Absolute Transition Probabilities in the Odd-Odd Nucleus Pr^{144}†

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The lifetimes of three levels of the odd-odd Pr^{144} nucleus were determined by coincidence measurements between the beta spectrum of Ce^{144} and the conversion lines de-exciting the levels under investigation, using a double-lens coincidence spectrometer. The measurements were carried out using both the conventional self-comparison method and a modified version of this technique particularly appropriate for low-energy transitions. The mean lifetimes of the 133.5-, 100-, and 80.1-keV levels were found to be: $(0.95\pm0.5)\times10^{-11}$ sec, $(1.0\pm0.2)\times10^{-9}$ sec, and $(1.8\pm0.2)\times10^{-10}$ sec, respectively. The transition probabilities agree very well with those derived from shell model calculations in terms of coupling between the odd neutron and odd proton, if values of the "effective moments" are used in the calculation.

The following assignments for the unpaired neutron-proton configurations provide a consistent description of the states:

Ground state: $|f_{7/2}, g_{7/2}; 0-\rangle$.
80-keV Level: $0.37\,|f_{7/2}, g_{7/2};\ 1-\rangle+0.93\,|f_{7/2}, d_{5/2}; 1-\rangle$.
100-keV Level: $|f_{7/2}, g_{7/2}; 2-\rangle$.
133-keV Level: $-0.93\,|f_{7/2}, g_{7/2}; 1-\rangle+0.37\,|f_{7/2}, d_{5/2}; 1-\rangle$.

1. INTRODUCTION

INFORMATION concerning the sequence of excited levels, their spin assignment, and transition probabilities of odd-odd nuclei are at present quite meager. There have been several theoretical attempts to analyze the sequence of levels of odd-odd nuclei and derive the rules governing the coupling of the unpaired nucleons according to the shell model,[1–3] or the collective model in the regions of deformed nuclei.[4]

Of great importance for the theoretical understanding of odd-odd nuclei is the determination of absolute transition probabilities, and here the data is particularly scarce. Only a few determinations of the lifetimes of excited states have been carried out in the region 10^{-9} to 10^{-12} sec in odd-odd nuclei. The ground states of these isotopes are unstable and consequently, two powerful methods for determining transition probabilities, namely, Coulomb excitation and resonant scattering, are not applicable. Except in a few special cases,[5] the only method available so far has been the use of delayed coincidences.

The odd-odd nucleus Pr^{144} has three neutrons outside a closed shell and possesses essentially a spherical shape. In this work absolute transition probabilities of several transitions in this nucleus were determined, and the results were interpreted in terms of the shell-model coupling scheme between neutron and proton configurations.

Of particular interest are the results of the present work for the 133.5-keV level which decays by three competing $M1$ transitions, two of which are not retarded in comparison with single-particle values. These unusually fast transitions are interpreted as taking place between levels belonging essentially to the same configuration. Comparison between theory and experiment then provides valuable information concerning the configurations of the levels, since the theoretical transition probabilities are quite sensitive to the particular configurations chosen.

The population of the Pr^{144} levels obtained by beta decay of Ce^{144} has been investigated by many researchers. Geiger *et al.*[6] investigated the conversion electron spectrum from Ce^{144} decay, using a high-resolution beta spectrometer, and constructed an unambiguous decay scheme including spin assignment of the levels, the multipolarities of the de-exciting transitions, and their relative transition probabilities. Figure 1 shows the decay scheme as constructed by Geiger *et al.*[6] In a recent paper Geiger *et al.*[7] have completely supported their previous work by coincidence measurements and have discarded some additional transitions and levels proposed by other researchers.

The first excited level at 59 keV disintegrates by an $M3$ transition to the ground state, with a lifetime that is too long to be measured by a delayed coincidence technique. In fact, Geiger *et al.*[7] failed to observe coincidences, with a resolving time of 1 μsec, between the 41-keV transition feeding the level and the $M3$ transition. No attempt has been made in this work to determine the lifetime of this first excited state. However, the lifetime of the three upper levels that are de-excited by $M1$ transitions were determined in this present work. The mean lifetimes of the 133-, 100-, and 80.1-keV levels were found to be: $(0.95\pm0.5)\times10^{-11}$ sec, $(1.0\pm0.2)\times10^{-9}$ sec, and $(1.8\pm0.2)\times10^{-10}$ sec, respectively.

† A short preliminary report of this work was published in Phys. Letters 1, 147 (1962).
[1] A. de-Shalit, Phys. Rev. **91**, 1479 (1953).
[2] C. Schwartz, Phys. Rev. **94**, 95 (1954).
[3] A. de-Shalit and J. D. Walecka, Nuclear Phys. **22**, 184 (1961).
[4] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).
[5] J. Burde and S. G. Cohen, Phys. Rev. **104**, 1093 (1956).
[6] J. S. Geiger, R. L. Graham, and G. T. Ewan, Nuclear Phys. **16**, 1 (1960).
[7] J. S. Geiger, R. L. Graham, and G. T. Ewan, Nuclear Phys. **28**, 387 (1961).

