Structure of Sn^{120} and the Effect of the Pairing Correlation on the Reduction of $E2$ Transition in Sn^{118} and Sn^{120}

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A new level scheme is proposed for Sn^{120}. The levels proposed are the 1.17 Mev, 2^+; 2.20 Mev, 4^+; 2.29 Mev, 5^-; and 2.49 Mev, 7^- levels, which is concluded from the revision of the order of the cascade transition from the upper levels; the revised order of radiations are 0.20 Mev, $E2$; 0.09 Mev, $E1$; 1.03 Mev, $E2$; and 1.17 Mev, $E2$. The transition probabilities of the 0.20- and 0.09-Mev gamma rays are also revised as 1.6×10^{-3} and 3.5×10^{-5} in units of a single-proton transition. A weak cross-over 1.12-Mev $E3$ transition is observed whose probability is also reduced by the factor of 1.5×10^{-1}. All the results of the present experiment together with other data are discussed in terms of the theory of Kisslinger and Sorensen. It is shown particularly that the striking reduction of the 0.26-Mev $E2$ transition in Sn^{118} as well as that of the 0.20-Mev $E2$ transition in Sn^{120} is explained as a consequence of the pairing correlation.

1. INTRODUCTION

RADIATIONS from the decay of 5.8-day Sb^{120m} and 16-min Sb^{120} were investigated previously, by one of the authors (H.I.).[1] He measured gamma-ray coincidences, $Ke^- - \gamma^2$ as well as $\gamma-\gamma$ directional correlations, polarization direction correlations,[3] and lifetimes of the third and fourth excited states of Sn^{120}. Afterwards he checked the previous data of the lifetime of the third excited state carefully, and found that the order of 0.20- and 0.09-Mev gamma rays should be interchanged, the poor energy resolution of plastic scintillation gamma-ray spectrometers being the main source of the previous incorrect assignment. Keeping this fact in mind, some of the previous experimental results such as the $\gamma-\gamma$ and $Ke^- - \gamma$ directional correlations have been reinvestigated. The conclusions on the third and fourth excited states in Sn^{120} have been revised. The final result thus confirmed by the present analysis is shown schematically in Fig. 1. This new level scheme is also supported by our present observation of a weak $E3$ gamma-ray transition between the third and first excited states. In Fig. 1 also is given for comparison the new level scheme of Sn^{118}, which has also recently been investigated[4] by Ikegami *et al.* in an experiment on the decay of 5.1-hr Sb^{118} and 6.0-day Te^{118}.[5]

On the theoretical side, following the suggestion of Bohr, Mottelson, and Pines,[6] many authors have successfully applied the technique of the theory of superconductivity[7] to the investigation of the effect of the pairing correlation on the various properties of nuclei.[8–10]

[1] H. Ikegami, Phys. Rev. **120**, 2185 (1960). The result concerning the order of the 0.20- and 0.09-Mev gamma transitions was revised at the Tokyo Meeting, April 1961 (unpublished); H. Ikegami and T. Udagawa, Institute for Nuclear Study Report INS-31, 1961 (unpublished).

[2] H. Ikegami, T. Yamazaki, and M. Sakai, unpublished data presented at Hiroshima Meeting, October 1959; J. Phys. Soc. (Japan) (to be published).

[3] M. Kawamura, A. Aoki, and H. Ikegami, unpublished data presented at Hiroshima Meeting, October 1959; J. Phys. Soc. (Japan) **16**, 1493 (1961).

[4] The following measurements were performed: lifetime of the fourth excited state; directional correlations of 1.22-Mev γ-1.03-Mev γ, 1.03-Mev γ-0.04-Mev γ, 0.04-Mev γ-0.26-Mev γ and 1.03-Mev γ-0.26-Mev γ; spectra of gamma ray and conversion electron from the decay of the 5.1-hr Sb^{118}; spectra of gamma ray, conversion electron, and positron from the 6.0-day Te^{118}; and gamma-ray spectrum from the 3.5-min Sb^{118} [H. Ikegami, T. Yamazaki, M. Sakai, H. Ohnuma, Y. Hasimoto, G. Fujioka, A. Hasizume and E. Takekosi, unpublished data presented at Tokyo Meeting, April 1961; Nuclear Phys. (to be published)].

[5] The lifetime of the third excited state in Sn^{118} is taken from the work of Bolotin and Schwarzschild [H. H. Bolotin and A. Schwarzschild, Bull. Am. Phys. Soc. **6**, 50 (1961)]. Hitherto, the 3.5-min (1+) state in Sb^{118} was placed above the 5.1-hr 8^- state. Ikegami *et al.* have observed, however, a 2.64-Mev positron in the decay of the 6.0-day Te^{118},[4] the result being in agreement with the recent data of Sorokin *et al.* [A. A. Sorokin, A. Bedesku, M. V. Klimentovskaya, L. N. Krukova, K. P. Mitrophanov, V. V. Muravieva, V. N. Rwibakou, G. Chandra and V. S. Shipineli, Izv. Acad. Nauk. USSR **24**, 1484 (1960)]. Resulting from this, the decay energy of the 3.5-min state is 3.64 Mev. However, Schwarzschild *et al.* showed that the 5.1-hr state of Sb^{118} lies about 3.9 Mev above the Sn^{118} ground state [A. Schwarzschild (private communication)]. The position of the 5.1-hour state relative to the 3.5-min state is therefore about 0.2 Mev. Therefore the decay schemes of Sb^{118m} and Sb^{118} become quite similar to those of the 5.8-day and 16-min Sb^{120}. (See Fig. 1.) In the decay of the 6.0-day Te^{118}, conversion electrons belonging to the 1.76-, 2.06- and 2.08-Mev transitions have been found. They are assigned as $E0$ transitions between excited 0^+ states and the ground state of Sn^{118}. Recently, Jensen *et al.* have reported on the structure of Sn^{116}, Sn^{118}, and Sn^{120} and independently Ramaswamy *et al.* have performed an experiment on the decay of the 5.1-hour Sb^{118} [B. S. Jensen, O. B. Nielsen, and O. Skilbreid, Nuclear Phys. **19**, 654 (1960); M. K. Ramaswamy, W. L. Skeel, D. L. Hutchins, and P. S. Jastram, Phys. Rev. **121**, 553 (1961)]. The conclusions of both groups should, however, be revised by considering the interchange of the order of the low-energy gamma rays in Sn^{118} and Sn^{120}.

