with the tentative assignment[1] of $\frac{5}{2}-$ to the 2.430-MeV level.

The proposed decay scheme of Li^9 is shown in Fig. 5. Although the coincidence data of Fig. 3 strongly suggest that Li^9 also populates higher excited states in Be^9 that emit neutrons which may have energies as high as 4.5 MeV these results are not considered to be conclusive. In order to obtain more information on beta-ray branching to such states in Be^9 it would be useful to study the energy spectrum of the Li^9 neutrons in more detail. This might be done by means of a beta-neutron time-of-flight technique following the procedures used recently by Gilat, O'Kelley, and Eichler[10] in a study of neutrons from N^{17}.

A calculation of the cross section for forming Li^9 at $E_n=15.5$ MeV was made by comparing the intensity of the Li^9 beta-ray spectrum with that of N^{16}. At this neutron energy the cross section for the $O^{16}(n,p)N^{16}$ reaction is close to 30 mb as determined by DeJuren, Stooksberry, and Wallis.[11] By taking into account the relative numbers of O^{16} and Be^9 atoms in the two samples and the transport and counting times a cross section of 0.7 mb (±50%) is found for the formation of Li^9 in the $Be^9(n,p)Li^9$ reaction using neutrons having an average energy of about 15.5 MeV. This result agrees the previous estimate[4] of ~0.6 mb for neutrons of the with same energy.

The author is indebted to Dr. B. M. K. Nefkens for suggesting this problem, to Dr. D. H. Wilkinson for helpful discussions, and to Dr. R. E. Middleton for communicating his unpublished results on the $Li^7(t,p)Li^9$ reaction. The pneumatic transport system was designed by Robert A. Lindgren.

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Beta Decay of Li^8†

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The beta decay of Li^8, formed in the $Li^7(d,p)Li^8$ reaction, has been studied by measuring the energy distribution of the alpha particles that come from the subsequent breakup of Be^8. The effects of the penetration into backing foils of the Li^8 recoils have been corrected for by comparing, for several deuteron bombarding energies, the alpha-particle spectra seen using a very thin foil target and the same target backed by a thick foil. The resulting "correct" alpha-particle spectrum is adjusted for various small effects including that due to electron-neutrino recoil and then compared with a prediction based on the empirical alpha-alpha scattering phase shifts, themselves adjusted by the subtraction of a hard-sphere phase shift. It is shown that the prediction is rather insensitive to the choice of hard-sphere radius. The agreement between the beta-decay data and the alpha-alpha phase shifts in the peak position (the "2.9-MeV state" of Be^8) is excellent as it is also in the shape of the transition probability distribution on the low- (alpha-particle) energy side of the peak where the falloff of intensity is here experimentally followed over two orders of magnitude. On the high-energy side of the peak, the familiar discrepancy is found in the sense that the transition probability is much too high to be explained by the first excited state alone. The present results, in addition to constituting an accurate comparison between Li^8 beta decay and alpha-alpha scattering, strengthen the interpretation of the reaction $Be^9(p,d)Be^8$ in terms of the "ghost" of the ground state of Be^8 and provide necessary data for discussing Li^8 and B^8 decay to regions of higher excitation in Be^8 where the effects of transitions to the tail of the first $T=1$ state of Be^8 are probably important.

INTRODUCTION

THE history of the excited state structure of Be^8 below the first $T=1$ state at about 17 MeV is a complicated one. Over the years, many levels have come and gone but for some time now we have believed the true situation to possess the simplicity expected of it on either the independent-particle model or the alpha-particle model, namely, the $J^\pi=0^+$ ground state fol-

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lowed by broad $J^\pi=2^+$ and 4^+ states at roughly 2.9 and 11.7 MeV, respectively. According to the independent-particle model these three states are, in the approximately valid LS coupling, the ^{11}S, ^{11}D, and ^{11}G states of the partition [4] while according to the alpha-particle model they represent rotational states of $l=0$, 2, and 4 of the alpha-alpha structure; the two views are effectively unified, in this case rather trivially, through the SU_3 classification.

All states of Be^8 are unbound against dissociation into two alpha-particles—the ground state itself by 94 keV. It is, therefore, natural to attempt to categorize the level structure in terms of the parameters of alpha-alpha elastic scattering,[1–6] an attempt that gives explicit expression to the alpha-particle model of the structure. Indeed, if the alpha-alpha (nuclear) scattering phase shifts are suitably adjusted by the appropriate "hard-sphere" or potential scattering phase shifts there result $l=0$, $l=2$, and $l=4$ phase shifts that depend resonantly on energy in a manner indicating the existence of the three states mentioned above; all display alpha-particle reduced widths of order unity such as are demanded by the alpha-particle model.[5,7] This use of a hard-sphere background scattering is, of course, a fiction, but it is quite difficult to do any better. (The alternative recipe that is preferable in most circumstances, namely, to caricature the background scattering as that of the appropriate optical model, is clearly not admissible here since the resonant states in question, those that we are attempting in this way to disentangle from the background, are themselves the states of the relevant optical-model potential.[8]) We may alternatively and qualitatively say that, in addition to the resonant states, we are involved in the tails of many higher levels not resonant in the region below 16 MeV. These higher levels contribute to the alpha-alpha scattering in a certain measure relative to the resonant states; they will contribute in, generally, different relative measure in other reactions leading to the formation of Be^8.