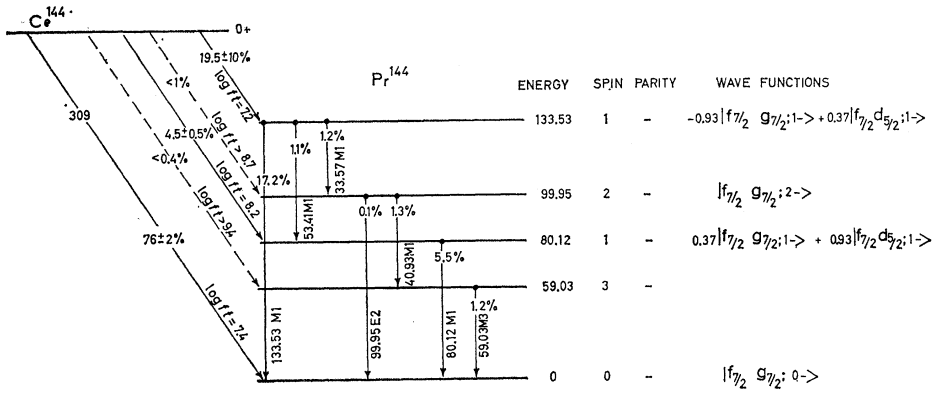

FIG. 1. Decay scheme of Ce^{144} as constructed by Geiger *et al.* (reference 6) with the configuration assignments of the present work.

The measurement of delayed coincidences between beta particles and conversion electrons using the self-comparison method seemed the most appropriate for the lifetime measurements of these low-energy levels, provided that the lifetime of the intermediate levels feeding them are sufficiently short in comparison.

The 133-keV upper level is only populated directly by beta decay. The 80-keV state is mainly fed by direct beta branch and partially via the 133-keV level. The 100-keV level is populated essentially via the 133-keV state. The lifetime measurement of the 133-keV level yielded a time that was much shorter than the lifetimes of the other two levels, so that no difficulty arises from the lifetimes of intermediate levels.

The lifetime measurement of the 133-keV level was carried out by the usual self-comparison method.[8] The lifetimes of the 80.1- and 100-keV levels were measured by using a new experimental method, which is essentially a modification of the conventional self-comparison method and is described in Sec. 4.

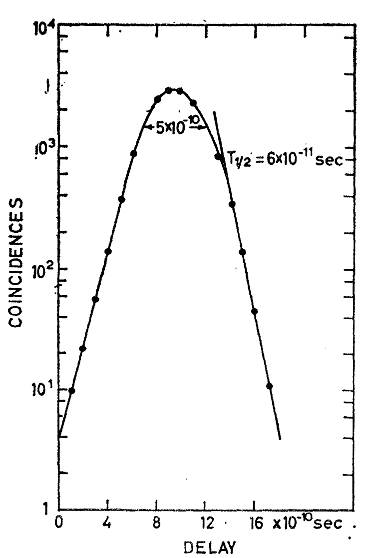

FIG. 2. Prompt coincidence curve obtained with Co^{60} source.

[8] R. E. Bell, R. L. Graham, and H. E. Petch, Can. J. Phys. **30**, 35, (1952).

Every conversion line focused in the spectrometer under the prevailing conditions of momentum resolution, however, contained, in addition, tails of conversion lines corresponding to transitions de-exciting other levels. Corrections arising from these contributions could be made rather precisely, since the lifetimes of all the levels whose de-exciting transitions contribute to coincidence were measured in this present work. The relative intensities of the interfering lines and their contribution to the coincidence rate were deduced from the work of Geiger *et al.*[6] and from the known shape of the conversion lines in our spectrometer. Thus, the lifetime determination of all the three levels increased the reliability of the lifetime measurements of each one of the levels.

2. EXPERIMENTAL ARRANGEMENT

Fission product Ce^{144} obtained from the Radiochemical Centre, Amersham, was stored for about one year. A 90-μC source of Ce^{144}, in the form of chloride, was deposited on a 1-mg/cm^2 Mylar foil covered with an evaporated thin film of gold. The source had a circular shape of about 5 mm in diam.

All the lifetime measurements in this work were carried out with the aid of a double-lens coincidence beta spectrometer,[9] and the delayed coincidences were recorded between the beta spectrum and the appropriate conversion line de-exciting the level under investigation. The transmission and momentum resolution were adjusted to about 5%.