[6] A. Bohr, B. R. Mottelson, and D. Pines, Phys. Rev. **110**, 936 (1958).

[7] N. N. Bogoliubov, Nuovo cimento **7**, 794 (1958); J. G. Valatin, *ibid.* **7**, 843 (1958).

[8] S. T. Belyaev, Kgl. Danske Videnskab. Selskab Mat.-fys. Medd. **31**, No. 11 (1959).

[9] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **32**, No. 9 (1960). This paper will be referred to as KS in the following.

[10] M. Kobayasi and T. Marumori, Progr. Theoret. Phys. (Kyoto) **23**, 387 (1960); T. Marumori, *ibid.* **24**, 331 (1960); R. Arvieu and M. Veneroni, Compt. rend. **250**, 992, 2155 (1960); M. Baranger, Phys. Rev. **120**, 957 (1960); S. Yoshida, *ibid.* **123**, 2122 (1961).

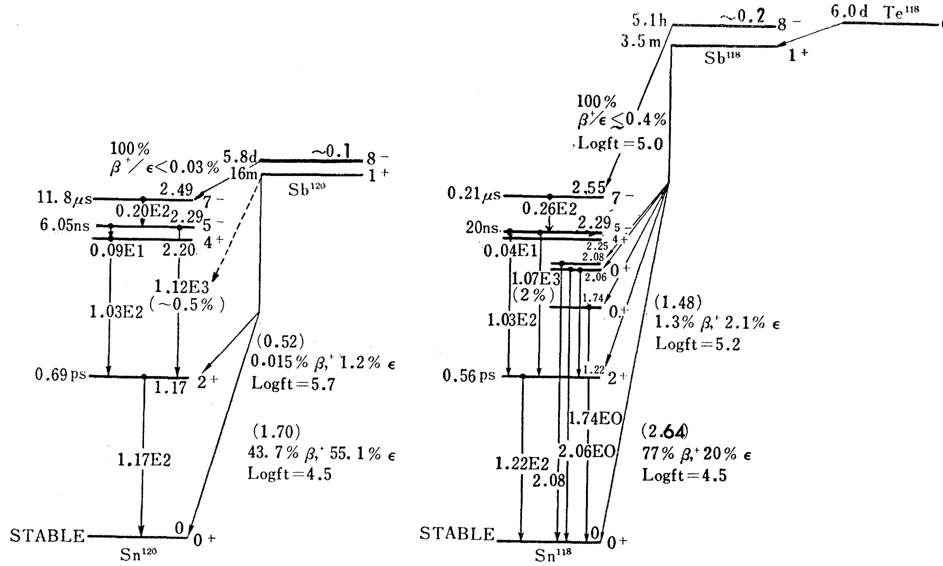

FIG. 1. Revised level scheme of Sn^{120}. For comparison, the level scheme of Sn^{118}, which has recently been investigated by Ikegami *et al.*[4] is also shown.[5]

The point is that in the intrinsic excitation spectra of nuclei there exists evidence for an energy gap corresponding to that considered in the electronic excitation of a superconducting metal, and that in the case of nuclear physics, a pairing correlation due to the short-range part of the residual nuclear force is responsible for the gap. As a consequence of these investigations, it is found that the assumption of the pairing correlation leads to an understanding of many characteristic features of the nuclear properties including those of the collective motions. In particular, Kisslinger and Sorensen[9] have performed calculations on the properties of both intrinsic and collective excitations of singly closed shell (SCS) nuclei where the effect of the quadrupole-quadrupole (Q-Q) force[9] is considered as well as the pairing interaction. They take into account the Q-Q force in the perturbation or deformed-field approximation[8] and succeed in deriving low-energy systematic features of the SCS nuclei.

Shell model calculations, with a suitable residual two-body interaction, have also been made by many authors in order to understand level structures of nuclei in the neighborhood of doubly closed shells. The results of these calculations, such as those of True and Ford[11] for several Pb isotopes, usually give better agreement with experiment than those of Kisslinger and Sorensen. Ordinary shell model calculations, however, become extremely involved in cases where the particle number outside of closed shells is increased and the effects of configuration mixing become important. In such cases the Kisslinger-Sorensen approach would be the only practicable way, and in this paper our experimental results will be analyzed in terms of this theory. Some consideration on the limitation of this theory will be given in Sec. 5.

2. LEVEL SCHEME OF Sn^{120}

(a) Order of 0.20- and 0.09-Mev Transitions

As was described in our previous paper,[1] the time interval between gamma-ray pulses is measured using a fast time-to-pulse-height converter which is an improved type of Green and Bells' circuit.[12] Gamma rays were detected using two plastic scintillators 30 mm in diameter and 30 mm long, coupled to selected RCA-6810A photomultipliers. With this apparatus it is not very hard to obtain the resolving time $2\tau=6\times10^{-10}$ sec for the 1.17- and 1.33-Mev cascade gamma rays from Co^{60}. In compensation with this high resolving time, the energy resolution of the gamma ray is not high. A gamma-ray spectrum from Sb^{120m} as seen by these detectors is shown in Fig. 2.

