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Isospin Conservation in the Reaction $C^{12}(\alpha,d)N^{14}$[†]

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Cross sections for the formation of 24 states between 0 and 13-MeV excitation in N^{14} via the $C^{12}(\alpha,d)N^{14}$ reaction were measured. Six $T=1$ levels could have been observed if the $\Delta T=0$ selection rule for this reaction had been violated. None of these $T=1$ levels were observed to be excited. From the upper limits on their cross sections, isospin impurities in the wave functions of the 8.06-, 9.51-, and 10.43-MeV $T=1$ levels were deduced to be less than 50, 15, and 24%, respectively. These experimental upper limits are still somewhat larger than crude theoretical estimates of the isospin mixing induced by the Coulomb interaction.

I. INTRODUCTION

CONSERVATION of isospin should prevent the formation of states other than those with $T=0$ in an (α,d) reaction proceeding from a $T=0$ target. An apparent violation of this isospin-selection rule can occur if the nuclear states involved are not pure.[1,2] In nuclei as light as C^{12} and N^{14} it is expected that the ground state will have high isospin purity,[2] but at sufficiently high-excitation isospin mixing from neighboring states will increase as the level density increases. A true violation of the $\Delta T=0$ selection rule will occur if there is a charge-dependent component of the interaction responsible for the (α,d) reaction, but such effects are expected to be small. The present work was undertaken to investigate the possibility of observation of highly excited ($\simeq$10-MeV) $T=1$ states populated through their small $T=0$ impurities. The $C^{12}(\alpha,d)N^{14}$ reaction was chosen since a great deal of experimental and theoretical information is available on N^{14}. The high-lying $T=1$ states in N^{14} are quite close to neighboring $T=0$ levels, so rather good energy resolution and low background (clean particle separation) were required.

At the 42-MeV bombarding energy used throughout this experiment, a direct reaction mechanism is expected to dominate over the compound-nucleus mechanism. Isospin mixing could take place in the compound nucleus,[1] but at these high-excitation energies it has been estimated[3] that isospin mixing will be very small because of the short lifetime of the compound system. Such an effect has been experimentally observed,[4] and it appears that this bombarding energy is sufficient to maintain effective isospin purity, whether or not there is a compound-nucleus contribution to the reaction cross section.

II. EXPERIMENTAL PROCEDURE

The bombardments with 42-MeV alpha particles were carried out in the 60-in. scattering chamber of the University of Washington 60-in. cyclotron. The external-beam system has been described previously.[5] The slit settings that were used gave approximately 90-keV energy spread in the incident beam.

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[1] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

[2] William M. MacDonald, in *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 932.

[3] D. H. Wilkinson, Phil. Mag. **1**, 379 (1956).

[4] R. H. Pehl, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-10993, 1963 (unpublished).

[5] See, for example, A. J. Liber, F. H. Schmidt, and J. B. Gerhart, Phys. Rev. **126**, 1496 (1962).

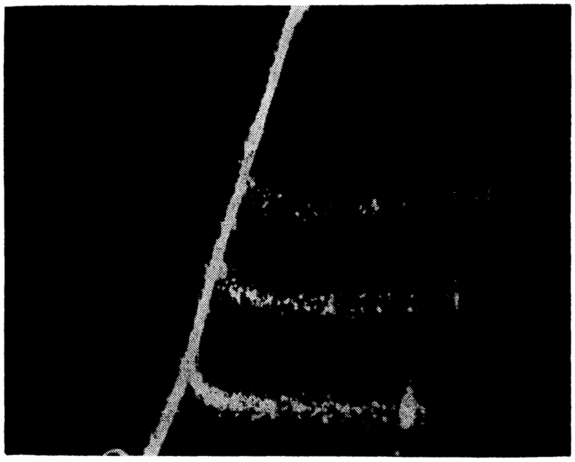

FIG. 1. x, y oscilloscope display of multiplier output verus $E+\Delta$ pulse. The three groups are due to protons, deuterons, and tritons from a 42-MeV alpha bombardment of a polystyrene target. In use, a window was set on the deuteron group, and a coincidence requirement between E and Δ removed the events in the ascending line due to particles which stopped in the delta counter.

Targets were prepared by floating a thin layer of polystyrene dissolved in benzene on warm water. The resulting films, 50–100 μg/cm^2, were then picked up on target frames.

