and

$$A(E_f/E_i)^{\frac{1}{2}}=\cos\theta_{\rm lab}+\{\cos^2\theta_{\rm lab}+B\}^{\frac{1}{2}},$$

where

$$A=(m_n+m_p+m_N)/m_p,$$

$$B=\left(\frac{m_n+m_p+m_N}{m_p}\right)^2\frac{E_p}{E_i}-1,$$

E_i= laboratory energy of the incident proton, E_f= laboratory energy of the final proton, Q= energy release in the reaction $=-1.666$ Mev, and $\theta_{\rm lab}$= laboratory angle of observation of the final proton, corresponding to θ in the center-of-mass system. With the equations above it is possible to determine, for any laboratory angle $\theta_{\rm lab}$, the laboratory energies corresponding to any desired center-of-mass proton energies.

In order to obtain a meaningful result for the relative differential cross section of such a reaction, it is imperative to take measurements at various angles of the number of scattered protons within some *constant center-of-mass energy interval.* The interval chosen in this investigation was $0.90\ (E_p)_{\rm max}\leq E_p\leq (E_p)_{\rm max}$. After calculation of the equivalent laboratory energies, and their equivalent ranges, it was possible to identify the corresponding interval of the observed proton spectra. As an example, these limits are shown by the arrows R_H and R_L in Fig. 15 which illustrates the observed data for $\theta_{\rm lab}=21°$. Because the 2.43-Mev inelastic peak and the pickup deuterons are superimposed on the continuum in this region, it was necessary to interpolate between the end point and a region where nothing interfered with the observation of the continuum alone. These interpolations were done linearly for simplicitly. Once the areas of the triangles of continuum so defined have been determined, calculations of the cross sections follow in the same way as those for a conventional reaction follow the determination of peak areas. The transformation from laboratory to center-of-mass was carried out using the $d\Omega_{\rm lab}/d\Omega$ and the $\theta_{\rm lab}$-to-θ correspondence appropriate to the median proton energy $0.95\ (E_p)_{\rm max}$.

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Parity Conservation in Strong Interactions: Introduction and the Reaction $He^4(d,\gamma)Li^6$†

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A discussion is made of the ways in which parity conservation in ordinary strongly interacting nuclear systems might be investigated. Three classes of experiment are proposed: in class I we look for violations of absolute selection rules based on strict parity conservation and are sensitive to $\mathfrak{F}^2$, the intensity of the irregular or parity-nonconserving part of the wave functions; in class II we look for longitudinal polarization of product heavy particles or circular polarization of gamma rays from initially unpolarized systems and are here sensitive directly to $\mathfrak{F}$; in class III we look for odd powers of $\cos\theta$ in the angular distributions or correlations of radiations emitted from well-isolated nuclear states and are again sensitive to $\mathfrak{F}^2$.

An experiment of class I is presented, namely a search for the radiative capture $He^4(d,\gamma)Li^6$ through the 0+ state at 3.56 Mev. It is concluded that the heavy-particle width of this state is zero within a standard deviation of 0.2 ev and that this corresponds to $\mathfrak{F}^2\lesssim 1\times 10^{-7}$.

INTRODUCTION

THE recent discovery that parity is not conserved in β decay[1] or in the π-μ-e decay[2] raises the question of its conservation in the strong interactions (nuclear and electromagnetic forces). Since the selection rules based on parity conservation have always seemed to hold good for both atomic and nuclear spectra, it is evident that any relaxation of parity conservation is here much less than in the weak couplings where it seems to be complete. However, just because the conservation has never been seriously doubted and seemed to be based on such general and reasonable considerations, no serious attempt was made deliberately to test it prior to the recent discoveries among the weak interactions. The evidence in the literature suggests that the admixture of parities in the eigenstates of atoms or in their electromagnetic transitions is less than about 10^{-6} in *intensity*. This means that the strength of the parity-nonconserving part of the electromagnetic coupling is less than about 10^{-3} of the parity-conserving part. The corresponding evidence for nuclear states and nuclear forces is much less good, owing chiefly

† Work performed under the auspices of U. S. Atomic Energy Commission.
* This work was performed while the author was Visiting Physicist at Brookhaven National Laboratory during the summer of 1957.
[1] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).
[2] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957); J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).

to the smaller characteristic values of kR in nuclear systems, where k is a typical wave number and R a typical size of the system, and to the fact that the ratio of the Compton wavelength of the relevant particle to the size of the system (a measure of v/c) is much bigger in nuclei than in atoms. It would be difficult to find reliable evidence of a parity-purity of better than 10^{-2} or 10^{-3} in *intensity* for nuclear states in the usual literature.

