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Inelastic electron scattering from ^{14}N at 180°

N. Ensslin
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544

L. W. Fagg
*Catholic University of America, Washington, D.C. 20064
and Naval Research Laboratory, Washington, D.C. 20375*

R. A. Lindgren
University of Massachusetts, Amherst, Massachusetts 01003

W. L. Bendel and E. C. Jones, Jr.
Naval Research Laboratory, Washington, D.C. 20375
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Inelastic electron scattering from ^{14}N at 180° has been studied at incident energies of 40.6, 50.6, and 60.2 MeV. Transitions to levels at 2.31, 9.17, and 10.43 MeV excitation energy were observed to be predominantly $M1$. The transition to the level at 16.11 MeV probably contains some $M2$ strength, and transitions to levels at 12.54, 13.27, and 13.76 appear to exhibit some $M1$ strength. Data on the 2.313 MeV transition, combined with earlier experiments, bring the observed reduced transition width into agreement with resonance fluorescence techniques. Transition widths for the other levels with reasonably certain multipolarities are also given.

[NUCLEAR REACTIONS ^{14}N(e,e'), $\theta=180°$, $E=40.6$, 50.6, 60.2 MeV; measured $\sigma(E)$; deduced Γ_0, multipolarities for transitions excited.]

I. INTRODUCTION

This experiment is the last of a series[1] on p- and sd-shell nuclei of mass $4N$ or $4N+2$ that have been carried out at the NRL 180° electron scattering facility. These experiments have shown strong concentrations of magnetic dipole strength in the self-conjugate nuclei of these shells. They have confirmed the predictions of Morpurgo[2] and Kurath[3] that the magnetic dipole strength should be concentrated into a few low-lying $T=1$ levels. Although these statements have been found to be generally true for ^{14}N, one of the purposes of this experiment was to locate the remaining $M1$ transition strength aside from the two well-known[4] strong transitions at 9.17 and 10.43 MeV.

However, of particular interest in this work is the 0^+ $T=1$ level at 2.313 MeV, which is the isobaric analog of the ^{14}C ground state. Because of the anomalously slow β decay of ^{14}C to ^{14}N, the mass-14 nuclei have provided an important test for the presence of tensor forces. Also, a recent study by Goulard *et al.*[5] of mass-14 nuclei concludes that meson-exchange currents may be as large as the contribution of the nucleons-only impulse approximation.

Bishop, Bernheim, and Kossanyi-Demay[6] have pointed out that the strength of the tensor force can be determined from the electron scattering cross section for the 2.313 state. A more recent experiment[7] performed, using the National Bureau of Standards (NBS) accelerator, measured this cross section and set constraints on the ^{14}N and ^{14}C ground-state wave functions. However, it was difficult to extrapolate the cross section to zero momentum transfer, and the measured lifetime of the state was not in agreement with γ-decay measurements.[8] Since this excitation is favored at back angles and since the lifetime is best determined from low energy cross sections, the NRL 180° scattering facility was well suited to make this measurement. The present experiment therefore provided three new low momentum transfer values for the form factor curve for this transition.

The next section outlines the experimental conditions and data analysis techniques, and describes the calculations by which our data is compared with theory.[9,10] The third section presents and discusses the experimental results.

II. EXPERIMENTAL APPARATUS AND DATA REDUCTION

Data for this experiment were collected by bombarding a ^{14}N gas target with 40.6-, 50.6-, and 60.2-MeV electrons from the NRL 65-MeV Linac. The gas target cell was a 5.08-cm long cylinder with 6-μm Havar end windows. It was filled with 9 atm of ^{14}N at dry ice temperature (−78°C), or 82 mg/cm^2 of ^{14}N. For normalization, the gas cell was filled with an equal number of hydrogen molecules and data were collected on the hydrogen elastic peak. The overall energy resolution due to the electron beam and Landau straggling in the target was typically 0.7%. The 180° electron scattering facility[1] and the essential designs upon which our scintillation counter detection system and refrigerated gas target system are based have been described in earlier publications.[11,12]