To investigate more precisely the order of the 0.20- and 0.09-Mev transitions, the following measurement is performed. One detector is fixed at the energy D indicated in Fig. 2, while the other detector is set at other energies A, B, and C and delayed coincidence curves are obtained for each setting; the results are shown in Fig. 3. The prompt coincidence part of the delayed curves is ascribed to the Compton tails of high-energy gamma rays. The ratio of delayed coincidence to this prompt coincidence part is monotonically decreased by changing the detection energy from A to C because of the relative increase of the Compton tail. In spite of the fact that no contribution from the 0.09-Mev gamma ray should exist in the energy range C, some delayed coincidence still exists there. It is thus concluded that there is an 8.73 nsec delay between the 0.20- and 1.03-Mev gamma rays. If it were assumed, however, that the order of the gamma rays is 0.09, 0.20, and 1.03 Mev, the delay would have to be ascribed to the 1.03-Mev

[11] W. True and K. Ford, Phys. Rev. **109**, 1675 (1958).

[12] R. E. Green and R. E. Bell, Nuclear Instr. **3**, 127 (1958).

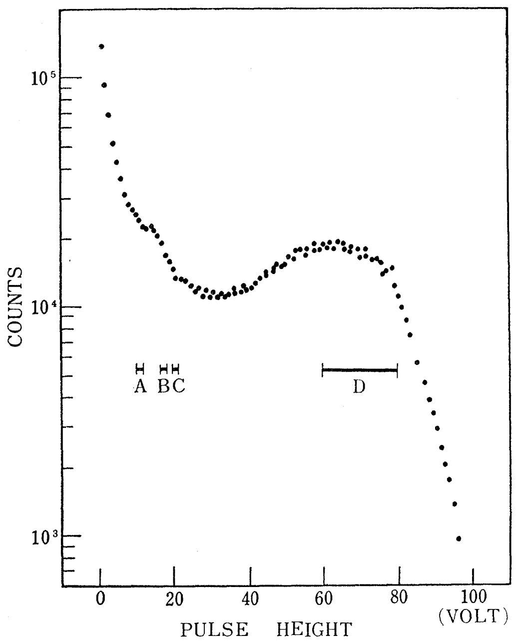

FIG. 2. Gamma-ray spectrum from natural Sn bombarded by 13-Mev protons, measured by plastic scintillator. The limits indicated by *A*, *B*, *C*, and *D* show the energy range of the two scintillation detectors in the measurement of the fast delayed coincidence.

transition, which has the highest energy among them; this would be very unnatural. Accordingly, the order of the gamma rays in Sn^{120} must be 0.20, 0.09, 1.03, and 1.17 Mev and is quite analogous to that of Sn^{118}.[5]

The interchange of the order of the 0.20- and 0.09-Mev gamma rays requires reinvestigation of the following data: the intensity ratio of the 0.20- and 0.09-Mev gamma rays coincident with *K* x rays, the $\gamma-\gamma$ directional correlations involving the low-energy gamma rays, and the directional correlations of the 0.20-Mev γ–0.09-Mev Ke^- and the 0.20-Mev Ke^-–0.09-Mev γ.

(b) Electron Capture Branch to 2.49-Mev Level

From the coincidence ratio $[(K$ x ray)-(0.09-Mev $\gamma)]/[(K$ x ray)-(0.20-Mev $\gamma)]=0.65\pm0.07$ at no delay with 1-μsec resolving time, and considering the conversion coefficient of these gamma rays and the larger decay time of the 2.49-Mev level as seen in Fig. 1, which reduces the coincidence efficiency of gamma rays with *K* x rays following electron capture, it is concluded that the 5.8-day Sb^{120m} feeds the 2.49-Mev state of Sn^{120} with more than 99% of its total transition.

(c) Spin Sequence of Sn^{120}

Previous data on the coefficients of Legendre polynomials in the directional correlation functions are summarized in Table I. It should be noted that all of these experimental correlation functions are completely consistent with the sequence 7^-(0.20-Mev $E2$)5^-(0.09-Mev $E1$)4^+(1.03-Mev $E2$)2^+(1.17-Mev $E2$)0^+, and also with the sequence 7^-(0.09-Mev $E1$)6^+(0.20-Mev $E2$)4^+(1.03-Mev $E2$)2^+(1.17-Mev $E2$)0^+ which was previously assigned.[1] Expected theoretical correlation functions for both sequences are also shown in Table I. The former sequence is chosen by considering the order of the 0.20- and 0.09-Mev gamma rays as described in Sec. 2(a).

Other possible spin and parity assignments were ruled out as follows:

As was described in our previous paper,[1] the sequence $4^+(E2)2^+(E2)0^+$ for the 1.03- and 1.17-Mev cascade was well established by the measurements of the 1.03-Mev γ–1.17-Mev γ directional correlation, direction-polarization correlation, and conversion coefficients. The conversion coefficients[1] of the 0.20- and 0.09-Mev gamma rays indicate $E2$ and $E1$ character, respectively, and imply odd parity of the third and fourth excited states in Sn^{120}. Spin assignments 5^-, 4^-, and 3^- to the 2.49-Mev excited state and 3^- to the 2.29-Mev state are all ruled out by the absence of the 0.29- and 1.12-Mev cross-over $E1$ transitions. Furthermore, the particle parameter b_2 of 0.09-Mev Ke^- tabulated by Biedenharn and Rose[13] is -1.92 for an $E1$ transition and $+1.34$ for an $M2$ transition, and thus the 0.20-Mev–0.09-Mev Ke^- directional correlation is very sensitive to an $M2$ mixture in the 0.09-Mev transition. The above