In the notation of Lee and Yang[3] we shall call the relative strength of the parity-nonconserving coupling $\mathfrak{F}$. We then expect the *amplitude* of the component of a nuclear wave function which has the irregular parity to be of order $\mathfrak{F}$. The probability that a reaction will proceed only via this irregular component is in general determined by the *intensity* of the irregular parity in the state, namely $\mathfrak{F}^2$, unless the system has been prepared in some special manner.

We take as our task the investigation of the magnitude of $\mathfrak{F}$ in nuclear interactions. We shall assume that all such interactions introduce the same amplitude of the irregular parity and all wave functions are written

$$\psi=\psi_{\text{regular}}+\mathfrak{F}\psi_{\text{irregular}}.$$

Some of our investigations are also sensitive to parity admixture in electromagnetic interactions. Although the evidence from atomic spectra is relatively good and although we should not expect any difference from this for the electromagnetic transitions between nuclear states, we must bear this sensitivity in mind in the relevant experiments. We shall not, however, consider it explicitly any further.

METHODS OF INVESTIGATION

There are several ways of approaching this conservation problem:

Class I *experiments* are those in which we make use of an *absolute* selection rule imposed by parity conservation. Such selection rules are not found among electromagnetic transitions between nuclear states because the only relevant absolute rule is that forbidding single photon emission between two states of spin zero and that rule is valid irrespective of whether a parity change is involved or not.[4] This absence of selection rules is due to the fact that the photon has an intrinsic spin of unity and may or may not change the parity for any spin change. With heavy particles we find particles of zero intrinsic spin and so absolute rules develop within the framework of complete parity conservation. For example, states of $J(-)^{J+1}$ are absolutely forbidden by parity conservation[5] to emit an alpha particle leaving the residual nucleus in a state of $0+$. Such transitions could, however, take place through the irregular parts of the wave functions and so would have a probability of order $\mathfrak{F}^2$ relative to a corresponding allowed transition. A search for such transitions, which are forbidden absolutely by parity conservation and which take place only through the irregular component, is therefore a way of approaching $\mathfrak{F}^2$.

A limitation on the sensitivity of experiments of this class comes from the possibility of the additional involvement of a soft unobserved photon which changes the parity. For example, a state of $1+$ could emit first of all a low-energy photon to the tail of remote $0+$, $1-$, $\cdots$ levels which could then emit an alpha particle to a $0+$ residual state. If the photon were of low energy such that the experimental resolution did not detect the lowered energy of the alpha particle, this would look like a nonconservation of parity. These effects are not serious in experiments performed using current techniques.

Class II *experiments* are those in which we examine a transition which is allowed to both regular and irregular components of the wave functions but where we can observe some phenomenon which indicates interference between these components and where the magnitude of the observed effect is a direct measure of $\mathfrak{F}$ rather than of $\mathfrak{F}^2$.

Such experiments are those in which, for example, we look for the longitudinal polarization of a heavy particle emerging from some reaction or the corresponding circular polarization of a photon (assuming always, of course, that the initial target nucleus and projectile have no longitudinal polarization). In this case the longitudinal or circular polarizations are a direct measure of $\mathfrak{F}$ because they represent directly interference terms between the parity-conserving and parity-nonconserving parts of the interactions.

Consider the particular case of a reaction such as $X(h_1,h_2\gamma)Y$ in which h_1 and h_2 are heavy particles (with or without intrinsic spin) and in which the final gamma ray comes from a well-isolated level Y^*. Such reactions are the most prolific in photons and so are the easiest to study; h_2 is not observed. If all the forces were strictly parity-conserving, then the gamma-emitting state Y^* would have no *polarization* relative to the incident particle beam h_1. (It could, of course, have an *alignment* in which the different magnetic substates m_1, m_2, $\cdots$ were unequally populated, but the positive and negative substates $+m_1$ and $-m_1$, etc., would be equally populated and so there would be no *polar-*

[3] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[4] When the energy difference between the states is greater than $2mc^2$, then electron-positron pair emission is allowed for Dirac-type couplings to first order only if both zero-spin states are of the same parity. It might therefore seem that a test of parity-conservation might come from a search for pair emission between $0-$ and $0+$ states. Unfortunately no such pair of states is known without the intervention of a state of nonzero spin which permits overwhelming competition by single-photon emission. In any case there is always the possibility of a parity-conserving *ad hoc* coupling which would allow this transition, so we are not confronted with an absolute rule. Similar remarks apply to the rules for internal conversion or conversion plus one photon, which take over below an energy difference of $2mc^2$.

