Direct measurement of the radiative tail in electron scattering from atomic nuclei

John LeRose, Peter D. Zimmerman, and C. C. Blatchley
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana

J. Friedrich, N. Voegler, and M. Pieroth
Institut für Kernphysik, Johannes-Gutenberg-Universität, D-6500 Mainz, Federal Republic of Germany
(Received 20 March 1985)

We have made a direct measurement of the radiative tail of the eleastic peak from several tungsten targets. The measured data have been compared to the results expected for both internal and external bremsstrahlung contributions. Even for targets as thick as 4% of a radiation length of tungsten, agreement between the results of the experiment and the predictions of the theory has been found to be unexpectedly good.

INTRODUCTION

Electron scattering, in principle, is unsurpassed as a tool for determining the radial charge distributions of atomic nuclei and for measuring the transition charge densities to excited states of nuclei.[1–4] Furthermore, electron scattering at large energy losses should provide much unique information concerning the nuclear momentum distribution and the production and propagation of nucleon resonances in nuclear matter.[5–8] The electromagnetic interaction is weak and well known. The high velocity of electron probes means that the interaction time is so short that the nuclear constituents do not rearrange themselves during the interaction. Unfortunately, a scattered electron must be accelerated, and hence emits photons. The process gives rise to a continuous background cross section which is termed the radiative tail. The elastic peak as well as every inelastic transition has such a tail. The tail of the elastic peak, in general, rises rapidly at large energy losses.[9]

The treatment of radiative processes is important in all electron scattering experiments, and is particularly so in measuring inelastic cross sections. There the radiative tail of the elastic peak becomes a background to be subtracted from the process of interest, while the inelastic level being measured has a radiative tail of its own, which also must be calculated in order to determine the true cross section for that level. At very large inelasticities, when the detected electron has lost one-half or more of its original energy, the cross section of the energy radiative tail begins to rise. This cross section can become the dominant process measured, larger than the sum of the quasielastic scattering plus resonant meson production.[7,8]

The Feynman diagrams contributing to the radiative tail of the elastic peak are shown in Fig. 1.

An electron which radiates a hard photon of momentum $\mathbf{k}$ before scattering elastically from the target nucleus [Fig. 1(a)] arrives at the target with its momentum reduced by $\mathbf{k}$ from its initial value. Because both the Mott cross section and the elastic form factor increase as the electron momentum and momentum transfer decrease, respectively, such an electron has an increased probability of scattering elastically. This enhancement in scattering probability is sufficiently large to result in a rapid increase in the radiative tail cross section at large energy losses, even though the probability that an electron will radiate a photon of momentum $\mathbf{k}$ is approximately proportional to $1/|\mathbf{k}|$. Figure 1(a) is the dominant contribution to the target-thickness independent part of the radiative tail. The process illustrated in Fig. 1(b) is less significant since it is not enhanced by increases in the Mott cross section or the form factor.

Many attempts to calculate the radiation process have been made, from Schwinger's treatment of potential scattering[10] through the peaking approximation of Schiff[11] and the more complete treatments of Meister and Yennie,[12] Maximon and Isabelle,[13] Borie,[14] and Mo and Tsai.[15] Numerical unfolding of the spectra[16] is the principal procedure used in order to separate the radiative background from the physically interesting quantities. The radiative tail is typically calculated using the methods of Ref. 15. For large inelasticities and, in particular, for massive, high Z nuclei, the validity of the various approximations used by experimentalists has been questioned. An uncertainty of up to a factor of 2 in the calculation might be expected on theoretical grounds in some cases.[17] Thus, experimentalists conventionally report data only in regions where a factor of 2 error in the magnitude of the radiative tail makes a much smaller contribution to the total uncertainty in the measurement. Many otherwise useful data have necessarily been discarded. These mea-

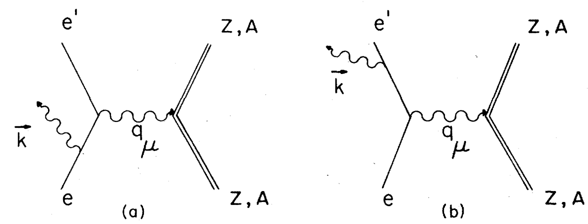

FIG. 1. Feynman diagrams for bremsstrahlung emission of a photon of momentum $\mathbf{k}$ before elastic scattering (a) and after elastic scattering (b).

surements represent an attempt to improve the credibility of published[7,8] and soon to be published deep inelastic electron scattering data. Since the greatest doubt exists regarding radiative tail calculations for large Z and thick targets, we feel that our results on a thick, large Z target warrant immediate attention.