The focused electrons were detected by plastic scintillators coupled to 56AVP Philips photomultipliers. The pulses from the collector were fed into a delay-to-pulse-height converter similar to that described by Green and Bell.[10] The pulses from the twelfth dynodes were introduced into linear amplifiers and after discrimination against the noise pulses, passed to a coincidence circuit having a resolving time of 10^{-7} sec. The outcoming pulses from the amplifiers were channeled within 30 to 40% width of the peak voltage. The pulses

[9] T. R. Gerholm, Rev. Sci. Instr. **26**, 1069 (1955).
[10] R. E. Green and R. E. Bell, Nuclear Instr. **3**, 127 (1958).

were passed to a slow-fast triple coincidence circuit having a resolving time of 2×10^{-6} sec. The pulses from the time to amplitude converter were fed into an 80-channel pulse-height analyzer and gated by the pulses from fast-slow coincidence circuit. A pile-up rejector circuit was also incorporated.

The performance of the experimental setup was tested outside the spectrometer with a Co^{60} source. The pulses were channeled at the end of the compton distribution to within about 15% of the respective peak voltages.

Figure 2 shows the prompt coincidence graph made with the Co^{60} source. The full width of the curve at half-maximum, thus obtained, was 5×10^{-10} sec with a slope of $T_{1/2}=6\times10^{-11}$ sec.

The complete experimental arrangement was checked when a ThB source was inserted into the spectrometer. Coincidences were recorded between the K conversion line of the 238-keV transition (thorium F line) and the beta spectrum at the higher energetic side of the line. The pulse-height resolution from the detectors at the energy of the focused electrons (about 150 keV) was around 40%. Figure 3 shows the coincident spectrum thus obtained when the outcoming pulses were channeled within 30% of the peak voltage. The full width of the graph at half maximum was 1×10^{-9} sec with a slope of $T_{1/2}=1.8\times10^{-10}$ sec. The latter graph obtained with the spectrometer is only broadened by a factor of 2 in comparison with the former curve, although the energy of the electrons are lower by a factor of 7 in the latter case. The self comparison method[8] was tested in the present setup with the thorium source between the beta particles and F line. The position of the centroid of the analyzed spectrum, obtained by the gated multichannel, at one setting of the spectrometers' current was compared with the position of the centroid when the role of the spectrometers was inverted in time by an appropriate change in both channels.[11,12] The shift between the centroid which corresponds to twice the mean lifetime of the excited state[13,14] was calibrated by introducing a 7×10^{-10}-sec delay cable between one of the limiters and the 6BN6 coincidence circuit. To eliminate time-dependent drifts, many sets of measurements of short duration were made. Every set included four measurements of 10 to 15 min each, and consisted of self-comparison measurements carried out for two different lengths of cables. The mean lifetime thus computed for this excited level of Bi^{212}, after analyzing about 33 000 coincidences, was $\tau=(0.62\pm0.6)\times10^{-11}$ sec. The counting rate at the peak of the conversion line was higher than in the case of the 133-keV conversion line of the Ce^{144} source, and the difference in counting rates, when one spectrometer was set on the line and the second off, was much larger in the former case. Even under these more stringent conditions, no significant finite lifetime could be detected. It is interesting to note that the single-particle value for this $M1$ 238-keV transition, taking into account the conversion enhancement, is about 1.3×10^{-12} sec.

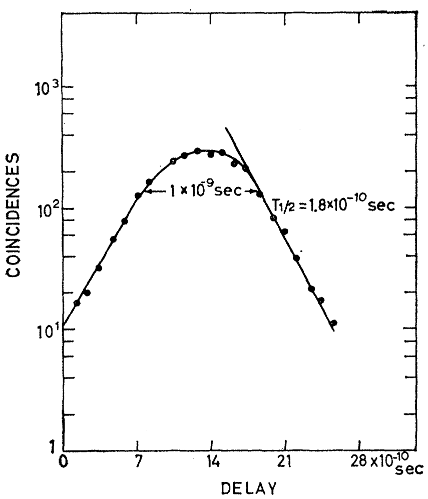

FIG. 3. Coincidence time delays between the beta spectrum and the K conversion line of the 238-keV transition (thorium F line) obtained with ThB source.

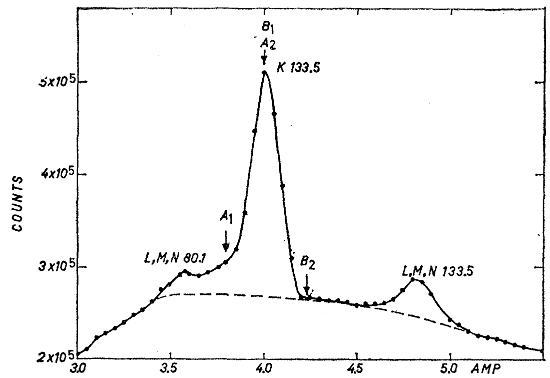

FIG. 4. The conversion spectrum superimposed on the continuous beta spectrum as obtained by one of the beta spectrometers. The arrows indicate the spectrometers' current settings in the self-comparison method measurement.

