# Weak Branchings in the Decay of $P^{34}$, $Cl^{34}$, and $P^{30}$†

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(Received December 5, 1955; revised version received June 12, 1956)

The gamma rays following the beta decays of $P^{34}$, $Cl^{34}$, and $P^{30}$ were investigated with a NaI scintillation spectrometer and a twenty-channel analyzer. An unsuccessful search was made for a gamma ray with an energy of 3.22 Mev from $P^{34}$ which should result from an allowed beta-decay branching to the second excited state in $S^{34}$. Since no such gamma ray was found, this branching, if it exists, is very weak, with a log $ft$ value higher than 5.6. Together with the known branching to the first excited state and the transition rates from the $Cl^{34}$ $3^+$ isomeric state, the above result suggests that the second excited state in $S^{34}$ has a configuration similar to that of the $Cl^{34}$ isomeric state and that the first excited state resembles the $P^{34}$ ground state. For explaining the transition rate to the ground state from $P^{34}$, the assumption of strong mixing of both types in the $S^{34}$ ground state seems to be necessary. This strong mixing in the $0^+$ ground state also gives an explanation for the inversion of the order of the lowest $T=0$ and $T=1$ states of $Cl^{34}$. An additional state of $S^{34}$ at 4 Mev, which is attained from both the $P^{34}$ and the $Cl^{34}$ $3^+$ state and is thus to be interpreted as a $2^+$ state, was found. In the case of $P^{30}$ a beta-decay branching to the first excited state of $Si^{30}$ was looked for. A weak gamma ray of 2.24 Mev was found, indicating a branching of 0.2% with a log $ft$ of 5.4.

## INTRODUCTION

THE variations in the beta-decay rates of light nuclei of mass $4n+2$ have long been a puzzle,[1] until the degree of inconsistency was largely reduced by the recent discoveries of the $0^+$, $T=1$, positron-emitting states in $Cl^{34}$, $K^{38}$ (and $Al^{26}$), and the extremely long-lived ground state of $Al^{26}$.[2–8] There are still, however, some problems left to be explained. One is the occurrence of several very slow allowed transitions in this group, as the transition from $Na^{22}$ to the 1.28-Mev state in the $Ne^{22}$ (log $ft=7.6$), and the $C^{14}$ to $N^{14}$ decay (log $ft=9.03$). In the last case the extremely large $ft$-value was shown to be due to an accidental cancellation of the matrix elements.[9] However, not all of these abnormal transition rates would seem to be due to *accidental* cancellations, and it would seem desirable to find another explanation. Another problem requiring an explanation is the fact that the $T=1$ state appears below the lowest $T=0$ state in $Cl^{34}$ and probably in some other, heavier, $4n+2$ self-conjugate nuclei.[10,11] Now that the basic idea about the decay of this series is quite well established, it is of interest to investigate these further peculiarities, especially by searching for more anomalous allowed transitions, and also by acquiring more knowledge about the states involved.

One of the possible slow allowed transitions is the decay from $P^{30}$ to the first excited state in $Si^{30}$ which is most probably a $2^+$ state. No gamma ray has been reported although a normal allowed transition rate would result in a branching of the order of one percent. More detailed studies are possible for $A=34$. This is the lowest $4n+2$ mass number for which the ground state of the $T=2$ nuclide ($P^{34}$) is known, and fairly complete data are available about the decay of $Cl^{34}$. Also, this is one of the few cases where the inversion of the $T=1$ and $T=0$ states takes place.

