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Core-Excited 5^+ State in ^{14}N†

J. W. Noé, D. P. Balamuth, and R. W. Zurmühle
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
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The proton and γ-ray decay of the $T=0$ level at $E_x=10.81$ MeV in ^{14}N has been studied with the reactions $^{12}C(^3He,p)^{14}N(p')^{13}C_{g.s.}$ and $^{12}C(^3He,p\gamma)^{14}N$ at an incident ^{3}He energy of 14 MeV. The state was populated in an axially symmetric geometry in which the outgoing reaction protons were detected at 0° to the incident beam direction at the focus of a magnetic spectrometer. Analysis of the decay proton and γ-ray angular correlations leads to an assignment of $J^\pi=5^+$ to the 10.81-MeV state. The γ-ray decay goes entirely to the $J^\pi=3^+$, $T=0$ state at $E_x=6.44$ MeV; the fractional γ-ray branch of the 10.81-MeV state was measured as $\Gamma_\gamma/\Gamma_{total}=(4.1\pm0.8)\%$.

I. INTRODUCTION

In the simple shell-model picture of ^{14}N [1] based on the coupling of two nucleons in the $1p_{1/2}$ and *sd* orbitals outside an inert $(1p_{3/2})^8$ core, discussed by Warburton and Pinkston,[2] True,[3] and others, only one 5^+ state can occur; True's calculation[3] places this $T=0$ $(d_{5/2})^2$ state at $E_x\cong 9.3$ MeV. The $(d_{5/2})^2|_{5^+}$ configuration is expected to be very strongly excited in the $^{12}C(\alpha,d)^{14}N$ reaction and consequently has been associated with the $J^\pi=5^+$ state[4,5] at $E_x=8.96$ MeV which is observed[6] to be strongly excited in that reaction.

We report here the identification of the $T=0$ level at $E_x=10.81$ MeV[7] as the second $J^\pi=5^+$ state in ^{14}N. [The strength of the 10.81-MeV level in the $^{12}C(^3He,p)^{14}N$ reaction led to its previous tentative assignment[8] as a two-particle shell-model state having $J^\pi=4^+$, $T=0$.] The present result was obtained from an analysis of the angular correlations of protons and γ rays resulting from the decay[9] of the 10.81-MeV state; the state was aligned by populating it in an axially symmetric geometry.

At the time of a preliminary report of the present experiments[10] no theoretical prediction of a second 5^+ state at such a comparatively low excitation energy in ^{14}N existed. Very recently however, Lie[11] has presented a calculation of ^{14}N levels based on the weak coupling of particle and hole configurations. The calculation predicts two 5^+ states below 11 MeV excitation in ^{14}N, one of which is the $(d_{5/2})^2$ state discussed above and the other of which is built out of core-excited configurations.

II. EXPERIMENTAL RESULTS AND ANALYSIS

The 10.81-MeV state was populated using the $^{12}C(^3He,p)^{14}N$ reaction at an incident ^{3}He energy of 14 MeV. The proton group corresponding to the 10.81-MeV state was detected by a position-sensitive detector located in the focal plane of a magnetic spectrometer placed at 0° with respect to the incident beam direction. Deexcitation γ rays were detected in coincidence with the 0° protons by an array of four 7.6×10.2-cm NaI(Tl) crystals. To study proton emission this assembly was replaced by four silicon surface-barrier detectors placed inside the target chamber. Coincidence data and the 0° proton singles spectrum were written on magnetic tape during the experiments using a PDP-9 computer; angular correlations were then obtained off line by a multiparameter sorting procedure using the same computer. The apparatus has been described in greater detail elsewhere.[12]

The angular correlation of protons emitted by an aligned state of spin a is given by[13]

$$W(\theta)=\sum_{\alpha b l l' k} w(\alpha)(a\alpha a-\alpha\,|\,k0)(-)^{b-\alpha}\overline{Z}(lal'a;bk)\times\langle a\|\,l\,\|b\rangle\langle a\|\,l'\,\|b\rangle^* P_k(\cos\theta)\,. \quad (1)$$

Here b denotes the channel spin in the final system, the $\overline{Z}$ coefficients are defined in Ref. 13, and the $P_k(\cos\theta)$ are Legendre polynomials. The population of the magnetic substate α is given by $w(\alpha)$. In the present work $w(\alpha)$ is zero for $|\alpha|>1$ and only the relative population of the $\alpha=0$ and $\alpha=\pm1$ magnetic substates must be determined from the analysis. The quantities $\langle a\|\,l\,\|b\rangle$ are reduced matrix elements for proton decay via orbital angular momentum l to channel spin b. Note that the sum over the allowed values of l, l' is coherent, whereas the sum over channel spins is incoherent. In fitting experimental data the over-all normalization is treated as a variable parameter, so that only ratios of reduced matrix elements can be measured. In the following we restrict our attention