3. LIFETIME MEASUREMENT OF THE 133-keV LEVEL

The 133-keV level lifetime measurement was carried out using the self comparison method[8] recording coincidences between the beta spectrum and the K conversion line de-exciting the level to the ground state, using the experimental setup described in the previous section. Figure 4 shows the conversion spectrum superimposed on the continuous beta spectrum

[11] J. Burde, M. Rakavy, and S. Ofer, Phys. Rev. **124**, 1911 (1961).
[12] J. Burde and M. Rakavy, Nuclear Phys. **28**, 172 (1961).
[13] T. D. Newton, Phys. Rev. **78**, 490 (1950).
[14] Z. Bay, Phys. Rev. **77**, 419 (1950).

as obtained by spectrometer No. 1 that is facing the source. A similar spectrum was obtained by spectrometer No. 2 for electrons passing through the backing of 1 mg/cm² of Mylar. The only noticeable difference between the spectra was a more pronounced broadening on the lower energy flank of the conversion line in the latter case. The arrows labeled by A_1 and A_2 indicate the currents in spectrometers No. 1 and No. 2, respectively, in one coincidence arrangement and those that are designated by B_1 and B_2 are the corresponding settings in the inverse position. The result for the mean lifetime of the level obtained by analyzing a total number of 150 000 coincidences, was $\tau'=(1.0\pm0.3)\times10^{-11}$ sec. This result, however, must be corrected to take into account the following:

(a) A small change in the difference of the transit time of the electrons in the spectrometers set at positions A and B, (10^{-12} sec).

(b) At position A_1 spectrometer No. 1 accepts about 14% of the total intensity of the conversion line and at position B_2 about 3%.

(c) At position A_1 spectrometer No. 1 accepts a tail of the 80-keV transition whose contribution to the coincidence counting rate is about 1.6%.

(d) The L, M, conversion of the 100-keV transition with a relative intensity of 0.5% is not resolved, under the experimental conditions, from the K conversion line of the 133-keV transition.

Corrections (c) and (d) are by no means negligible, bearing in mind that the lifetime of the 80-keV level is about 20 times longer and that of the 100-keV state two orders of magnitude larger, as will be shown below. The corrections due to (b) and (c) increase the lifetime of the level under investigation, whereas those due to (a) and (d) shorten it. Taking into account all these corrections, the mean lifetime of the 133-keV state is $\tau=(0.95\pm0.5)\times10^{-11}$ sec. The estimate of the error was increased to take into account the small uncertainty in determining the exact shape of the tails of the conversion line and also the exact contribution of the interfering transitions, to the coincidence counting rate.

4. LIFETIME DETERMINATION OF THE 80-keV LEVEL

The lifetime measurement of the 80-keV level was carried out using the same experimental setup, but using a new experimental method, which is essentially a modification of the conventional self-comparison method, of the type used in the previous section. Figure 5 shows the K conversion line of the 80-keV transition and L conversion line of the 41-keV transition de-exciting the 100-keV level on the lower energetic side of the former line. A conventional self-comparison lifetime measurement would require a very thin source backing to enable the low-energy electrons to be detected by the second spectrometer. Moreover,

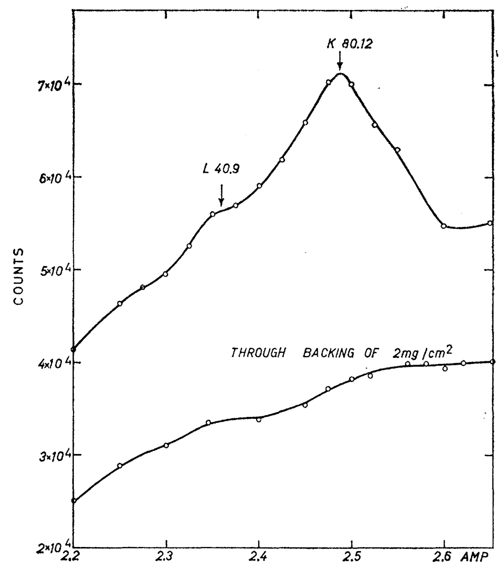

FIG. 5. Upper curve shows the conversion spectrum of the 80.12- and the 40.9-keV transitions superimposed on the continuous beta spectrum. Lower graph gives the spectrum when the electrons are transmitted through the source backing of 2 mg/cm².

