Parity of the 2.13-MeV First Excited State of B^{11}†

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The positron-electron pair-line spectrum of the 2.13-MeV transition in B^{11} has been measured by means of an intermediate-image pair spectrometer using the reaction $B^{11}(p,p')B^{11*}$ at the 2.66-MeV proton resonance. Comparison measurements were made on the pair line of the 3.09-MeV $E1$ transition in the $C^{12}(d,p)C^{13}$ reaction at $E_d=1.7$ MeV. Gamma-ray yields from the two reactions were monitored by means of a 5-in.×5-in. NaI crystal spectrometer. The ratio $R\equiv(N_{\text{pair line}}/N_\gamma)_{3.09}/(N_{\text{pair line}}/N_\gamma)_{2.13}$ was found to be 3.3±0.7. Calculations of the spectrometer pairline efficiency versus transition energy were made for $E0$, $E1$ to $E4$, and $M1$ to $M4$ multipoles based on angular correlation formulas of Oppenheimer and of Rose. The values of R derived from the efficiency curves are 1.81, 3.51, 2.78, and 5.42 corresponding to $E1$, $M1$, $E2$, and $M2$ multipolarities, respectively, for the 2.13-MeV B^{11} transition. The experimental result establishes that there is no parity change between the ground and first excited states and therefore that the latter is of odd parity since the ground state of B^{11} is $3/2^-$.

I. INTRODUCTION

THE first excited state of B^{11} at 2.13 MeV (the mirror state in C^{11} is at 1.99 MeV) has, for many years, had a certain mystery attached to it. The present work was designed to settle that mystery, at least phenomenologically. The problem can be stated in a brief historical perspective.

The first suggestions as to the spin of the state came from the $B^{10}(d,p)B^{11}$ and $Li^7(\alpha,\gamma)B^{11}$ reactions. The gamma rays coming from this state in the former reaction were found[1] to be isotropic to about 10%. The simplest explanation was that $J=1/2$. In the second reaction no feeding of the state was found[2] from the $J=5/2$ state at 9.28 MeV to a degree that would have been surprising for other than the assignment $J=1/2$. So by 1952 the assignment of $J=1/2$ was strongly hinted at. This was very reasonable because a low-lying $J^\pi=1/2^-$ state is expected on both LS and jj coupling and the work of Inglis[3] soon made it plausible that the same should be true in intermediate coupling. Since there was no nearby contender for the expected $J^\pi=1/2^-$ state, it was generally assumed that the first excited state was indeed it. The discordant note was struck by measurements of the $B^{10}(d,p)B^{11}$ stripping which showed a clear $l=1$ pattern for the 2.13-MeV level.[4] Because $l=1$ neutron transfer cannot link the $J^\pi=3^+$ ground state of B^{10} with the putative $J^\pi=1/2^-$ state of B^{11} by a regular stripping mechanism, a spin of at least $J=3/2$ was indicated. Since that time, evidence has accumulated for the strict isotropy of the gamma radiation under a wide variety of modes of excitation and a wide range of bombarding energies. A possible, but unlikely, reconcilation of the gamma-ray and stripping results could be that $J^\pi=3/2^-$ and the radiation to the $3/2^-$ ground state were pure $E2$, in which case there would always be exact isotropy. This possibility was disproved by the demonstration[5] that the lifetime of the state is so short as to demand that the radiation be predominantly dipole. Since that time it has been virtually certain that $J=1/2$. But no work, other than the stripping, has been parity sensitive to any high degree although there is a considerable amount of circumstantial evidence in favor of odd parity. The complete body of data has been summarized[6] recently and it was concluded that $J^\pi=1/2^+$ must remain a possibility. Indeed the stripping results at certain energies indicate $l=2$ and so even parity.[7]

Because of this rather confused situation, because of the considerable importance for nuclear models should the parity turn out to be even, and because of the important place this state has in discussing the beta decay of Be^{11}, itself probably of "anomalous" parity,[6,8] we embarked on an experiment designed to determine the parity unambiguously, namely a measurement of the internal pair formation probability in the de-excitation to the ground state—this probability is model independent to a very high degree but is markedly different for the $E1$ and $M1$ possibilities.