It is, therefore, of considerable interest to correlate the production of Be^8 in nuclear reactions with the alpha-alpha elastic scattering phase shifts. We may hope in this way to gain a more complete understanding of the low-lying resonant states themselves and also, perhaps, some insight into the properties of states that may not be directly accessible but which reveal themselves through their contribution to the "background." It may be questioned whether the first excited state will display an energy and a form independent of its mode of formation. It is very broad; so short-lived a structure may not interpose a sufficient period of "forgetting" between its formation and decay to enable us to treat it as a quasistationary condition. Indeed, its width, as recorded in a range of reactions, appears to vary from 0.8 to 2.0 MeV.[9] Before regarding this as a truly significant variation, we should correlate the observed profile in any given reaction with expectation based on some "standard" description of the state such as is provided most naturally by the alpha-alpha phase shifts. The present work is a contribution on this point.

The present investigation is of the production of Be^8 in the decay of Li^8; it bears on the general problem at two further specific points. The first concerns the question of the "ghost" of the ground state of Be^8; the second concerns the properties of the first $T=1$ state of Be^8 (probably that at[10] 16.62 MeV). If a nuclear state is stable, or just unstable, to charged particle emission, then it will be very narrow as seen in a reaction leading to it, in the latter case because the Coulomb barrier strongly inhibits its decay. But as we move to higher excitations the rapid increase in barrier penetrabilities may cause the increasing numerator of the density-of-states function,[7]

$$\rho\sim\Gamma(E)/[(E-E_r)^2+\tfrac{1}{4}\Gamma(E)^2],$$

to outstrip the increase of the denominator that is due to moving further from the resonance. In this case, the population of the state will show a second, broad, maximum perhaps some MeV away from the narrow maximum. This broad maximum is not, then, a new state but is the "ghost" of the narrow maximum. Since the ground state of Be^8 is very narrow ($\simeq$7 eV) due to its near stability, it may be expected to show such a ghost.[7,11] It is interesting and important to check this prediction since Be^8 is a uniquely simple example and a full understanding of the phenomenon here is necessary if we are to make confident predictions about the role of ghost states in more complicated situations such as present themselves in C^{12} (see Ref. 7),[12] O^{16} (see Ref. 7), and elsewhere. The reaction Be$^9(p,d)$Be^8 seems to show evidence for the ghost[7,11] in that the group of deuterons leading to the first excited state is lopsided towards lower excitation in Be^8 (at a channel energy in Be^8 of about 1–2 MeV. However, such a situation could arise either from a ghost or from the intervention of another Be^8 state of $J^\pi=0^+$ or 2^+ (the width of the "effect" rules out higher spins and states not belonging to $J^\pi=\text{even}^+$). Li^8 is $J^\pi=2^+$ in its ground state and so

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will decay only negligibly to $J^\pi=0^+$ states of Be^8. It should, therefore, not decay to the "effect" if that is indeed the ghost of the $J^\pi=0^+$ ground state. Agreement between the shape of the first excited state as revealed in Li^8 decay and expectation based on the resonant $l=2$ alpha-alpha phase shifts (which show no lopsidedness) would argue against any true $J^\pi=2^+$ structure in the region of the first excited state, or strong effect of finite lifetime, and so would support the hypothesis that the "effect" is at least of $J^\pi=0^+$ and so a possible "real ghost." The second objective of the present experiment is, by a thorough study of the Li^8 beta decay to the immediate neighborhood of the first excited state, to clear the ground for an understanding of the decay of Li^8 and B^8 to the region between that state and the first $T=1$ state. As is well known,[13] the population of Be^8 at high excitation in these beta decays exceeds by a large factor what can be understood in terms of the participation of the first excited state alone. It may be that the excess should be interpreted in terms of the superallowed transitions to the tail of the first $T=1$ state, in which case it contains information on the energy dependence of the $T=0$ isotopic spin impurity of the $T=1$ state, itself information of considerable interest and impossible of access by any other technique. We reserve for a later paper, in which we shall report the results of measurements on the decay of Li^8 and B^8 to Be^8 at higher excitation, a full discussion of this matter. We content ourselves here with the remark that the decay to the higher regions of Be^8 cannot be analyzed until the contribution of the low-lying resonance itself is fully explored and correlated with the alpha-alpha phase shifts. Such is our present aim.