focusing electrons on the lower energetic side of 80.1-keV K conversion line would accept a high portion of the 41-keV transition and K Auger electrons following the K conversion of the 133- and 80-keV transitions. Under these conditions, measurement of the lifetime by the conventional method would be impossible. It was decided therefore to focus electrons, whose original energy, when emitted from the source, were "off line," by utilizing to advantage the absorption of the energy of the electrons that pass through the relatively thick backing. The source on a backing of 1 mg/cm² of Mylar was introduced facing spectrometer No. 1 when the currents in *both* spectrometers were adjusted exactly to accept electrons of energy equal to the K conversion line of the 80.12-keV transition. In this arrangement the first spectrometer accepted the conversion line whereas the absorption through the backing shifted the energy of the line to a lower value so that it would not be focused by spectrometer No. 2. Instead of electrons due to the conversion line, beta particles with initial energy of about 7 keV higher, after some degradation of their energy by passing through the backing, were focused by the second spectrometer. The role of the spectrometers in time was inverted by rotating the source, which was situated between the two spectrometers, through 180° about an axis in the plane of the source (Fig. 6). In this experimental arrangement both spectrometers accept exactly the same energy of electrons in the direct and inverse positions. In this method no corrections have to be made due to a change in the transit time of the electrons in the spectrometers and no assumption concerning the change in the delay due to a small

alternation in energy of the electrons focused on the detectors.

The result for the mean lifetime of the 80.12-keV level obtained by this method was $\tau' = (2.08 \pm 0.15) \times 10^{-10}$ sec. A total number of 30 000 coincidences were recorded.

The measurements were repeated with the same source and the same experimental arrangement but using a thicker backing of 2 mg/cm^2. The result obtained after analyzing 22 000 accumulated coincidences was $(2.07 \pm 0.17) \times 10^{-10}$ sec. The excellent agreement between the results showed that a backing of 1 mg/cm^2 sufficed to shift the energy of the conversion line so that no tail of this line was accepted by the spectrometer facing the backing. The combined result of the two measurements was $\tau' = (2.08 \pm 0.12) \times 10^{-10}$ sec.

In arriving at the final result, the contributions to the coincident counting rate due to the interfering transitions had to be subtracted. At the peak of the K conversion line of the 80.1-keV transition a tail of the 41-keV transition, de-exciting the 100-keV level, is accepted by the spectrometer. This tail was chiefly due to the M conversion of the 41-keV transition and contributed about 4% to the coincident counting rate. Another contribution of about 1% to the coincident counting rate due to the Auger electrons following the K conversion of the 133-keV transition had to be taken into account. The last contribution could be considered as prompt since the lifetime of the 133-keV level is short, whereas the former contribution was calculated taking into account the longer lifetime of the 100-keV level, the measurement of which is described below.

The final result for the mean lifetime of the 80.1-keV level after carrying out the corrections is $\tau = (1.8 \pm 0.2) \times 10^{10}$ sec. The estimate of the error takes into account the uncertainty in determining the exact contribution of the interfering transitions.

5. LIFETIME MEASUREMENT OF THE 100-keV LEVEL

The lifetime of the 100-keV level was carried out by delayed coincidence technique between beta particles and the L conversion line of the 41-keV transition de-exciting the 100-keV level. The measurement was made using the same modified self-comparison method described in the previous section, rotating the source on a backing of 2 mg/cm^2 of Mylar. The arrow in Fig. 5 at the energy corresponding to the L 41-keV conversion line shows the positions of currents used in both spectrometers. The lower curve gives the spectrum measured by the spectrometers through the backing of 2 mg/cm^2 of Mylar. The mean lifetime obtained after analyzing 28 000 coincidences was $\tau' = (5 \pm 0.5) \times 10^{-10}$ sec. But, at the peak of the L conversion line of the 41-keV transition, the spectrometer accepted a relatively high fraction of the K conversion line of the

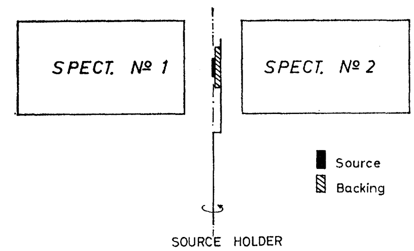

FIG. 6. A schematic diagram illustrating the rotation of the source and backing in the modified self-comparison method. In the position shown, spectrometer No. 1 accepts the conversion electrons and spectrometer No. 2 the continuous beta rays.

80.1-keV transition and K Auger lines of various transitions. The relative intensities of the lines are known rather precisely from the work of Geiger *et al.*[6] and, in principle, the contribution could be deduced from our knowledge of the profile of the main interfering line in the spectrometer. However, because of the low energy and finite thickness of the source, the shape of the low-energy flank of the conversion line was much less defined in comparison with the higher energy side, owing to the absorption of the energy of the electrons in source material. It was decided to estimate the interfering contribution by comparing the coincidence rate at the peak of the L conversion line of the 41-keV transition to that at the K conversion of the 80.1-keV transition, in the actual experimental setup. From the decay scheme it was estimated that this ratio of the coincidence rate should be equal very nearly (within 1%) to the ratio of the intensities of the two conversion lines which is 0.23, if there were no other contributions. The experimental ratio between the coincidence rates, however, was 0.50 ± 0.05. This shows that there are relatively large contributions from other transitions. These extra contributions to the coincidence counting rate at the L 41-kev peak are listed as follows: (a) M, N conversion of the 33.5-keV transition with a relative intensity of 8%; (b) K conversion of the 53.4- and 133.5-keV transitions, through the Auger K lines; (c) K conversion of the 80.1-keV transition through the Auger lines and also because the low-energy tail of the conversion line. Coincidences due to (a) and (b) are between the beta particles and electrons that de-excite the 133.5-keV level and might be considered as prompt ones. Those due to (c) involve the lifetime of the 80.1-keV level.

