Discovery of a 6^-, $T=1$ Resonance in ^{24}Mg via High-Resolution Inelastic Electron Scattering*

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The unique high-resolution and high-energy features of the electron-scattering facility at the MIT—Bates Accelerator were used to locate a dominant narrow resonance at 15.045 ± 0.035 MeV in ^{24}Mg. A spin-parity assignment of 6^- and an isospin $T=1$ assignment were made. The $M6$ form factor was measured and compared to the prediction of a theoretical calculation which uses the open-shell random-phase approximation on a shell-model ground state for ^{24}Mg.

Electron scattering experiments in the past, while demonstrating the potential of the electron as a probe of nuclear structure, have been seriously handicapped by inadequate resolution and low intensities. With the new accelerators, this situation has dramatically changed. Thus with a 400-MeV electron beam, we are now able to achieve a 0.015% momentum resolution on a ^{24}Mg target of thickness ~ 10 mg/cm^2. With momentum transfers of up to ~ 800 MeV/c, we are able to enhance high-multipolarity magnetic and electric transitions and observe high-spin states in ^{24}Mg of up to $J=10$. In this respect, electron scattering is therefore becoming comparable to heavy-ion transfer reactions which have been used, for example, to demonstrate the existence of narrow high-spin states of excitation energies of 10–20 MeV in ^{24}Mg with large many-particle–many-hole configuration amplitudes.[1] However, quite unlike the heavy-ion reactions, the inelastic electron scattering cross section is dominated by resonances with a large one-particle–one-

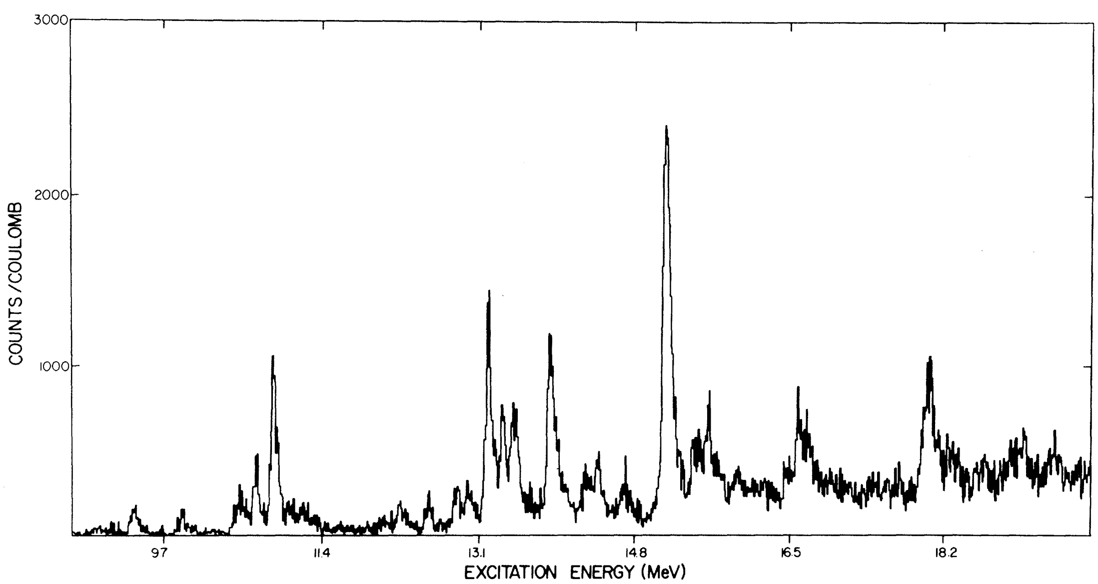

FIG. 1. ^{24}Mg(e,e') data taken at $\theta=160$ deg and $q=2.13$ fm^{-1}.