EXPERIMENT: HISTORICAL

There have been many studies of Li^8 beta decay as revealed through the distribution of the alpha particles from the subsequent breakup of the Be^8. Among these some have been concerned not with the details of the population of Be^8 but, through studies of alpha-alpha[14] and beta-alpha[15] correlations, with the establishment of predominantly Gamow-Teller nature of the beta transition together with the $J^\pi=2^+$ character of[14] Li^8 and with the establishment of the axial-vector character of the Gamow-Teller interaction.[15] Detailed measurements of the beta-alpha correlations[16] (including that from B^8) also yield evidence on the hypothesis of the conserved vector current.[17] The studies with which we are concerned in the present paper are rather those that seek to determine the population of Be^8 as a function of energy of excitation, i.e., the transition probability in the beta decay as a function of this residual excitation. Of such studies there have been many. They divide into two classes. In the first class are measurements carried out with good statistical precision using Li^8 sources prepared in the reaction Li$^7(d,p)$Li^8 and determining, using various detectors, the energy distribution of single alpha particles from the breakup of Be^8. Typical experiments here are those of Frost and Hanna[18] who used a magnetic spectrometer to analyze the alpha-particle energy distribution and Farmer and Class[19] who used a CsI detector looking directly at the decaying Li^8. Such experiments, carried out using thin lithium targets but deposited on thick backing foils, are useless for giving any accurate picture of the population in the immediate neighborhood of the first excited state, particularly on its low-energy side, because of the penetration, due to the deuteron bombardment and subsequent proton emission, of the recoil Li^8 into the backing foil and the consequent energy loss of the decay alpha particles in emerging from the foil into the detector. Even for deuteron bombarding energies as low as 500–600 keV, typical energy losses suffered by the alpha particles coming from the maximum of the first excited state are of the order of 200–400 keV as compared with their initial energy of about 1.5 MeV. Since we wish to examine the spectra at least down to initial alpha-particle energies of 700 keV, it is clear that such a method of experimentation must be rejected. A further disadvantage of this class of experimentation, in which single alpha particles are observed, is that their energy is affected non-negligibly by the electron-neutrino recoil. However, now that the nature of the beta-decay interaction is thoroughly understood, a correction on this account could be applied with good accuracy if the true energy distribution of single alpha particles could be determined. The second class of experiment avoids the recoil problem by observing the point of decay. For example, Li^8 nuclei ejected from nuclei of the photographic emulsion under various types of bombardment come to rest then beta decay; the consequent Be^8 breakup into two alpha particles forms a "hammer track." Measurements on the head of the hammer allow, in principle, the determination of the summed energies of the two alpha particles without any loss due to recoil penetration or distortion due to electron-neutrino recoil and, hence, a true picture of the excitation produced in Be^8 by the beta decay.[20] In practice, statistics are very poor and, in any case, the method is useless for the region of present interest due to the very short ranges of the alpha particles and the associated lack of adequate energy resolution; there is also a bias

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against the recognizing of events corresponding to low excitation in Be^8. Another type of experimentation in this same class is represented by the remarkable work of Bonner, Evans, Malich, and Risser.[21] These experimenters introduced Li^8 into a cloud chamber and photographed the Be^8 breakup. Although statistics were poor, and the results somewhat unsure due to heavy fogging in the cloud chamber, this experiment has stood as the only one giving significant information about the population of the low-energy side of the first excited state. It shows that the population falls off rapidly towards zero in the manner qualitatively to be expected from the behavior of the $l=2$ phase shifts. This experiment takes us down in intensity by approximately one order of magnitude below the peak of the distribution on the low-energy side but is not accurate enough for quantitative comparison with the alpha-alpha phase shifts. We regard this work as the effective take-off point of the present investigation; it is far superior, in terms of information about the beta decay to the first excited state, to anything done in the intervening 15 years.

EXPERIMENT: PRESENT

Our objective was to use semiconductor particle detectors to achieve good statistics with good energy resolution and with them to determine the alpha-particle spectrum coming from an effectively thin Li^8 source. This cannot easily be done directly, using solid targets, because, even if a thin target and thin backing are used, the majority of the Li^8 formed in the reaction $Li^7(d,p)Li^8$ used for producing them will recoil from the target-plus-backing and some of them will bury themselves in parts of the apparatus from which the counter may be seen. This effect may be minimized by a design of target-plus-counter chamber such that, for a low deuteron bombarding energy that results in a predominantly forward emission of the Li^8 ($Q=-0.19$ MeV), the recoiling Li^8 come to rest in parts of the chamber that cannot see the detector. However, one cannot rely on such arguments because scattering of the low-energy Li^8 recoils is very heavy and they find their way everywhere. It is, after all, chiefly by virtue of the great straggle in range of such ions, itself closely allied to the heavy scattering, that Li^8 ions stop in a thin target foil at all. Possible solutions are the use of a stopping gas to transfer Li^8 to a counter or a mechanical transfer system for the thin target-plus-backing. We have adopted another method based on our confidence that there should be effectively no beta decay to regions of sufficiently low excitation in Be^8; cf. the rapid vanishing of the $l=2$ phase shift (see later). Our method contains a built-in check of this point. Briefly, we compare alpha-particle distributions resulting from the bombardment of thin targets on thin and on thick backings and subtract them appropriately to reveal the genuine undistorted distribution.

We bombarded a target foil made of a layer of approximately 10 $\mu g/cm^2$ of LiF evaporated onto a carbon support of approximately 7 $\mu g/cm^2$. This target was inclined at an angle of 45° to beams of deuterons of various energies and was examined by a semiconductor particle detector at 90° to the beam. The bias on the detector was adjusted so that the sensitive depth was slightly more than the range of the most energetic alpha-particle that could come from Be^8 following the beta decay of Li^8. Throughout the experiment, the response of the entire system was checked at frequent intervals using a pulser applied to the input of the preamplifier in parallel with the detector. We also frequently calibrated the counter using the alpha particles from Pu^{239} and Am^{241}.

The deuteron beam came from the Brookhaven research Van de Graaff and was interrupted by a shutter that rotated at 1800 rpm 13 ft upstream from the target. A second shutter, synchronous with the first, rotated between the target and the detector so that the detector could not see the target while the deuteron beam was on the target. Mean beam currents of a few tenths of a microampere were used in a deuteron bombarding duty cycle of about $\frac{1}{9}$ and a counting duty cycle of about $\frac{2}{3}$. Since the half-life of Li^8 is about 0.8 sec the decay per cycle was slight.

