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Measurement of magnetic monopole transition in electron scattering from ^{16}O as direct test of dispersive effects

N. Voegler* and J. Friedrich
Institut für Kernphysik der Johannes-Gutenberg-Universität, D6500 Mainz, Germany

E. A. J. M. Offermann,† C. W. de Jager, and H. de Vries
Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF-K), P.O. Box 41882, 1009 DB Amsterdam, The Netherlands
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For the first time an experiment has been performed to measure a magnetic monopole transition in inelastic electron scattering. In ^{16}O the $0^+ \rightarrow 0^-$ transition to the level at $E_x = 10.957$ MeV has been observed with a cross section of $d\sigma/d\Omega = (5.4 \pm 3.8) \times 10^{-37}$ cm^{-2}/sr. Measurement of this transition is a direct signature of two-step contributions in electron scattering. Our measurement is in good agreement with the strength calculated for this transition.

I. INTRODUCTION

The measurement of elastic electron-scattering cross sections has reached such an accuracy and a completeness that one has to worry about the influence of higher-order effects when interpreting the data in terms of static charge distributions. While radiative corrections are applied at least up to first order, the intermediate excitation of the nucleus, the so-called dispersion contribution, is normally not accounted for in the analysis; its size is certainly small, but the main reason for neglecting it is that it is theoretically not under control. Therefore, in the past decade efforts have been concentrated on an experimental determination of such two-step contributions to the scattering cross section.

There are basically three methods by which one can obtain an experimental estimate of dispersive effects. (i) With an energy dependence of this effect in mind, elastic-scattering measurements are performed with different incident energies while covering the same region of momentum transfer; the inconsistency of the data (when interpreted in terms of a static charge distribution) is the signature for higher-order contributions (experimental results have been published recently[1,2]). (ii) While e^- and e^+ cross sections are equal in lowest order, the leading dispersive contribution outside the minima depends on the sign of the charge of the scattering probe and can thus be detected in a comparative measurement; recently, experiments have been performed at Saclay.[3] (iii) Due to selection rules, certain levels cannot be excited in inelastic scattering by a one-step process. Therefore, their observation is a direct manifestation of dispersive effects. While in experiments of types (i) and (ii), the dispersive contribution is only a small correction to the dominating one-step scattering amplitude, in a type-(iii) experiment, the full signal is the effect one is looking for. The price one has to pay is that the signal is expected to be extremely small. In this article we report on the first measurement of this kind.

II. EXPERIMENTAL CONSIDERATIONS

An appropriate candidate is a $0^+ \rightarrow 0^-$ (magnetic monopole) transition for which a one-step excitation is strictly forbidden. From the experimental point of view, the 0^- level at 10.957 MeV in ^{16}O (Ref. 4) is well suited since it is separated by 0.123 MeV from its nearest neighbor. A problem, however, is to find an oxygen target with the following properties: (a) The target should not have contaminations which will have excited states in the region of the 0^- excitation. (b) The target should stand high currents which are necessary for measuring the expected very small cross section. (c) The target construction should not deteriorate the energy resolution which is important to get a sufficient signal-to-noise ratio with the large unavoidable background from the radiative tails of lower-lying levels. A target has been constructed which fulfills all three requirements. It consists of a stable water lamella which is spanned between two wires by pressing a continuous water flow through a slit.[5] The water lamella is enclosed in a cell filled with hydrogen gas at atmospheric pressure. This cell is positioned inside the evacuated scattering chamber. The water which is highly enriched with ^{16}O (Ref. 6) is pumped around in a closed circuit. Since irradiated water is highly aggressive, care has to be taken that it only gets into contact with resistant materials. In a first version of the target many parts were made of glass[5] which later on were replaced by stainless steel.[7] Compared to the first version, the amount of water needed in the circuit has been reduced from 1500 to about 400 ml.