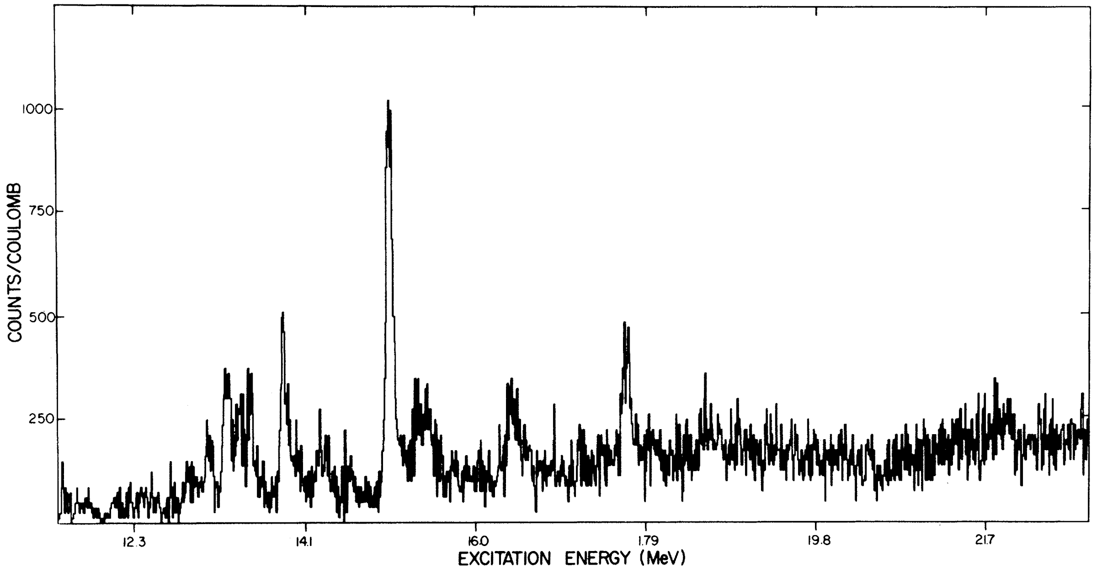

FIG. 2. ^{24}Mg(e,e') data taken at $\theta = 120$ deg and $q = 2.07$ fm^{-1}.

hole amplitude; and, since the electromagnetic interaction is well understood, their form factors can be compared directly with nuclear structure predictions. High-momentum-transfer inelastic scattering is therefore particularly appropriate for the study of giant multipole states of high angular momentum. Furthermore, the particle-hole calculations of such states, formerly limited to closed-subshell nuclei,[2,3] have been extended in recent years to open-shell nuclei[4] and are a valuable adjunct to the interpretation of these experiments.

In this Letter, we report the observation of high-spin resonances at 8–20-MeV excitation in ^{24}Mg, isolated using the unique high-energy and high-resolution features of the electron-scattering facility at the MIT Bates Accelerator Laboratory.[5] The form factors have been measured for ~15 strong and well-resolved resonances between 10- and 20-MeV excitation. Specifically, measurements were made at 160° for incident energies of 108.0, 127.6, 165.1, 215.0, 259.2 MeV and at 120° for 237.6 MeV. Two of the runs are shown in Figs. 1 and 2. For the purposes of this Letter, we concentrate on a $T=1$, $M6$ resonance discovered in the experiment at 15.045 ± 0.035 MeV.

A target of thickness 9.93 mg/cm^2 and area $4\frac{1}{2}$ cm $\times$ 4 cm was used in the transmission mode at both scattering angles. The target contained 99.4% ^{24}Mg isotopic purity. The measurements were made relative to the observed elastic peak, and to the inelastic peaks of the 2^+ state at 1.369 MeV and the 4^+ state at 6.010-MeV excitation in ^{24}Mg. The Coulomb form factors for these states are well known.[6,7] The measurements were also made relative to the observed elastic peak of the proton using a polyethylene CH_2 target of thickness 25 mg/cm^2 in the reflection mode at both scattering angles.

The form factor for inelastic electron scattering to an isolated resonance is given by[8]

$$F_{C\lambda}^2(q) + \left[\tfrac{1}{2} + \tan^2\left(\frac{\theta}{2}\right)\right] F_{T\lambda}^2(q) = \frac{d\sigma/d\Omega}{4\pi\sigma_M R},$$

where $d\sigma/d\Omega$ is the measured cross section with radiative correction applied,

$$\sigma_M = \frac{\alpha^2 \cos^2(\theta/2)}{4E_e^2 \sin^4(\theta/2)}, \quad R = \left[1 + \left(\frac{2E_e}{M_T}\right)\sin^2\left(\frac{\theta}{2}\right)\right]^{-1},$$

E_e is the incident electron energy and θ is the electron scattering angle. $F_{C\lambda}^2(q)$ is the Coulomb form factor and $F_{T\lambda}^2(q)$ is the transverse form factor which may be electric or magnetic. A comparison of Figs. 1 and 2 reveals a strong transverse contribution to the form factors of most of the observed resonances. This is particularly true of the strong narrow resonance at 15.045 MeV, which is found to be entirely transverse within the experimental accuracy and which is therefore identified as a magnetic excitation.

