PHYSICAL REVIEW C VOLUME 23, NUMBER 4 APRIL 1981

Magnetization distribution of ^{51}V studied by elastic electron scattering through 180°

K. Arita
Department of Physics, College of Science and Engineering, Aoyama Gakuin University, Tokyo, Japan

A. Enomoto, S. Oguro, Y. Mizuno, T. Nakazato, S. Ohsawa, T. Saito, T. Terasawa, and Y. Torizuka
Laboratory of Nuclear Science, Tohoku University, Sendai, Japan

(Received 18 August 1980)

Scattering from the $M3$, $M5$, and $M7$ moments of the ground state of ^{51}V has been observed by a 180° scattering experiment of electrons. The observed $M3$ and $M5$ form factors are much smaller than those expected from the single-particle model. The features are reasonably reproduced by the calculation which takes into account the effect of the configuration mixing including the polarization of the ^{48}Ca core.

[NUCLEAR REACTIONS $^{51}\mathrm{V}(e,e)$ $E=80.84$–229 MeV, $\theta=180°$, measured $\sigma(E,180°)$; deduced magnetic moment form factor.]

I. INTRODUCTION

Backward scattering of electrons provides detailed information on the spatial distribution of the nuclear magnetic moments. Stimulated by theoretical studies,[1,2] many electron scattering experiments have been performed recently to study high magnetic multipole moments of medium and heavy nuclei in the region of rather high momentum transfer q through scattering angles of around 150° (Refs. 3–7). It is, however, very difficult to extend the investigation to a lower-multipole moment, e.g., $M3$, by this method of experiment since charge scattering increases rapidly with lower momentum transfer and it is difficult to separate the magnetic and charge scattering contributions. Actually, there were few observations of magnetic scattering from nuclei heavier than ^{40}Ca in the region $1\ \mathrm{fm}^{-1} < q < 1.8\ \mathrm{fm}^{-1}$ until the recent experiment[8] on ^{93}Nb. In this note we report that using a 180° scattering apparatus for medium energy electrons, we observed the magnetic scattering over a wide range of transferred momenta so that we can extract information on all multipole moments of the ground state magnetization distribution of the single-closed nucleus ^{51}V.

II. EXPERIMENTAL METHOD AND RESULTS

The experiment was performed using the 180° scattering apparatus at Laboratory of Nuclear Science Tohoku University[9] (see Fig. 1). The electrons from the electron linear accelerator are directed to the 180° scattering apparatus within a precision of ±0.05° and ±1.5 mm from the center by two sets of the steering coils and the beam position monitor targets. The electron beam is deflected by 15° through a circular magnet 250 mm in diameter with a 65 mm gap in front of the target, and backward scattered electrons are also deflected by the same magnet and reach the high-resolution 350 MeV/c double focusing magnetic spectrometer, whose solid angle in this experiment was about 2.4 msr. This spectrometer analyzes the electron momenta and the electrons were detected by the counter telescope made of three solid state detectors.

The electrons passing through the target go through a dipole magnet (ditching magnet) which deflects the outgoing electron beam in parallel to the incident beam line. So the final line is apart from the incident beam line by 259 mm. Then the damped beam is monitored by a secondary emission monitor.

A ^{51}V foil of 33 mg/cm^2 thick was used as the target. Elastically scattered electrons were measured in the range of incident momenta from 80.84 to 229 MeV/c. The average incident beam currents were from 10 to 30 μA.

Inelastic scattering from the 15.1 MeV 1^+ level of ^{12}C and elastic scattering from ^{9}Be were also

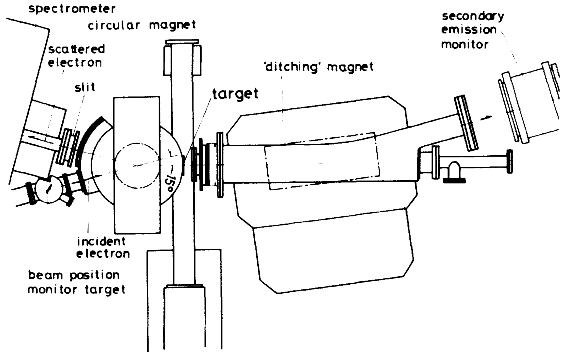

FIG. 1. The 180° scattering apparatus at Laboratory of Nuclear Science Tohoku University.

measured to determine the effective solid angles using the previously measured cross sections[10-12] of ^{12}C and ^{9}Be. The effective solid angles obtained from ^{12}C and ^{9}Be were consistent at all incident energies.

