the nuclear coordinate system, j_p is the proton angular momentum, and Ω its projection on the symmetry axis. The primed quantities refer to the odd neutron. Where j is not a good quantum number, the different components of the wave function must be separately symmetrized. We note when $\Omega=-\Omega'$ and $K=0$ that the wave function may be factored as follows:

$$\psi=\left(\frac{2I+1}{16\pi^2}\right)^{\frac{1}{2}}[\chi_\Omega(p)\chi_{-\Omega}(n) +(-)^{I-j_p-j_n}\chi_{-\Omega}(p)\chi_\Omega(n)]D_{M0}{}^I(\theta_i).$$

If we now consider a residual force acting between neutron and proton, it will in general give rise to an energy term with sign alternating with spin, I. This energy term is a cross term connecting the first and second parts of the wave function and is essentially due to a component of the force which scatters the proton and neutron into states with equal and opposite projections of the angular momentum. Whether the odd or even spins are elevated in energy depends on details of the wave functions. Further theoretical study will aim to predict the sign and magnitude of the displacement. In the special case of $K=0$ and $|\Omega|=|\Omega'|=1/2$ there will be an additional odd-even displacement energy due to a term $(\hbar^2/\mathcal{I})\mathbf{j}_p\cdot\mathbf{j}_n$ in the collective rotational part of the Hamiltonian. The combination of both proton and neutron $|\Omega|=1/2$ orbitals may occur in the short-lived isomer of Pa^{234}.

IV. ACKNOWLEDGMENTS

We wish to acknowledge the aid of Raymond Gatti, Llad Phillips, Helen V. Michel, and Arlene Fregulia in these experiments. Their purification of the americium and separations of americium from curium were essential to the success of this work.

PHYSICAL REVIEW VOLUME 120, NUMBER 3 NOVEMBER 1, 1960

Rare $E2$ Transition in C^{13}†

R. E. Pixley, J. V. Kane, and D. H. Wilkinson*
Brookhaven National Laboratory, Upton, New York

(Received June 22, 1960)

By means of a coincidence method it is shown that the $\frac{5}{2}+$ state of C^{13} at 3.86 Mev has an $E2$ branch of relative strength $(9.3\pm2.0)\times10^{-3}$ to the $\frac{1}{2}+$ state at 3.09 Mev. From consideration of the likely strengths of the competing $E1$ transition to the $\frac{3}{2}-$ state at 3.68 Mev and the $M2$ transition to the ground state it is deduced that this branching ratio implies an $E2$ transition speed of the order of a single-particle (proton) unit. This in turn demands the substantial participation of at least one excited state of C^{12} in the parentage of at least one of the C^{13} states with respect to the $1d$ or $2s$ neutron. This eliminates in particular a jj-coupling description of C^{13} in which the two states in question are $1d_{\frac{5}{2}}$ and $2s_{\frac{1}{2}}$ neutron states and more generally a weak-coupling model in which the ground state of C^{12} is the unique parent for the C^{13} states (with respect to $1d$ and $2s$ neutrons).

INTRODUCTION

Electric quadrupole transitions in the light elements are of considerable interest. Although the independent-particle model (IPM) in intermediate coupling gives a generally excellent account of level schemes, magnetic moments, and dipole transition probabilities in the $1p$ shell and just beyond,[1] it fails badly in its account of the $E2$ rates. The sense of the failure is that the predicted rate is too low and this has suggested that configuration mixing must be an essential ingredient in our IPM account of the light nuclei; an alternative description is in terms of some form of collective model and a good beginning has been made in establishing the relationship between the two descriptions.[2] Any extension of our knowledge of $E2$ transitions in the light elements, particularly in the $1p$ shell where our account of the level schemes via the IPM is seen at its most successful, is very welcome and valuable.[3] The present investigation is to establish one such transition in C^{13} and to determine its probability relative to competing $E1$ and $M2$ transitions. It is the $E2$ transition between the $\frac{5}{2}+$ state at 3.86 Mev and the $\frac{1}{2}+$ state at 3.09 Mev.

This particular $E2$ transitions has an additional interest because it takes place in C^{13}. Although the IPM analysis[1] of $A=13$ gives the best account at $a/K\sim5$ it has frequently been suggested that in fact C^{12} is close to jj coupling. In this case we should primitively attempt to describe these $\frac{5}{2}+$ and $\frac{1}{2}+$ states as single-particle neutron states $1d_{\frac{5}{2}}$ and $2s_{\frac{1}{2}}$, respectively. This view is in fact encouraged by the empirical observation that the fractional parentage coefficients for the ground

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* Permanent address: Clarendon Laboratory, Oxford, England.
[1] See, e.g., D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957). J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955); **A242**, 57 (1957). A. M. Lane Proc. Phys. Soc. **A66**, 977 (1953); **A68**, 189 and 197 (1955).
[2] D. Kurath and L. Picman, Nuclear Phys. **10**, 313 (1959).
[3] D. Kurath, Nuclear Phys. **14**, 398 (1960).