The form factor for this resonance is plotted in Fig. 3 versus the effective momentum transfer, i.e., the measured momentum transfer renormal-

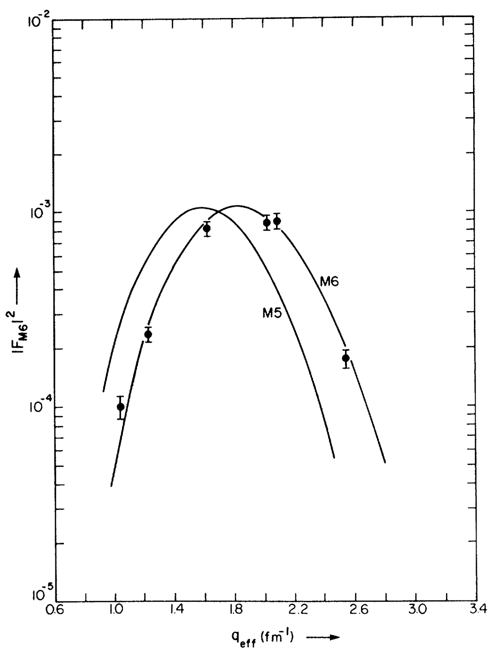

FIG. 3. The form factor $|F_{M6}(q)|^2$ for the 6^-, $T=1$ resonance at 15.045 ± 0.035 MeV in ^{24}Mg. The open-shell random-phase approximation calculation for $M6$ is shown as a solid line. An $M5$ curve (see text) is added for comparison purposes.

ized to account for distorted-wave corrections. The theoretical $M6$ curve was calculated, in the plane-wave Born approximation, using the open-shell RPA for a shell-model ground state[4,9]; the effects of center-of-mass motion and of the nucleon form factor were included. In Fig. 3, the magnitude of this form factor has been reduced by a factor of 2.1 ± 0.1 to fit the data, and an oscillator parameter of $b = 1.82$ fm has been used. The latter exceeds by 1.5% the value $b = 1.79$ fm used by Donnelly and Walker[10] and by 2.1% that used by Lees *et al.*[11] for the ^{24}Mg ground state. The fit of the $M6$ curve to the six data points has a χ^2 of 7.2 which is very satisfactory. By way of contrast, an $M5$ form factor, calculated in plane-wave Born approximation with identical nuclear currents, is seen clearly to be quite inconsistent with the data. We therefore make a spin and parity assignment of 6^- for the 15.045-MeV resonance. Furthermore, we assign it isospin $T = 1$, for were it to have $T = 0$, its $M6$ strength would exceed the RPA prediction by a factor of approximately 12, which is highly unreasonable.

The corrections to the momentum transfer q due to distortion were determined using the distorted-wave code DUELS,[12] which has been modified recenlty be Lee[13] and by Chow and Rowe[14] to include multipolarities larger than $\lambda = 5$ and to accept microscopic transition charge and current densities. A full distorted-wave calculation of the cross section was done using open-shell RPA transtion densities for each of the six energies and two scattering angles. A comparison with a plane-wave Born-approximation calculation of the cross section, using the same source densities, gave the effective momentum transfer q_{eff} for the data points plotted in Fig. 3. The procedure above required that the two calculations give the same cross sections. This is equivalent to a direct comparison of the data with the distorted-wave Born approximation (DWBA) calculation. The nucleon form factor and center-of-mass recoil corrections were not included in the above procedure used to determine q_{eff} and the effect is negligible.

In the open-shell RPA model, the 6^- resonance is dominated by the $1f_{7/2}$-$(1d_{5/2})^{-1}$ particle-hole excitation and has the largest angular momentum that can be generated by a simple one-nucleon jump from the $2s$-$1d$ shell to the $2p$-$1f$ shell. The ratio of the theoretical to the measured cross section, $\sigma_{th}/\sigma_{expt} = 2.1 \pm 0.1$, may be compared to the corresponding ratio for the sum of $M1$ transitions to the 1^+, $T=1$ states at 9.85, 9.97, and 10.70 MeV in ^{24}Mg, which is 2.0 ± 0.1.[2] Thus it appears that the well-known de-enchancement of $M1$ transitions, which has yet to be satisfactorily explained, may be a more general feature of magnetic transtions, which are dominated by the nuclear magnetization current. It has been suggested that a renormalization of the magnetization current density operator in nuclei may be necessary.[15,16]

In conclusion, we remark that all the other negative-parity states observed in these experiments on ^{24}Mg are currently being compared with the particle-hole model. As Donnelly and Walecka have suggested,[17] electron scattering to isolated resonances of a dominant particle-hole nature can be used to determine the one-body transition densities and thereby assist in the interpretation of other reactions; e.g., the weak interactions. It has also been proposed that the cross section for excitation of the 6^-, $T=1$ resonance in ^{24}Mg via inelastic proton scattering should be measured and compared with the electron results presented here to give a measure of the tensor part of the proton-nucleon interaction.[18]

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[1]L. K. Fifield, R. W. Zurmühle, D. P. Balamuth, and J. W. Noé, Phys. Rev. C 8, 2203, 2217 (1973).