If one summarizes the known facts about the decay for $A=34$, the following peculiarity is noticed: The $3^+$ isomeric state of $Cl^{34}$ decays by allowed transitions to the two lowest excited states of $S^{34}$, at 2.10 and 3.22 Mev.[12] From $P^{34}$, both the ground state and the first excited level are reached by allowed beta decays.[13] The spin of $P^{34}$, therefore, must be $1^+$, and that of the 2.10-Mev level $2^+$. The same assignment is made probable for the 3.22-Mev level by the existence of the ground-state gamma transition. There seems to be a pronounced difference in the two excited states: the 2.10-Mev level is reached rather readily from $P^{34}$ (log $ft=4.7$), whereas the transition from $Cl^{34}$ is slow (log $ft=6.1$). The $Cl^{34}$ decay to the second excited state, on the other hand, is fast (log $ft=4.8$), but no transition to this state has been reported from $P^{34}$. It is suspected, therefore, that the beta decay from $P^{34}$ to the second excited state of $S^{34}$ is rather slower than an average allowed transition and further that the two lowest excited states in $S^{34}$ have rather different configurations, the 2.10-Mev state being similar to the $P^{34}$ ground state and the 3.22-Mev state resembling the $Cl^{34}$ $3^+$ state. In order to check this assumption, an attempt was made to find the branching ratio of the beta decay from $P^{34}$ to the second excited state of $S^{34}$ by a careful search for the 3.22-Mev gamma rays. Also, a similar reduction may take place in the transition from $P^{30}$ to the first

† Work supported in part by the U. S. Atomic Energy Commission.

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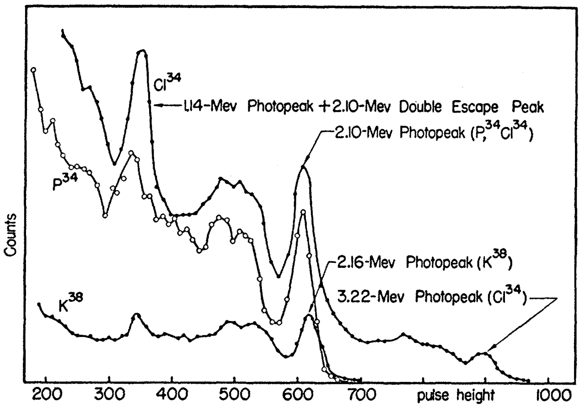


FIG. 1. Scintillation spectra of the $P^{34}$, $Cl^{34}$, and $K^{38}$ gamma rays.

excited state of $Si^{30}$ (2.24 Mev). A search for the 2.24-Mev gamma ray from $P^{30}$ was, therefore, undertaken.

## EXPERIMENTAL PROCEDURE AND RESULTS

$P^{34}$ was produced by bombarding sulfur cylinders of 2-inch diameter and 1.5-inch thickness with Be-*d* neutrons from the Purdue cyclotron. After 40 seconds of irradiation they were placed as close as possible to a NaI crystal with enough aluminum interposed to absorb the 5-Mev beta rays. The counting was started about 10 sec after the end of the bombardment and was continued for about 30 seconds. The pulse-height distribution obtained with a twenty-channel analyzer is shown in Fig. 1 together with those from $Cl^{34}$ and $K^{38}$ taken with a similar geometry. Compared to $Cl^{34}$, $P^{34}$ is seen to have an extremely small amount of gamma radiation above 2.1 Mev, as was suspected.

The part of the $P^{34}$ spectrum above 2 Mev was remeasured by repeated irradiation, with the result shown in Fig. 2. There is no appreciable indication of a 3.22-Mev radiation, but instead there is a definite group of peaks due to a 4.0-Mev gamma ray, with the most intense peak being the double-escape pair peak.

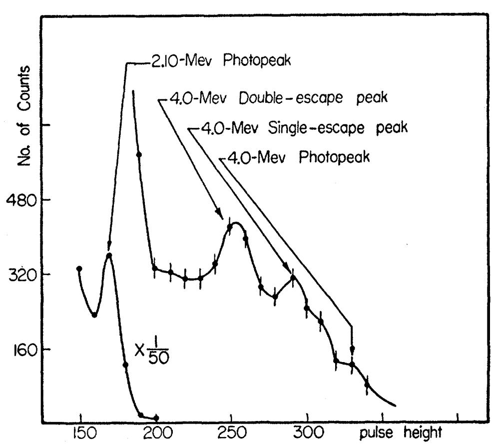


FIG. 2. High-energy portion of the $P^{34}$ spectrum.