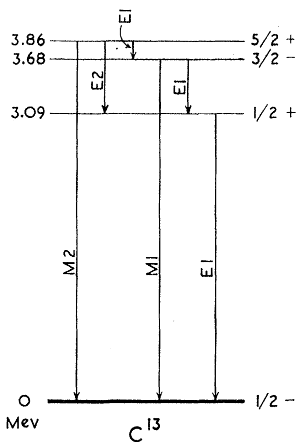

FIG. 1. Level scheme of C^{13} showing transitions of interest in this investigation.

state of C^{12} of these two states of C^{13} with respect to d-wave and s-wave neutrons, respectively, are very large (the evidence of the reduced proton widths of the 3.56-Mev and 2.37-Mev states of N^{13}). However, the extraction of the coefficient from the experimental width is hazardous and there is plenty of room for an adequate participation of excited states of C^{12} in the parentage of the states of C^{13} in a manner enabling the $E2$ transitions to take place quite strongly. (With the ground state of C^{12} as unique parent—the weak-coupling model—the $E2$ rate is, of course, very small—for harmonic oscillator wave functions, identically zero.)

The competing transitions from the 3.86-Mev $\frac{5}{2}+$ state of C^{13} are the $E1$ to the 3.68-Mev $\frac{3}{2}-$ state and the $M2$ to the $\frac{1}{2}-$ ground state. The ratio of intensities of these two transitions, $E1$ to $M2$, is 0.32 ± 0.07.[4] The ratio expected by taking the "most probable" value[5] $|M|^2=0.045$ (in terms of the Weisskopf unit on a radius constant $r_0=1.2\times10^{-13}$ cm) for the $E1$ transition and, *faute de mieux*, a single-particle unit for the $M2$ transition is 1.2. It therefore seems likely that these two transitions are nothing out of the ordinary and may be used as a rough measure of the $E2$ probability. If the $E2$ transition were itself of the order expected for a neutron transition (primitive jj coupling or weak coupling with C^{12} ground state as unique parent), its relative probability would be negligibly small. If, on the other hand, the $E2$ transition were of the order of a single-particle (proton) unit we should expect it to show a branching ratio of a few times 10^{-3}. This latter result would imply a more complicated parentage for the C^{13} states such as would automatically be provided by an admixture of collective motion into a, possibly, predominant IPM prescription.

THE EXPERIMENT

The branching ratio about which we speak is already known to be low (<0.02)[4] and a coincidence experiment in which the $E2$ transition is detected in coincidence with the subsequent $E1$ transition from the 3.09-Mev $\frac{1}{2}+$ state to the ground state (see Fig. 1) is indicated. Its intensity can then be determined relative to that of the branch to the 3.68-Mev state which will give a 170-kev gamma ray in coincidence with the subsequent 3.68-Mev transition to the ground state. In this way we need only to determine relative and not absolute detector efficiencies.

The 3.86-Mev state is readily reached in the reaction $B^{10}(\alpha,p)C^{13}$ at an alpha-particle bombarding energy of 1.64 Mev: A resonance of width (laboratory) 20 kev populates the 3.86-Mev state with a cross section of 52 mb while that for reaching the neighboring state at 3.68 Mev is only 2.4 mb and that for making fast neutrons, always a nuisance in delicate coincident searches, in only 3.2 mb.[6]

A separated elemental B^{10} target of thickness about 40 kev for alpha particles of 1.6 Mev was used; it left us clear of neighboring resonances at 1.52 and 1.68 Mev (respective widths 20 kev and 7 kev).

The high-energy gamma rays were detected in a 5-in.×5-in. cylindrical NaI(Tl) crystal placed at approximately 80° to the alpha-particle beam. A lead collimator in the form of a hollow truncated cone of height $2\frac{1}{4}$ in., base diameter $1\frac{3}{4}$ in., and entrance diameter $\frac{1}{2}$ in. was placed directly in front of this crystal. The entrance to this collimator was $\frac{7}{16}$ in. from the center of the B^{10} target. The low-energy gamma rays were detected at 90° to the alpha-particle beam, opposite the high-energy detector, in a 3-in.×3-in. cylindrical NaI(Tl) crystal whose front face was $\frac{7}{16}$ in. from the center of the B^{10} target. A coincidence resolving time of about 0.1 μsec was used and a convenient beam current was found to be about 1 μa.

A large number of coincidence runs was taken, displaying a coincidence counts in the 3-in.×3-in. crystal on a bias of 1.55 Mev in the larger crystal. The beam current was held constant to better than 5% during this set of runs. The bias on the large crystal as well as its response to a number of gamma rays of both lower and higher energy than those of interest here were accurately determined since the quantitative interpretation of the results depends on a knowledge of the relative efficiency of the larger crystal, above its bias, to gamma rays of 3.1 and 3.7 Mev.

Calibration runs for the smaller crystal were made using several standard sources placed successively at the position of the target. The first purpose of these runs was to provide an accurate energy calibration of the crystal (for this purpose the alpha-particle bombardment continued at its usual level to avoid any pos-

[4] R. J. Mackin, W. R. Mills, and J. Thirion, Phys. Rev. **102**, 802 (1956).

