. \quad (1)$$

The attenuation correction for the finite geometry of the detector was made according to Stanford and Rivers.[13] The coefficients are obtained as follows:

$$A_2=+0.271\pm0.013,$$
$$A_4=+0.026\pm0.042.$$

The possible spin sequences for the levels at 1893, 588, and 313 keV in the above cascade [Fig. 6(b)] are as follows:

(A) $\frac{1}{2}^+(M2)\frac{5}{2}^-(E2)\frac{1}{2}^-$,
(B) $\frac{1}{2}^+(E1, M2)\frac{3}{2}^-(E2, M1)\frac{1}{2}^-$,
(C) $\frac{3}{2}^+(E1, M2)\frac{5}{2}^-(E2)\frac{1}{2}^-$,
(D) $\frac{3}{2}^+(E1, M2)\frac{3}{2}^-(E2, M1)\frac{1}{2}^-$.

[12] R. E. Green and R. E. Bell, Nucl. Instr. Methods 3, 127 (1958).
[13] A. L. Stanford, Jr. and W. K. Rivers, Jr., Rev. Sci. Instr. 30, 719 (1959).

The spin and parity assignment to the 1893-keV level are based on the allowed nature of the beta transition to this state. The values of the coefficients A_2 and A_4 were calculated using the standard formulas.[14] It is found that the spin sequence (A) given above does not reproduce the observed gamma-gamma directional correlation. In the case of cascade (C) the angular correlation function depends on the mixing ratio of $E2$ to $M1$ in the $\frac{3}{2}^-$ to $\frac{5}{2}^-$ transition. If this ratio is so chosen as to agree with the observed A_2 value then the calculated value for A_4 comes out to be -0.09, which is not in agreement with the observed A_4 value ($+0.026\pm0.042$). Thus the observed angular correlation does not fit with the spin sequence (C). In the remaining spin sequences (B) and (D) the intermediate spin is $\frac{3}{2}$ which makes the A_4 term zero. The observed value of the A_2 coefficient can be fitted in both the cascades with various mixing ratios of $E2$ to $M1$ in either or both the transitions. Hence it is not possible to assign definite multipolarities to the two transitions in the 1306–274-keV cascade but in any case it is evident from the above discussion that the spin and parity of 588-keV level is $\frac{3}{2}^-$. The negative parity is indicated by the log ft value (7.8) of the beta transition to this state and the systematics of energy levels in these nuclei. It may further be noted that the value of A_2 for this cascade as measured by Mancuso *et al.*[8] is ($+0.020\pm0.01$). This value does not agree with our measurement but their spin assignment to the 588-keV level is same as ours.

B. Beta-Gamma Directional Correlation

The directional correlation function between the betas in the energy interval 650–850 keV and the following 261-keV gamma transition as obtained in the decay of 53-h Cd^{115} (Fig. 6a) was expressed in the form

$$W(\theta)=1+A_2(W)P_2(\cos\theta)+\cdots. \qquad (2)$$

The solid-angle attenuation correction was applied according to Breitenberger[15] and Stanford and Rivers.[13] The correlation coefficient was obtained as follows:

$$A_2(W)=-0.16\pm0.02.$$

Since this directional correlation is not isotropic, an assignment of spin-$\frac{1}{2}$ for the 598-keV level in In^{115} [Fig. 6(a)] is ruled out. However, if the spin and parity of the level at 598 keV are considered to be $\frac{5}{2}^-$, then the beta transition at this level would be of the first-forbidden unique type and the following gamma transition would be a pure $E2$ in character. Under these circumstances the value of $A_2(W)$ in Eq. (2) can be theoretically predicted,[14] and it comes out to be $A_2(W)$ unique $=+0.38$. The observed value $A_2(W)=-0.16\pm0.02$ does not agree with this "unique" value and hence the assignment $\frac{5}{2}^-$ is also ruled out. Thus the only possible spin and parity assignment to the 598-keV level consistent with the present data is $\frac{3}{2}^-$. The parity assignment is negative because the beta-gamma directional correlation is not isotropic and the beta transition has log $ft=8.3$, which indicates that it is first-forbidden in character.