Elastic scattering from ^{52}Cr which was 48 mg/cm^2 thick was also measured to estimate the charge scattering contribution of ^{51}V, resulting from its finite solid angle. The charge scattering contribution was found to be negligible in the incident momentum higher than 140 MeV/c. One of the spectra after the relative efficiency correction for the solid state detectors is shown in Fig. 2. All cross sections were corrected for radiative effects.

For interpretation in terms of the plane wave Born approximation (PWBA), we introduce a reduced magnetic cross section $(d\sigma/d\Omega)^{\text{mag}}_{\text{red}} = \eta(d\sigma/d\Omega)^{\text{mag}}/[\sigma_M(\frac{1}{2}+\tan^2\theta/2)]$ as a function of effective momentum transfer $q_{\text{eff}} = q(1+fZ\alpha/RE)$, where σ_M is the Mott cross section for charge Z, $\sigma_M = [Z\alpha\cos(\theta/2)/2E\sin^2(\theta/2)]^2$, and η is the recoil factor $\eta = 1+(2E/M_Tc^2)\sin^2(\theta/2)$. The parameter $f = 1.1$ in q_{eff} is determined from comparison between the distorted wave Born approximation (DWBA) and PWBA form factors. The experimental data are summarized in Table I. The data of the reduced magnetic cross section from this experiment are also illustrated in Fig. 3 together with those of Amsterdam[13] and those from the 155° experiment of Saclay[7] to be compared with the single-particle form factors of an $f_{7/2}$ proton (solid line). The form factors of each multipole are also shown in this figure. A harmonic oscillator radial wave function is adopted with the size parameter $b = 1.85$ fm and the center-of-mass and nucleon form factor corrections are taken into account by multiplying by factors $\exp[(1/A)(bq/2)^2]$ and $1/(1+q^2/18.23)^2$, respectively. As can be seen in Fig. 3, observation of all multipole form factors of the ground state of ^{51}V from $M1$ to $ML_{\text{max}} = M7$ has been attained. The general feature of the total form factor, a large $M1$ diffraction maximum and a plateau followed by a sharp drop, is reproduced by the single-particle model. Quantitatively, however, the observed form factor is smaller than the calculated one in the range 1 fm$^{-1} < q < 2$ fm^{-1} where the $M3$ and $M5$ form factors dominate. The suppression of the $M3$ form factor has also been observed experimentally in nuclei ^{17}O and ^{25}Mg (Refs. 8, 14). In the range $q > 2$ fm^{-1}, the agreements between calculations and experiments are quite good.

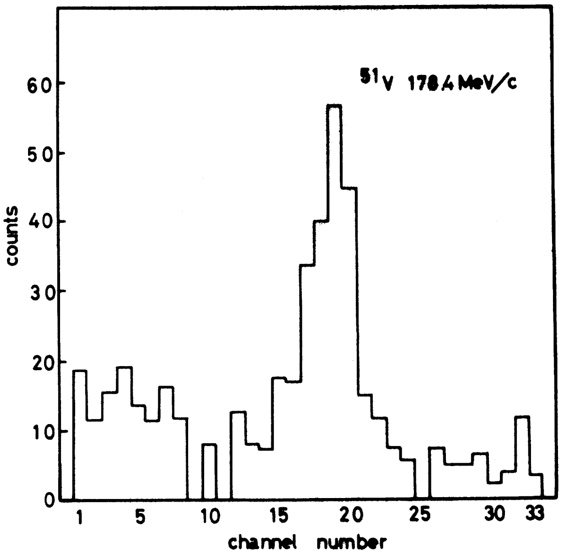

FIG. 2. One of the spectra after the relative efficiency correction for the solid state detectors.