The half-life of the spectrum above 2.5 Mev was measured to be about 12 sec, the period of $P^{34}$. The failure of observing the 3.22-Mev gamma ray sets the lower limit of the partial half-life of the beta decay to the 3.22-Mev state at $\sim$1 hour which corresponds to a log *ft* value of 5.6. Here, the beta-decay energies and the branching ratio to the ground state and the 2.10-Mev state were taken from reference 13, and the upper limit of the intensity of the 3.22-Mev gamma ray was estimated by using relative counting efficiencies for the 2.10-Mev (photopeak) and the 3.22-Mev (photopeak and single-escape peak) radiations derived from the $Cl^{34}$ pulse-height distribution (Fig. 1) and the known gamma-ray intensity of $Cl^{34}$.[14]

In order to estimate the intensity of the 4.0-Mev transition, it is necessary to know the relative efficiencies of producing peaks in the spectra by 2.1-Mev and 4.0-Mev gamma rays. Since the relative efficiency of the 2.10-Mev photopeak and the 3.22-Mev pair peaks is known, only the ratio of the pair-peak efficiencies of the 3.22-Mev and the 4.0–Mev gamma ray is needed. It was taken to be equal to the ratio of the pair production cross sections calculated for NaI.[15] Since the double-escape peak of the 4.0-Mev radiation (Fig. 2) is to be compared with the single-escape peak of the 3.22-Mev radiation (Fig. 1), the intensity ratio of the double and the single-escape pair peaks (which depends mainly on the crystal, but very little on the gamma-ray energy) was determined with the aid of the $Na^{24}$ and $K^{38}$ spectra taken with the same crystal. The intensity of the 4.0-Mev gamma ray was thus found to be about 0.2% of the total decay.

Branching transitions from the 4.0-Mev state to the excited states would give rise to gamma rays with energies of about 1.8 and 0.8 Mev but they were not found to stand out from the statistics in the spectrum. The upper limit of the log *ft* value which corresponds to no branching to the excited states is 4.9. Here an error of $\pm 0.3$ is introduced by the uncertainty in the beta-ray energy.

In order to investigate the characteristics of the 4.0-Mev state established in the $P^{34}$ decay the high-energy part of the $Cl^{34}$ spectrum was examined carefully. A strong source at a large distance from the crystal was used to avoid the summing of 3.22-Mev radiation and annihilation radiation. The portion of the spectrum above 3.0 Mev is shown in Fig. 3. The part above the 3.22-Mev peak shows a decay with a half-life of about half an hour, which assigns this portion to $Cl^{34}$. The part corresponding to the double-escape peak of the 4.0-Mev gamma ray is masked by the 3.22-Mev photopeak, but there is an indication of the single-escape pair peak and the shape of the spectrum resembles well the one from

[14] D. Green, thesis, University of California, Los Angeles (unpublished), quoted by H. E. Handler and J. R. Richardson, Phys. Rev. **102**, 833 (1956).
[15] P. R. Bell, *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 133.

$P^{34}$. The contribution of the continuous spectrum due to the annihilation in flight of the 4.5-Mev positrons, which should decrease rapidly with energy, seems to be negligible.

The intensity of the 4.0-Mev gamma ray from $Cl^{34}$ is estimated to be about 0.2% of the total decay, ignoring a possible contribution from the annihilation in flight. If no branching of gamma rays to the lower excited states is assumed, the value of log *ft* of the positron decay to the 4.0-Mev state is 5.4. The difference in the log *ft* values from $Cl^{34}$ and $P^{34}$, which is a quantity independent of the branching to the excited states, is about 0.5.