The cross sections for all transitions observed in ^{14}N were determined relative to the Rosenbluth cross section for the proton. The proton form factor was represented by

$$F_{\text{charge}} = F_{\text{magnetic}} = \exp(-q^2 a_p^2/4), \qquad (1)$$

where q = momentum transfer and $a_p^2 = 0.427$ fm^2. At low momentum transfer this form factor is in agreement with experiment.[13] Peak areas were corrected for small variations from gas target cell pressure as measured with the accelerator beam off. These variations (1% − 2%) represented the loss of gas from the sealed target chamber during the course of the experiment. The peak areas were then corrected[1] for ionization, bremsstrahlung, and Schwinger radiation effects.

The uncertainties given for the measured cross sections include counting statistics for ^{14}N and ^{1}H, peak shape uncertainties for unresolved transitions, and base line uncertainty. The last-mentioned contribution was usually the largest, since the baseline was estimated from plots of the spectra.

The generalized Helm model[10] was usually used to determine tentative multipolarity assignments by comparing calculated cross section curves for various multipolarities with the experimental cross sections. The parameters used were

$$R = \bar{R} = 2.80 \text{ fm}, \ \gamma_{L_-} = 1, \ \gamma_{L_+} = \gamma_{L_0} = 0,$$

$$\beta_L = 1, \ \text{and } g = \bar{g} = 0.77$$

(see Ref. 10). The multipolarity selection was limited to $E1$, $M1$, $E2$, and $M2$, since multipolarities of $L > 2$ have virtually never been observed at our incident energies.

To determine values for the magnetic dipole ground-state transition width, Γ_0 ($M1$), as well as to confirm the tentative $M1$ assignments indicated by the generalized Helm model, our data were fitted with a distorted-wave Born approximation (DWBA) calculation using shell-model harmonic-oscillator wave functions[9] (except for the 2.31-MeV transition). A single-particle proton and neutron transition from a $p_{3/2}$ to a $p_{1/2}$ orbit was assumed and an oscillator parameter value of 1.73 fm was used to calculate the $M1$ cross sections. No s-d shell configurations were included. In each case the magnitude of the experimental cross section curve was compared with that of the appropriate theoretically calculated