III. COMPARISON WITH THEORY AND CONCLUSIONS

The importance of the core polarization effect on magnetic form factors has been shown by some

TABLE I. Total cross section σ^{tot} measured at the incident momentum p_0 and scattering angle 180°, charge cross section σ^{ch}, magnetic cross section $\sigma^{\text{mag}} = \sigma^{\text{tot}} - \sigma^{\text{ch}}$, and reduced magnetic cross section $\sigma^{\text{mag}}_{\text{red}}$.

p_0 (MeV/c)	q_{eff} (fm^{-1})	$10^{33}\ \sigma^{\text{tot}}$ (cm^2/sr)	$10^{34}\ \sigma^{\text{ch}}$ (cm^2/sr)	$10^{34}\ \sigma^{\text{mag}}$ (cm^2/sr)	$10^5\ \sigma^{\text{mag}}_{\text{red}}$
80.84	0.90	6.08 ± 0.98	1.41 ± 0.41	4.67 ± 1.06	1.12 ± 0.25
97	1.06	2.97 ± 0.52	0.20 ± 0.08	2.77 ± 0.53	0.944 ± 0.203
112	1.21	2.66 ± 0.31	0.26 ± 0.08	2.40 ± 0.32	1.09 ± 0.15
140	1.49	1.64 ± 0.19		1.64 ± 0.19	1.17 ± 0.14
160	1.69	1.37 ± 0.15		1.37 ± 0.15	1.28 ± 0.14
178.4	1.88	1.36 ± 0.10		1.36 ± 0.10	1.58 ± 0.12
215	2.24	0.485 ± 0.047		0.485 ± 0.047	0.821 ± 0.080
229	2.38	0.257 ± 0.044		0.257 ± 0.044	0.494 ± 0.085

authors.[4,15-17] The first-order perturbation on the unperturbed wave function $|(j=f_{7/2})^3 v=1, J=j\rangle$ causes not only the excitation of the ^{48}Ca core but the excitation of a valence proton from the j orbit which affects the form factors by blocking the excitation to the j orbit. The matrix element of an ML scattering operator $\hat{T}(ML)$ in this framework is given by[18]

$$\begin{aligned}\langle {}^{51}\text{V g.s.}\,||\hat{T}(ML)||\,{}^{51}\text{V g.s.}\rangle &= (j\,||\hat{T}(ML)||\,j) + 2\sum_{ph}\langle jj|V'|ph\rangle_L (p\,||\hat{T}(ML)||\,h)/(\epsilon_h-\epsilon_p)\\ &\quad +\tfrac{1}{3}\times 2\sum_{p\neq 1}\langle jj|\,V'|pj\rangle_L (p\,||\hat{T}(ML)||\,j)/(\epsilon_j-\epsilon_p) - \tfrac{1}{3}\times 2\sum_{h}\langle jj|V'|jh\rangle_L\\ &\quad \times (j\,||\hat{T}(ML)||\,h)/(\epsilon_h-\epsilon_j)\,,\end{aligned}$$

where p and h are single-particle and single-hole orbits associated with the intermediate states and the empirical values are adopted for the single-particle energies ϵ. The sums run over all possible one-particle excitation states up to $(L+1)\hbar\omega$. The bracket $\langle|V'|\rangle$ is a matrix element of particle-hole type, $\langle ab|V'|cd\rangle_L = -\sum_J (2J+1)W(abdc;LJ)\langle da|V|bc\rangle_J$, and for the perturbation interaction V, a central force of Gaussian shape $V_0\exp[-(r/r_0)^2]$ with the range parameter $\lambda = r_0/(\sqrt{2}\,b) = 0.6$ and the strength $V_0 = -40$ MeV was adopted. As in Ref. 4, the Serber and Rosenfeld mixtures are considered to find the exchange character dependence of the effect.