In order to look for the 2.24-Mev gamma ray from $P^{30}$ an aluminum foil was bombarded with alpha particles from the cyclotron. At first the source was placed about one foot from the crystal and a small aluminum absorber was placed in the middle of the gamma-ray path to minimize the annihilation radiation hitting the crystal. The spectrum above the annihilation radiation (0.5 Mev) showed, however, a long tail due

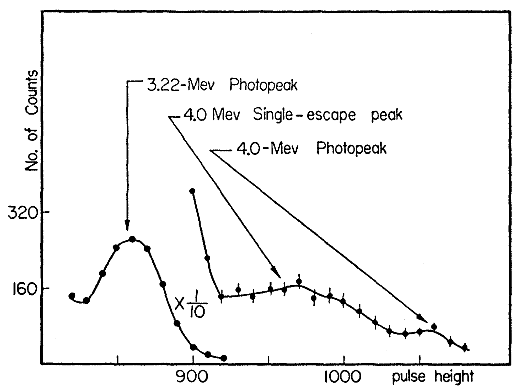


FIG. 3. High-energy portion of the $Cl^{34}$ spectrum.

to annihilation in flight and the statistics in this part prevented one from detecting peaks due to weak gamma rays around 2 Mev. To reduce this difficulty the path of the positrons was bent by a magnetic field so that the gamma rays due to the annihilation in flight could be avoided, except for those produced in the source and the short air path before the magnetic deflection (Fig. 4). The spectrum thus taken shows a definite hump at around 2.24 Mev due to the gamma ray expected in $Si^{30}$ (Fig. 5). There is still a considerable background from the annihilation in flight. The intensity of the gamma ray was determined with the aid of $K^{38}$, which has a single gamma ray with almost the same energy (2.16 Mev) and positrons with almost the same end point, the number of the gamma rays being the same as the number of the positrons. The gamma-ray spectra from $P^{30}$ and $K^{38}$ were taken in identical geometry and the number of the positrons from the same sources were counted with a Geiger counter under identical geometry. From this comparison, the

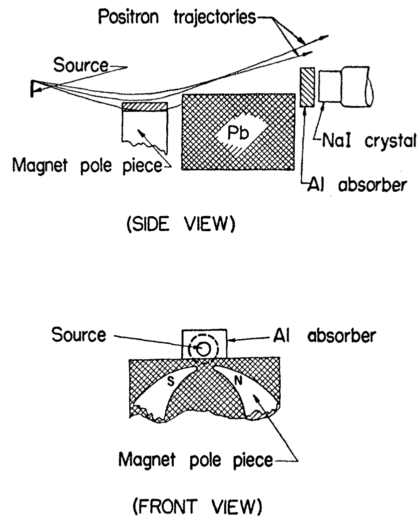


FIG. 4. Source and crystal geometry used for avoiding annihilation-in-flight background.

branching of the positrons from $P^{30}$ to the 2.24-Mev state in $Si^{30}$ was estimated to be 0.5%. This corresponds to a log *ft* value of 5.4.

## DISCUSSION

The results for $A=34$ are shown in Fig. 6. The failure to observe the beta-ray branching from $P^{34}$ to the second excited state of $Cl^{34}$, setting the lower limit of log *ft* for this transition at 5.6, allows one to draw a relatively simple picture to explain the alternation of transition rates of beta decays from $P^{34}$ and $Cl^{34}$ to the lower states in $S^{34}$, as was mentioned in the introduction: Namely, it is suspected that the first excited state of $S^{34}$ has a configuration easily attained by beta transition from $P^{34}$ but rather hard to be attained from the $3^+$ isomeric