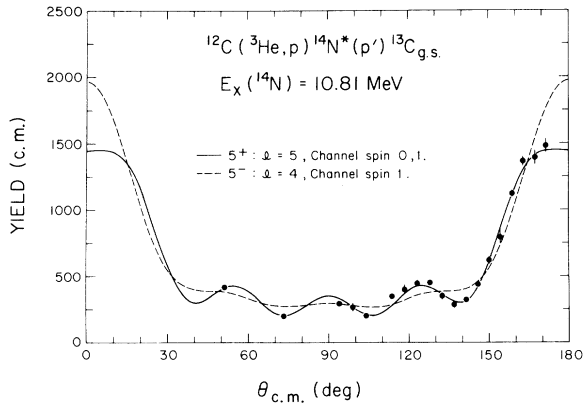

FIG. 1. Angular correlation of decay protons from the 10.81-MeV state in ^{14}N to the ^{13}C ground state with best fits for $J^\pi = 5^+$ and 5^-.

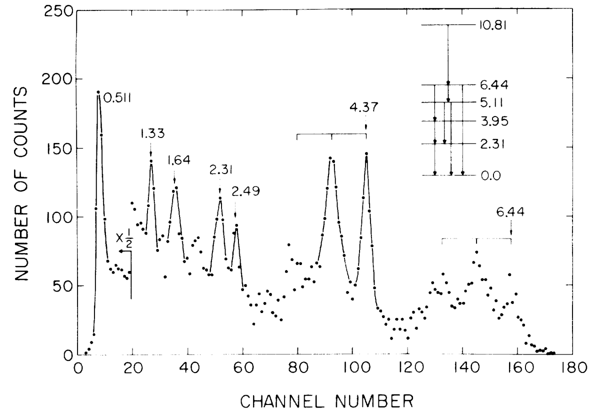

FIG. 2. Four-crystal sum spectrum of γ rays observed in true coincidence with protons populating the 10.81-MeV state. The decay scheme of the 6.44-MeV level is taken from Ref. 1.

to proton decay to the $J^\pi = \frac{1}{2}^-$ ground state of ^{13}C; the possible channel spins are then 0^- and 1^-. For a natural-parity state with $J \neq 0$ in ^{14}N the conservation of angular momentum and parity restricts the channel spin to 1^- and permits orbital angular momenta $l = J \pm 1$. For states with unnatural parity l must equal J; however, both channel spins 0^- and 1^- are allowed and the channel-spin ratio $\delta_c = |\langle a \| l \| 0\rangle| / |\langle a \| l \| 1\rangle|$ is an additional unknown parameter that must be determined from the analysis. In the case of natural-parity states, a completely general treatment would require varying the quantity $\delta_l = \langle a \| l+2 \| 1\rangle / \langle a \| l \| 1\rangle$ where the coherence in the sum over l, l' requires that both the magnitude and phase of δ_l be known. Since the reduced matrix elements contain the penetrability for orbital angular momenta $l+2$ and l, respectively, as factors, it is reasonable to assume that $|\langle a \| l+2 \| 1\rangle| \ll |\langle a \| l \| 1\rangle|$, that is to consider only the lowest allowed l value. It should be noted, however, that structural effects can compensate for differences in penetrabilities, so this approximation should be applied with caution.

No assumption concerning the l value need be made to restrict the spin of the 10.81-MeV state to $J \geq 5$. This follows from the presence of a nonzero coefficient ($a_{10} = -0.76 \pm 0.06$) of $P_{10}(\cos\theta)$ if the experimental correlation is fitted to even-order Legendre polynomials. [The coefficient $(\alpha a\, a - \alpha | k0)$ in Eq. (1) is zero for $k > 2a$.] A best fit to the data was next determined for spins J^π