Reaction products were detected and identified with a ΔE–E system. The ΔE counter was a 200-μ-thick fully depleted surface barrier detector for some of the runs and a 200-μ-thick fully depleted phosphorous-diffused junction detector for the remainder. The E detector was a 2-mm-thick lithium-drifted silicon detector. A field-effect transistor multiplier[6] provided particle discrimination. Figure 1 shows an x, y oscilloscope display of the multiplier output versus energy. A total energy pulse was obtained by summing the preamplifier outputs. Multiplier pulses corresponding to deuterons gated a 512 channel analyzer which recorded the total energy spectrum. Energy calibrations were carried out by observing deuteron groups corresponding to well-known levels in N^{14}. Over-all energy resolution was typically 125-keV full width at half-maximum.

III. RESULTS

Figure 2 shows a deuteron energy spectrum taken at an angle of 20° (lab). The locations of known N^{14} levels are indicated on the figure. Two new states are seen, one at 10.85-MeV excitation and the other at 13.05-MeV. The 10.85-MeV level was observed to shift in energy properly between 7° and 60° (lab) and the 13.05-MeV level between 7° and 40° (lab). At larger angles, the deuteron groups were too low in energy to be detected. The average excitation energies obtained were (10.85 ± 0.020) and (13.05 ± 0.020) MeV. The former state appears to correspond to the state observed by Pehl *et al.*[7] at an assigned excitation energy of 10.71 MeV and by Harvey *et al.*[8] at an assigned excitation energy of 10.85 MeV.

The absence of a deuteron group corresponding to the

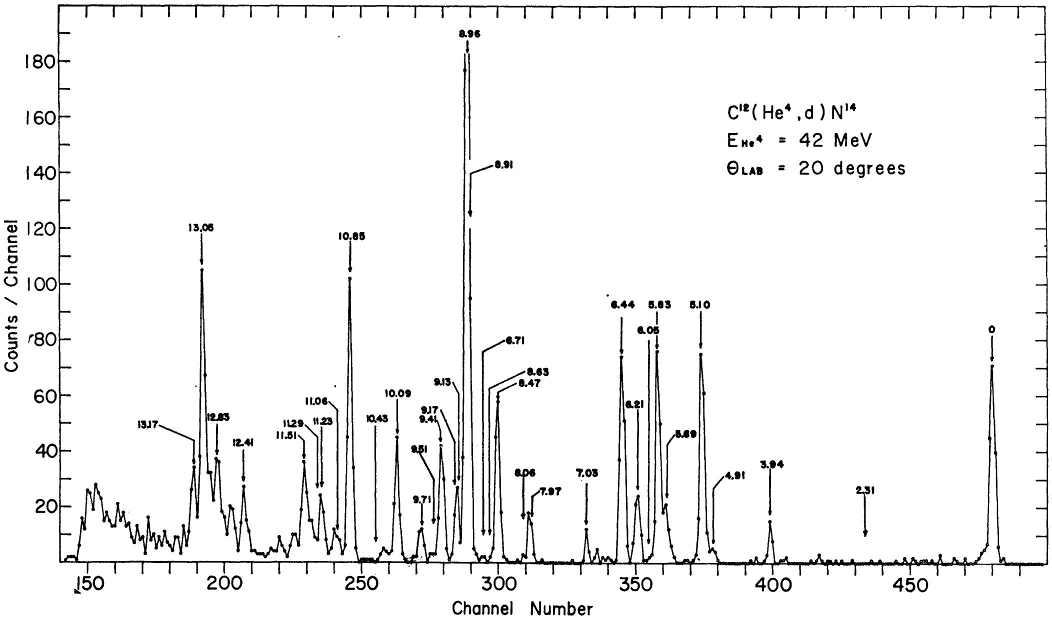

FIG. 2. Energy spectrum of deuterons from 42-MeV alpha bombardment of a polystyrene target taken at 20° (lab).

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[6] G. L. Miller and V. Radeka, in Proceedings of the National Conference on Instrument Techniques in Nuclear Pulse Analysis, Monterey, California, 1963 (to be published).

[7] Richard H. Pehl, Ernest Rivet, Joseph Cerny, and Bernard G. Harvey, Phys. Rev. **137**, B114 (1965).