[5] We do not here question the conservation of angular momentum.

ization.) Also, if parity is strictly conserved, the gamma ray represents a unique parity change and so no circular polarization can arise from interference terms between electric and magnetic radiations (say $M1$ and $E2$). The fact that Y^* has itself no polarization therefore means that no circular polarization arises due to any cause. (This conclusion is independent of the possible strong overlapping of levels of opposite parity in the compound system $X+h_1$.) If, on the other hand, we have a parity-nonconserving interaction of relative strength $\mathfrak{F}$, two things happen. Firstly the state Y^* will now have a longitudinal polarization of order $\mathfrak{F}$ due to interference between the parity-conserving and parity-nonconserving couplings. This of itself gives rise to a circular polarization of the subsequent gamma ray with an *intensity* of order $\mathfrak{F}$ because the photons emitted in the direction of the spin of the nucleus have one handedness and those emitted against the spin have the other handedness. However, in the de-excitation we now have a mixed transition of two different parity changes but of the same multipolarity (say $M1$ and $E1$) and this results in a circular polarization of *intensity* of order $\mathfrak{R}\mathfrak{F}$ whether Y^* is polarized or not. $\mathfrak{R}$ is a matrix element factor that measures the intrinsic transition amplitude of the radiation from or to the irregular components relative to that from or to the regular components of the wave functions concerned. There is a difference between these two contributions to the circular polarization: the handedness of the first is different at directions of observation θ and π-θ relative to the h_1 beam whereas the handedness of the second is the same at θ and π-θ. This class of experiment is therefore intrinsically more sensitive than Class I because we are sensitive to $\mathfrak{F}$ rather than to $\mathfrak{F}^2$. It is, however, much more difficult technically to carry out.

Class III *experiments* are those where again the transition is allowed to both components of the wave functions and where we observe an interference phenomenon but where the experiment measures $\mathfrak{F}^2$ rather than $\mathfrak{F}$. Such are experiments in which we make use of the fact that odd powers of $\cos\theta$ can develop in an angular distribution or correlation only if the state emitting the particle or gamma ray is one of mixed parity. This state of affairs is familiar in nuclear reaction studies where the compound-nucleus state is in the continuum and frequently consists of several overlapping levels of both parities. If, however, we have strict parity conservation and if the observed radiation comes from a well-isolated level then only even powers of $\cos\theta$ are to be found.

Suppose, as in the illustration of the class III experiments, we examine an $X(h_1,h_2\gamma)Y$ reaction where again h_2 is not observed. Then, owing to the parity-nonconserving forces the emitting state Y^* will be formed with a longitudinal polarization of order $\mathfrak{F}$. In the class II experiments this was already enough to ensure an observable effect of order $\mathfrak{F}$ because the phenomenon examined, the circular polarization, depended on the direction of emission of the radiation forwards or backwards relative to the spin direction of the nucleus. In the present case, however, the polarization of the emitting state is a necessary but not sufficient condition for the observing of odd powers of $\cos\theta$. This is because the phenomenon examined, the intensity of emission of the radiation, is now symmetrical backwards and forwards relative to the spin direction of the emitting nucleus and so polarization does not by itself give an asymmetry. In order to display odd powers of $\cos\theta$ we must further use the fact that the transitions from the regular and irregular components of the wave functions can interfere with each other and, since they carry orbital angular momenta differing by one unit, will give an asymmetry to the radiation pattern. This interference effect is again proportional to $\mathfrak{R}\mathfrak{F}$ but, since it is only manifest through the initial polarization of order $\mathfrak{F}$ of the emitting state, the coefficients of the odd powers of $\cos\theta$ are of order $\mathfrak{R}\mathfrak{F}^2$. The two effects which worked in parallel to give the circular polarization now operate in series and so we are sensitive only to $\mathfrak{F}^2$ rather than to $\mathfrak{F}$.