The object of the following analysis is to estimate the various contributions and suitably subtract them in order to obtain the corrected value for the lifetime of the 100-keV level.

From earlier work on Auger spectra[15,16] it was inferred in our work that at the L 41-keV line the spectrometer accepted 37% of the K Auger lines,

[15] E. H. S. Burhop, *The Auger Effect* (Cambridge University Press, New York, 1952).
[16] M. Maldjenović and H. Slätis, Arkiv Fysik 9, Nr. 4 (1954).

TABLE I. Measured lifetimes and absolute transition probabilities of excited states in Pr^{144}.

Energy of the level in keV	Mean lifetime of level in sec	Transition energy in keV	Multipolarity of transition	Gamma absolute transition probability in sec^{-1}	Single-proton values in sec^{-1}
133.5	$(0.95\pm0.5)\times10^{-11}$	133.5	$M1$	$(5.9_{-2.1}^{+6.5})\times10^{10}$	6.7×10^{10}
		53.4	$M1$	$(7.2_{-2.5}^{+8})\times10^{8}$	4.3×10^{9}
		33.5	$M1$	$(1.2_{-0.4}^{+1.3})\times10^{9}$	1.06×10^{9}
100	$(1.0\pm0.2)\times10^{-9}$	41	$M1$	$(2.6_{-0.5}^{+0.6})\times10^{8}$	1.9×10^{9}
		100	$E2$	$(2.4_{-0.4}^{+0.6})\times10^{7}$	1.2×10^{6}
80.1	$(1.8\pm0.2)\times10^{-10}$	80.1	$M1$	$(1.6_{-0.2}^{+0.2})\times10^{9}$	1.1×10^{10}

mainly due to the $K\rightarrow LM$ band, whereas at the K 80.1-keV conversion line 6% of the K Auger lines were accepted together with a tail of relative intensity of 5% due to the 41-keV M conversion line.

Denoting the Auger yield by a_K, the intensities of the conversion lines by I, and the portion of the K conversion line of the 80.1-keV transition accepted at the position of L 41-keV line by f, we have for the ratio of the coincidence counting rates at the L 41-keV peak to that at the K 80.1-keV peak:

$$\frac{I_{41}{}^{L}+[0.37a_K(I_{53.4}{}^{K}+I_{133.5}{}^{K})+0.08I_{41}{}^{L}]+I_{80.1}{}^{K}(f+0.37a_K)}{I_{80.1}{}^{K}(1+0.06a_K)+0.06a_K(I_{53.4}{}^{K}+I_{133.5}{}^{K})+0.05I_{80.1}{}^{K}}=0.5. \quad (1)$$

Assuming $a_K=0.1$, we get $f=0.18$ which is quite compatible with the expected line shape on the lower energy side of the K 80.1-keV line. We use now the values for a_K and f to calculate the relative values of the three separate terms in the numerator which are the contributions to the coincidence counting rate at the L 41-keV peak. These are (1) 43% due to the 41-keV transition de-exciting the 100-keV level; (2) 16% de-exciting the 133-keV level; and (3) 41% de-exciting the 80.1-keV level.

These relative intensities and the measured lifetimes as stated earlier were used to correct our earlier value of 5×10^{-10} sec. We obtain finally for the mean lifetime of the 100-keV level $\tau=(1.0\pm0.2)\times10^{-9}$ sec. We see that a factor 2 is involved in this correction. The estimate of the error in this lifetime determination takes into account the uncertainty in specifying the relative contributions to the coincidence rate, and the statistical error in the time delay determination.

6. THE ABSOLUTE TRANSITION PROBABILITIES

In Table I are shown the calculated values of the absolute transition probabilities of the gamma transitions, using the data of the lifetime measurements obtained in the present work, the results of Geiger *et al.*[6] concerning the branching ratios of the transitions de-exciting the levels and conversion coefficients of Sliv.[17] The errors in the transition probabilities shown in the table takes into account only the errors arising from the determination of the lifetime of the relevant levels in the present work. Theoretical single-particle values are included in the table for comparison (Moszkowski[18]).

The most striking features concerning the modes of decay of the excited levels as is apparent from Table I are

1. The $M1$ transitions from the 133.5-keV level to the ground state and to the 100-keV level are not retarded in comparison with the single-particle value.
2. The $E2$ transition de-exciting the 100-keV level to the ground state is enhanced by a factor of 20.
3. The 53.4-keV transition populating the 80.1-keV level from the 133.5-keV state and the 80.1-keV transition de-exciting the corresponding level are retarded by about a factor of 7.