[8] B. G. Harvey, J. R. Merriwether, and J. Mahoney, Phys. Rev. **146**, 712 (1966).

6.05-MeV level should not, necessarily, be taken as further evidence that it does not exist,[8] since the $C^{12}(\alpha,d)N^{14}$ reaction could not populate a 0^+ state through the direct reaction mechanism.[9]

The "giant peak"[7] at about 9-MeV excitation energy and the barely resolved level just above it appear to correspond to the $T=0$ states observed at 8.963 and 9.129 MeV by Detenbeck *et al.*[10]

Angular distributions between 7° and 90° (lab) were obtained for many of the observed states. The integrated 10°–90° (c.m.) yield for each level studied is shown in Table I. At no angle was a deuteron group seen which corresponded to a known $T=1$ level in N^{14}. For the $T=1$ levels, an upper limit to the differential cross section was set at each angle of observation. These upper bounds were integrated from 10° to 90° (c.m.) to obtain an upper bound for the forward-hemisphere yield to compare with that for the observed levels. Table I also gives the dominant shell-model configurations for the N^{14} states calculated by True[11] for two nucleons outside a C^{12} core which is assumed to be inert.

IV. DISCUSSION

From the upper limits obtained for the $T=1$ cross sections, we would like to assign an upper limit to the $T=0$ impurity for each such state. We assume as explained in the Introduction, that the (α,d) reaction conserves isospin at this energy and that the C^{12} ground state is essentially pure $T=0$.

Treating the Coulomb force as a perturbation we can write:

$$\Psi_\alpha' = a\Psi_\alpha + \sum\nolimits_\nu{}' \, b_{\alpha\nu}\Psi_\nu ,$$

where

$$b_{\alpha\nu} = \frac{\langle\Psi_\nu|H_c|\Psi_\alpha\rangle}{E_\alpha - E_\nu} \tag{1}$$

and H_c is the Coulomb potential. The prime on the sum indicates omission of the term with $\alpha=\nu$. For a given $T=1$ state, Ψ_α, only those $T=0$ states, Ψ_ν, with identical J and π will contribute to the impurity, and further, only nearby states are important since the energy denominator reduces contributions from distant states. In principle, several neighboring states can mix. In such a case, the cross section for an (α,d) reaction is not simply related to the degree of mixing.[12] However, if only one $T=0$ impurity is mixed into the predominantly $T=1$ state, the situation is greatly simplified. Any yield observed will be simply proportional to the square of the amplitude of the $T=0$ admixture. We will show that for the states observed in N^{14}, only one $T=0$ state typically mixes into a given $T=1$ state. The argument rests on an assumption that True's wave functions[11] are appropriate and that the inert core consisting of 6 protons and 6 neutrons is spherically symmetric.

TABLE I. Cross section (relative to ground state) integrated from 0°–90° (c.m.) for levels observed in N^{14}. Except as noted, quantum numbers were taken from Lauritsen and Ajzenberg-Selove[a] and shell-model configurations from True.[b]

E_x (MeV)	$\sigma/\sigma_{g.s.}$	J^π	T	Dominant configuration
0	1.00	1^+	0	$p_{1/2}^2$
2.311	<0.0027	0^+	1	$p_{1/2}^2$
3.945	0.31±0.03	1^+	0	$p_{3/2}^{-1}p_{1/2}^{-1}$
4.91	0.162±0.051	$(0)^{-c}$	0	$p_{1/2}s_{1/2}$
5.10	1.32±0.09	2^{-c}	0	$p_{1/2}d_{5/2}$
5.69	0.11±0.05	1^{-c}	0	$p_{1/2}s_{1/2}$
5.83	0.97±0.07	3^{-c}	0	$p_{1/2}d_{5/2}$
6.05	<0.022	...	...	?
6.21	0.24±0.03	1^+	0	$s_{1/2}^2$
6.44	1.15±0.11	3^{+d}	0	$s_{1/2}d_{5/2}$
7.03	0.18±0.07	2^{+c}	0	$p_{3/2}^{-1}p_{1/2}^{-1}$
7.97	0.16±0.05	2^-	0	$p_{1/2}d_{3/2}$
8.06	<0.027	1^-	1	$p_{1/2}s_{1/2}$
8.489	0.53±0.04	$(4^-)^e$	0	$p_{3/2}^{-1}p_{1/2}^2d_{5/2}$?[e]
8.63	<0.018	0^+	1	$s_{1/2}^2$
8.71	...	0^-	1	$p_{1/2}s_{1/2}$
8.91	...	3^-	(1)	$p_{1/2}d_{5/2}$
8.963	3.67±0.08	$(5^+)^e$	0	$d_{5/2}^2$?[e]
8.98	...	2^{+f}	0	?
9.129	0.30±0.07	$(2^-)^e$	0	$p_{3/2}p_{1/2}s_{1/2}$ or $p_{3/2}^{-1}p_{1/2}^2d_{5/2}$
9.17	...	2^+	1	core excited
9.41	0.30±0.06	$2^-, 3^{-f}$	0^g	?
9.51	<0.30	2^-	1	$p_{1/2}d_{5/2}$
9.71	0.18±0.02	1^+	0^g	$d_{5/2}^2$
10.09	0.5±0.04	2^{+h}	0	$s_{1/2}d_{5/2}$?
10.22	...	1^-		?
10.43	<0.03	2^+	1	$s_{1/2}d_{5/2}$
10.85	0.62±0.09	...	0^i	$s_{1/2}d_{5/2}$?
13.05	j			