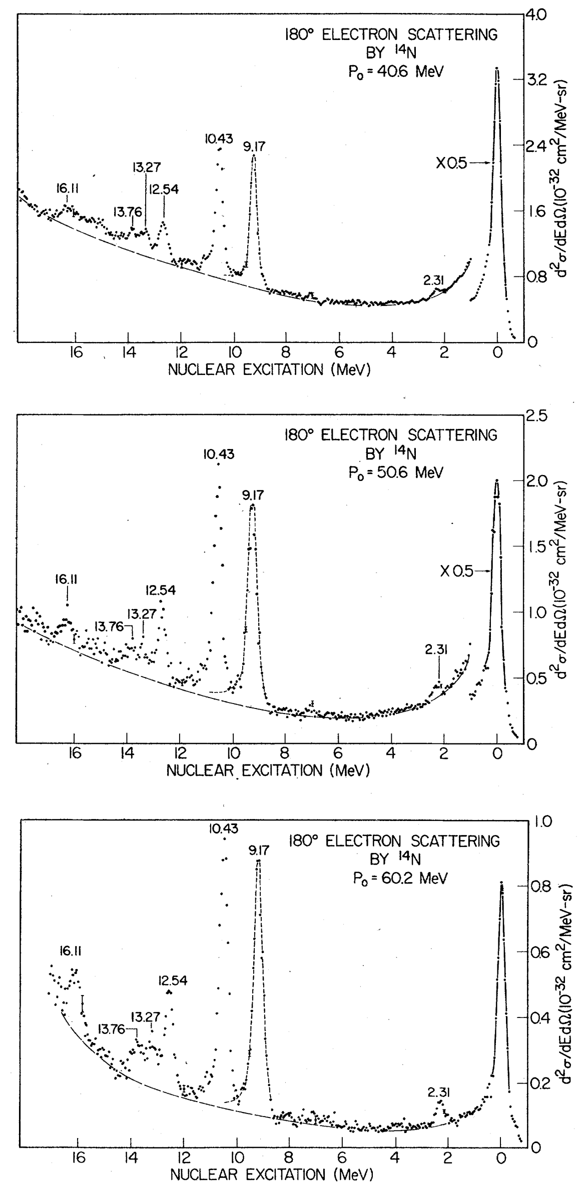

FIG. 1. Spectra of (a) 40.6-, (b) 50.6-, and (c) 60.17-MeV electrons scattered from ^{14}N at 180° covering the excitation region from 0 to about 16.5 MeV. The baseline shown for each spectrum, indicated by dashed curves at 9.17 MeV show the approximate curve shapes that were fitted to the peaks in the data. An indication of the statistical uncertainties involved is given by the error bars on selected points of the spectra.

curve to obtain the scale factor used to determine a value of Γ_0.

However, in the case of the 2.31 MeV transition, since data from other experiments were used in our final determination, Γ_0 was obtained by directly extrapolating the form factor curve to $q=\omega$. The value of $B(M1, \omega)$ obtained from this extrapolation was in turn used to determine Γ_0.

III. RESULTS AND DISCUSSION

The spectra resulting from 40.6, 50.6, and 60.17 MeV incident electrons scattered at 180° from ^{14}N and covering an excitation region from 0 to approximately 16.5 MeV is presented in Figs. 1(a), 1(b), and 1(c), respectively. In all three spectra inelastic peaks are observed at 2.31, 9.17, 10.43, 12.54, 13.27, 13.76, and 16.11 MeV, with uncertainties of about 0.1 MeV. Known from previous work are the transitions at 2.31 MeV (0^+),[6,7] the strong doublet at about 10 MeV ($2^+, 2^+$),[4] and some strength[14] at 13.75 MeV. (The value of $\Gamma_0 = 4$ meV reported in Ref. 14 for this transition constitutes only a small part of the intensity observed in our work.) However, the peaks at 12.54, 13.27, and 16.11 MeV, to our knowledge, have not been reported using electron scattering.

The experimentally determined cross section values for the observed transitions are presented in Table I. Only those transitions were treated which has a measurable intensity at all three incident energies. To determine tentative multipolarity assignments, these cross section values were compared with appropriately normalized generalized Helm model cross section curves for the four possible multipolarities mentioned in the previous section.

These comparisons indicate rather clearly that the known 9.17- and 10.43-MeV transitions can be assigned an $M1$ multipolarity. The 2.31-MeV transition is also known to have and $M1$ assignment. The $M1$ character of the 12.54-, 13.27-, and 13.76-MeV transitions is in doubt with $E2$, $E2$ or $M2$, and $E1$, respectively, being alternative possibilities. However, the experimental points do favor the choice of $M1$ for the 12.54- and 13.76-