[2]A. Johnston and T. E. Drake, J. Phys. A 7, 903 (1974).

[3]T. W. Donnelly, Jr., J. D. Walecka, G. E. Walker, and I. Sick, Phys. Lett. 32B, 545 (1970).

[4]D. J. Rowe and S. S. M. Wong, Nucl. Phys. A153, 561 (1970).

[5]W. Bertozzi *et al.*, unpublished.

[6]P. Junk, Ph.D. thesis, Universität Mainz, 1970 (unpublished).

[7]G. C. Li, M. R. Yearian, and I. Sick, Phys. Rev. C 9, 1861 (1974).

[8]T. DeForest, Jr., and J. D. Walecka, Adv. Phys. 15, 1 (1966).

[9]Details of the open-shell random-phase approximation calculations for ^{24}Mg will be given in S. S. M. Wong, D. J. Rowe, and H. Chow (to be published).

[10]T. W. Donnelly and G. E. Walker, Ann. Phys. (N.Y.) 60, 217 (1970).

[11]E. W. Lees, C. S. Curran, T. E. Drake, W. A. Gillespie, A. Johnston, and R. P. Singhal, J. Phys. G 2, 105 (1976).

[12]S. T. Tuan, L. E. Wright, and D. S. Onley, Nucl. Instrum. Methods 60, 70 (1968).

[13]H. C. Lee, Atomic Energy of Canada Ltd. Report No. AECL-4839, 1974 (unpublished).

[14]H. Chow and D. J. Rowe, "FORKS, a program to calculate the nuclear electromagnetic four-current from microscopic wave functions," Theoretical Physics Internal Report, University of Toronto, 1976 (unpublished).

[15]H. C. Lee, private communication.

[16]B. H. Wildenthal, private communication.

[17]T. W. Donnelly and J. D. Walecka, Annu. Rev. Nucl. Sci. 25, 329 (1975).

[18]G. Nolan, private communication.

Multiple Scattering Aspects of the π-Nucleus Low Equation*

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The π-nucleus Low equation, under certain assumptions (implicit in conventional multiple-scattering theory), is equivalent to a linear equation. The propagator of this equation includes a factor of $(z/H_0)^2$ which vastly reduces off-shell scattering. As a result, the Kisslinger singularity is eliminated, and the size of the Lorentz-Lorenz effect and local-field corrections is reduced.

The understanding of π-nucleus reactions is being pursued with great vigor. One interesting aspect of this problem is that the basic π-nucleon interaction is, to a large extent, given by a single pion absorption by, or emission from, a nucleon instead of potential scattering. Such dynamics require the use of a field-theoretic approach.

Modern treatments of π-nucleus field theories began with the work of Dover and Lemmer[1] who obtain the optical potential in terms of a π-nucleon scattering amplitude which is a solution of a medium-modified π-nucleon Low equation. This approach has been further pursued by Ingraham[2] and others.

Another approach, initiated by Cammarata and Banerjee,[3] is to solve the π-nucleus Low equation. The Low equation plays a role in field theory analogous to the Schrödinger equation in potential scattering, and its solution is of great relevance in understanding π-nuclear scattering. Under certain approximations, the nonlinear Low equation is equivalent to the linear equation of conventional multiple-scattering theories except for a striking propagator modification which arises from the energy dependence $(1/z)$ of the driving term.[4]

Here we present the implications of the propagator modification for three effects of current interest. These are the Kisslinger singularity, Lorentz-Lorenz effect, and local-field corrections.

The π-nucleus Low equation of Ref. 3 is

$$T_{fi}(z) = \frac{V_{fi}}{z} + \sum_n \frac{T_{nf}{}^\dagger T_{ni}}{z - E_n + i\eta}, \tag{1}$$

where n, i, and f represent the quantum numbers of the intermediate, initial, and final π-nuclear states, respectively, and E_n consists of a nuclear excitation energy and pion energy. The driving term, V/z, is determined by a commutator of two pion current operators. Because the fundamental pion current is a single-nucleon operator we may write $V/z = \sum_i v_i/z$, where the sum is