C. Half-Life of the 747-keV Excited State in In^{117}

The time-to-pulse-height conversion (TPC) spectrum of the 435-keV transition in coincidence with the beta transition to the 747-keV level is given in Fig. 5. The half-life of the 747-keV level as inferred from the slope of the TPC curve is 4.9 ± 0.2 nsec.

IV. DISCUSSION

The low-lying energy levels of In^{115} and In^{117} are given in Figs. 6(a) and 6(b), respectively. In the earlier work, Varma *et al.*[2] have an assigment $\frac{5}{2}^-$ to the 598-keV level in In^{115} on the basis of the log ft value 8.3 which indicates the first-forbidden unique character of the beta transition to this level. However, it is well known that the high log ft value is not a sufficient criterion for a beta transition to be first-forbidden unique in character (e.g., beta transition from $\frac{11}{2}^-$ isomeric state of Cd^{115m} to the $\frac{9}{2}^+$ ground state of In^{115} has log $ft\sim8.9$). The beta-gamma directional-correlation data as given above

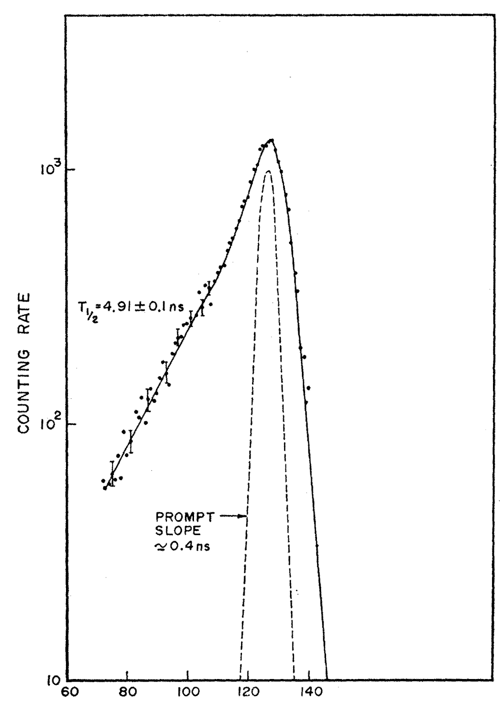

FIG. 5. The time-to-pulse-height conversion spectrum as obtained in the study of the half-life of the 747-keV excited state in In^{117}. The prompt spectrum taken under identical conditions using a Co^{60} source is shown by the dashed curve.

[14] *Alpha, Beta, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Chap. XIX A.

[15] E. Breitenberger, Proc. Phys. Soc. (London), **A66**, 846 (1953).

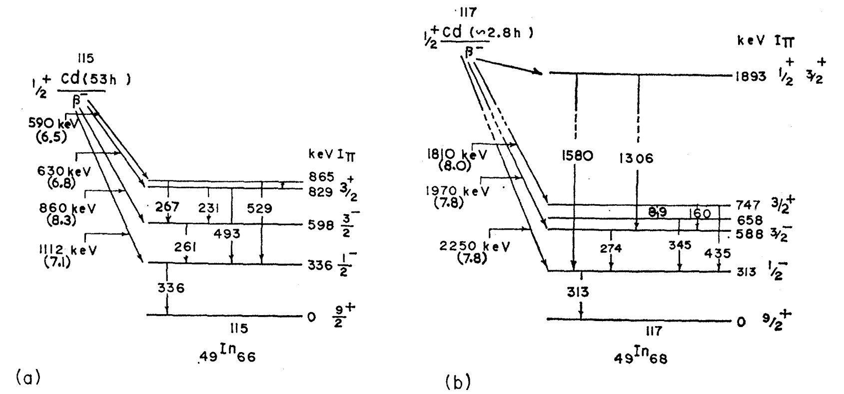

FIG. 6. (a) Decay scheme of 53-h Cd^{115}. (b) Partial decay scheme of (~2.8-h) Cd^{117}. A level at 400 keV in In^{117}, as shown by Ref. 8, is not included in the decay scheme because we feel that the experimental evidence supporting it is not yet complete.