These remarks assume of course that the incident particles are not purely s waves and that spin-zero states are not exclusively involved in the compound system $X+h_1$ or as state Y^*. (Incident s waves, however, do not preclude the $\mathfrak{R}\mathfrak{F}$ circular polarization.) We must also ignore possible chance cancellations in matrix elements and so on.

The other obvious place to look for nonconservation of parity is in anomalously high widths for gamma radiation or particle transitions which are "parity-forbidden" in the usual sense, *viz.*, which, because of the parities of the states, have to be magnetic instead of electric in character or which must carry one more unit of orbital angular momentum than the spin differences alone demand. However, as we implied earlier, such tests are very insensitive in nuclear systems and we shall not consider them as a class of profitable experimentation.

There seems to be some interest in carrying out experiments in the three classes enumerated to improve our knowledge of $\mathfrak{F}^2$ and this is being done.

Some general remarks are in order. The first is that in all these classes of experiment we have nothing to tell us what the detailed behavior would have been if parity had been completely unconserved. The question has no meaning. Accordingly we can do no more than measure the strength of the observed effect or our limit on the absence of an effect against some typical number which represents such neighboring and similar transitions as are allowed by parity conservation. This means that we should work as far as possible in regions where allowed transitions show the smallest spread in their reduced widths. This is among the very light elements or for states of low excitation. For states of high excitation in the heavier elements where levels are very close together we have strong configuration interaction and reduced widths are both diminished in magnitude and increased in their relative dispersion. These considerations are familiar from the somewhat similar problem of estimating isotopic-spin impurities from the strengths of forbidden transitions. The isotopic-spin situation must be considered in the present case also. There is no *a priori* reason why the parity-nonconserving interaction should conserve isotopic spin. Indeed the simplest such interaction with which we are actually familiar, namely a uniform electric field, *must* change the isotopic spin in a self-conjugate nucleus. We should not therefore rely on experiments in which the possible isotopic spin of the irregular part of the wave functions can be of any importance.

Both these remarks apply to some degree to an experiment of class I already reported by Tanner[6] in which he looked for alpha particles emitted from the 1+ 13.19-Mev state of Ne^{20} to the ground state of O^{16}. In this region of excitation, levels are only about 100 kev apart and indeed show an enormous range of alpha-particle widths. The accompanying uncertainties have been amply stressed by the author[6] himself. Unfortunately not much is known about reduced widths for transitions to the ground state of O^{16} whose uniquely high symmetry properties make it a rather special case. Under reasonable assumptions Tanner concludes the $\mathfrak{F}^2 \lesssim 4\times10^{-8}$, implicitly assuming that the parity-nonconserving forces do not change the isotopic spin. So far as the present author is aware, this was the first experiment deliberately carried out to test parity conservation in strong interactions.

Finally, in this cautionary vein, we must say that, because in all experiments of this type the absence of an effect may be due to chance cancellations or unpropitious couplings or the like, we should not rely on an isolated observation but rather try to build up a number of examples of comparable sensitivity preferably drawn from all the possible classes of experimentation and be impressed only by this statistical evidence indicating parity conservation.

ESTIMATE OF $\mathcal{R}$

Experiments of class II and class III involve interference between electric and magnetic gamma-ray transitions and we have introduced the matrix element factor $\mathcal{R}$ to measure the relative amplitudes in such transitions. This must now be estimated.

In the light nuclei with which we work, both $M1$ and $E1$ transitions are quite strong.[7] In particular they tend to be of approximately single-particle strength between states of low excitation. It therefore seems a reasonable procedure, when such low-lying states are involved, to take for $\mathcal{R}$ the estimate of the single-particle model[8] and so we have

$$\mathcal{R}_{E1/M1} \sim McR/3\hbar,$$

where M is the nucleon mass and R is the nuclear radius. This we shall use unless there is some special reason for taking a different value—for example, if the $E1$ transition should be forbidden by the isotopic-spin rule. In such a case we shall take a measured or estimated value for the forbidden $E1$ strength and the single-particle estimate for the $M1$ transition.

Since $\mathcal{R}$ figures in the sensitivity of the experiment, we shall obviously do well to choose examples where the irregular components of the wave functions give $E1$ transitions and the regular components $M1$. It would be a poor choice, for example, to study 2+ to 0+ transitions where the regular components give $E2$ transitions, which are frequently enhanced in the light nuclei, and the irregular components give $M2$ transitions.