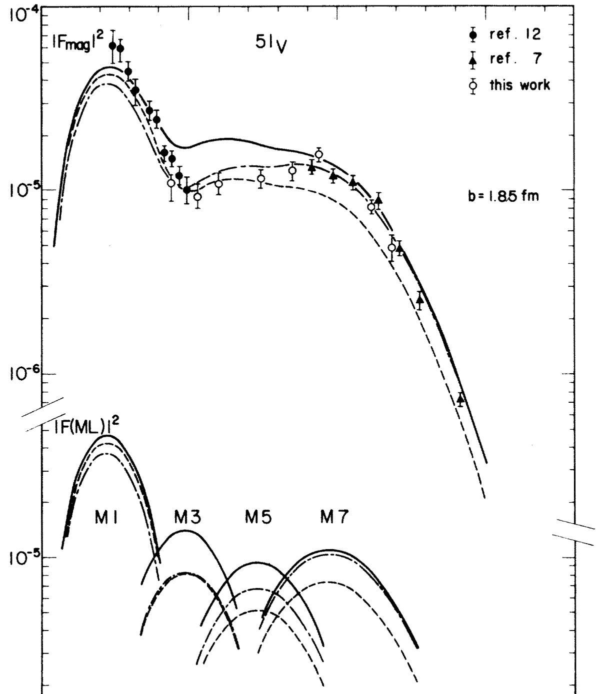

FIG. 3. Experimental and calculated magnetic form factor squared (reduced cross sections). The single-particle form factor is shown by a solid line. The dashed and dash-dotted lines represent the calculated form factors including the effects of configuration mixing with the Serber and Rosenfeld forces, respectively. Squared form factor of each multipole are shown in the lower half with the same convention.

The results of the calculations including the first-order effect are shown along with the experimental data in Fig. 3. The intermediate-multipole form factors $M3$ and $M5$ are significantly suppressed by the effect with both the Serber and Rosenfeld forces as noted previously.[15-17] On the other hand, the effect on the $ML_{\max}$ form factor is sensitive to the type of the exchange character. The Rosenfeld force is insensitive to the $M7$ form factor, while it is considerably reduced by the Serber force which works equally on singlet and triplet states. This tendency is common to the calculated results on other nuclei,[15,16] e.g., ^{209}Bi and ^{87}Sr. The experimental data agree better with the calculation with the Rosenfeld force. A definite conclusion concerning the exchange character of the perturbation interaction, however, should be drawn carefully, since Suzuki, Hyuga, and Arima[19] and Dubach[20] pointed out the importance of the meson exchange current effect in this region of q.

In Fig. 3, the agreement between theory and experiment in the region of the $M1$ form factor becomes worse when the effect of configuration mixing is included. However the magnetic dipole moment of ^{51}V observed by NMR[21] is $\mu_{\text{expt}} = 5.148\ \mu_N$, which is smaller than the Schmidt value $\mu_{\text{Sch}} = 5.793\ \mu_N$. Thus, it is reasonable to expect that the $M1$ form factor may be reduced approximately by a factor $(\mu_{\text{expt}}/\mu_{\text{Sch}})^2 = 0.8$ from the single-particle form factor. Really, the calculation mentioned above predicts the smaller values of $M1$ moment, $\mu_{\text{calc}} = 5.575$ and $5.289\ \mu_N$, respectively, with the Serber and Rosenfeld forces and the maximum of the $M1$ form factor is lowered as seen in Fig. 3. The data in Ref. 13, however, show the tendency opposed to the expectation. Possible interpretation would be given in terms of the exceptionally complicated shape of the magnetization distribution or extremely enhanced $[\sigma \times Y^{(2)}]^{(1)}$ distribution, both of which are unlikely to occur in the nucleus ^{51}V with relatively simple structure.

In conclusion, the $M3$ and $M5$ form factors, as well as $M7$, have been observed without larger disturbance of charge scattering by means of a 180° scattering experiment. The observed suppression of the $M3$ and $M5$ form factors has been well interpreted in terms of the first-order configuration mixing applied to the simple j-j coupling wave function.