The energy loss, in the foil, of alpha particles of energies that concern us here is small and so those alpha particles that come to the counter from the foil itself represent very nearly the "true" distribution that we are seeking. However, as has been remarked, the counter will inevitably also see some alpha particles from Li^8 ions that have buried themselves in various parts of the chamber and so which give an alpha-particle spectrum appropriate to a thick, rather than to a thin, backing. We, therefore, also measured the alpha-particle spectrum found after backing the thin-foil target described above by a foil of nickel thick enough to stop all Li^8 recoils. In this latter case the distribution is due chiefly to the Li^8 recoils that stop in the nickel, but with some contribution from the thin-target foil itself. In all cases, with both thin and backed targets, we see an alpha-particle spectrum that has a peak with a valley at lower alpha-particle energy before the final rise at yet lower energies due to beta particles entering the detector. An interesting index is this peak-to-valley ratio that we display as a function of deuteron bombarding energy in Fig. 1. As may be seen, at high bombarding energies the peak-to-valley ratio is poor and not very different for the backed and thin targets; this shows that the bulk of the counts in both cases comes from Li^8 ions that have recoiled from the parent foil. For lower bombarding energies the ratio both for backed and unbacked targets improves, as should be expected from the lower penetration of the Li^8 recoils, and there is an increasingly significant difference between the two types of target which indicates an increasingly important contribution from the thin foil itself in the unbacked spectra.

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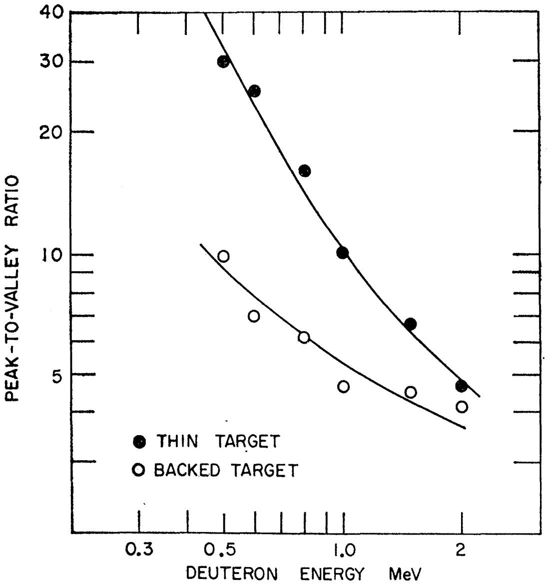

FIG. 1. Ratio of counts per channel in the peak of the alpha-particle spectrum to counts per channel in the valley before the exponential rise due to noise and electron pulses. Data are shown both for the thin target alone (10 $\mu g/cm^2$ LiF) and for the thin target backed with thin nickel foil to stop all Li^8 recoils. The deuteron bombarding energies are 0.5, 0.6, 0.8, 1.0, 1.5, and 2.0 MeV. The lines through the points are purely eye-guides and are not used in the analysis.

We now argue that if the spectrum from the unbacked target is due partly to Li^8 ions stopped in the target itself (the "true" spectrum) and partly to recoils fully embedded elsewhere, while that from the backed target is due to a relatively increased proportion of fully embedded recoils, then an appropriate subtraction of the two spectra should reveal the "true" spectrum as represented by Li^8 ions stopped in the target foil itself. The appropriate subtraction we take to be that which gives no alpha-particles at low enough alpha-particle energies since the probability of the beta transition must tend to zero when the corresponding alpha-alpha (nuclear) phase shift tends to zero, which it must do at finite alpha-particle energies due to the influence of the centrifugal barrier. An obvious test of the admissibility of this procedure in practice is that it should result in a subtracted alpha-particle spectrum that is zero over a recognizably finite energy range at low energies, i.e., that the backed and unbacked spectra should have the same form, before subtraction, at low enough alpha-particle energies. This we call the first test. It is clear that this method of backing a thin target will not result in precisely the same spectrum from the backing, due to stopped recoils, as comes from the rest of the chamber in the thin-target case, since the history of the recoils is different in the two cases. However, the differences, if they are important, will certainly depend strongly on deuteron bombarding energy. A further necessary test of the whole procedure is, therefore, that the subtracted spectra should be independent of the deuteron bombarding energy even though, as may be seen from Fig. 1, the individual spectra themselves are strongly dependent on the bombarding energy. This we call the second test.

The experimental spectra are shown in Fig. 2 for the four lowest bombarding energies. The backed target spectra are in superior statistics and the experimental points are omitted to avoid confusion of the figure. The thin and backed target spectra have been normalized at the lower channel numbers and it is seen that the two indeed run together over several channels before the unbacked spectra rise above the backed—the first test. The spectra are shown only above the region where the electron pulses are significant. This exponential rise at lower channel numbers has been extrapolated to provide a correction to the first point or sometimes two points of the spectra displayed in the figure; the correction was small here and negligible elsewhere.