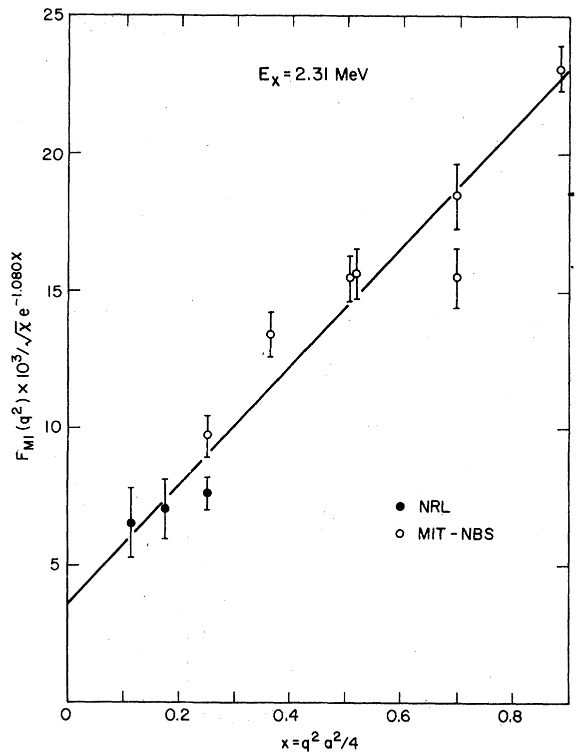

FIG. 2. Plot of $F_{M1}(q^2) \times 10^3/\sqrt{x}\, e^{-1.080x}$ vs $x = q^2a^2/4$ for the 2.31-MeV level, where $e^{-1.080x}$ is the analytical approximation to the hydrogen form factor given in the denominator of the left-hand side Eq. (2). The combination of NRL and MIT-NBS points gives an accurate extrapolation to $x=0$.

TABLE I. Values of cross sections for excitation of the nuclear transitions studied at the three incident energies of 40.6, 50.6, and 60.17 MeV.

Excitation energy (MeV)	Cross section (10^{-32} cm^2/sr) 40.6 MeV	50.6 MeV	60.17 MeV
2.31	0.064 ± 0.026	0.064 ± 0.020	0.062 ± 0.010
9.17	1.319 ± 0.077	1.167 ± 0.050	0.932 ± 0.035
10.43	1.317 ± 0.107	1.148 ± 0.079	0.850 ± 0.059
12.54	0.344 ± 0.078	0.354 ± 0.034	0.370 ± 0.040
13.27	0.114 ± 0.081	0.098 ± 0.030	0.133 ± 0.037
13.76	0.114 ± 0.090	0.087 ± 0.029	0.078 ± 0.036
16.11	0.101 ± 0.073	0.150 ± 0.038	0.168 ± 0.036

TABLE II. Multipolarities and ground-state transition widths for states in ^{14}N electroexcited at 180°.

Excitation energy (MeV)	J^π, T [a]	Multipolarity	Γ_0 (eV) This work	Γ_0 (eV) Other work
2.31	0^+, 1	$M1$	$(6.1\pm 2.0)\times 10^{-3}$	$(6.2\pm 0.6)\times 10^{-3}$ [b] $(7.6\pm 1.1)\times 10^{-3}$ [c]
9.17	2^+, 1	$M1$	6.6 ± 1.3	7.7 ± 0.9
10.43	2^+, 1	$M1$	9.6 ± 1.9	12.1 ± 1.5
12.54	d	$(M1, E2)$	$[(14.7\pm 3.2)/s]$ [f]	
13.27	d	$(M1, M2, E2)$		
13.76	e	$(M1, E1)$		
16.11	d	$(M2)$		

[a] Spins and parities from Ref. 19.
[b] Reference 8 and Ref. 15 but with uncertainty, $\pm 0.9\times 10^{-3}$.
[c] Reference 14.
[d] $J=0,1,2,3$.
[e] $J=0,1,2$.
[f] Where $s=2J+1$.

MeV transitions. The 16.11-MeV transition may have an $M2$ multipolarity. The determination of level spins and parities from these multipolarity assignments is, of course, complicated by the fact that the ^{14}N ground state spin is 1^+.

Following is a discussion of each of the observed transitions with particular emphasis being placed on that at 2.31 MeV.

2.31 MeV (0^+,1)

Our experiment in conjunction with that of earlier work makes possible a useful measurement of the $M1$ transition strength for this transition. The previous electron scattering experiments[6,7] interpreted the excitation of this level as a pure $M1$ transition within the $1p$ shell. The form factor for such a transition is[13]

$$\frac{F_{M1}(q^2)}{\sqrt{x e^{-(x+d)}}}=0.0146[A_1+\tfrac{2}{3}(B_1-A_1)x], \qquad (2)$$

where a = harmonic oscillator parameter (1.68 fm), $x=q^2a^2/4$, $d=q^2[a_p{}^2-(a^2/A)]/4$, $a_p{}^2=\frac{2}{3}$ (rms proton radius)$^2=0.427$ fm^2, $A=14$, and the coefficient 0.0146 is derived from kinematic factors. In Eq. (2) the form factor has been linearized, showing explicitly that the q intercept depends solely on the angular coefficient A_1, while the slope depends on (B_1-A_1). Figure 2 illustrates the results of the present experiment and the earlier NBS experiment displayed in this manner.