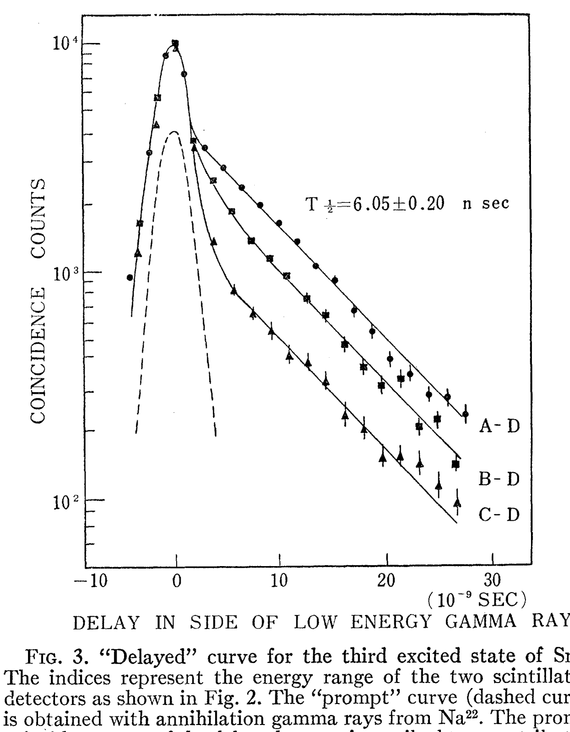

FIG. 3. "Delayed" curve for the third excited state of Sn^{120}. The indices represent the energy range of the two scintillation detectors as shown in Fig. 2. The "prompt" curve (dashed curve) is obtained with annihilation gamma rays from Na^{22}. The prompt coincidence part of the delayed curves is ascribed to a contribution from Compton tails of high-energy gamma rays.

[13] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

TABLE I. Summary of all the experimental directional correlation functions. The theoretical directional correlation functions expected from the sequences 7^-(0.20-Mev $E2$)5^-(0.09-Mev $E1$)4^+(1.03-Mev $E2$)2^+(1.17-Mev $E2$)0^+ or 7^-(0.09-Mev $E1$)6^+(0.20-Mev $E2$)4^+(1.03-Mev $E2$)2^+(1.17-Mev $E2$)0^+ are also presented.

Directional correlation	Observed coefficients of correlation function A_2	A_4	Theoretical coefficients of correlation function A_2	A_4
1.03 Mev γ–1.17 Mev γ	$+0.106\pm0.005$	$+0.012\pm0.006$	$+0.102$	$+0.009$
0.20 Mev γ–1.03 Mev γ	$+0.101\pm0.005$	$+0.007\pm0.006$	$+0.102$	$+0.009$
0.20 Mev γ–1.17 Mev γ	$+0.105\pm0.005$	$+0.010\pm0.006$	$+0.102$	$+0.009$
0.20 Mev γ–0.09 Mev γ	-0.069 ± 0.003	-0.006 ± 0.004	-0.071	0
0.20 Mev Ke^-–0.09 Mev γ	-0.130 ± 0.006	-0.010 ± 0.007	-0.132	0
0.20 Mev γ–0.09 Mev Ke^-	$+0.134\pm0.005$	-0.006 ± 0.006	$+0.136$	0

experimental result shows that the $M2$ component in the 0.09-Mev transition is negligibly small. Thus the remaining spin sequences for the 0.20- and 0.09-Mev cascade are $7^-(E2)5^-(E1)4^+$ and $6^-(E2+M1)5^-(E1)4^+$ with $\delta=-3.46$ or $\delta=-0.36$, where δ denotes the ratio of the matrix element of the quadrupole transition to that of the dipole transition as defined by Biedenharn and Rose.[13] The internal conversion coefficient of the 0.20-Mev gamma ray rules out the last assignment of $\delta=-0.36$. It is, however, difficult to decide whether the spin and parity assignment of the 0.20- and 0.09-Mev cascade is $7^-(E2)5^-(E1)4^+$ or $6^-(E2+M1)5^-(E1)4^+$ with $\delta=-3.46$ by considering the internal conversion coefficient of the 0.20-Mev gamma ray. Furthermore it is not so definite to decide these assignments by means of the 0.20-Mev γ–1.17-Mev γ or the 0.20-Mev γ–1.03-Mev γ directional correlation coefficients, because of the somewhat small difference of A_4 coefficients. The value of A_2 is exactly the same in both cases. The expected 0.20-Mev Ke^-–0.09-Mev γ directional correlation coefficients for these sequences are, respectively,

$$A_2=-0.132 \quad \text{for} \quad 7^-(E2)5^-(E1)4^+,$$
$$A_2=+0.162 \quad \text{for} \quad 6^-(E2+M1)5^-(E1)4^+, \quad \text{with} \quad \delta=-3.46$$

while the experimental correlation coefficient is (see Table I)

$$A_2=-0.130\pm0.006;$$

this means that the sequence $7^-(E2)5^-(E1)4^+$ is the most reasonable.

3. GAMMA TRANSITION PROBABILITY

(a) 0.20-Mev Transition

The lifetime of the fourth excited state of Sn^{120} was previously determined[1] as $T_{\frac{1}{2}}=(1.18\pm0.05)\times10^{-5}$ sec $[\tau=(1.71\pm0.08)\times10^{-5}$ sec$]$. The 2.49-Mev state is de-excited through the 0.20-Mev transition as shown in Sec. (2a). The transition is of pure $E2$ type and the experimental value of its conversion coefficient α is 0.133.[1] Then, the partial mean life of the 0.20-Mev gamma transition is given as

$$\tau_\gamma=(1+\alpha)\tau=(1.93\pm0.10)\times10^{-5} \text{ sec.}$$

(b) 0.09-Mev Transition

The previous data gave[1] the lifetime of the third excited state as $T_{\frac{1}{2}}=(6.05\pm0.20)\times10^{-9}$ sec $[\tau=(8.73\pm0.30)\times10^{-9}$ sec$]$. As the experimental value of the conversion coefficient of the 0.09-Mev transition is known[1] to be 0.24, the partial mean life of the 0.09-Mev gamma transition is $\tau_\gamma=(1.08\pm0.05)\times10^{-8}$ sec.