In order to avoid absolute measurements as far as possible, the experiment was performed primarily as a comparison between the internal pair formation from the boron level—excited by $B^{11}(p,p')B^{11*}$ at the resonant proton energy of 2.66 MeV—and that from the 3.09-MeV level in C^{13}—excited by $C^{12}(d,p)C^{13*}$ at a bombarding energy of 1.7 MeV—which is known to de-excite by an $E1$ transition to ground. An intermediate-image pair spectrometer was used. The results taken together with the known lifetime[9] of the B^{11} 2.13-MeV level

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[1] J. Thirion, Compt. Rend. **232**, 2418 (1951).
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[9] F. R. Metzger, C. P. Swann, and V. K. Rasmussen, Phys. Rev. **110**, 906 (1958).

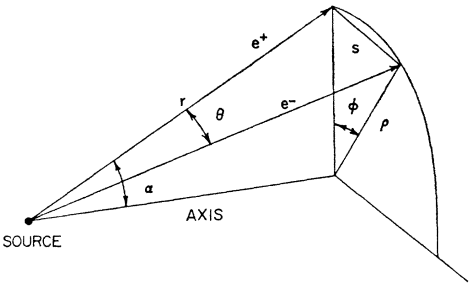

FIG. 1. Diagram illustrating the geometry used in the intermediate image spectrometer pair-line efficiency calculations.

indicate unambiguously that the parity of this state is odd.

II. SPECTROMETER PAIR-LINE EFFICIENCY

An accurate understanding of the efficiency of the pair spectrometer is crucial to its use in the present manner and so we begin with a detailed discussion of this problem.

In the intermediate-image pair spectrometer[10,11] positron-electron pairs from the source are focused onto a coincidence detector which consists of two semicircular scintillation crystals, light pipes, photomultipliers, and a fast coincidence circuit. Coincidences are obtained under the following conditions: (a) both pair components enter the acceptance solid angle; (b) their energies are nearly the same, i.e., $E_+ \cong E_- \cong \frac{1}{2}(E_\gamma - 1.022)$ MeV; (c) the spectrometer magnetic field is adjusted to focus electrons of that energy; (d) the two pair components enter opposite detectors after passing through the baffle system; and (e) the pulses from the two crystals trigger the fast coincidence circuit and have amplitudes lying above bias levels in the slow section of the coincidence circuit.

The spectrometer efficiency is defined as the number of counts, after background subtraction, at the peak of a pair coincidence line per transition.

As an aid in explaining the calculations we refer to Fig. 1. For the time being we ignore the effects of finite energy resolution and finite angular opening and assume that there is no preferred direction in space. In order for the pairs to pass through an annular opening of very small radial extent, they must both emerge from the source with the mean entrance angle α which is constant for a given spectrometer. We take θ as the angle between the pairs and ϕ as the difference in their azimuthal angles. The efficiency as defined above is given by the relationship,

$$\epsilon_l = \frac{f(k)T^2R}{2\pi}\frac{(\frac{1}{4}k^2-1)}{\frac{1}{2}k}\int_0^{2\pi}\gamma_l d\phi = 4\pi f(k)T^2R\epsilon_l', \quad (1)$$

where k is the transition energy in units of m_0c^2, T is the transmission of the spectrometer for monoenergetic electrons expressed as a fraction of a sphere, R is the momentum resolution $\Delta p/p$ for pair lines (about 0.7 times that for monoenergetic electrons), and γ_l is the probability per unit energy interval, for the condition $W_+ = W_- = k/2$ (where $W_+ = E_+ + 1$), that the β^+ and β^- particles are emitted with an angle θ between them per $|d\cos\theta|$. The experimentally determined factor, $f(k)$, corrects for the following counting rate losses: (1) losses in the fast coincidence circuit, (2) the loss of those events whose pulse heights lie below the bias levels in the slow circuit, and (3) the loss of those pairs which are intercepted by a tungsten absorber which is located between the two crystal detectors. Equation (1) has been normalized so as to allow for the fact that only those pairs for which the two components enter different crystals can be counted. In separate tests[12] it has been shown that the total angle of rotation of electrons in passing from the source to the detector is 225° and that for this condition the two components of the pair have a probability of 0.5 of entering different crystals regardless of the angular correlation between pairs (neglecting the effect of the tungsten absorber between the crystals).