The excitation of the 0^- state is at least a two-step process consisting of a magnetic and an electric transition. As a result, the reduced cross section $[=(d\sigma/d\Omega)/(d\sigma/d\Omega)_M$, where $(d\sigma/d\Omega)_M$ is the Mott cross section$]$ depends not only on the momentum transfer q but also strongly on the scattering angle of the electron. One can take advantage of this particular dependence by selecting kinematical conditions for the measurement in which the 0^- excitation is enhanced with respect to excitations of lower-lying states which are dominantly electric.

The best kinematics for observing the excitations of the $0^+ \rightarrow 0^-$ transitions in ^{16}O can be estimated from the expression for the cross section given by Borie and Drechsel:[8]

$$\frac{d\sigma}{d\Omega} = \alpha^4 \frac{\mu_p^2}{M^2} \cos^2\frac{\Theta}{2} \left[\pi^2 + 4\sin^2\frac{\Theta}{2} \right] \frac{4}{9} x(1-x)^2 e^{-2x} . \tag{1}$$

Here, α is the fine-structure constant, $\mu_p = 2.79$ is the proton's magnetic moment, and M its mass. Θ is the scattering angle and $x = (qr_0/2)^2$, where q is the momentum transfer and r_0 is the oscillator parameter ($r_0 = 1.76$ fm). Equation (1) has been derived under the assumption of a pure $(1p_{1/2})^{-1}(2s_{1/2})$ configuration for the 0^- state, and plane waves have been assumed for the electron wave functions. Furthermore, the intermediate-energy loss is neglected so that closure could be used to sum over all intermediate states.

The calculation predicts cross sections of the order 10^{-36} cm^2/sr and, very optimistically, in 1971 Borie and Drechsel judged this to be measurable. It took several years before elastic cross sections of this order and below could be measured.[9] The inelastic cross section, however, has to be separated from the unavoidable background produced by radiative tails of lower-lying levels of which the excitation is larger by orders of magnitude.

III. RESULTS AND DISCUSSION

First measurements were performed with the Mainz linear electron accelerator at two kinematics (150 MeV, 136° and 249 MeV, 133°). These measurements demonstrated that the waterfall target stands currents as high as 50 μA and, in fact, gives background-free oxygen spectra. The systematic and statistical uncertainties, however, were such that the cross section extracted at the position of the known 0^- state had an error of about 100%. Therefore, a further experiment was performed with the high-resolution electron-scattering facility at National Instituut voor Kernfysica en Hoge-Energiefysica (NIKHEF-K) where a better signal-to-noise ratio was achievable. From an analysis of the previous measurements, the optimal ratio was expected under kinematical conditions around 255 MeV and 111°.

Figure 1 shows the measured spectrum in the excitation energy region from 6.5 to 14.0 MeV. This spectrum has been obtained with a beam current of 20 μA on a 31-mg/cm^2 water target collecting a total charge of 5.6 C. A resolution of 49 keV has been achieved after careful optimization of the imaging properties of the QDD (Quadrupole Dipole Dipole) spectrometer.[10,11] The most significant improvement was made by correcting for kinematic broadening caused by the ± 40 mrad scattering-angle acceptance of the spectrometer. The quality of the waterfall as a background-free oxygen target is immediately obvious from the fact that, for the first time in an electron-scattering experiment, the excitation of the broad 1^- and 3^- levels at 9.565 ± 0.004 and 11.496 ± 0.008 MeV, respectively, are observed with widths of 0.300 ± 0.012 and 0.738 ± 0.038 MeV. Several of these numbers are different with respect to the previous ones[4] by more than the claimed uncertainty; in particular, the width of the broad 1^- state is considerably smaller.

Special care has been taken to minimize effects of channel-by-channel efficiency fluctuations in the wire chambers of the detector setup. Data were collected during 56 runs of 100 mC each. From run to run, the spectrometer field was changed such that the spectrum was shifted over a distance corresponding to the spacing between two wires. During each data-taking run, the detector system was moved in 16 steps over one wire distance[12] (the energy width corresponding to one such step is called fine channel). With this procedure effects of fluctuations in wire spacing and in widths of the fine channels are averaged out. Off line, further corrections could be performed by determining the fine-channel response from overlapping parts of spectra taken at different field settings.