[a] T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1962), NRC 61-65-6.

[b] Reference 11.

[c] B. G. Harvey, J. Cerny, R. H. Pehl, and E. Rivet, Nucl. Phys. 39, 160 (1962).

[d] E. K. Warburton, J. W. Olness, D. E. Alburger, D. J. Bredin, and F. L. Chase, Jr., Phys. Rev. 134, B338 (1964).

[e] Reference 10.

[f] Reference 14.

[g] Reference 7.

[h] Taken from Ref. 11. There is now some doubt concerning this assignment.

[i] This is apparently the level located at 10.71 MeV in Ref. 7.

[j] Observation of this level indicates it is $T=0$.

Consider, as an example, True's wave functions[11] for the 5.69-, the 8.06-, and the 9.41-MeV levels in N^{14}, each of which has $J^\pi = 1-$.[13] The dominant configuration for each can be written as

$$\Psi = \sum_{m_1 m_2} C(\tfrac{1}{2},j,1;m_1 m_2 M) \times \frac{1}{\sqrt{2}} |\Psi_{p^{1/2}}{}^{m_1}(p)\Psi_j{}^{m_2}(n) \pm \Psi_{p^{1/2}}{}^{m_1}(n)\Psi_j{}^{m_2}(p)| \tag{2}$$

with j being $s_{1/2}$ or $d_{3/2}$ depending on the state considered and the + sign taken for the $T=0$ state. The

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[9] Bernard G. Harvey and Joseph Cerny, Phys. Rev. **120**, 2162 (1960).

[10] R. W. Detenbeck, J. C. Armstrong, A. S. Figuera, and J. B. Marion, Nucl. Phys. **72**, 552 (1965).

[11] William W. True, Phys. Rev. **130**, 1530 (1963).

[12] See, for example, Norman K. Glendenning, Phys. Rev. **137**, B102 (1965).

[13] The 9.41-MeV level has recently (Ref. 14) been shown to have $J^\pi = 2^-$ or 3^-. Thus the example used should be taken as illustrative only.

TABLE II. Fractional impurities of $T=1$ states calculated according to the procedure described in the text. Configurations taken from Table I.

Level (MeV)	Configuration	Dominant impurity	Fractional impurity
2.311	$p_{1/2}{}^2$, 0^+, $T=1$	...	...
8.06	$p_{1/2}s_{1/2}$, 1^-, $T=1$	5.69, 1^-, $T=1$	<0.5
8.63	$s_{1/2}{}^2$, 0^+, $T=1$	...	...
9.51	$p_{1/2}d_{5/2}$, 2^-, $T=1$	5.10, 2^-, $T=0$	<0.15
10.43	$s_{1/2}d_{5/2}$, 2^+, $T=1$	10.09, (2^+), $T=0$	<0.24

functions, $\Psi_j{}^m$, are harmonic-oscillator wave functions with total angular momentum j and magnetic quantum number m. The coefficient of Eq. (1) vanishes for the 9.41-MeV level because of the orthogonality of the $d_{3/2}$ and $s_{1/2}$ wave functions as long as the perturbing potential is spherically symmetric. The potential which mixes isospin states is the Coulomb potential and is spherically symmetric for a spherically symmetric core. Departure from spherical symmetry will introduce some $p_{1/2}d_{3/2}$ configuration, but certainly the $p_{1/2}s_{1/2}$ configuration will give the largest contribution to the $T=0$ impurity.