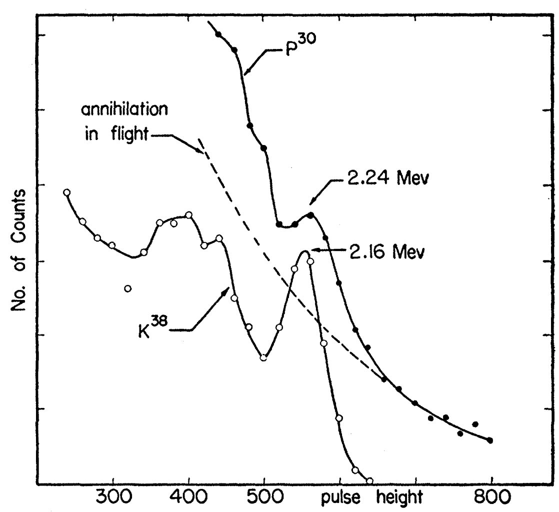


FIG. 5. Gamma-ray spectrum of $P^{30}$. The annihilation-in-flight background has been adjusted to leave a pulse-height distribution for the nuclear gamma ray similar to that of the $K^{38}$ gamma ray.

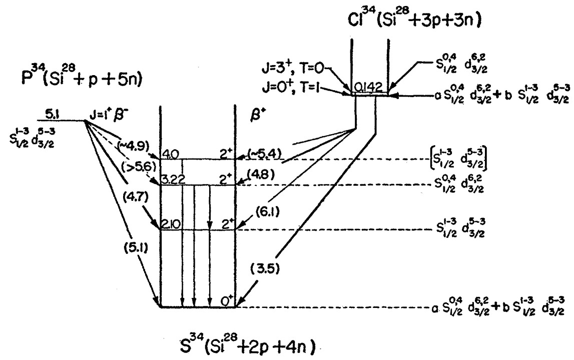


FIG. 6. Decay scheme of the $A=34$ triplet. The numbers in parentheses indicate the values of log *ft*. The two types of levels are symbolized by the total numbers of $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ orbits possible in the proposed predominant configurations.

state in $Cl^{34}$, and with the second state of $S^{34}$ the situation is reversed. One may try, further, to give a more detailed interpretation on the basis of some $jj$-coupling shell-model assignment.

The easiest approach is to use the configurations of six nucleons outside the $Si^{28}$ core and to consider $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ orbits only. For the $0^+$ and $2^+$ states of $S^{34}$, configurations involving from zero to four $s_{\frac{1}{2}}$ orbits (for neutrons and protons) are possible. The same is true for the two states of $Cl^{34}$, for which the straightforward shell-model assignment is $(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_p(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_n$. In the case of $P^{34}$ $(1p+5n)$, on the other hand, not more than three particles (one proton and two neutrons) can be put into the $s_{\frac{1}{2}}$ orbit because of the Pauli principle, and there has to be at least one $s_{\frac{1}{2}}$ neutron. The most plausible assignment is $(s_{\frac{1}{2}})_p(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}}{}^3)_n$. The two mutually exclusive sets of configurations, then, might be those with zero and four $s_{\frac{1}{2}}$ orbits (for the $3^+$ state of $Cl^{34}$ and the second excited state of $S^{34}$) on one side, those with one to three $s_{\frac{1}{2}}$ orbits (for $P^{34}$ and the 2.10-Mev level of $S^{34}$) on the other side. There are so many possible mixing configurations within each set, that in Fig. 6 the two types of levels are characterized only by the total number of $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ orbits of the proposed dominant configurations, i.e., $s_{\frac{1}{2}}{}^{0,4}$ $d_{\frac{3}{2}}{}^{6,2}$ and $s_{\frac{1}{2}}{}^{1-3}$ $d_{\frac{3}{2}}{}^{5-3}$. The question, why these two types exist in $S^{34}$ and $Cl^{34}$ and what the relative strengths of the various possible configurations are, can only be answered by detailed calculations. The purity of the two types seems fairly high, as evidenced by the large *ft*-values of those transitions that have to proceed through small admixtures. The value of $\log ft=4.8$ for the decay from $Cl^{34}$ ($3^+$) to the second excited state may seem high for a transition between states involving the same configurations, presumably with good overlap of the wave functions; according to King,[16] however, a value of 4.3 would be expected in the $jj$-coupling model even for pure states

$$[(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_p(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_n\rightarrow(s_{\frac{1}{2}}{}^2)_p(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}}{}^2)_n],$$

since $|\int\sigma|^2=6/25$ in this case.