After the efficiency correction, the spectrum was fitted with a function which is the sum of peak shapes representing all known levels of ^{16}O (Ref. 13) in the excitation region studied running from 0 to 14 MeV. For each level with an internal width less than 5 keV a hyper-Gaussian function was chosen as line shape.[14] On the high-excitation side this line shape is continued by a sum of hyperbolic functions up to second order representing the radiative tail. The excitations with internal widths larger than 5 keV are represented by a Lorentzian line shape convoluted with the fitted line shape of the nearest sharp peak.

The parameters of the line-shape function were determined simultaneously for all peaks in a least-squares fit. In this fit the excitation region was split in two parts. First, the peak parameters were determined in the part which runs from 0- to 6.5-MeV excitation energy. Then the line-shape parameters were fitted in the second part which runs up to 14 MeV while keeping the parameters in the first part constant. Due to the optimization of the spectrometer imaging properties, many of the line-shape parameters do not vary in first order along the focal plane. As a result, many of the parameters in the least-squares fit could be linked together. The best fit of the excitation region from 6.5 up to 14 MeV has a χ^2 per degree of freedom ν of 970/525. In the same fit, the energy measurement is calibrated by fitting the parameters of a fourth-order dispersion polynomial by the comparison of the positions of the dominant peaks in the spectrum with the known excitation energies.[4] While the fit determines the positions of the peaks with an average standard deviation of 1 keV, the resulting excitation energies in our spectrum reproduce the values of Ref. 4 to within better than 3 keV, a number which corresponds roughly to the accuracy claimed in Ref. 4.

The major contribution to χ^2 comes from those parts of the spectrum where the radiative tail of a peak is matched to the hyper-Gaussian line shape. This dominant contribution hinders the parametrized radiation tail to correctly follow the measured spectrum and therefore may unduly influence the extraction of the amplitude for a weak peak on top of this smooth background. In order to regain full flexibility in describing the background under the 0^- excitation, another step was made on the extraction of the 0^- cross section: First, line shapes of all peaks between 0 and 14 MeV were subtracted from the spectrum, except for the 0^- contribution at 10.957 MeV. Then part of the resulting spectrum, which is shown as the inset in Fig.1, was fitted with a linear background function and a peak at the well-known 0^- position (χ^2 per data point of 44/39); the form of this peak was taken from the nearest narrow peak. The resulting peak is shown in Fig. 1 as the shaded area; it corresponds to a cross section for the $0^+ \rightarrow 0^-$ transition of

$$d\sigma/d\Omega=(5.4\pm3.8)\times10^{-37}\ \mathrm{cm}^2/\mathrm{sr}\ .$$

In a last step we have investigated the strength of the remaining fluctuations on the spectrum in the energy region between the two neighboring excitations, i.e., from 10.5 up to 11.1 MeV. To this end, a peak has been fitted through the spectrum in steps of 25 keV with a shape as given by the nearest large narrow peak. The results are shown in Fig. 2. Figure 2(a) shows the spectrum that has been analyzed in this way. It is obtained by subtracting the fitted linear background and the 0^- peak from the remaining spectrum shown in the inset of Fig. 1. The resulting cross section for this peak is shown in Fig. 2(b) as a function of this peak's energy. This cross section is statistically distributed around zero with a variance equal to the statistical uncertainty of the 0^- cross section.