If isospin mixing is small, the ratio of the cross section of the $T=1$ state to that of the $T=0$ state which is its chief impurity will be the square of the coefficient of that impurity in the $T=1$ state, since, for small mixing, the coefficient a of Eq. (1) will approximately equal unity. Since no known $T=1$ states were observed, only upper bounds can be put on the impurities in these levels. The procedure outlined above was followed for each known $T=1$ level which could have been observed, and the results are presented in Table II.

Some of the dominant impurities listed in Table II may well be in error. The 9.41-MeV level has recently been shown[14] to have $J^\pi=2^-$ or 3^- and could, because of its proximity, mix significantly with the 9.51-MeV level. The 10.43-MeV level is by no means known to be a 2^+ level. Further, if it is, the 2^+ state at 9.17 MeV may appreciably admix since it may contain some $s_{1/2}d_{5/2}$ component.[15] A more trustworthy estimate of chief admixtures will have to await more detailed spectroscopic information for N^{14}.

From Table I it can be seen that the upper limits on the cross sections for formation of $T=1$ states are quite small compared to the ground-state cross section. However, as shown in Table II, the upper limits that could be set for the amplitude of the $T=0$ impurities were quite large—from 15 to 50%. In order to compare these experimental limits with a theoretical value, we calculated, as an example, the mixing coefficient of Eq. (1) for the contamination of the 8.06-MeV $T=1$ level by the 5.69-MeV $T=0$ level. The Coulomb potential was taken to be that due to a spherically symmetric C^{12} core. A uniform-charge distribution with a radius of either 2.65 or 3.37 F was assumed, and the dominant term in the wave functions[11] for the 8.06-MeV level and the 5.69-MeV level was used. The harmonic-oscillator well parameter was $\alpha^2=0.3\ \mathrm{F}^{-2}$. The coefficient thus obtained was between 0.06 and 0.08, depending on the choice of radius for the charge distribution.

The above result follows from assuming the principal configuration according to True's assignment. Use of his configuration-mixed wave functions would add about 10% of the dominant configuration of the 9.41-MeV state to the 5.69-MeV state. The use of more realistic wave functions would probably not greatly affect these estimates. The important point is that isospin impurities of 5–10% can easily occur in the excited states of N^{14}. The impurities calculated arise entirely from the Coulomb interaction between the C^{12} core and the last pair of nucleons.

V. CONCLUSIONS

We have set experimental upper limits on the extent of isospin mixing in excited states of N^{14}. Some of these upper limits are close to predictions of isospin mixing based on simple wave functions. Since we have not considered a true violation of the $\Delta T=0$ selection rule due to a charge-dependent part of the interaction responsible for the (α,d) reaction, it would seem that such an effect must be small.

The large difference in cross sections observed for $T=0$ and $T=1$ states makes the (α,d) reaction in this energy range a useful method of assigning and verifying isospin assignments.

ACKNOWLEDGMENTS

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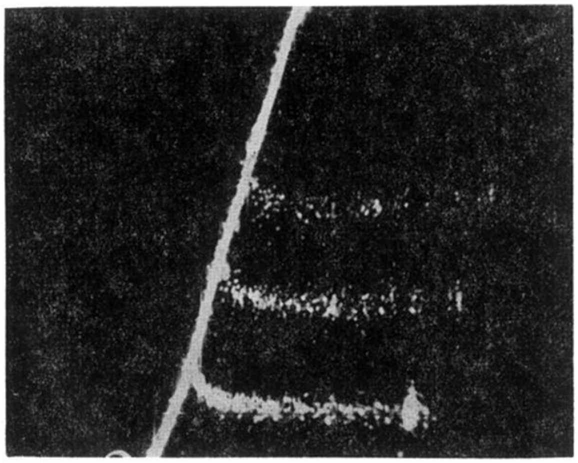
[14] V. A. Latorre and J. C. Armstrong, Phys. Rev. 144, 891 (1966).

[15] E. K. Warburton and W. T. Pinkston, Phys. Rev. 118, 733 (1960).



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