We now apply the second test and ask whether the subtracted spectra obtained by subtracting the backed from the unbacked spectra of Fig. 2 are identical for all four deuteron bombarding energies. This is done in Fig. 3 where the four subtracted spectra have been spread out vertically in an arbitrary manner to facilitate comparison. Within the statistics of the points

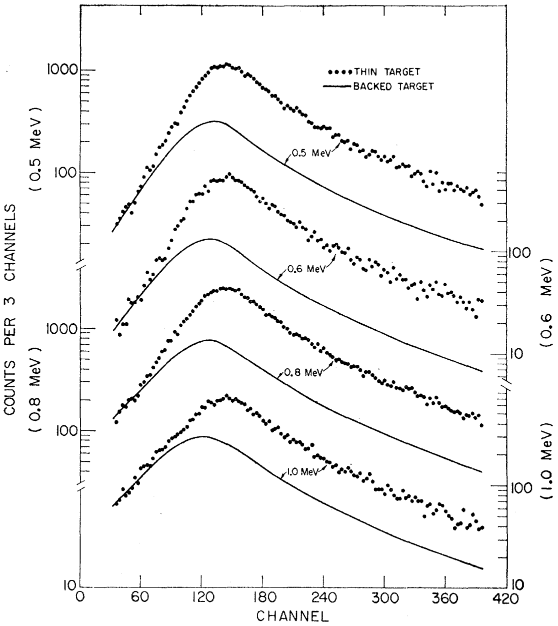

FIG. 2. Alpha-particle spectra for thin and backed targets at deuteron bombarding energies, as indicated on the distributions, of 0.5, 0.6, 0.8, and 1.0 MeV. The exponential rise at low-channel numbers due to noise and electron pulses is not shown. A correction obtained by extrapolating this rise has been applied to the last two points of these distributions. The correction to these points is small and is negligible for higher points. The backed-target distributions have relatively good statistics and the actual data points are not shown; they have been adjusted in ordinate to run through the thin-target distributions at the lowest channel numbers.

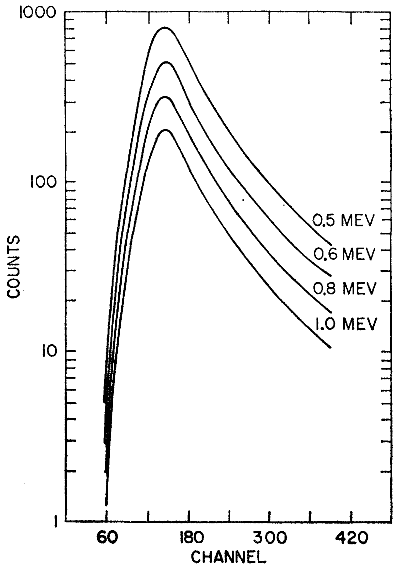

FIG. 3. Logarithmic plots of the alpha-particle difference spectra resulting from the subtraction of the thin-target and backed-target distributions of Fig. 2. The curves have been arbitrarily spaced in ordinate to facilitate comparison between them. There is no absolute meaning to the ordinate scale and the purpose of the figure is merely to demonstrate that the same true spectrum, obtained by the subtraction procedure, results at each deuteron bombarding energy.

themselves, which have been omitted to avoid confusion of the figure, the four subtracted spectra are identical and the test is passed. We may now, therefore, sum these subtracted spectra to get our best spectrum representing the true thin-target alpha-particle energy distribution as seen by the solid-state counter. This is done in Fig. 4 which omits the data obtained at a deuteron bombarding energy of 1.0 MeV; they were not of as high an accuracy in the subtracted spectrum as those taken at the three lower energies. The experimental points are shown and also the best line that can be passed through them. It is this line that we use from now on and call the experimental spectrum. Note that the first seven or eight experimental points dot around zero before the increase begins—the first test applied to the summed spectrum.

TREATMENT OF THE EXPERIMENTAL SPECTRUM

Before the experimental spectrum of Fig. 4 can be compared with any theoretical expectation it must be corrected in several ways.

The first correction concerns the importance of a possible dead layer (window) on the surface of the solid state counter. This we investigated by two independent methods. The alpha particles of 5.15 and 5.48 MeV from Pu^{239} and Am^{241} gave two calibration points of pulse height versus alpha-particle energy. We provided eight others in the range 0.5 to 2.0 MeV by scattering into the counter accelerated alpha particles of accurately known energy from the Van de Graaff generator using as scatterer a thin layer of gold evaporated onto a thin VYNS film. The resulting data indicated a window of 65 keV reduced to an incident alpha-particle energy of 0.565 MeV. In the second method the counter was exposed to the accelerated and scattered alpha-particle beam in good geometry and the effect on pulse height of tilting it through 60° was determined. This experiment indicated a window, again reduced to incident alpha particles of 0.565 MeV, of 68 keV. These data were combined and used to construct the corresponding small energy-dependent correction to the experimental spectrum of Fig. 4.

The second correction is on account of the finite resolution of the solid-state counter but is completely negligible in its effect on the experimental spectrum.

The third correction concerns the energy loss of alpha particles in getting out of the LiF-C target foil. This correction is very small and was applied on the assumption of a uniform distribution in depth, within the foil, of the decaying Li^8.

The fourth correction is a thoeretical one on account of the electron-neutrino recoil. We are interested in determining the relative probability of the production of Be^8 following the beta decay of Li^8 as a function of the residual excitation in Be^8. But for the electron-neutrino recoil, the excitation energy (defined relative to two free alpha-particles not to the ground state of Be^8) would, for each alpha particle detected, be just twice the energy of that alpha particle. However, on account of the momentum taken away by the leptons, a distribution in alpha-particle energy results for transitions to a fixed excitation in Be^8 and so the alpha-particle spectrum does not directly image the beta-transition probability which we want to know.