Having discussed the chief experimental methods of approach to the conservation problem, we present the first experiment which is in class I.

REACTION $He^4(d,\gamma)Li^6$

The second excited state of Li^6 at about 3.56 Mev is the first $T=1$ state of that nucleus and is 0+. The evidence for this is that it corresponds fairly well in position with the ground state of He^6 suitably corrected for the Coulomb energy and the n-p mass difference.[9] There is no other state in Li^6 known within 1.0 Mev. That it is of $T=1$ is demonstrated by the fact that although it is easily excited by $Li^6(p,p')Li^{6*}$ it is not detectably excited at all[10] by $Li^6(d,d')Li^{6*}$. This conclusion is reinforced by the fact that the state of B^{10} at 8.89 Mev emits alpha particles almost entirely to the 3.56-Mev level of Li^6 even though considerably more energy is available for transitions to the ground state and the intermediate 3+ state at 2.19 Mev, both of which are of $T=0$.[11] This suggests strongly that the isotopic spin of the 3.56-Mev state is different from that of the two lower states. When the Li^6 state is excited by $Be^9(p,\alpha)Li^6$ through this 8.89-Mev state of B^{10}, both the angular distribution of the gamma rays with respect to the proton beam and the angular correlation between the alpha particles and the gamma rays are isotropic as expected for a state of spin zero.[12] Finally, although it is unstable by 2.1 Mev against breakup into an alpha particle and a deuteron, gamma-ray emission to the 1+ ground state is a successful competitor to heavy-particle emission.

This last remark is the starting point of this investigation. The 0+ 3.56-Mev state is rigorously forbidden

[6] N. Tanner, Phys. Rev. **107**, 1203 (1957).
[7] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).
[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[9] See, e.g., D. H. Wilkinson, Phil. Mag. **1**, 1031 (1956).
[10] C. P. Browne and C. K. Bockelman, Phys. Rev. **105**, 1301 (1957).
[11] R. Malm and D. R. Inglis, Phys. Rev. **95**, 993 (1954).
[12] Stoltzfus, Friichtenicht, and Nelson, Bull. Am. Phys. Soc. Ser. II, **1**, 329 (1956).

to break up into $\alpha+d$ if parity is strictly conserved. Such breakup could take place, however, through the irregular component of the wave functions introduced by the parity-nonconserving interaction and we should then find a heavy-particle width $\Gamma_{d\alpha}$ for the 0+ state of order $\mathfrak{F}^2$ of what we should have expected for the corresponding breakup allowed by parity conservation.

We now ask how best to investigate $\Gamma_{d\alpha}$. There are two ways of doing this. We could prepare Li^6 in the 0+ state and then look for the heavy-particle breakup, measuring its probability in terms of the de-excitation by gamma-ray emission. We should then have to measure or calculate Γ_γ, the radiative width, in order to get an absolute value or limit for $\Gamma_{d\alpha}$. This investigation would be rather difficult because the lifetime of the 0+ state is less than the slowing-down time[13] of the recoiling Li^6 for any convenient way of preparing the state such as $Be^9(p,\alpha)Li^{6*}$. Because of this the disintegration products have a distribution of momenta of any angle of observation and do not form a sharp spectrum. We adopt here the alternative approach which is to search for the reaction $He^4(d,\gamma)Li^6$ passing resonantly through the 0+ state. In such a case the total yield of the reaction, when a thick target is used so that we integrate over the resonance, is determined solely by the *smaller* of the two widths involved, Γ_γ and $\Gamma_{d\alpha}$, whichever that may be, provided that they are not close together. Accordingly the interpretation of the experiment is not directly dependent on an estimate of Γ_γ as was the first approach. All that is necessary is that we should be confident that Γ_γ must be bigger than the value of or limit for $\Gamma_{d\alpha}$ that we deduce from the total yield. The actual value of Γ_γ is here immaterial to our deducing an absolute value for $\Gamma_{d\alpha}$.