(c) 1.12-Mev Transition

Recently, Ikegami *et al.* found a weak internal conversion electron lines belonging to the 1.07-Mev crossover $E3$ transition in Sn^{118}.[4] The observation of this cross-over transition confirms the order of the 0.26- and 0.04-Mev gamma rays; the order of the gamma rays was also found by Bolotin and Schwarzschild.[5]

A similar cross-over transition might also be expected to occur in Sn^{120}. It seems, however, to be impossible to observe such a transition by measuring the conversion electrons because of rather smaller yield of the 5.8-day Sb^{120m}. The gamma-ray spectrum concident with the 1.17-Mev gating gamma ray is therefore measured with a 40-channel pulse-height analyzer and a coincident circuit with an effective resolving time of 5×10^{-8} sec. Absorbers of 9-mm thick lead are put in front of each crystal, $1\frac{3}{4}$ in. in diameter and 2 in. long, coupled to RCA-6342A photomultipliers, to eliminate a summing effect of the 1.03- and 0.09-Mev gamma rays. The window of the gating radiation is carefully set as shown in Fig. 4 so that the contribution of 1.03-Mev gamma rays in the window becomes less than 0.1%. To check this arrangement a similar measurement is also performed for the 1.17- and 1.33-Mev gamma rays from Co^{60}. The result seems to indicate, although not so definitely as for Sn^{118}, a competition of this 1.12-Mev cross-over transition with the 0.09-Mev $E1$ transition, the branching ratio of the former being estimated to be about 0.5% which leads to $\tau_\gamma(E3)=2\times10^{-6}$ sec.

(d) 1.03-Mev Transition

If the 2.21-Mev level is the second collective state, its mean life is estimated as about 2×10^{-12} sec assuming that the matrix elements of the 1.03- and 1.17-Mev gamma transitions are nearly equal. On the other hand, the mean life is estimated as about 4×10^{-9} sec if the

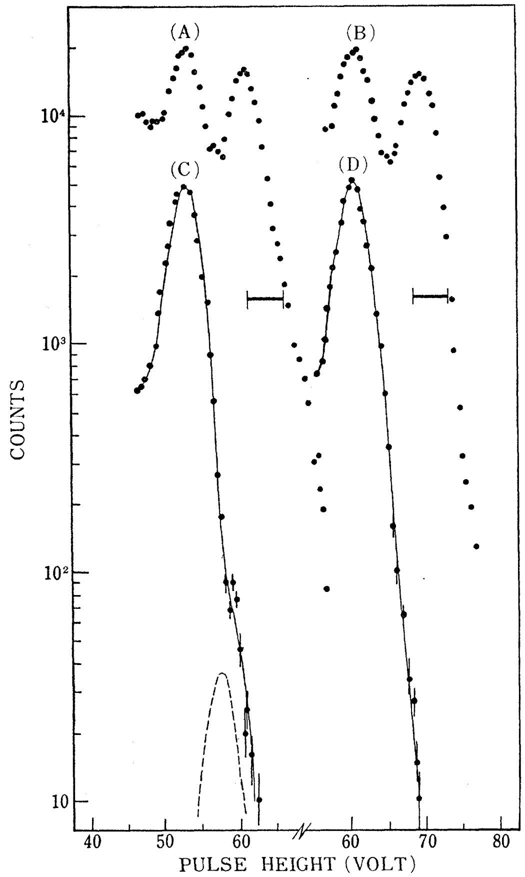

FIG. 4. Spectra of gamma rays from Sb^{120m} and Co^{60}. (A) and (B) are single gamma-ray spectra from Sb^{120m} and Co^{60}. The other curves (C) and (D) represent 1.03 Mev γ rays in coincidence with 1.17-Mev γ rays from Sb^{120m} and 1.17-Mev γ rays coincidence with 1.33-Mev γ rays from Co^{60}, respectively. The horizontal bars represent the energy ranges of the gate window opened in the measurement of coincidence spectra. In (C) the dashed curve shows the possible 1.12-Mev γ ray estimated from the shape of the 1.17-Mev γ spectrum in (D).

2.21-Mev state is of a two-quasi-particle character, as will be described in Sec. 4(a). It is thus possible to decide whether the 2.20-Mev level has a collective nature of a quasi-particle excitation character by measuring the lifetime with the use of fast delayed-coincidence techniques. Energy resolution of the close-lying radiations is, however, the most important problem.

(e) 1.17-Mev Transition

By a Coulomb excitation experiment,[14] the mean life of the first excited state of Sn^{120} is determined as 1.0×10^{-12} sec and its value agrees well with the main features of the systematics of the first excited states of even-even nuclei.

All of these results for the gamma transitions in Sn^{120} are summarized in Table II.

4. THEORETICAL ANALYSIS

In this section our experimental results as summarized in Fig. 1 and Table II, together with other data, will be discussed in terms of the KS theory.[9] Especially it will be shown that the large reduction of the 0.20-Mev $E2$ transition may be due to the effect of the pairing correlation. Although many characteristic features of Sn^{120} can be successfully interpreted in the KS scheme, there exist several experimental data which can not be explained satisfactorily.

TABLE II. Comparison of the experimental transition probabilities with Moszkowski's unit of a single-proton transition.[a]

Transition	τ_γ(exp) (sec)	$F=\tau_\gamma$(s.p.)/τ_γ(exp)
1.17 Mev ($E2$)	1.00×10^{-12}	4.4
1.12 Mev ($E3$)	$\sim2\times10^{-6}$	$\sim1.5\times10^{-1}$
0.20 Mev ($E2$)	1.93×10^{-5}	1.6×10^{-3}
0.09 Mev ($E1$)	1.08×10^{-8}	3.0×10^{-5}

[a] See reference 15.

(a) The First and Second Excited States

Our final results concerning the energies, spins, and parities of the first and second excited states of Sn^{120} are the same as those obtained previously.[1] The first-excited 2^+ state is known to be a collective state from the Coulomb excitation experiment[4] and from a recent experiment on the (d,d') reaction performed by Cohen and Price.[16]

KS calculated the energy of this collective vibrational state and the $2^+\rightarrow0^+$ $E2$ transition probability by introducing collective coordinates to describe the collective motion. Their calculated values are 1.22 Mev for the energy and 0.28×10^{-48} e^2 cm^4 for the $B(E2)$, which are in very good agreement with the experimental values 1.17 Mev and 0.22×10^{-48} e^2 cm^4, respectively.