It seems very reasonable to conclude from the high transition probability of the 133.5-keV transition that the 133.5-keV level and the ground state have essentially the same configuration. This is supported by the fact that the two branches of beta transitions populating them have about the same ft values.

The $E2$ transition de-exciting the 100-keV level is enhanced by about a factor of 20 in comparison with the single-particle value, a behavior which perhaps might indicate some collective excitation. However, due to the low energy of excitation it is improbable that this is a vibrational level. Moreover, a shell-model calculation based on the assumption that the 100-keV and ground state both have the same neutron-proton configuration shows that very considerable enhancement can be obtained for the $E2$ transition. The assumption is further supported by the unhindered transition between the 133.5-keV level and 100-keV level.

[17] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Reports 57 ICCK 1 and 58 ICCL 1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

[18] S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. XIII, p. 382.

TABLE II. Comparison of the transition probabilities of the $M1$ transitions, from the 133.5-keV level with shell-model theory.

Energy of transition in keV	P/E^3 transition probabilities divided by the cube of transition energy using effective values in sec^{-1} MeV^{-3}	P/E^3 transition probabilities divided by the cube of transition energy using Schmidt values in sec^{-1} MeV^{-3}	P/E^3 experimental transition probabilities divided by the cube of transition energy in sec^{-1} MeV^{-3}
33.5(1− → 2−)	3.59×10^{13}	1.42×10^{13}	$(3.2_{-1,1}^{+3.5})\times10^{13}$
54.4(1− → 1−)	$6.8\ \times10^{12}$	1.66×10^{13}	$(4.7_{-1,8}^{+5.2})\times10^{12}$
133.5(1− → 0−)	$1.9\ \times10^{13}$	$7.4\ \times10^{12}$	$(2.5_{-0,9}^{+2.7})\times10^{13}$

The hindered feeding to the 80.1-keV level and the retarded transition of this level to the ground state is compatible with the assumption that this state is predominantly that of another configuration. As further support for this conclusion, it is interesting to note that the beta feeding to the 80.1-keV level is retarded by a factor of 10 in comparison with the transition to the 133.5-keV state, despite the fact that both levels have the same assignments.

According to this interpretation we are thus led to believe that the three levels, 133.5 keV, 100 keV, and the ground state, have dominantly the same configuration, whereas the 80.1-keV level has essentially a different configuration.

From the systematics of the neighboring odd-neutron nuclei it is apparent that the 85th neutron is in the $f_{7/2}$ orbit. The situation is rather more ambiguous with respect to the 59th proton. This unpaired proton may be either in the $d_{5/2}$ or the $g_{7/2}$ orbit. Adopting a configuration that places the neutron in the $f_{7/2}$ orbit and the proton in the $g_{7/2}$ orbit for the ground state, gives the experimental 0− assignment according to Nordheim's rule.[19] This same configuration is also assigned to the 100- and the 133.5-keV states, in the spirit of the above reasoning.

It is then plausible to assume that the last proton in the different configuration attributed to the 80.1-keV level is in the $d_{5/2}$ orbit. The unpaired neutron in both configurations is placed in the $f_{7/2}$ orbit. However, a pure configuration assignment to the 80.1-keV level would mean that the $M1$ transitions feeding it from the 133.5-keV level and de-exciting it to the ground state would be l forbidden. The experimental retardation of these transitions is too small to be accounted for by such hypothesis.

The other alternative is to assume that both 1− levels have mixed configurations. We describe therefore the 133.5-keV level in terms of a dominant $(f_{7/2},g_{7/2})$ configuration together with a small admixture of the $(f_{7/2},d_{5/2})$ configuration, whereas the 80.1-keV state is described as belonging mainly to the $(f_{7/2},d_{5/2})$ configuration. The admixture in the 80.1-keV state determines, of course, the mixing of the two configurations in the 133.5-keV state, due to the requirement of orthogonality. The ground state and the 100-keV level were assumed to have pure $(f_{7/2},g_{7/2})$ configurations.

An attempt was made to calculate the transition probabilities theoretically assuming such configuration mixing, using the expression given by Elliot and Lane.[20]

$$P=\frac{e^2}{3M^2c^5\hbar^2}\sum_{M'(q)}\langle JM|\mu_q|J'M'\rangle^2, \tag{2}$$

where M is the nuclear mass, (JM) and $(J'M')$ the angular momenta and their Z projections for the initial and final states, respectively, and μ_q is the q component of the magnetic moment operator.