The factor $(\frac{1}{4}k^2-1)/\frac{1}{2}k$ in Eq. (1) is required to convert from momentum to energy units according to the relationship,

$$\Delta W = \frac{\frac{1}{4}k^2-1}{\frac{1}{2}k}\frac{\Delta p}{p}. \quad (2)$$

The quantity γ_l has been taken from the Born approximation calculations of Rose.[13] For the required condition $W_+ = W_-$ the expressions for γ_l, $l \geqslant 1$, are the following:

$$\gamma_{El}(\theta) = \frac{2^{2l-5}(\frac{1}{4}k^2-1)^{l-2}}{\pi(137)(l+1)k^{2l-1}[1/(\frac{1}{4}k^2-1)+1-\cos^2(\theta/2)]^2} \times\{[(3l+1)(\frac{1}{4}k^2)+l+1][\cos^2(\theta/2)]^{l-1} - (5l+1)(\frac{1}{4}k^2-1)[\cos^2(\theta/2)]^l + (8l/k^2)(\frac{1}{4}k^2-1)^2[\cos^2(\theta/2)]^{l+1}\}, \quad (3)$$

$$\gamma_{Ml}(\theta) = \frac{2^{2l-3}(\frac{1}{4}k^2-1)^{l-1}}{\pi(137)k^{2l+1}[1/(\frac{1}{4}k^2-1)+1-\cos^2(\theta/2)]^2}\{(\tfrac{1}{4}k^2+1)[\cos^2(\theta/2)]^l - (\tfrac{1}{4}k^2-1)[\cos^2(\theta/2)]^{l+1}\}, \quad (4)$$

[10] D. E. Alburger, Rev. Sci. Instr. **27**, 991 (1956).
[11] D. E. Alburger, Phys. Rev. **111**, 1586 (1958).
[12] E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Jr. (to be published).
[13] M. E. Rose, Phys. Rev. **76**, 678 (1949).

for electric and magnetic multipoles of order l, respectively.

In evaluating the spectrometer efficiency it is more convenient to integrate over the variable ϕ rather than over the angle θ between the pair components. From Fig. 1 we derive an expression for $\cos^2(\theta/2)$ in terms of ϕ as follows:

$$\tfrac{1}{2}s=\rho\sin(\phi/2)=r\sin(\theta/2), \tag{5}$$

$$\cos\theta=1-2\sin^2(\theta/2)=1-2\sin^2\alpha\sin^2(\phi/2), \tag{6}$$

$$\cos^2(\theta/2)=1-\sin^2\alpha\sin^2(\phi/2). \tag{7}$$

By using Eqs. (3), (4), and (7) the factor ϵ_l' in Eq. (1) can be put in the form

$$\epsilon_{El}'=A(l)\sum_{n=0}^{l+1}G_n(l)I_n(2\pi) \tag{8a}$$

for El radiation, and

$$\epsilon_{Ml}'=B(l)\sum_{n=0}^{l+1}H_n(l)I_n(2\pi) \tag{8b}$$

for Ml radiation. In Eq. (8) the factors $A(l)$ and $B(l)$ are given by

$$A(l)=\frac{2^{2l-6}(\frac{1}{4}k^2-1)^{l-1}}{(137)\pi^2(l+1)k^{2l}}, \tag{9a}$$

$$B(l)=\frac{2^{2l-4}(\frac{1}{4}k^2-1)^{l}}{(137)\pi^2k^{2l+2}}. \tag{9b}$$

The $G_n(l)$ and $H_n(l)$ factors, which are functions of k and l are as follows:

$$\begin{aligned}
&G_0(l)=2(l+1)+8l/k^2,\\
&G_1(l)=\tfrac{1}{4}(l+1)k^2-(2l^2-3l-1)-8l(l+1)/k^2,\\
&G_2(l)=\tfrac{1}{4}(-l^2+2l+1)k^2+(l^3-5l^2-l+1)\\
&\qquad\qquad+4l^2(l+1)/k^2,\\
&G_3(l)=-\tfrac{1}{6}(l-1)[\tfrac{3}{4}(-l^2+5l+2)k^2\\
&\qquad+(2l^3-17l^2-l+6)+8l^2(l+1)/k^2],\\
&G_l(l)=(-)^l(\tfrac{1}{4}k^2-1)\\
&\qquad\times[(2l^2-3l-1)-8l(l+1)/k^2],\\
&G_{l+1}(l)=(-)^{l+1}(\tfrac{1}{4}k^2-1)^2 8l/k^2,
\end{aligned} \tag{10a}$$

$$\begin{aligned}
&H_0(l)=2,\\
&H_1(l)=\tfrac{1}{4}k^2-(2l+1),\\
&H_2(l)=-l(\tfrac{1}{4}k^2-l),\\
&H_3(l)=\tfrac{1}{6}l(l-1)(\tfrac{3}{4}k^2-2l+1),\\
&H_l(l)=(-)^{l+1}(\tfrac{1}{4}lk^2-l-2),\\
&H_{l+1}(l)=(-)^l(\tfrac{1}{4}k^2-1).
\end{aligned} \tag{10b}$$

The factors $I_n(2\pi)$ in Eq. (8) contain all of the dependence on α, i.e.,

$$I_n(2\pi)=\frac{1}{2\pi}(\sin^{2n-4}\alpha)J_n(2\pi);$$

$$J_n(2\pi)=\int_0^{2\pi}\frac{\sin^{2n}(\phi/2)}{[b+\sin^2(\phi/2)]^2}d\phi, \tag{11}$$

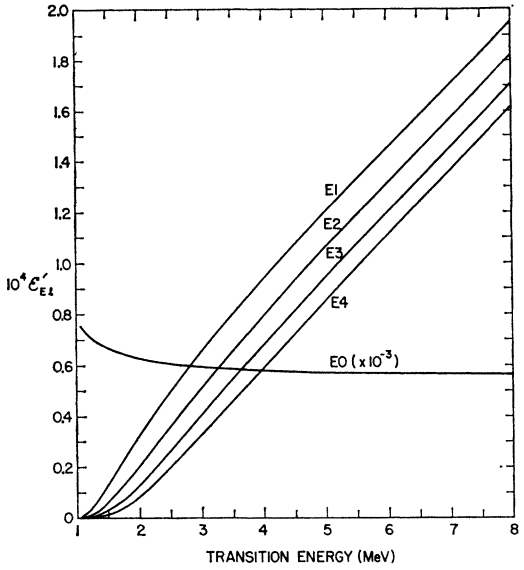

FIG. 2. Calculated pair-line efficiency factor ϵ_{El}' versus transition energy for $E0$ through $E4$ multipoles.

where $b^{-1}=(\sin^2\alpha)(\frac{1}{4}k^2-1)$. The integrals $J_n(2\pi)$ are given by

$$J_0(2\pi)=\frac{\pi(2b+1)}{(b^2+b)^{3/2}};\quad J_1(2\pi)=\frac{\pi b}{(b^2+b)^{3/2}}, \tag{12a}$$

and the recurrence formula for $n\geqslant 2$,

$$J_n(2\pi)=\int_0^{2\pi}\sin^{2n-4}(\phi/2)d\phi -2bJ_{n-1}(2\pi)-b^2J_{n-2}(2\pi). \tag{12b}$$