Theoretically two 4^+ states are expected to appear around 2.21 Mev, the observed energy of the second excited 4^+ state; one is a member of the two-phonon triplet and the other is a two-quasi-particle state with the $(h_{11/2})^2$ configuration. The experimental information concerning this state, however, is still too incomplete to make any more detailed discussion meaningful. As was noted in section 3(d), it is of a great interest to measure the lifetime of this state to decide whether it has a collective nature or not. In Pb^{204}, in an energy region below twice the energy of the first excited 2^+ state, two 4^+ states are found[17] and these have been interpreted by

[14] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. **2**, 69 (1957).
[15] S. A. Moszkowski, Phys. Rev. **89**, 474 (1953); *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. XIII. In this table, statistical factors are neglected (i.e., $S=1$ in Moszkowski's notation).
[16] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).
[17] A. W. Sunyar, D. Alburger, G. Friedlander, M. Goldhaber, and G. Scharff-Goldhaber, Phys. Rev. **79**, 181 (1950); V. E. Krohn and S. Raboy, Phys. Rev. **95**, 1354, 608 A (1954); C. J. Herrander, R. Stockendal, J. A. McDonnell, and I. Bergström, Nuclear Phys. **1**, 643 (1956); A. R. Fritsch and J. M. Hollander J. Inorg. & Nuclear Chem. **6**, 165 (1958); R. Stockendal, T. Novakov, B. Johansson, and M. Schmorak, Arkiv. Fysik **14**, 65 (1958).

KS as two quasi-particle states by considering the $E5$ transitions to these states from the higher excited 9^- state, and the strong reduction of de-excitation of these states to the first-excited collective 2^+ state.

Fortunately the mean life of the lower 4^+ state of Pb^{204} has been measured[17]; its value is 3.8×10^{-7} sec. Assuming the same transition matrix element of $4^+\rightarrow 2^+$ transition, we can estimate the mean life of the 4^+ state of Sn^{120} to be 4×10^{-9} sec. This value of the lifetime may help in deciding whether or not the 4^+ state has a collective nature.

(b) Third and Fourth Excited States

In the energy region 2–3 Mev, one 7^- and two 5^- states are expected to appear from the calculated scheme of KS. These states are all considered as two quasi-particle state with configurations $(h_{11/2},d_{3/2})_{7^-}$, $(h_{11/2},d_{3/2})_{5^-}$, and $(h_{11/2},s_{1/2})_{5^-}$, respectively. Therefore the observed 7^- state is uniquely identified as a $(h_{11/2},d_{3/2})$ If we denote the $(h_{11/2},d_{3/2})$ and $(h_{11/2},s_{1/2})$ states by α and β, the energies of these quasi-particle states are, respectively,

$$E_\alpha^{(0)}=2.27 \text{ Mev},\quad E_\beta^{(0)}=2.33 \text{ Mev}.$$

These value are obtained by using the values of half the energy gap, $\Delta=1.07$ Mev, and the Fermi energy, $\lambda=2.26$ Mev, tabulated in KS, neglecting the Q−Q interaction. The resulting energy difference of the states α and β is about 0.06 Mev and thus the two possible 5^- states are very close together in energy. The effect of the Q−Q interaction is first to shift the energies of these states due to its diagonal element, and then to separate them due to its nondiagonal elements. As will be shown below, however, this separation is strongly reduced as a consequence of the pairing correlation, so that the energy separation of the 5^- and 7^- states is essentially determined by the energy shift. The resulting separation 0.19 Mev is in good agreement with experiment.

The energy shifts $\Delta E_\alpha{}^J$ and ΔE_β and the nondiagonal matrix element G are written as follows:

$$\Delta E_\alpha{}^J=\sum_{i=1,2}[1/(2j_i+1)]\sum_j f_2(ii,jj)\times[u_i^2-(u_iu_j-v_iv_j)^2]-F_J(12,12),\quad (1)$$

$$\Delta E_\beta=\sum_{i=1,3}[1/(2j_i+1)]\sum_j f_2(ii,jj)[u_i^2-(u_iu_j-v_iv_j)^2],\quad (2)$$

$$G=-F_J(12,13),\quad (3)$$

with

$$F_J(jj_1,jj_2)=(-)^{j-j_2}[f_2(jj_1jj_2)W(j_2jjj_1;22)\times(u_ju_{j1}-v_jv_{j1})(u_ju_{j2}-v_jv_{j2})+(-)^J f_2(jj_1j_2j)\times W(jjj_2j_1;22)(u_j^2-u_j^2)(u_{j_1}u_{j_2}-v_{j_1}v_{j_2})],\quad (4)$$

and

$$f_2(i_1i_2j_2j_1)=\chi\langle j_1\|r^2Y_2\|i_1\rangle\langle j_2\|r^2Y_2\|i_2\rangle.\quad (5)$$

χ is the coupling constant of the Q−Q force[9] and u_j, v_j, etc., describe the fractional occupation of the single-particle state j. The subscripts 1, 2, and 3 specify the states $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$, respectively, and J is the total spin of the state α and β.

First we consider the energy shift. As is seen from Eq. (1), the energy shift of the $(h_{11/2},d_{3/2})_J$ states are J dependent due to the presence of the last term which splits the 5^- and 7^- states of this configuration. This term, however, contains a factor $(u_ju_{j'}-v_jv_{j'})$ which represents the pairing correlation effect and takes a very small value if the j- and j'-orbits are both very close to the Fermi energy. As the $h_{11/2}$ and $d_{3/2}$ orbits lie near the Fermi energy in this case, a strong reduction of this term due to the above factor is expected. In fact, taking the value $X=(5/4\pi)\langle r^2\rangle^2\chi\simeq1$ Mev defined by KS and using values of the additional parameters calculated by KS, the splitting of the 5^- and 7^- states due to the term $F_J(12,12)$ is found to be 2 kev which is certainly negligibly small. Thus, neglecting this term and calculating ΔE_α and ΔE_β, the final energies of the states α and β are obtained as

$$E_\alpha\simeq2.72 \text{ Mev},\quad E_\beta\simeq2.53 \text{ Mev},$$

which give 0.19 Mev for the separation of the α and β states.