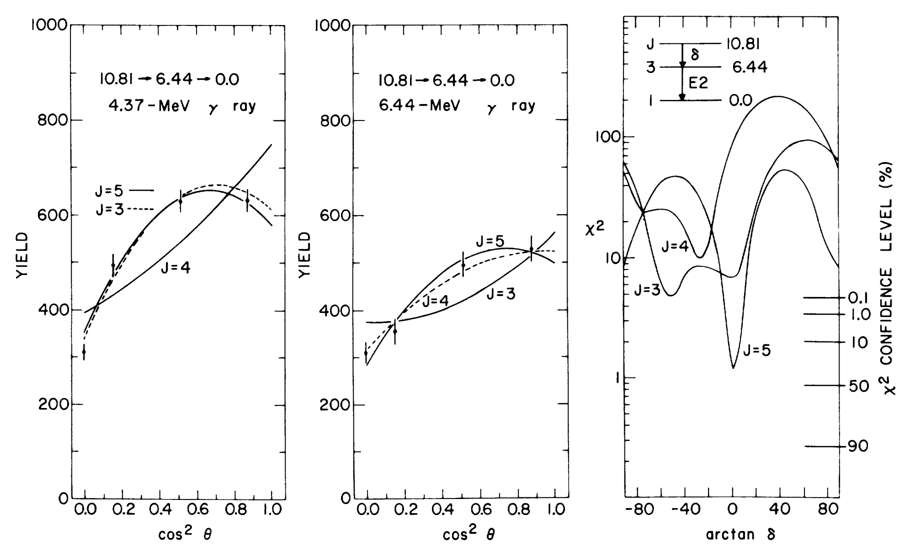

FIG. 3. Experimental γ-ray correlations for the 10.81→6.44 MeV and 6.44→ground-state transitions, with best fits for $J = 3$, 4, and 5 and corresponding χ^2 plot. Not shown here, $J = 0$, 1, 2 and $J = 6$ ($\delta = 0$) are excluded at the 0.1% confidence level.

$= 5^+$, 5^-, 6^+, and 6^- using Eq. (1). All physical values of the parameters $w(\alpha)$ and δ_c were considered, but for $J^\pi = 5^-$ and 6^+ the l value was restricted to $l = 4$ and 5, respectively. With this restriction only the choice $J^\pi = 5^+$ gives an acceptable fit to the data (see Fig. 1).

The properties of the 10.81-MeV state were further investigated by studying its electromagnetic decay. Although unbound to proton emission by ~3 MeV the 10.81-MeV state was expected to have an observable γ decay due to the low penetrability of $l = 5$ protons. A four-crystal sum spectrum of the observed γ rays is shown in Fig. 2. The decay scheme of the 10.81-MeV state is identical to that reported[4,5] for the $(d_{5/2})^2$ 5^+ state at 8.96 MeV; the decay occurs entirely (>90%) to the 3^+, $T = 0$ state at 6.44 MeV. The angular correlations of the 10.81 → 6.44 MeV and 6.44 → ground-state transitions were analyzed in the standard manner[14] with the computer code[15] $M2$. As shown in Fig. 3, a unique assignment of $J = 5$ to the 10.81-MeV state results from this analysis. The mixing ratio obtained for the 10.81 → 6.44-MeV primary transition is consistent with pure quadrupole radiation; the secondary transition is known[1] to be pure $E2$. By comparison of the proton singles at 0° with the observed number of γ rays the width ratio $\Gamma_\gamma/\Gamma_{\text{total}}$ was deduced to be $(4.1 \pm 0.8)\%$. The efficiencies of the γ-ray detectors required for this comparison have been measured separately in the same experimental geometry. A similar comparison was made for the decay protons to the ^{13}C ground state, and the p_0 and γ branches are estimated to account for >95% of the decay strength.

The angular-correlation results presented here lead to a model-independent spin assignment of $J = 5$ to the 10.81-MeV state. A parity assignment cannot be made in a model-independent way from these data. However, in order to fit the observed proton-decay angular correlation for $J^\pi = 5^-$ an $l = 6$ amplitude of about 15% is required. When the relative penetrabilities for $l = 4$ and 6 are considered, this implies that the $l = 6$ reduced width is greater than the $l = 4$ reduced width, which is considered to be unlikely. In addition, the fact that the observed γ decay is identical with that of the known 5^+ state at 8.96 MeV is strongly suggestive of positive parity. A 5^- state, on the other hand, might be expected to decay by $E2$ radiation to the 3^-, $T = 0$ state[1] at 5.83 MeV. The observed decay would then correspond to a $\Delta T = 0$ $M2$ transition, which should[16] be retarded in a self-conjugate nucleus.

III. DISCUSSION

On the basis of this evidence, we assign $J^\pi = 5^+$ to the 10.81-MeV state in ^{14}N. Concerning the configuration of the new 5^+ state, it is clear that it must involve a broken $p_{3/2}$ core. Also, any suggested configuration must accommodate the fact that the state is quite strongly populated[6,8] in two-nucleon transfer on ^{12}C. As mentioned above, the recent calculation[11] of Lie predicts two 5^+ states, the higher of which is predicted to have essentially no strength in two-nucleon transfer, being composed principally of two nucleons in the sd shell coupled to the 2^+ first excited state of ^{12}C. If this is the dominant configuration of the 10.81-MeV state, then it can be excited only by multistep processes in the (^{3}He, p) and (α, d) reactions. However, as Lie emphasizes, his calculations have neglected any tensor component in the particle-hole interaction. The effect of any such tensor interaction would be to mix the two 5^+ states in the model, the lower one of which is very strongly excited[6,8] in two-nucleon transfer. This could possibly explain the observed strength of the higher 5^+ state.

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