Another interesting feature of the decay of this triplet is the low value (5.1) of log *ft* of the transition from $P^{34}$ to the $S^{34}$ ground state. If the latter were purely of the type $s_{\frac{1}{2}}{}^{0,4}d_{\frac{3}{2}}{}^{6,2}$ (like the second excited state and the $3^+$ isomer of $Cl^{34}$), this transition should be slow. Therefore, there must be a considerable admixture of configurations corresponding to those occurring in the $P^{34}$ ground state. The existence of such a mixture of several configurations in the $0^+$ ground state has already been mentioned by Redlich[17] in calculations on $O^{18}$, by Alburger and Pryce[18] in the study of the energy levels of $Pb^{206}$, and by Levinson and Ford[19] in the calculation of the energies of the lowest states of $Ca^{42}$.

The evidence for the mixed character of the $S^{34}$ ground state is especially interesting in connection with the abnormal $T=1$ ground state of $Cl^{34}$,[4] which must consist of the same configurations (with one neutron changed into a proton) since it is a member of the same $T=1$ multiplet. If the $0^+$ state were of the same type as the $3^+$ isomer (presumably with the configurations $(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_p(s_{\frac{1}{2}}{}^2d_{\frac{3}{2}})_n$ and $(d_{\frac{3}{2}}{}^3)_p(d_{\frac{3}{2}}{}^3)_n$), it would be expected to have a somewhat higher energy than the latter because of the spin-spin interaction which favors the triplet state. This interaction, however, decreases with increasing size of the nucleus and for $Cl^{34}$ it may well be overcompensated by the configuration interaction due to the admixture of $s_{\frac{1}{2}}{}^{1-3}d_{\frac{3}{2}}{}^{5-3}$ type configurations which lowers the energy of the $0^+$ state, making it the "abnormal" $T=1$ ground state.

The state found at 4.0 Mev is also assigned to be a $2^+$ state since it can be attained from both sides, from the $Cl^{34}$ isomer and $P^{34}$. The slightly lower *ft*-value of the transition from $P^{34}$ may indicate that this state is more similar to the first excited state than to the second.

The results on the decay of $P^{30}$ are shown in Fig. 7. The ground state of $P^{30}$ is probably $(s_{\frac{1}{2}})_p(s_{\frac{1}{2}})_n$. The slow transition to the ground state of $Si^{30}$ may indicate that the latter has only a rather weak component of $(s_{\frac{1}{2}}{}^2)_n$,

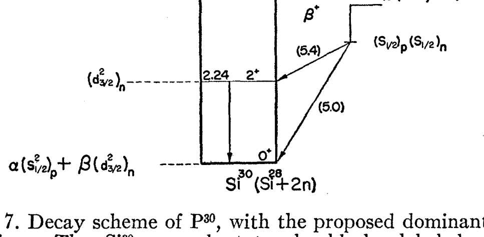


FIG. 7. Decay scheme of $P^{30}$, with the proposed dominant configurations. The $Si^{30}$ ground state should be labeled $\alpha(s_{\frac{1}{2}}{}^2)_n+\beta(d_{\frac{3}{2}}{}^2)_n$.

[16] R. W. King (private communication).
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[18] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).
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the main configuration being possibly $(d_{\frac{3}{2}}^2)_n$. Within the approximation considered ($Si^{28}$ core+two nucleons), the first excited state cannot have a $(s_{\frac{1}{2}}^2)_n$ configuration at all, since it could not give rise to a $2^+$ state. This gives a qualitative explanation for the fact that the transition probability of the decay to the first excited state, after correction for the statistical factor, is about ten times smaller than that for the ground-state decay.

## ACKNOWLEDGMENTS

The authors are indebted to Dr. R. W. King and Dr. D. C. Peaslee for many helpful discussions.