PROCEDURE AND RESULTS

We have used the Mainz linear accelerator[18] to measure directly the radiative tail in an effort to determine the degree to which a standard calculation based on the work of Mo and Tsai agrees with the background actually seen by experimentalists. Estimates of the resonant pion production cross sections indicate that contributions from that process would be negligible at low momentum transfers; i.e., at forward scattering angles and relatively low incident energies. A zero temperature relativistic Fermi gas model calculation of the quasielastic cross section indicates that, at 300 MeV incident energy and a 30° scattering angle in tungsten, the cross section goes to zero at a final energy of about 210 MeV (see Fig. 2). Of course at such low momentum transfers a very simple zero temperature Fermi gas model approach to quasielastic scattering is not expected to reproduce the quasielastic scattering very well. We use it here only as an indication of where the quasielastic strength should be. Data were taken from four tungsten targets of different thicknesses at a bombarding energy of 300 MeV and at a 30° scattering angle. Tungsten was chosen because reasonably good charge distribution measurement exists for it at low momentum transfers,[19] because it is a stable target capable of withstanding intense electron beams and because it has a high enough atomic number, Z, to test the method by which distorted waves are introduced into the calculation. Measurements have also been made from carbon and at lower incident energies for both targets. The results of these measurements will be reported later.

It may be seen from Eqs. (II.1) and (A16) of Mo and Tsai that at large energy losses the radiative tail is approximately given by:

$$\left[\frac{d^2\sigma}{d\Omega\, d\omega}\right]_{\text{complete}} = \left[\frac{d^2\sigma}{d\Omega\, d\omega}\right]_{\text{internal}} + \left[\frac{d^2\sigma}{d\Omega\, d\omega}\right]_{\text{external}}, \tag{1}$$

where $(d^2\sigma/d\Omega\, d\omega)_{\text{internal}}$ is the internal bremsstrahlung (Schwinger) contribution and $(d^2\sigma/d\Omega\, d\omega)_{\text{external}}$ is due to straggling in the target and has the approximate form:

$$\left[\frac{d^2\sigma}{d\Omega\, d\omega}\right]_{\text{external}} = c_s t e^{b_s t}, \tag{2}$$

where c_s and b_s are complicated expressions, depending upon incident and final electron energies, the scattering angle and the atomic number of the target, and derived from expressions given in Mo and Tsai. t is the target thickness in radiation lengths. Data from three or more targets of varying thicknesses are therefore sufficient to permit an extrapolation to $t=0$, and the extraction of the internal bremsstrahlung contribution to the radiative tail.

To determine the validity of the Mo and Tsai treatment of target-thickness dependent effects, we used four different thicknesses of tungsten (56, 102.4, 132.7, and 268 mg/cm^2, corresponding to 0.83%, 1.5%, 1.96%, and 3.96% of a radiation length). [The radiation lengths were calculated according to Eq. (3.65) in Tsai.[20] This formula differs significantly from earlier versions found elsewhere.] Data obtained from a set of carbon targets are presently being analyzed.

Measured cross sections for a 132.7 mg/cm^2 tungsten target are shown in Fig. 2. The smooth curve is the calculated radiative tail. The calculation follows the formalism of Tsai[15] modified to include Thomas-Fermi atomic form factors[20] instead of using screening approximations for calculating bremsstrahlung. The Schwinger term was modified to include radiation by the recoiling nucleus. The necessary elastic cross sections were calculated using the Heinel DWBA phase-shift code and the charge distributions of Ref. 19. We note that theory and experiment agree to within a few percent, except in the regions of the quasielastic peak and other known nuclear excitations where the data are known to consist of more than just the radiative tail. This agreement is particularly good at final electron energies less than about 200 MeV corresponding to energy losses greater than 100 MeV. There is no indication that the calculated radiative tail is in error anywhere by as much as 10%, let alone a factor of 2.