EXPERIMENT

We must know the energy of the Li^6 level relative to the $\alpha+d$ system. There are two accurate estimates of the level position in Li^6. The first[13] comes from a measurement of the gamma-ray energy of the ground state transition and is 3.546±0.012 Mev. (We have applied the appropriate Doppler-shift correction[14] in quoting this figure.) The second[10] comes from the reactions $Li^6(p,p')Li^{6*}$ and $Be^9(p,\alpha)Li^{6*}$ and is 3.560±0.006 Mev. We combine these and have used 3.557±0.006 Mev. This places the level 2.080±0.027 Mev above the system $\alpha+d$ and so we expect the resonance in the bombardment of helium by deuterons at $E_d=3.126\pm0.040$ Mev.

When deuterons are used as bombarding particles, there is inevitably a large background of gamma rays produced either from excited states of residual nuclei or from the large flux of fast neutrons that is generated.[15] It is therefore a rather difficult matter to set a low upper limit on a cross section for the radiative capture of deuterons. As we have explained, however, it is important for the present investigation that our limit should be low enough to exclude the possibility that it is Γ_γ which controls the reaction. Otherwise we learn nothing at all about $\Gamma_{d\alpha}$.

The experimental setup was designed to minimize the background effects. The target consisted of a tube approximately 3 meters long which was filled with helium. The deuterons passed into this tube through a nickel foil of nominal thickness 50 micro-inches taken from samples whose measured stopping power for protons of 1.9 Mev was 80±3 kev. Before impinging on this window the deuteron beam had been collimated so that it did not strike the support but passed cleanly through the nickel. The initial length of this tube containing the helium was of diameter 1 inch but the greater part was of diameter $2\frac{1}{2}$ inches. This very long target tube was used so that the deuterons should spend their energy in helium which is relatively innocuous from the point of view of gamma-ray and neutron production rather than be intercepted by any solid material from which they would have produced a large neutron yield by the *d-d* reaction if by no other means.

The gamma-ray detector was a NaI(Tl) crystal, a 3-inch right cylinder. It was positioned approximately 10 inches along the helium target from the nickel window and its face was drawn back 5 cm from the axis of the target tube. It was very heavily shielded on all sides by lead which extended forward to the target tube itself at the sides of the crystal so that the detector effectively examined a rather narrow length of helium. The crystal was calibrated by using various gamma rays up to the 4.43-Mev gamma ray from the first excited state of C^{12} (Pu-Be source). The calibrations were frequently repeated during the experiment to check the stability.

Owing to the very heavy background observed, even though the crystal was shielded by 15 cm of lead in the direction of the nickel window, a direct search for the resonant gamma rays was impracticable. The method of search adopted was to examine the spectrum observed in the detector at a variety of energies of the bombarding deuterons. In this way the resonance could be made to pass along the helium tube where for the most part it was heavily shielded from the detector, pass in front of the crystal, and then pass to the heavily shielded region on the other side. The background is nonresonant and so changes slowly and steadily with changing deuteron energy. Accordingly, if we subtract the spectrum measured at those deuteron energies where the

[13] R. Mackin, Phys. Rev. **94**, 648 (1954).

[14] J. Rose and E. Warburton (private communication). These authors observe a full Doppler shift in the ground-state transition and conclude that the mean life $\tau<4\times10^{-14}$ sec.

[15] It would obviously have been preferable to investigate the reaction $H^2(\alpha,\gamma)Li^6$ which would have been much cleaner. However, alpha particles of the required energy (6.2 Mev) were not available.