The matrix element $G=-F_J(12,13)$ between the two 5^- states can be calculated by inserting the value of the parameters of KS into Eq. (4) to give

$$G\simeq0.012 \text{ Mev},$$

which is very small compared with the above separation energy 0.19 Mev. The reduction of this matrix element is due to the same reason as that of $F_J(12,12)$.

From the above consideration it can be concluded that the observed 5^- state is identified as an almost pure $(h_{11/2},s_{1/2})$ configuration, and that the 5^- state of the configuration $(h_{11/2},d_{3/2})$ is approximately degenerated with the 7^- state of the same configuration. The calculated energy separation between the 5^- and 7^- states are in agreement with experiment but the absolute positions of these states are higher than the experimental ones. This indicates that the parameters of KS employed in the calculations should be changed. This point will be discussed later.

In addition to the 7^- and 5^- states, other odd-parity states with spins 6^- and 4^- with the configurations $(h_{11/2},d_{3/2})_{6^-}$, $(h_{11/2},s_{1/2})_{6^-}$, and $(h_{11/2},d_{3/2})_{4^-}$ are expected to appear in the same energy region. As will be discussed in section 4(e), states with spin smaller than 6 cannot be fed from the decay of Sb^{120m} if the spin of the latter is 8^-. On the other hand, the 6^- state with configuration $(h_{11/2},s_{1/2})$, which according to our analysis is expected to lie close to the observed 5^- state, should have been observed through a $M1$ and/or $E2$ de-excitation from the 2.49-Mev 7^- state. The fact that there is no evidence of this transition is rather hard to explain in the frame-

TABLE III. Experimental and theoretical values of the reduction factor F for the 0.26- and 0.20-Mev $E2$ transitions in Sn^{118} and Sn^{120}, respectively. The first column gives the experimental value and the second and third columns give the theoretical values calculated by using the parameters of KS and TU, respectively.

Nucleus	Experimental reduction factor	Theoretical reduction factor KS	TU
Sn^{118}	2.3×10^{-2}	5.8×10^{-3}	5.5×10^{-2}
Sn^{120}	1.6×10^{-3}	2.6×10^{-2}	3.6×10^{-5}

work of the present theory and thus remains as one of the difficulties.

(c) Reduction of the 0.20-Mev $E2$ Transition

KS point out the possibility that if the initial and final states in odd nuclei are both one-quasi-particle states of the (free) shell-model orbits very close to the Fermi energy, the electric transitions between these states are strongly reduced as a consequence of the pairing correlation.[18] As was discussed above, 7^- and 5^- states can be interpreted as two-quasi-particle states of configurations $(h_{11/2},d_{3/2})$ and $(h_{11/2},s_{1/2})$, and thus the 0.20-Mev $E2$ transition between these states is essentially a $(d_{3/2})\rightarrow(s_{1/2})$ quasi-particle transition. Noting that the $d_{3/2}$ and $s_{1/2}$ orbits are both slightly below the Fermi energy, the large reduction suggested by KS can also be expected to occur in this 0.20-Mev $E2$ transition. If we employ the expression $B(E2)=(\langle r^2\rangle^2/4\pi)e^2F$, then the factor F is just the reduction factor we seek and it is found that $F=2.6\times10^{-2}$ (see Table III).

The effect of the pairing correlation is contained in F through a factor $(u_ju_{j'}-v_jv_{j'})^2$ which in our case equals 3.6×10^{-2}, and thus it is seen that the smallness of F is mostly due to the pairing effect. Compared with the experimental value $F=1.6\times10^{-3}$, the above theoretical value $F=2.6\times10^{-2}$ is still too large. It should be noted, however, that the factor $(u_ju_{j'}-v_jv_{j'})^2$ is very sensitive to the choice of the parameters, especially to the energies of the shell-model orbit. In the calculation of KS the calculated $7/2^+$ and $11/2^-$ states in Sn^{119} and Sn^{121} lie well above and below the experimental ones, respectively. In a calculation recently performed by Tamura and one of the authors (TU),[19] the energies of the free $g_{7/2}$ and $h_{11/2}$ orbits are assumed to be 0.42 and 2.4 Mev. Employing the other parametric values of KS, improved agreement is obtained for the level positions of the above odd Sn isotopes. Moreover, the absolute positions of the 7^- and 5^- states of Sn^{120} discussed in section 5(b) are also improved to be 2.51 and 2.26 Mev, respectively, which are in fairly good agreement with experiment. Using the results of this calculation, the factor $(u_ju_{j'}-v_jv_{j'})^2$ is reduced much more and $F=3.6\times10^{-5}$ is obtained (see also Table III). The truth may lie in between. The admixture of the $(h_{11/2},d_{3/2})_{5^-}$ state to the $(h_{11/2},s_{1/2})_{5^-}$ state would not very much weaken the above strong reduction, because the $h_{11/2}\rightarrow h_{11/2}$ and $d_{3/2}\rightarrow d_{3/2}$ quasi-particle $E2$ transitions are also reduced due to the same reason as for the $d_{3/2}\rightarrow s_{1/2}$ transition. In fact the reduction factor F of the $(h_{11/2},d_{3/2})_{7^-}\rightarrow(h_{11/2},d_{3/2})_{5^-}$ $E2$ transition, calculated by using the parameters of KS again, is estimated to be 2.3×10^{-5} which justifies the above argument.