For $E0$ transitions the probability per unit energy interval, for the condition $W_+=W_-=k/2$, that the β^+ and β^- particles are emitted with an angle θ between them per $|d\cos\theta|$ is obtained from the Born approximation calculation of Oppenheimer,[14] and is given by

$$\gamma_{E0}(\theta)=\frac{(\frac{1}{4}k^2-1)^2(1+\cos\theta)}{4I(E0)}, \tag{13}$$

where

$$I(E0)=\int_1^{k/2}\{[(k-W)^2-1](W^2-1)\}^{1/2}\times[(k-W)W-1]dW. \tag{14}$$

For $E0$ transitions no gamma rays are emitted and the spectrometer efficiency, ϵ_l, defined as the number of counts per transition, is obtained by inserting the factor ϵ_{E0}' into Eq. (1) where ϵ_{E0}' is given by

$$\epsilon_{E0}'=\frac{(\frac{1}{4}k^2-1)^3(1-\frac{1}{2}\sin^2\alpha)}{4\pi kI(E0)}. \tag{15}$$

[14] J. R. Oppenheimer, Phys. Rev. **60**, 164 (1941).

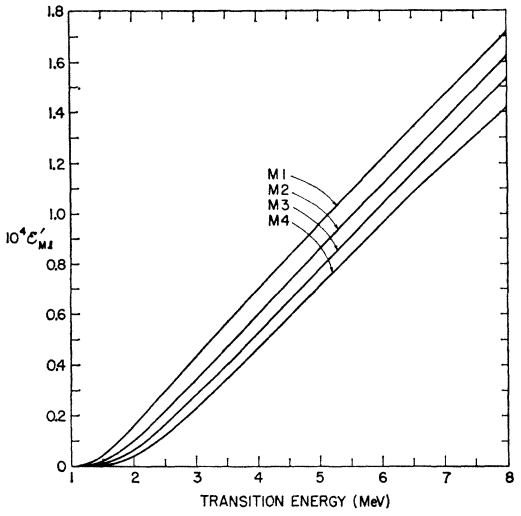

FIG. 3. Calculated pair-line efficiency factor ϵ_{Ml}' versus transition energy for $M1$ through $M4$ multipoles.

Using Eqs. (8) and (15) ϵ_l' was calculated for El and Ml radiation with $l=1$, 2, 3, and 4 and for $E0$ radiation, each for 40 values of the transition energy between 1.07 and 19.4 MeV. A value of 45.7° was used for the mean acceptance angle α in these calculations, this angle having been measured with an accuracy of $\pm 1°$ in an experiment to be described subsequently.[12] The results for transition energies up to 8 MeV are shown in Figs. 2 and 3. To a good approximation, all the curves of Figs. 2 and 3 are straight lines for transition energies above 8 MeV. It was necessary to obtain $I(E0)$ in Eq. (15) by numerical integration. This was done to better than 0.05% accuracy using an IBM-7090 computer.

The calculation of the spectrometer efficiency described above is based on the Born approximation calculations of Rose[13] and of Oppenheimer.[14] The validity of the Born approximation has been examined by Horton and Phipps[15] for El and Ml transitions and by Dalitz[16] for $E0$ transitions. In the latter case higher order corrections to the case of the 6.06-MeV $0^+ \rightarrow 0^+$ transition in O^{16} were estimated and found to be only of the order 1%. For all El and Ml transitions, Horton and Phipps[15] found that an error of $\leqslant 5\%$ results for $Z \leqslant 30$ and electron or positron kinetic energies $\geqslant 1$ MeV or for $Z \leqslant 20$ and particle kinetic energies $\geqslant 100$ keV if the Born approximation results are multiplied by the Sommerfeld factors[17] of the positron and electron. The product of these factors is

$$f(\xi_+,\xi_-)=\frac{2\pi\xi_+ 2\pi\xi_-}{(e^{2\pi\xi_+}-1)(1-e^{-2\pi\xi_-})}, \qquad (16)$$

where $\xi_\pm = Z/137\beta_\pm$, $\beta_\pm = v_\pm/c$. Because we are concerned with $Z \leqslant 10$ and particle kinetic energies $\geqslant 500$ keV, an acceptable criterion for the accuracy of the Born approximation is the deviation from unity of $f(\xi_+,\xi_-)$. For $W_+=W_-$, $\beta_+=\beta_-=[1-(2/k)^2]^{1/2}$, and for transition energies $\geqslant 1.5$ MeV and with $Z \leqslant 10$ we find that the factor $f(\xi_+,\xi_-)$ deviates from unity by less than 3%.