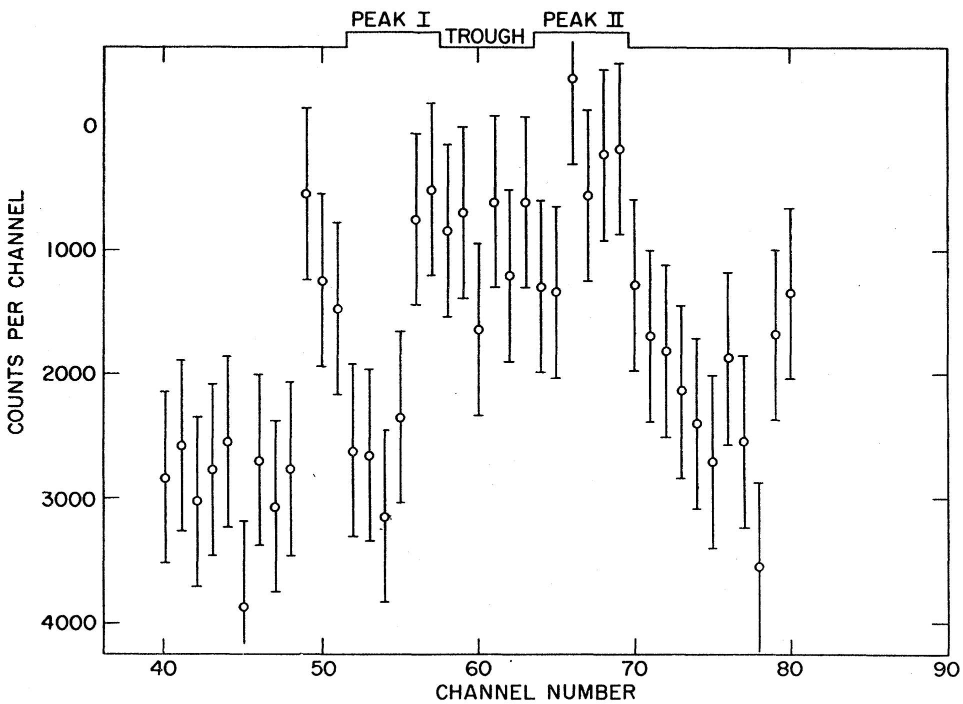

FIG. 1. This spectrum is found by subtracting one $He^4(d,\gamma)Li^6$ spectrum from a spectrum obtained at a deuteron bombarding energy 100 kev lower. The deuteron energy necessary for the $He^4(d,\gamma)Li^6$ resonance occurred at a position close to the NaI crystal detector for the lower deuteron bombarding energy and occurred at a point approximately 24 cm away and shielded by lead from the detector for the higher deuteron bombarding energy. The ordinate scale reads negative numbers. The region labelled "Peak I" is that where we expect to find the "one-annihilation-quantum escape peak" of a gamma ray of 3.56 Mev (centered on channel $54\frac{1}{2}$). Similarly "Peak II" is the region where the full energy peak of the same gamma ray is expected (centered on channel $66\frac{1}{2}$).

resonance is far away and hidden behind lead from that measured at an energy where it is opposite the counter and unshielded, we approximate to the contribution from the resonance itself. The background effects of course do depend on the deuteron energy and we do not look for a complete cancellation. The helium tube was operated at various pressures in the region of a quarter of an atmosphere where a change in deuteron energy by only 100 kev moves the resonance by more than 20 cm—that is, to a remote and heavily-shielded region. Over a range of deuteron energy of 100 kev the background effects were found to change only by about 2–3%.

A large number of spectra were taken at deuteron energies between 2.9 and 3.6 Mev. The deuteron current was approximately 0.1 μa. As expected, these spectra showed only smooth changes as the deuteron energy was changed. They were not themselves smooth and featureless but showed a few unidentified peaks that were presumably due to gamma rays following heavy-particle reactions in traces of impurity in the helium.

As an example of the subtraction spectra, we show in Fig. 1 the spectrum observed under conditions which for the stated mass balance would position the resonance at the crystal minus that observed at a deuteron energy 100 kev higher where the resonance would be approximately 24 cm away "downstream" and having only a negligible effect on the detector.

Because of the considerable error in our knowledge of the $Li^6-(He^4+H^2)$ mass difference we cannot be sure of the resonance position to better than about ± 10 cm in terms of the helium target. Accordingly several such pairs of spectra were compared to be sure of having one in which the resonance was near the center of the crystal at one of the deuteron energies. The spectrum at each deuteron energy consisted of 21 independent runs interleaved with those at the other deuteron energy. Each spectrum totalled 885 microcoulombs of deuteron current. There was no normalization between the spectra other than that of charge. The full-energy peak (peak II) of a 3.56-Mev gamma-ray is expected at channel $66\frac{1}{2}$ of the figure and that corresponding to pair creation with the subsequent escape of one annihilation quantum (the "one-escape" peak—peak I) is expected at channel $54\frac{1}{2}$. In fact the spectrum is rather flat in this region. The fall above channel 70 and that below channel 50 are due to two of the unidentified peaks due to impurities. These peaks were present at all deuteron energies from 2.9 to 3.6 Mev and increased in intensity slowly with increasing deuteron energy. Accordingly they appear in the subtracted spectrum as negative peaks because in that spectrum the runs at the higher deuteron energy are subtracted from those at the lower. In order to estimate the importance of a possible 3.56-Mev line, a procedure was adopted which is not sensitive to a general tilt of the subtracted spectrum. In the 3 in. $\times 3$ in. crystal the full energy and "one-escape" peaks are the most important features of the spectrum in this region of gamma-ray energy. We accordingly consider those two peaks and the trough between them grouping the channels as shown in the figure so that there are equal numbers of channels for each peak and an equal number of channels in trough. Consider now the sum of the counts in the two peaks minus twice the number in the trough. If there is a true gamma ray present this will be a positive quantity but otherwise it will be zero, irrespective of any tilt to the whole spectrum. These two peaks and the trough are shown in the figure. By interpolation between spectra taken at 2.76 Mev (Na^{24}), 4.43 Mev (Pu-Be) and 6.14 Mev ($F^{19}+p$ at low proton energy) it was found that, for the crystal used, the function of the spectrum that we have just described amounts to 15% of the total number of gamma-rays interacting with the crystal. For the results displayed in the figure this function amounted to -4024 ± 4000 counts. We therefore say that the 3.56-Mev gamma-ray yield is zero within a standard deviation of 4000 counts.[16]