We need to know the distribution of alpha-particle energies $P(E)$, in the laboratory system, that results from beta transitions that leave an excitation of $2E_\alpha$ (above two free alpha particles) in Be^8 (in its own center-of-mass system). This must, in general, be computed numerically from the appropriate Fermi function. However, in our present case, the energy release in the

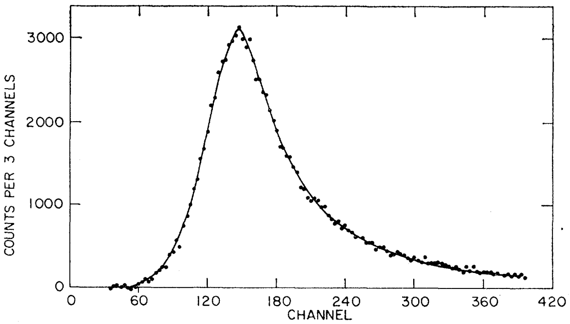

FIG. 4. The sum of the difference spectra obtained at 0.5, 0.6, and 0.8 MeV deuteron bombarding energy. The line through the points is the one treated in the subsequent analysis and finally compared with the theoretical distribution.

beta decay is so high and the nuclei are so light that a very good approximation to the Fermi-distribution is given by the purely statistical distribution function in the lepton momenta. We may also, in good approximation, write $E=pc$ for the beta particles of interest here. We next assume that the transition goes purely through the axial vector coupling, i.e., that the electron-neutrino angular correlation has the form $1-\frac{1}{3}\cos\theta_{\beta\nu}$ where $\theta_{\beta\nu}$ is the angle between the directions of emission of electron and neutrino. This assumption is well justified since although the spins of the nuclei involved admit a contribution from the vector coupling, this is zero to the degree that isotopic spin is conserved and the first $T=1$ state of Be^8 at 16.62 MeV is not mixed into the first excited state. Finally, we assume that the breakup of Be^8 into two alpha particles is isotropic in its own center-of-mass system. This assumption is also very good, being violated to a totally negligible degree (for our present purposes) by the slight admixture of second-forbidden transitions of various types into the allowed beta decay.[16] Within these assumptions we may write

$$P(E)=5(1-3\phi+2\phi^2)/[6(2E_\alpha E_m)^{1/2}],$$

where $\phi=E_m^{-1}(E+E_\alpha-2(EE_\alpha)^{1/2})$ and E_m is the maximum recoil energy that can be transmitted to the Be^8 for this value of E_α.

The adequacy of this expression has been checked at three values of E_α by direct numerical computation relaxing the above four assumptions as far as the information available allows; it is very good. This expression for $P(E)$ must now be "unfolded" from the experimental spectrum to obtain, finally, the beta transition probability as a function of excitation energy in Be^8. As a first step in this it may be noted that both the experimantal spectrum and $P(E)$ may be caricatured as Gaussians. This enables us very easily to apply the bulk of the correction and the rest was achieved, to an accuracy as great as that allowed by the statistics of the experiment, by numerical successive approximations.

The application of these four corrections to the experimental spectrum of Fig. 4 resulted in as close an approach as we can make to the distribution of transition probability in the decay of Li^8. We refer to this as the experimental transition probability curve remembering that the excitation energy in question in Be^8 is always taken relative to two free alpha particles.

ANALYSIS

We ask for the degree to which the experimental transition probability can be understood in terms of the first excited state of Be^8 alone and, in particular, whether the transitions to the low-energy side of that state reveal any possible structure that might be responsible for the apparent ghost seen in $\mathrm{Be}^9(p,d)\mathrm{Be}^8$ and referred to in the Introduction.

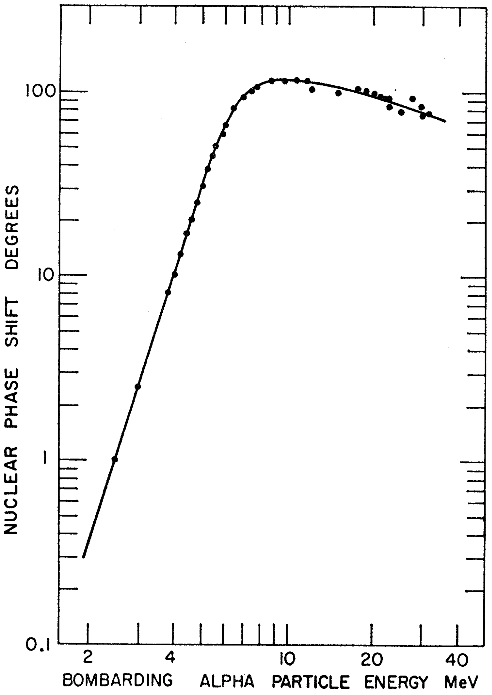

FIG. 5. Experimental nuclear phase shifts for alpha-alpha scattering and the line through them used in the theoretical analysis. Only phase shifts up to a bombarding alpha-particle energy of 16 MeV are used in the analysis but experimental points are shown at higher energies since they were used in constructing the line in the region below 16 MeV. The experimental points come from the work of many authors referred to in the text.