We now wish to consider the effects of finite energy and angular resolution. In the Born approximation the energy spectra of the β^+ and β^- particles emitted as nuclear pairs are flat at $W_+=W_-=k/2$. Therefore the finite energy resolution has a negligible effect on our efficiency calculations. The effects of the finite angular opening of the spectrometer must be considered in more detail because the correlation between the pairs is very sharp except for $E0$ transitions. To estimate the effect it was assumed that one of the pair components is emitted at the angle α with respect to the axis of the spectrometer and the other at an angle $\alpha+\delta$. The finite angular opening correction was calculated to order δ^2. For the largest transmission setting (17-mm annulus width) δ varies between $-6.0°$ and $+6.0°$. Under such conditions the correction was found to be 0.04% for $E0$, less than 1% for $E1$ and $M1$ transitions with transition energies less than 4 MeV, and about 6% for $E1$ and $M1$ with transition energies of 10 MeV. The calculation is estimated to have an accuracy of 25% or better.

The spectrometer efficiency has been calculated for the condition that there is no preferred direction in space for the momentum $\mathbf{q}=\mathbf{p}_+ + \mathbf{p}_-$.[13] In the general case a nuclear reaction is used to populate a nuclear level and the magnetic substates of this level will not be populated equally. Then the momentum $\mathbf{q}$ will have a preferred direction in space and the efficiency ϵ of the spectrometer must be modified accordingly.[18,19] In the present experiment, however, we are concerned with transitions from $J=1/2$ states (i.e., the first excited states of B^{11} and C^{13}), there is no preferred direction in space for $\mathbf{q}$ and the calculations of Rose are strictly applicable.[20]

The calculations of Rose are for pure Ml or El radiation. In general there can be an interference term for mixed El, Ml' radiation; however, for equal population of the magnetic substates (as in the present application) the interference term vanishes[18] and the El and Ml' contributions add incoherently. For instance, for an intensity ratio of quadrupole to dipole radiation of δ^2 the efficiency will be given by $[\epsilon_1+\delta^2\epsilon_2]/(1+\delta^2)$, where ϵ_1 and ϵ_2 are the efficiencies for pure dipole and quadrupole transitions, respectively.

[15] G. K. Horton and E. Phipps, Phys. Rev. **96**, 1066 (1954).
[16] R. H. Dalitz, Proc. Roy. Soc. (London) **A206**, 521 (1951).
[17] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1953), p. 259.
[18] G. Goldring, Proc. Phys. Soc. (London) **A66**, 341 (1953).
[19] S. Devons and L. J. B. Goldfarb, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, p. 362.
[20] This statement strictly applies to the center-of-mass system. However, because $v/c \approx 1$ for the electron-positron pairs, there is negligible difference between the center-of-mass and laboratory systems and the statement is, for all practical purposes, true for the laboratory system also.

The uncertainty in the spectrometer efficiency calculations, which have been described, is estimated to be 10–15% for transition energies >1.5 MeV depending on the energy and multipolarity of the transition. Most of this uncertainty is due to that in the transmission T which is itself uncertain to 5–10%. The transmission does not enter into a determination of the relative efficiencies of two different transitions so that the error in determining the relative efficiency is considerably less. Again the uncertainty depends on the energies and multipolarities, but for two transitions which do not have widely different energies and multipolarities the uncertainty in the relative efficiency is estimated to be 2–3%.

III. EXPERIMENTAL PROCEDURES

The intermediate-image pair spectrometer and procedures for its use have been described previously.[10,11] In the measurement of pair-line spectra for transitions above 3 MeV, semicircular Pilot-B scintillation crystals $1\frac{1}{2}$ in. in diameter by $\frac{1}{2}$ in. thick have generally been used. However, when these crystal were tried in the initial stages of the present work background difficulties were experienced which resulted from positron activities induced in the targets. When the spectrometer field current is set to focus electrons of ~0.5 MeV (for a 2-MeV transition), the bias settings on the discriminators in the coincidence circuit are optimum for the coincidence detection of "cross talk" between crystals, i.e., the entrance of a positron into one crystal and the absorption of its annihilation radiation by the opposite crystal. Even at a focusing energy of 1 MeV the "cross talk" effect is noticeable because of the need for accepting a spread of pulse heights in the coincidence circuit.