---

[1] T. W. Donnelly and J. D. Walecka, Nucl. Phys. A201, 81 (1973).

[2] J. F. Prewitt and L. E. Wright, Phys. Rev. C 9, 2033 (1974).

[3] I. C. Nascimento, J. R. Moreira, J. Goldemberg, S. Fukuda, T. Terasawa, T. Saito, K. Hosoyama, and Y. Torizuka, Phys. Lett. 53B, 168 (1974).

[4] J. R. Moreira, I. C. Nascimento, K. Arita, J. Friedrich, A. Enomoto, T. Terasawa, and Y. Torizuka, Phys. Rev. Lett. 36, 566 (1976).

[5] P. K. A. de Witt Huberts, J. B. Bellicard, B. Frois, M. Huet, Ph. Leconte, A. Nakada, Phan Xuan Hô, S. Turck, L. Lapikás, H. de Vries, and I. Sick, Phys. Lett. 60B, 157 (1976).

[6] I. Sick, J. B. Bellicard, J. M. Cavedon, B. Frois, M. Huet, Ph. Leconte, A. Nakada, Phan Xuan Hô, S. Platchkov, P. K. A. de Witt Huberts, and L. Lapikás, Phys. Rev. Lett. 38, 1259 (1977).

[7] P. K. A. de Witt Huberts, L. Lapikás, H. de Vries, J. B. Bellicard, J. M. Cavedon, B. Frois, M. Huet, Ph. Leconte, A. Nakada, Phan Xuan Hô, S. K. Platchkov, and I. Sick, Phys. Lett. 71B, 317 (1977).

[8] R. C. York and G. A. Peterson, Phys. Rev. 19, 574 (1979).

[9] A. Enomoto, S. Oguro, Y. Mizuno, T. Nakazato, S. Ohsawa, H. Miura, A. Nakada, T. Saito, T. Terasawa, K. Nakahara, Y. Torizuka, Y. Kawazoe, A. Hotta, and K. Arita, Proceedings of the Sendai Conference on Electro- and Photo-Excitations, Sendai, Japan, 1977, Tohoku University Laboratory of Nuclear Science Research Report, Supplement, 1977 (unpublished), Vol. 10, p. 173.

[10] R. E. Rand, R. Frosch, and M. R. Yearian, Phys. Rev. 144, 859 (1966).

[11] A. Yamaguchi, T. Terasawa, K. Nakahara, and Y. Torizuka, Phys. Rev. C 3, 1750 (1971).

[12] T. W. Donnelly, J. D. Walecka, I. Sick, and E. B. Hughes, Phys. Rev. Lett. 21, 1196 (1968).

[13] H. de Vries, Ph.D. thesis, University of Amsterdam, 1973 (unpublished).

[14] M. V. Hynes, H. Miska, B. Norum, W. Bertozzi, S. S. Kowalski, F. N. Rad, C. P. Sargent, T. Sasanuma, W. Turchinetz, and B. L. Berman, Phys. Rev. Lett. 42, 1444 (1979).

[15] K. Arita, Genshikaku Kenkyu 22, 119 (1977).

[16] K. Arita, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, 1977* (International Academic, Tokyo, 1977), p. 252.

[17] A. Arima, Y. Horikawa, H. Hyuga, and T. Suzuki, Phys. Rev. Lett. 40, 1001 (1978).

[18] H. Noya, A. Arima, and H. Horie, Prog. Theor. Phys. Suppl. 8, 33 (1958).

[19] T. Suzuki, H. Hyuga, and A. Arima, in *Proceedings of the International Conference on Nuclear Physics with Electromagnetic Interactions, Mainz, 1979* (Springer, Berlin, 1979); and private communication.

[20] J. Dubach, quoted by J. W. Negele, Proceedings of the Conference on Modern Trends in Elastic Electron Scattering, Amsterdam, 1978 (unpublished), p. 73.

[21] W. D. Knight and V. W. Cohen, Phys. Rev. 76, 1421 (1949).