Since the only significantly open channel in Be^8 at the excitations involved here is the breakup into two alpha particles we should be able, within the conventional description of nuclear reactions, to characterize the profile of the first excited state by $\sin^2\delta_{r2}$ where δ_{r2} is the contribution to the total nuclear $l=2$ phase shift in elastic alpha-alpha scattering that is due to the resonant first excited state. Our problem is now to extract δ_{r2} from the total nuclear $l=2$ phase shift δ_{t2}, the quantity that is determined in the alpha-alpha scattering experiment. As mentioned in the Introduction, the only presently available method to get δ_{r2} out of δ_{t2} is to treat the residual nonresonant contribution as that due to a hard sphere of some radius plausibly related to the "size of the alpha-particle". In this case we use the hard-sphere phase shift δ_{h2} and write: $\delta_{r2}=\delta_{t2}+\delta_{h2}$. Here $\delta_{h2}=\tan^{-1}(F_2/G_2)$, where F_2 and G_2 are the regular and irregular solutions to the Coulomb radial wave equation belonging to $l=2$ and evaluated at the "hard-sphere radius" R.

The theoretical transition probability due to the first excited state is now given by

$$\text{transition probability}=\text{constant}\times k^{-1}(F_2^2+G_2^2)\sin^2\delta_{r2}f(W),$$

where k is the wave number of the final state and $f(W)$ is the usual Fermi function of the total energy W of the

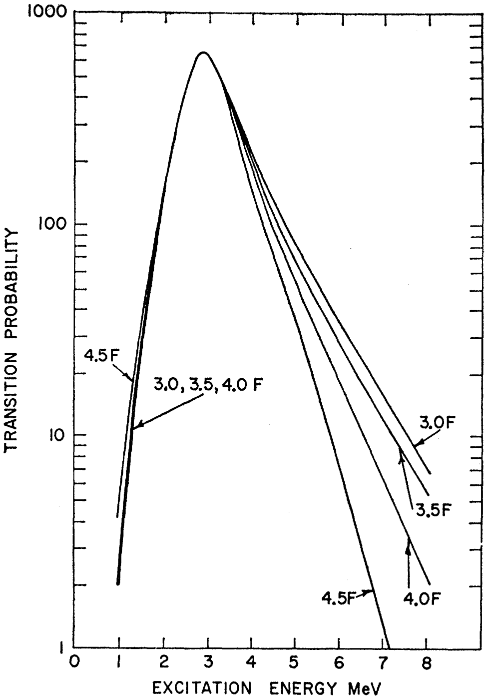

FIG. 6. Theoretical transition probability in the decay of Li^8 due to the 2.9-MeV state of Be^8 as a function of the excitation in Be^8 (defined relative to two free alpha particles, not to the ground state of Be^8). The line of Fig. 5 has been taken to represent the alpha-alpha nuclear phase shifts and the resonant phase shift has been extracted from the total nuclear phase shift using hard-sphere radii of 3.0, 3.5, 4.0, and 4.5 F. The curves for hard-sphere radii of 3.0, 3.5, and 4.0 F are all contained within the thickline shown at low excitation energies.

beta decay, which goes rather accurately like W^5 for the high energies and low Z value of this work.

In order to compute the theoretical prediction we must now fix on values for δ_{t2} and the "hard-sphere radius" R. We have taken the total nuclear phase shifts δ_{t2} from the literature[1–6] and display them in Fig. 5 which also shows the best line that we have fitted through them and have used in the subsequent analysis. Since the hard sphere is a fiction the determination of its radius is tricky. The most popular value is around $R=3.5$ F (see, e.g., Ref. 7) but values between 3 and 4.5 F may be thought reasonable. Figure 6 shows the above expression for the theoretical transition probability computed for $R=3.0$, 3.5, 4.0, and 4.5 F. It is seen that the theoretical distribution is rather insensitive to the choice of R in the immediate region of the peak and on the low-energy side, but is much more sensitive at higher energies of excitation. Before comparing theory and experiment, we ask for the sensitivity of the theoretical distribution to the errors in the experimental determination of the scattering phase shifts. This is shown in Fig. 7 where we display, for $R=3.5$ F, the theoretical distributions resulting from the full line of Fig. 5 and from the phase shifts obtained by redrawing the full line taking as its points, first, the upper error limits of all the phase shifts (raise); and second, the lower error limits of all the phase shifts (lower). This is, of course, a violent exaggeration of the true possible over-all error in the prediction since it assumes that all the individual errors in the phase shifts may be correlated in the same sense. It is seen that the sensitivity of the peak and the behavior elsewhere is quite low and that the curves of Fig. 6, therefore, cannot be sensibly in error on account of the uncertainties in the experimental phase shifts.