In order to reduce this background effect the $\frac{1}{2}$-in.-thick crystals were replaced with $\frac{3}{16}$-in.-thick crystals. These completely absorb electrons of up to ~1.3 MeV which enter at a mean angle of 45.7° with respect to the axis and are therefore adequate for measuring transitions of up to 3.6 MeV. The pair-line measurements were made with a coincidence resolving time setting of 3.5×10^{-9} sec which gave ~100% coincidence counting efficiency for the 2.13-MeV B^{11} line.

A 5-in.×5-in. NaI scintillation counter was used to measure the gamma-ray yields. This was located 95 in. from the target such that the line from the target to the center of the crystal was at an angle of 42° with respect to the spectrometer axis. In that direction the wall of the vacuum chamber was the only solid material lying between the target and the crystal unit. Furthermore, the magnetic field from the spectrometer had a low enough value at the gamma detector position that a simple iron shield was sufficient to virtually eliminate the effect of the magnetic field on the photomultiplier gain. The output of the phototube was recorded on a multichannel pulse-height analyzer.

For the experiments on the $B^{11}(p,p')B^{11*}$ reaction the target material consisted of a layer of boron 120 $\mu g/cm^2$ thick evaporated on 1-mg/cm² thick gold foil. Since the energy loss of 2.7-MeV protons in the boron layer is considerably less than the 48-keV width of the 2.66-MeV resonance, a higher yield was obtained by clamping two pieces of the material in the target holder such that the boron layers were adjacent. The peak of the resonance was located by recording a gamma-ray yield curve.

The carbon target for the $C^{12}(d,p)C^{13}$ reaction consisted of a 1-mg/cm² thick layer of aquadag evaporated on a 1-mg/cm² thick Ni foil. The target was oriented so that the beam passed first through the Ni backing. An effective beam energy of 1.7 MeV was used. At this energy the intensities of the 3.68- and 3.86-MeV gamma rays from the second and third excited states of C^{13} were negligible compared with the yield of the 3.09-MeV gamma rays. In order to be sure that most of the 3.09-MeV gamma rays that were detected by the 5-in.×5-in. crystal came from the target all of the tantalum apertures and the beam-collecting cup were thoroughly cleaned so as to remove carbon deposits. At the end of each run on the pair line the beam was deflected electrostatically off the target so that it still struck the regulating slits and some of the collimators. It was found the "nontarget" yield of 3.09-MeV gamma rays was at most a few percent of the yield from the target.

Runs on the two reactions were each made by counting the number of spectrometer pair-line coincidences occurring for a given integrated beam and by periodically measuring the gamma-ray spectrum from the NaI crystal for the same counting interval. At each field setting the gains of the spectrometer semicircular crystal detecting systems were adjusted so as to maintain the peak of the pulse-height spectrum in a selected channel. This insured that a nearly constant fraction of pulses were above a fixed bias level in the coincidence circuit. The fraction of the total number of counts which fell above the bias level was determined from the shape of the complete pulse-height spectrum as recorded at the peak of the pair line. In this way the relative $f(k)$ factors for the two pair lines was obtained.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows the pair lines from the $B^{11}(p,p')B^{11*}$ and $C^{12}(d,p)C^{13}$ reactions taken at the maximum transmission setting of the spectrometer. In the B^{11} reaction the proton beam intensity was 2 μA and in the $C^{12}(d,p)C^{13}$ reaction a 1.7-MeV deuteron beam of 0.2 μA was used. In both cases a background, which rises with decreasing energy, results partly from the production of pairs in the source mount and partly from induced positron activities. Peak net yields of the two lines were obtained by subtracting the estimated backgrounds indicated by dashed lines.