We have for the lower and upper 1− mixed states:

$$|80.1\text{ keV}\rangle = x|f_{7/2}g_{7/2};1-\rangle+(1-x^2)^{1/2}|f_{7/2}d_{5/2};1-\rangle, \tag{3}$$

$$|133.5\text{ keV}\rangle = -(1-x^2)^{1/2}|f_{7/2}g_{7/2};1-\rangle+x|f_{7/2}d_{5/2};1-\rangle. \tag{4}$$

The 100-keV and ground state are represented by

$$|100\text{ keV}\rangle=|f_{7/2}g_{7/2};2-\rangle, \tag{5}$$

$$|0\text{ keV}\rangle=|f_{7/2}g_{7/2};0-\rangle. \tag{6}$$

The amount of mixing in Eq. (3) is deduced from the experimental transition probability of the 80.1-keV transition between the states represented by Eqs. (3) and (6) using Eq. (2). The value obtained for x, using the corresponding Schmidt values for the magnetic dipole moments, is 0.30.

Table II shows the reduced transition probabilities calculated in this way for the three $M1$ transitions de-exciting the 133.5-keV level. The results are in fair agreement with experiment but nevertheless show some deviation.

De-Shalit[21–23] has suggested that a much better representation of state of affairs might be attained if Schmidt values for the magnetic moments used in our calculations would be replaced by the corresponding experimentally effective values of the neighboring odd-neutron and odd-proton nuclei. In this way the

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residual interaction between the unpaired nucleons and the core is taken into account.

Adopting the experimental value[24] of -0.7 nm of Nd^{145} for the magnetic moment of the neutron configuration, $+3.9$ nm of[25,26] Pr^{141} for the $d_{5/2}$ proton configuration, and $+2.76$ nm of[27] La^{139} for the value of the $g_{7/2}$ proton configuration, the transition probabilities were calculated using Eq. (2). Table II also shows the theoretical results for the $M1$ transition probabilities using the effective values for the magnetic moments and the corresponding value of configuration mixing in the 1− states as deduced from the transition probability of the 80.1-keV transition (x^2 equal to 0.14 instead of 0.30).

As is clear from Table II, a rather striking agreement is attained between the theoretical and the corresponding experimental values, when effective magnetic dipole moments taken from the experimental data of the neighboring odd nuclei are assumed in the calculation. The theoretical $E2$ transition probability of the 100-keV transition was calculated using the equation[21]:

$$P(E2)=\frac{4\pi E^5}{75\hbar(\hbar c)^5}\frac{|\langle J\|Q\|J'\rangle|^2}{2J+1}, \tag{7}$$

where Q is the electrical quadrupole moment operator, J is the angular momentum of the 100-keV level, and J' is the angular momentum of the ground state.

Assuming that the 0− ground state and the 2− 100-keV level possess the same $(f_{7/2},g_{7/2})$ configuration, we get for the reduced matrix element, using the well-known Racah algebra for the decoupling of angular momenta:

$$\begin{aligned}\langle j_pj_nJ\|Q\|j_pj_nJ'\rangle &= (2J+1)^{1/2}[W(j_nJ'j_p2|j_pJ)\langle j_p\|Q_p\|j_p\rangle \\ &\quad +W(j_pJj_n2|j_nJ')\langle j_n\|Q_n\|j_n\rangle].\end{aligned} \tag{8}$$

W is the Racah coefficient and j_p and j_n are the total angular momenta of the proton and neutron, respectively.

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De-Shalit[21,28] pointed out that the reduced matrix elements on the right side of Eq. (8) can be deduced from the experimental values of the electric quadrupole moments of the nearby odd nuclei possessing the same configuration for the odd particles. The connection is given in our case by the relations

$$\langle j_p\|Q_p\|j_p\rangle=[15e/(42\pi)^{1/2}]\bar{Q}_p \tag{9}$$

and

$$\langle j_n\|Q_n\|j_n\rangle=[15e/(42\pi)^{1/2}]\bar{Q}_n, \tag{10}$$

where $\bar{Q}_p$ and $\bar{Q}_n$ are the experimental electric quadrupole moments for the corresponding odd-proton and odd-neutron nuclei, respectively. Noticing that the two Racah coefficients in Eq. (8) are equal in the present case, we have the final expression for the transition probability

$$P(E2)=\frac{4\pi E^5}{75\hbar(\hbar c)^5}\frac{(15e)^2}{42\pi}\frac{1}{40}(\bar{Q}_p+\bar{Q}_n)^2. \tag{11}$$

The contribution of the odd neutron was taken from the experimental value of the quadrupole moment of Nd^{145} (1 b),[29] and that due to the unpaired proton from La^{139} (as 0.3 b).[30] The reduced transition probability thus calculated is equal to $B(E2)=0.72\times10^{-48}$ cm^4, which is smaller by only a factor 2–3 than our experimental corresponding figure $B(E2)=(1.9_{-0.35}^{+0.5})\times10^{-48}$ cm^4. It might be that the contribution of the odd proton to the $E2$ transition probability as deduced from the nucleus La^{139} which has a closed shell of neutrons and which is somewhat distant from the present nucleus, is an underestimation.

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