Possible background contributions are investigated by looking at the number of events measured in front of the elastic ^{16}O peak. In this way, both the influence of target impurities and real background events are checked. Two counts are observed in a 100-mC run in the energy region between the elastic ^{16}O peak and the position that would correspond to an impurity with infinite mass. The position of these counts corresponds to elastic scattering from ^{17}O. By scaling the ^{17}O data of Manley et al.[15] by these two events, we estimate that a possible excitation of ^{17}O in the 0^- region is at least 3 orders of magnitude smaller than the observed 0^- strength. In the region not accessible to anything that scattered from the target and reached the focal plane in a regular way, five counts were

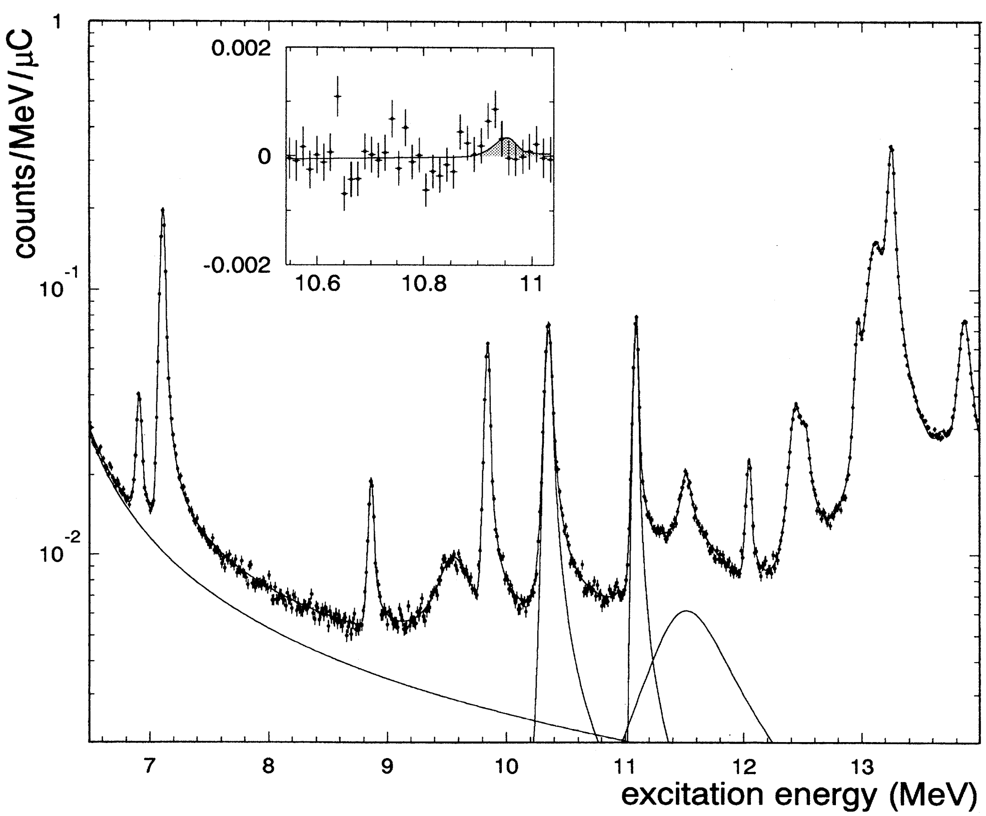

FIG. 1. Spectrum of electrons with an incoming energy of $E=255$ MeV scattered inelastically from ^{16}O through an angle $\theta=111°$. The solid line through the data points shows the fit to the spectrum, including radiative tails of lower-lying levels. Line shapes of transitions to several levels around the 0^- excitation are shown separately. The amplitude of the 0^- state is below the logarithmic scale of the graph. The inset shows a spectrum which is obtained by subtracting the line shapes of all peaks in ^{16}O up to 14 MeV from the measured spectrum except for the 0^- contribution. The shaded area represents the fitted peak at the 0^- position.