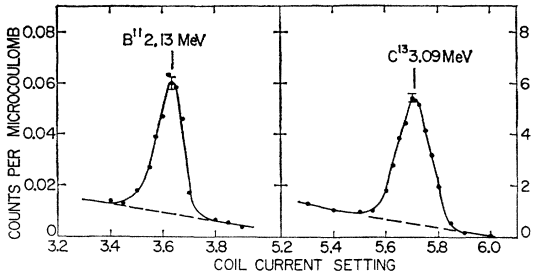

FIG. 4. Pair-line spectra observed in the $B^{11}(p,p')B^{11*}$ and $C^{13}(d,p)C^{13*}$ reactions.

Relative gamma-ray yields in the two experiments were derived from the areas under the full-energy-loss peaks in the 5-in.×5-in. NaI spectra. These areas were corrected for the pulse-height analyzer dead times and for the loss of gamma rays by absorption in the $\frac{1}{4}$-in.-thick brass vacuum chamber wall. Data on full-energy-loss peak efficiency times solid angle versus gamma-ray energy given by May and Marinelli[21] for various sizes of NaI crystals were used to obtain a value of 0.782 for relative full-energy-loss peak efficiencies in a 5-in. ×5-in. crystal for gamma rays of 3.09 and 2.13 MeV. The corrected photopeak areas were divided by the efficiencies in order to obtain the relative gamma-ray emission rates from the two targets. By combining the results of the various measurements we find

$$R\equiv\frac{(N_{\text{pair line}}/N_\gamma)_{3.09}}{(N_{\text{pair line}}/N_\gamma)_{2.13}}=3.3\pm0.7.$$

(Notice that no correction is needed for angular distribution of either the boron or the carbon radiations since both radiating states have $J=1/2$.)

This value for R may be compared with predictions based on the efficiency curves presented in Figs. 2 and 3. The 3.09-MeV $1/2^+$ first excited state of C^{13} can de-excite only by the emission of $E1$ radiation since the ground state is of $1/2^-$. By assigning various multipolarities to the 2.13-MeV radiation of B^{11} the corresponding expected values of R, as defined above, are as follows:

$$E1,\ 1.81;\quad M1,\ 3.51;\quad E2,\ 2.78;\quad M2,\ 5.42.$$

The experimental result is consistent with assignments of $M1, E2$, a mixture of $M1$ and $E2$, or an approximately equal mixture of $E1$ and $M2$. An assignment of pure $E1$ or $M2$ is definitely excluded. In order to rule out an approximately equal mixture of $E1$ and $M2$, and so a parity change, the speed of the B^{11} 2.13-MeV transition must be invoked. The mean lifetime of the B^{11} 2.13-MeV level is $(4.6\pm0.6)\times10^{-15}$ sec.[9] A limit on the maximum speed of an $E2$ transition can be placed with the aid of various sum rules. This has been done[5] previously for the B^{11} 2.13-MeV transition. Sum rules are not available for $M2$ transitions; however, we make the reasonable assumption that the speed of an $M2$ transition could not be larger than the limit given by the $E2$ sum rules. With this assumption the limit[5] on the $E2$ speed combines with the measured lifetime[9] to give a limit $\delta^2<0.01$, where δ^2 is the intensity ratio of quadrupole to dipole for the B^{11} 2.13-MeV transition. With this restriction on δ^2 it is clear from the present result that the B^{11} 2.13-MeV transition is chiefly $M1$ and since the ground state of B^{11} is known to have a spin-parity of $3/2^-$ the parity of the 2.13-MeV level is therefore odd.

V. CONCLUSION

The present result establishes that the parity of the first excited state of B^{11} is odd. The same conclusion has recently been reached[22] from a measurement of the angular correlation between the members of the pairs in the same process of internal pair conversion that we have studied here from a different point of view.

[21] H. A. May and L. D. Marinelli, Proceedings of the Total Absorption Gamma Ray Spectrometry Symposium, Gatlinburg, Tennessee [Atomic Energy Commission Report TID-7594, 1960 (unpublished)].

[22] S. Gorodetzky, F. Scheibling, P. Chevallier, P. Mennrath, and G. Sutter, Phys. Letters 1, 24 (1962).