[5] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, New York, 1960), Vol. II, p. 852.

[6] E. S. Shire, J. R. Wormald, G. Lindsay-Jones, A. Lundén, and A. G. Stanley, Phil. Mag. **44**, 1197 (1953).

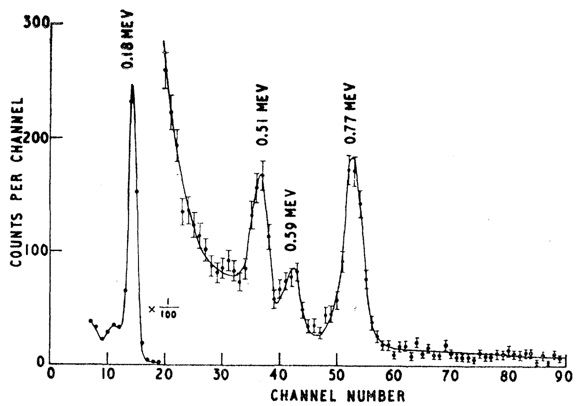

FIG. 2. Low-energy gamma rays seen in coincidence with high-energy gamma rays ($E>1.6$ Mev) from the bombardment of B^{10} with α particles of 1.64 Mev.

sible effect of rate-dependent gain—the calibration sources made only a slight change to the current in the photomultiplier). The second purpose was to determine the shape of the pulse distribution for various monochromatic gamma rays to enable an accurate decomposition of the coincidence spectrum to be made (for this purpose there was no beam on the target and the N^{13} was allowed to die away).

The coincidence spectrum seen in the smaller crystal is shown in Fig. 2. The intense peak at channel 14 is of about 0.18 Mev and is the $E1$ transition between the $\frac{5}{2}+$ state at 3.86 Mev and the $\frac{3}{2}-$ state at 3.86 Mev (expected energy[7] 0.1695 ± 0.0004 Mev). That at channel $36\frac{1}{2}$ is of measured energy 508 ± 7 kev and is due to annihilation radiation; that at channel $42\frac{1}{2}$ is of measured energy 590 ± 15 kev and is due to the $E1$ transition between the $\frac{3}{2}-$ state at 3.86 Mev and the $\frac{1}{2}+$ state at 3.09 Mev—it is of considerable interest in its own right and has been discussed elsewhere[8]; that at channel $52\frac{1}{2}$ is of measured energy 765 ± 8 kev and is due to the $E2$ transition that we seek (expected energy[7] 765 ± 12 kev).

RESULTS AND DISCUSSION

The 765-kev peak of Fig. 2, compared with the very much more intense 170-kev coincidence peak, gives us the required branching ratio after suitable correction for peak-to-total ratios, relative absorption efficiences of the various radiations in the smaller crystal, the slightly different efficiency of the larger crystal above the 1.55-Mev bias for the 3.1- and 3.7-Mev lines, and a few insignificant effects of absorption in the target assembly, crystal covering and so on. The angular correlations involved can be computed from data[9] in the literature which fix the channel spin ratios; they are not strong and are effectively integrated out by the very bad geometry ($\pm74°$) of the smaller crystal. The final value for the strength of the $E2$ de-excitation relative to all decays of the 3.86-Mev level is $(9.3\pm2.0)\times10^{-3}$, consistent with the earlier limit (this stated uncertainty includes that in the $E1$ versus $M2$ branching ratio).

This branching ratio is seen to be of the order expected for an $E2$ transition of single-particle (proton) strength: If we guess that the 170-kev $E1$ transition is of "usual" strength, the predicted $E2$ branching ratio is 1.1×10^{-3}; if we alternatively guess that the 3.86-Mev $M2$ transition is of single-particle strength, the predicted $E2$ branching ratio is 4.2×10^{-3}. It is therefore clear that this $E2$ transition, rather than being heavily inhibited, is probably of single-particle order and that at least one state of C^{12} in addition to the ground state is quite strongly involved in the parentage of at least one of the states of C^{13} at 3.68 and 3.86 Mev with respect to a $1d$ or $2s$ neutron or both. The "weak-coupling" or unique parentage model is eliminated. (In principle the parentage need not be with respect to these particular states, but the evidently large fractional parentage coefficients for the ground state of C^{12} with respect to these neutrons make it rather unlikely that parentage with respect to any other neutron orbitals underlies the $E2$ transition. As it is, we may guess that the transition "behind" the $E2$ that we study here is that involving the ground state of C^{12} and the $2+$ first excited state at 4.4 Mev. This transition is fast ($|M|^2\sim6$) and so the participation of the $2+$ state in the C^{13} parentage, although substantial, need not be very great to produce the observed effect.)

A determination of the absolute speed of the $E2$ transition via a measurement of the lifetime of the 3.86-Mev level would be most valuable and may be feasible.

[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[8] J. V. Kane, R. E. Pixley, and D. H. Wilkinson, Phil. Mag. (to be published).
[9] A. G. Stanley, Phil. Mag. **45**, 430 (1954).