As can be seen from Fig. 2, the present data provide three new measurements of the form factor at low q. When incorporated with the earlier data, to give a reasonable range for a least-squares fit, the data lead to a significantly lower value for the reduced transition probability, $B(M1,\omega)\uparrow=(1.56\pm 0.51)\times 10^{-4}e^2$ fm^2 than reported in Ref. 7. The new result, equivalent to $\Gamma_0=6.1\pm 2.0$ meV, as shown in Table II, brings the electron scattering results for this transition into agreement with γ-decay measurements.

The most recent such results are those of Rasmussen and Metzger, 6.2 ± 0.6 MeV, via ^{14}N(γ,γ) resonant scattering of bremsstrahlung,[8] and those of Bister, Anttila, and Keinonen, 6.2 ± 0.9 meV, via ^{13}C(p,γ) Doppler shift attenuation.[15] The larger uncertainties for the present experiment again point to the difficulty of the electron scattering measurement and extrapolation to the photon point. However, as can be seen in Table II, it is encouraging that the present experiment, the new measurement by Frey *et al.*,[14] and the γ-decay results are all consistent within their uncertainties.

9.17 (2^+,1) and 10.43 (2^+,1) MeV

These two strong transitions have been reported as $M1$ by several workers,[4,16-18] and, as mentioned earlier, the experimental cross section values match the $M1$ Helm calculation quite well. As shown in Table II, our values of 6.6 ± 1.3 and 9.6 ± 1.9 eV for the 9.17- and 10.43-MeV transitions, respectively, are somewhat lower than the values of 7.7 ± 0.9 and 12.1 ± 1.5 eV reported by Clerc and Kuphal.[4] However, there is still agreement within the uncertainties reported.

12.54 MeV

There appears to be some ambiguity between an $M1$ and an $E2$ multipolarity assignment for the

12.54-MeV transition. A value of $\Gamma_0(E2)$ was estimated using the generalized Helm model. That is, a theoretical value was calculated using this model and then scaled in the ratio of the experimental to Helm model cross section. The resulting value was unreasonably high by about two orders of magnitude. Therefore, although some $E2$ strength may indeed by present, the transition is judged to have a strong $M1$ component. Other unresolved contributions may be combining to cause the ambiguity. However, a tentative value to $\Gamma_0(M1)$ is given in Table II. It might be noted that, using other nuclear reactions, levels have been reported[19] at 12.47, 12.497, and 12.594 MeV, but only the last one is given an assignment, namely 3^+.

13 to 16 MeV region

Since there is an ambiguity ($M1$, $M2$, or $E2$) in the multipolarity assignment for the 13.27 MeV transition, no value of Γ_0 was calculated for this transition. Using other nuclear reactions, levels are reported[19] at 13.243 MeV, 2^-, and 13.30 MeV (2^-) or 1. There is the distinct possibility that an unresolved combination of these two levels was excited in our work.

Although the 13.76 MeV transition appears to be $M1$ from generalized Helm comparisons, it is felt that further evidence may be needed to claim that all or most of the strength is $M1$. Recent electron scattering results[14] at more forward angles and much higher resolution report a value of $\Gamma_0(M1) = 4 \pm 1$ MeV for a transition at 13.75 MeV. With the ability to detect such a small amount of $M1$ strength, more strength in this region would undoubtedly have been reported by Frey *et al.*, if it were observed. A 1^+ level at 13.71 MeV has been observed using the (π^-, γ) reaction[20] as well as other reactions.[19] Again using other nuclear reactions, levels at 13.714 MeV, 2, 3^+, and at 13.72 MeV have been reported.

Comparison with the generalized Helm model indicates that the 16.11 MeV transition probably contains considerable $M2$ strength. Due to background uncertainties in this high excitation region an attempt was not made to determine a value of $\Gamma_0(M2)$ for this transition. Other nuclear reactions[19] indicate the presence of a level at 16.21 MeV.

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