When this result is used together with the calculated[17] efficiency of the NaI(Tl) crystal, we find a limiting width for the reaction of zero within a standard deviation of 0.2 ev. The spectra evaluated for other pairs of deuteron energies give similar results, and so we may use this result with confidence despite our lack of precise knowledge of the nuclear masses.

DISCUSSION

Before we can interpret this result as a limit on $\Gamma_{d\alpha}$ we must, as mentioned above, be sure that it is less than Γ_γ. Now Γ_γ is completely unknown. The lower limit from the Doppler-shift[14] observation is not immediately helpful. However, in so light a nucleus as Li^6 it is known that LS coupling gives a good account of the level structure,[18] and we can therefore have reasonable confidence (say a factor of 3) in its predictions about ($M1$ or $E1$) gamma-ray transition probabilities between low-lying levels provided that very small probabilities are not predicted. According to this scheme, the 3.56-Mev 0+ $T=1$ state is $^{31}S_0$ and the 1+ $T=0$ ground state is $^{13}S_1$. The calculated radiative width for the $M1$ transition between these states is $\Gamma_\gamma=7$ ev.[19] It therefore seems quite safe to interpret our limit of 0.2 ev as referring to the heavy-particle breakup.

We must now enquire what width we should have expected for the heavy-particle decay of this state ($l=1$) had it been allowed by the parities. This is equivalent to asking for the most likely values for reduced widths in this region. Since the nucleus is so light we might expect allowed reduced widths for the $\alpha+d$ breakup to be large. This is confirmed by the available evidence[20] which is, for the levels in Li^6, at 2.19, 4.52 and about 5.4 Mev. These have reduced widths which are, respectively, 0.5, 0.6 and 0.2 to 0.6 of the Wigner single-particle limit of $3\hbar^2/2mR$, where m is the reduced mass of the system and R the reaction radius. It is therefore reasonable to take one-half of the Wigner limit as the assumed reduced width in our case. When the Coulomb penetrability for $l=1$ is evaluated on a reaction radius of 3.0×10^{-13} cm, we find an allowed width of 1.8 Mev.

When this is compared with the limit of 0.2 ev for $\Gamma_{d\alpha}$ we conclude, following the argument of the Introduction, that

$$\mathfrak{F}^2 \lesssim 1\times10^{-7}.$$

We must note that this result assumes that the parity-nonconserving interaction does not conserve isotopic spin since the Li^6 state we consider is chiefly of $T=1$ while the product particles are chiefly of $T=0$. In this sense the present result complements that of Tanner[6] where the assumption was that the isotopic spin is conserved. It is obviously desirable to carry out these experiments of class I on systems where the possible conservation or otherwise of the isotopic spin is of no consequence. Such experiments are now under way.

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[16] We should expect some radiative capture from the tails of remote levels. Such capture is expected to be rather weak and not to be strongly energy dependent. It may be calculated to make a quite negligible contribution to the subtracted spectrum.

[17] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report NRL-4833, 1956 (unpublished).

[18] D. Kurath, Phys. Rev. **106**, 975 (1957).

[19] I am grateful for a communication from Dr. D. Kurath in which he informs me that this estimate is in fact almost independent of the degree of intermediate coupling.

[20] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).