We, finally, compare, in Fig. 8, the experimental transition probability curve, obtained through the procedure detailed in the preceding section, with the theoretical transition probability curve–the curve of Fig. 6 for $R=3.5$ F. The two curves have been normalized at the peak. We see that the experimental and theoretical peak energies agree perfectly (to within the statistical error of the experimental determination) and that, on the low-energy side, the two distributions follow each other very accurately until the transition probability has fallen by more than a factor of 15 below its peak value. Beyond this some divergence may be apparent, possibly reaching a factor of 3 when the intensity has fallen by a factor of 300 below its peak value. However, by this time, the errors on the experimental distribution

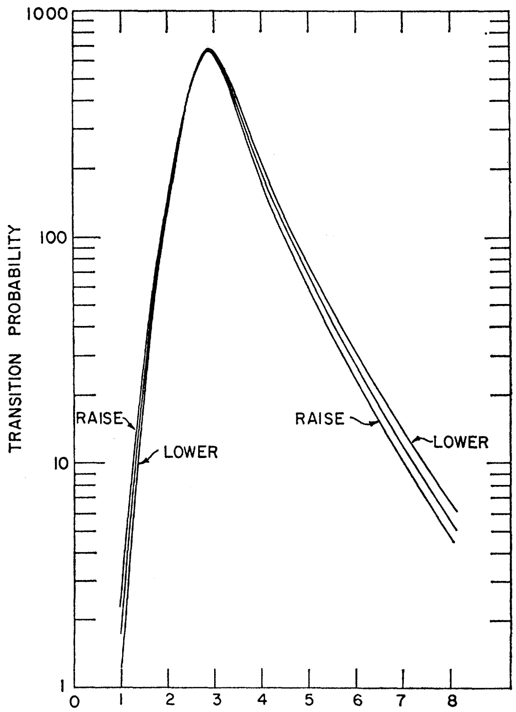

FIG. 7. Theoretical transition probability as in Fig. 6 for a hard-sphere radius of 3.5 F and also for phase-shifts obtained by moving the curve of Fig. 5 upwards and downwards as far as the error limits on the individual points allow. This is a much larger movement than is allowed if the points are considered all together.

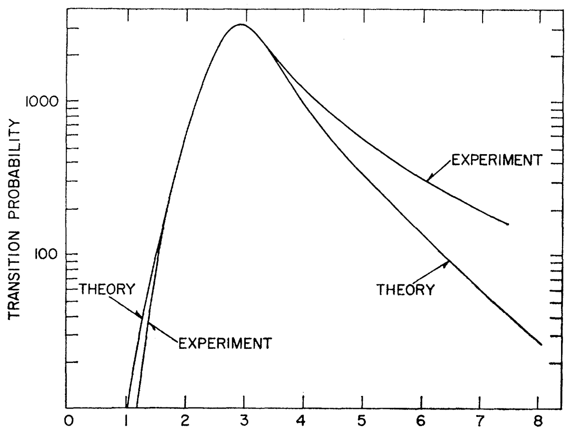

FIG. 8. Comparison of experimental and theoretical transition probabilities. The theoretical curve is that of Figs. 6 and 7 for a hard-sphere radius of 3.5 F and the best curve through the experimental phase shifts as given in Fig. 5. To obtain the experimental curve from that drawn in Fig. 4 corrections have been applied for the counter dead layer, target foil thickness, the effects of electron-neutrino recoil, and counter resolution as described in the text.

are very considerable (see Fig. 4) and it would easily be possible to draw an acceptable line through the experimental points of Fig. 4 that would accommodate the bulk of the discrepancy apparent in Fig. 8.

We consider that, so far as the peak and its low-energy side go, the correlation between the beta-decay probability and the alpha-alpha phase shifts is essentially perfect and at least the great bulk of the beta decay can be ascribed to the first excited state of Be^8. Above the peak the situation is quite different. The two distributions agree well until the transition probability has decreased by a factor of about 1.5 only, after which the discrepancy grows rapidly. Figure 6 shows that there is no hope of remedying the situation by juggling R (indeed a decrease of R even to 3.0 F is not admissible since the associated reduced width of the first excited state as deduced from the alpha-alpha scattering phase shifts diverges before this value is reached[7]–the same is true of the ground state also). This discrepancy on the high-energy side is well known[13] and becomes much worse at yet higher energies. As mentioned in the Introduction, we have (in collaboration with Dr. A. Gallmann) made a separate study of the transition to the higher energy regions of Be^8 using both Li^8 and B^8 decay. The situation will be fully discussed in the report on that work. Here we merely note that beta transitions can take place into the subtracted-off nonresonant part of the total nuclear phase shift δ_{t2} that we have caricatured as the hard-sphere scattering δ_{h2} and then ignored from the point of view of the beta decay and that the matrix element for such transitions may be large, in particular, that for the super-allowed transition to the (tail of the) first $T=1$ state of Be^8 at 16.62 MeV. It is obviously necessary to slightly revise the fitting of the main peak itself when these extra contributions are taken into account. This adjustment is not very significant and is made in our later paper. It has been suggested[13] that one should use the full nuclear phase shift δ_{2t} rather than the resonant part δ_{2r} in the present comparison between scattering and beta decay. If this is done, agreement between the two is very much improved. However, we cannot feel that so simple a solution can be justified in view of the necessary interpretation of the background scattering in terms of the effects of distant levels with matrix elements for beta decay different from that appropriate to the first excited state that is represented by δ_{2r}. We discuss this also in the later paper.

CONCLUSIONS

We have found no evidence for any irregular behavior in the properties of the first excited state of Be^8 as revealed in the beta decay of Li^8; the profile of the state across the peak and down the low-energy side is accurately given by the alpha-alpha scattering phase shifts; this strengthens the interpretation of the reaction $Be^9(p,d)Be^8$ that includes the participation of the ghost of the ground state.