clearly indicate that the transition is not of first-forbidden unique type and the most likely spin and parity of the 598-keV level is $\frac{3}{2}^-$. The gamma-gamma directional-correlation measurement of the 230–262-keV cascade, carried out by Hans *et al.*,[5] has again indicated the possibility of $\frac{5}{2}^-$ to the 598-keV level, based mainly on the small, finite and positive value of A_4 term obtained by them. The value of A_4 (0.05 ± 0.04) as quoted by Hans *et al.*[5] is just on the border line of the error quoted. For an assignment of $\frac{3}{2}$ to the 598-keV level, the A_4 term should be zero. The conclusion arrived at from the beta-gamma directional correlation thus seems to be more relevant.

In In^{113}, In^{115}, and In^{117} a $\frac{3}{2}^-$ state appears above the $p_{1/2}$ isomeric state with a nearly constant separation of ~265 keV. The excitation of the proton hole in the $p_{3/2}$ orbital can give rise to a $\frac{3}{2}^-$ level in these isotopes. Using the expression[16] $4.1\times(1/A^{1/3})\mathbf{l}\cdot\mathbf{S}$ for the spin-orbit coupling, it is found that the $p_{3/2}$ level lies about 1.2 MeV above the $p_{1/2}$ isomeric level. On the other hand, as has been discussed in the introduction, the $\frac{3}{2}^-$ level due to the coupling of one phonon with the $p_{1/2}$ proton hole will also be about 1.2 MeV (which is the first phonon energy in this region) above the $\frac{1}{2}^-$ isomeric state. Thus it is evident that the energies of the two $\frac{3}{2}^-$ levels, one being the single particle $p_{3/2}$ and the other being a member of ($p_{1/2}+\hbar w$) doublet, are quite close to each other and they may interact strongly. In this way one of the resulting $\frac{3}{2}^-$ excited states may be lowered in energy. Silverberg[9] has considered a P_2 plus short-range n-p interaction and has suggested the lowest $\frac{3}{2}^-$ level at about 1 MeV, which is about 700 keV above the $p_{1/2}$ isomeric state. This energy difference again appears to be much more than the difference of about 265 keV, which is observed in the present work.

The level at 747 keV in In^{117} is populated by a beta transition from the $\frac{1}{2}^+$ ground state of Cd^{117} and a gamma transition from the 1070-keV level[6] (spin and parity $\frac{7}{2}^+$) in In^{117}. Hence the possible spin and parity assignments to this level could be $\frac{5}{2}^-$ and $\frac{3}{2}^+$. The 829-keV level in In^{115} has possible spin and parity assignments[3] $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{3}{2}^-$. These two levels appear to be similar in nature since they lie in the same energy region and have same half-lives (~5 nsec). A $\frac{3}{2}^+$ assignment is possible for both these levels. On the basis of this assignment the beta transitions would be allowed and their observed log *ft* values (6.8 in Cd^{115} and 8 in Cd^{117}) would appear to be too large. Such a $\frac{3}{2}^+$ state in these isotopes can arise either as a three-particle state or due to the coupling of the $g_{9/2}$ hole with the 4^+ two-phonon state of the even-even tin core. Such configurations can explain the retardation of the gamma transitions from these levels as well as the beta transitions to those levels. It is however difficult to understand such a level appearing so low in energy.

ACKNOWLEDGMENTS

We are grateful to Professor B. V. Thosar for his continued interest in the present work. Thanks are also due to Shrimati Radha Menon and Shri A. T. Rane for the chemical purification of the sources carried out by them.

[16] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **27**, No. 16 (1953).