The reduction with the factor 2.3×10^{-2} of the 0.26-Mev $E2$ transition recently observed by Ikegami *et al.*[4] in Sn^{118} can also be interpreted in a quite identical manner to that described above, and the results of the numerical calculation are presented in Table III. The observed trend that the reduction factor of Sn^{118} is larger than that of Sn^{120} can be understood if the above-mentioned parameters of TU are employed, but is inconsistent with the results calculated by using the parameter of KS.

(d) 0.09-Mev $E1$ Transition and 1.12-Mev $E3$ Transition

As was discussed in section 4(a), the second excited 4^+ state is either a member of the two-phonon triplet or a $(h_{11/2})^2$ two-quasi-particle state. Since the 5^- state is a $(h_{11/2},s_{1/2})$ two-quasi-particle state, a strong reduction of the 0.09-Mev $E1$ transition is expected from simultaneous j and l forbiddenness, if the transition proceeds as $(h_{11/2},s_{1/2})_{5^-}\rightarrow(h_{11/2})^2{}_{4^+}$. It is also evident that this transition is reduced if the 4^+ state is taken as a two-phonon state. Therefore the experimental reduction factor 3.0×10^{-5} of this transition is understandable.

The 1.12-Mev $E3$ transition is considered as a $(h_{11/2},s_{1/2})\rightarrow$ (one-phonon state) transition which might again be expected to be reduced strongly because of the forbiddenness of the simultaneous one-phonon creation and two-quasi-particle annihilations. The observed reduction factor, however, is not as small as expected. It is very interesting to calculate this reduction factor by describing the collective 2^+ state with particle coordinates.[10] This sort of calculation is, however, beyond the scope of this paper and will be performed elsewhere.

In Sn^{118} the 0.04-Mev $E1$ and 1.07-Mev $E3$ transitions corresponding to the 0.09- and 1.12-Mev transitions in Sn^{120} are also observed. The reduction factors of these transitions are 4.5×10^{-5} and 2.6×10^{-1}, respectively, which are almost the same values as those of Sn^{120} (see Table II). The interpretation of these transitions in Sn^{118} can also be made in a similar way to that for Sn^{120}.

[18] The possibility of the reduction of the electric transition caused by the pairing correlation is also suggested by Grin [Y. Grin, *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 769].

[19] T. Tamura and T. Udagawa, unpublished data presented at Tokyo Meeting, April 1961. This calculation will be referred to as TU in the following.

(e) Spin and Level Spacing of the 5.8-day Sb^{120m} and 16-min Sb^{120}

The absence of positron emissions in the decay of the 5.8-day Sb^{120m} implies that its decay energy to the 2.49-Mev Sn^{120} level is less than 1.1 Mev. The $\log ft$ value for the decay then lies between 5.0 and 6.0, which is compatible with an allowed transition. The possible spin assignment to this level is therefore 6^-, 7^-, or 8^-. The absence of the feeding of the 2.29-Mev 5^- state in Sn^{120}, which was described in section 2(b), rules out the assignment 6^- to the 5.8-day Sb^{120m}. On the other hand, as was discussed in section 4(b), 4^-, 5^-, 6^-, and 7^- states are expected from $(h_{11/2},d_{3/2})$ and $(h_{11/2},s_{1/2})$ configurations. Nonobservation of such a 6^- state in Sn^{120} may imply that the 5.8-day Sn^{120m} has spin 8^- and is characterized as $(d_{5/2})_p(h_{11/2})_n$. Assuming that the $\log ft$ value of beta-decay to the 7^- state in Sn^{120} from the 5.8-day state of Sb^{120} is the same as that of the beta decay to the 7^- state in Sn^{118} from 5.1-hr state of Sb^{118} ($\log ft=5.0$),[5] the decay energy is estimated to be about 0.3 Mev. The position of the 5.8-day state of Sb^{120} relative to the 16-min state is therefore about 0.1 Mev.

The ground state of Sb^{120} (16 min) is known to be a 1^+ state which can be represented by the configuration $(d_{5/2})_p(d_{3/2})_n$.

The level scheme of Sb^{118} presented in Fig. 1 can also be interpreted in an identical way, and the inversion of the 3.5-min and 5.1-hr states of Sb^{118} pointed out in reference 5 is consistent with the calculated scheme of KS.

5. CONCLUDING REMARKS

As was explained in detail in section 4, it is found that the KS theory explains most of our experimental results, and particularly the large reduction of the 0.20- and 0.26-Mev $E2$ transitions in Sn^{120} and Sn^{118} are well explained as caused by the pairing correlation. It is interesting to note here that in general the reduction factors of the electric transitions of quasi-particles between orbits very close to the Fermi energy depend rather sensitively on the energies of the (free) shell-model orbits as well as on the strength of the pair interaction, and thus the measurements of the reduction factors of such transitions will serve in determining precisely the energies of the shell-model orbits. From the comparison of the experimental reduction factors of the above two $E2$ transitions with the calculated ones, it is found that the values of the parameters used in the calculation of KS had better be revised somewhat. In fact it is shown that the observed trend of these reductions of $E2$ transition can be successfully explained, if use is made of the parametric values found in the calculation of TU. A similar revision of the KS parameters is found useful also for the calculation of the level positions of the 5^- and 7^- states.[20]

The observed $E3$ transition between the third and first excited states does not occur within the present scheme of analysis. To get a finite probability for this transition, we would have to take into account the admixture of some two-quasi-particle states to the first excited 2^+ state (which is treated as a pure collective state in the present analysis); or perhaps it is better treated by expressing the collective 2^+ state solely in terms of the quasi-particle description. Such work will be considered on another occasion.

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[20] These are the conclusions to which one might be led, if he attempts to analyze the experimental data solely within the framework of KS. It should be noted, however, that in KS only the pair and Q-Q interactions are assumed, and it is expected that there are other kinds of interactions working. Therefore, although it is found that a pretty good explanation of the experimental data could be made based on KS with revised parameter values, it should be kept in mind that a somewhat more realistic calculation would have to be made concerning the finer details of the experimental situation.