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

# Measurement of the Mass of $He^5$

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(Received May 21, 1956)

A $Q$ value of $15.15\pm0.04$ Mev for the reaction $Li^6(t,\alpha)He^5$ has been obtained through a measurement of the energy of the alpha particles. The mass of $He^5$ is then $5.01390\pm0.00004$ amu or $He^5\rightarrow He^4+n+0.97\pm0.04$ Mev. The width of the ground state is $0.7\pm0.2$ Mev.

## INTRODUCTION

A NUMBER of determinations of the mass of $He^5$ have been made by measuring the energies of charged particles from nuclear reactions in which $He^5$ is one of the products. The reactions used were $He^4(d,p)He^5$, $Li^6(d,He^3)He^5$, $Li^6(n,d)He^5$, $Li^7(d,\alpha)He^5$ and $T(He^3,p)He^5$. References to these measurements are given in Table I. As can be seen there, there is a considerable variation in the values obtained for the instability of $He^5$ for neutron emission and for the width of its ground state. A further experiment thus seemed justified.

From the point of view of accuracy, the last two of the reactions mentioned above have the advantage that the energy of the bombarding particles can be relatively low, most of the energy of the products coming from the $Q$ of the reaction. This reduces the effects, on the mass derived for $He^5$, of target thickness, errors in bombarding energy, and errors in the angle at which the reaction products are measured. A further reaction with similar advantages, $Li^6(t,\alpha)He^5$, has been used in the present experiment. The $Q$ value was obtained by measuring the energy of the alpha particles with a large proportional counter. This counter was calibrated with alpha particles from ThC′ and ThC.

## METHOD

The tritons were accelerated to 235 kev by a 250-kv accelerator. A thick target was formed by melting $Li^6F$ onto a stainless steel backing. The target was one-eighth inch square and held at an angle of 22.5° to the beam. This surface, in conjunction with a one-quarter inch diameter diaphragm 13 inches away, formed a collimating system for the beam. The target chamber is illustrated in Fig. 1. The angle between the observed alpha particles and the triton beam could be varied by rotating the lid of the target chamber, on which the counter was mounted.

The side-window counter, similar to one described by Allen *et al.*,[1] is five inches in diameter and sixteen inches long. It was filled with an argon-$CO_2$ mixture to a pressure of 70 cm of Hg. The central wire had a diameter of 0.005 inches and was held at a potential of 1600 volts. With these conditions, the gas multiplication was six. Particles entered the counter through a gold-sputtered mica window, 1.1 mg/cm² thick.

TABLE I. Summary of measurements of the instability of $He^5$.

| Reaction | $Q$ (Mev) | Instability (Mev) | Γ (Mev) | Reference |
|---|---|---|---|---|
| $Li^6(t,\alpha)He^5$ | $15.15\pm0.04$ | $0.97\pm0.04$ | $0.7\pm0.2$ | a |
| $T(He^3,p)He^5$ | $11.18\pm0.07$ | $0.90\pm0.07$ | | b |
| | | $0.95\pm0.07$ | | c |
| $He^4(n,n)He^4$ | | $0.95\pm0.05$ | | d |
| $He^4(d,p)He^5$ | $-3.10\pm0.05$ | $0.87\pm0.05$ | $\geqslant 0.32$ | e,f |
| $Li^6(n,d)He^5$ | $-2.57\pm0.10$ | $1.09\pm0.1$ | 1.1 | g |
| $Li^7(d,\alpha)He^5$ | $14.2\pm0.1$ | $0.9\pm0.1$ | $0.3\pm0.1$ | h |
| | $14.2\pm0.1$ | $0.9\pm0.1$ | | i |
| | 14.3 | 0.8 | 0.25 | j,k |
| | 13.43 | 1.7 | | l |
| | 14.26 | $0.86\pm0.09$ | $0.66\pm0.2$ | m |
| $Li^6(d,He^3)He^5$ | $0.91\pm0.09$ | $0.88\pm0.09$ | $0.69\pm0.2$ | m |

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