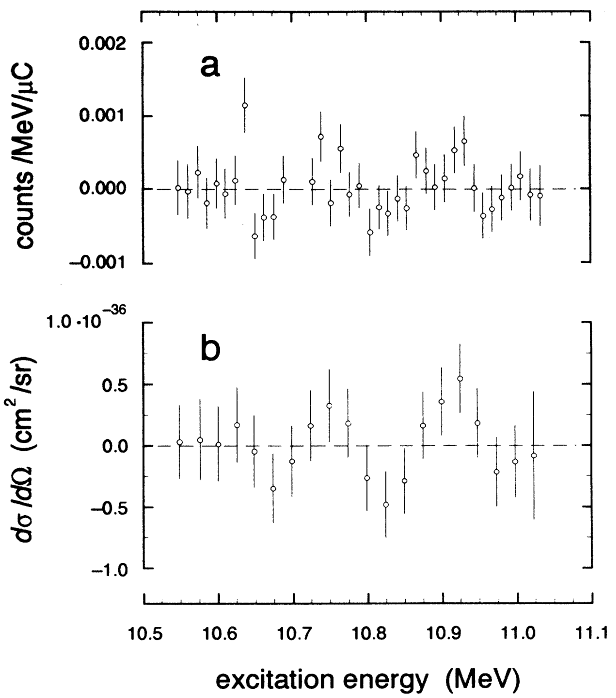

FIG. 2. (a) Rest spectrum obtained by subtraction of the line shapes of all peaks in ^{16}O up to 14 MeV from the measured spectrum. (b) Cross sections contained in the rest spectrum as extracted by fitting a peak with a shape as given by the nearest narrow peak at the energetic positions shown.

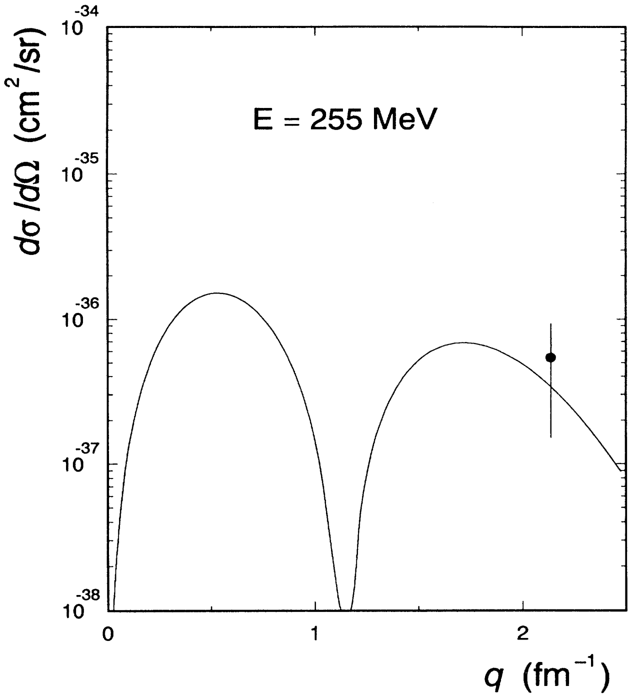

FIG. 3. Inelastic electron-scattering cross section for the excitation of the 0^- level at 10.957 MeV in ^{16}O by scattering of 255-MeV electrons. The solid curve represents the PWBA calculation by Borie and Dreschsel (Ref. 8) as a function of momentum transfer q. The circle shows the measured value plotted at its effective momentum transfer. Only statistical error is shown.

observed in the 100-mC run in a 6-MeV energy range, corresponding to a cross section as small as

$$(d\sigma/d\Omega)/dE=(2\times10^{-38}\ \mathrm{cm}^2/\mathrm{sr})/\Delta E_{\mathrm{peak}}\ .$$

In summary, we conclude that the strength observed at the position of the 0^- level is due to inelastic scattering from ^{16}O.

The resulting cross section is compared to the calculation by Borie and Drechsel in Fig. 3. The plane-wave Born approximation (PWBA) calculation is plotted as a function of momentum transfer q while the measured value is shown at the effective momentum transfer. The measurement agrees within one standard deviation with the calculation. However, the uncertainty in our measurement is so large that it cannot be regarded as a serious test of the numerous approximations that have been made in the calculation. For a more stringent test, both the statistical and the systematic uncertainty have to be reduced, which would imply a major effort.

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*Present address: Burster Präzisionsmesstechnik, Talstr. 1-7, D7562 Gernsbach, Germany.

†Present address: Institut für Kernphysik der Johannes-Gutenberg-Universität, D6500 Mainz, Germany.

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