The uncertainty band enclosing the data points has been established primarily by uncertainties in measuring the thickness of the targets. Statistical errors were typically less than 1%, and dead-time corrections never exceeded 1%. The background from electron-positron pair production was measured by reversing the polarity of the spectrometer. The cross section for positive particles was at all times much less than 1% of the cross section for negative particles. From this we also conclude that the background from electroproduced negative pions mimicing electrons was also negligible. No problems with "ghost peaks" or poor baffling of the spectrometer were encountered in this part of the experiment. The situation may be less favorable at our lower bombarding energies of 240 and 180 MeV. The analysis of these additional data is

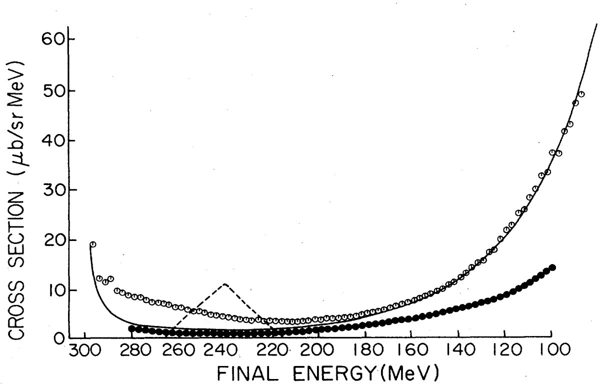

FIG. 2. Radiative tail for 132.7 mg/cm^2 tungsten target at $E_0=300$ MeV and scattering angle is 30°. The open circles are the data points. The smooth curve is the result of the calculation described in the text. The dark circles are the internal bremsstrahlung contribution to the smooth curve. The dashed line is a relativistic zero temperature Fermi gas calculation of the quasielastic electron scattering cross section. The statistical error bars are smaller than the size of the plotted data points.

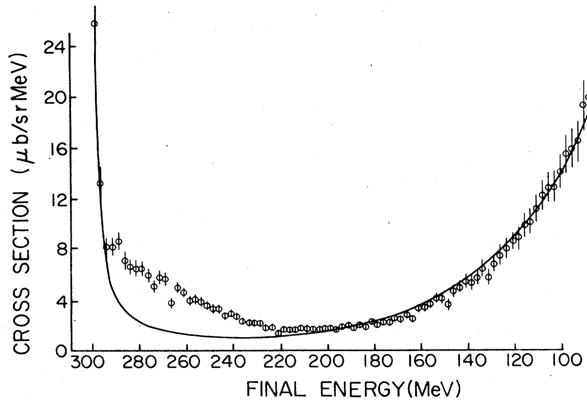

FIG. 3. Internal bremsstrahlung contribution to the radiative tail from tungsten under the same kinematic conditions as Fig. 2. The smooth curve is the internal bremsstrahlung contribution to the calculation described in the text. The error band reflects a 2–3 % uncertainty in the measurement of target thicknesses as well as a statistical error of less than 1%.

still under way.

The internal bremsstrahlung contributions have been extracted by fitting the measured cross sections to the approximate theoretical form of the radiative tail [Eqs. (1) and (2)]. The result of this procedure is shown in Fig. 3 for tungsten. The smooth curve represents the internal bremsstrahlung contribution to the previously described calculations. The calculation and the experiment agree quite well. There is some indication that the data lie systematically below the calculated curve in the region from 190 to 120 MeV final electron energy. This discrepancy may be due to a small and diminishing contribution of the radiative tail from the quasielastic peak, which would affect the thick target data more than the thin target data and result in a slightly lowered final result when one extrapolates to zero target thickness. One can see evidence of this effect in the 220–160 MeV region of Fig. 2 as well. The uncertainty in Fig. 3 arises primarily from the extrapolation procedure used to obtain the cross section for zero target thickness.

CONCLUSIONS

The validity of the interpretation of electron scattering experiments depends to a great extent upon the accurate calculation of the internal and external bremsstrahlung contributions to the measured cross sections. This is a particularly sensitive problem for large values of the energy loss usually encountered in deep-inelastic scattering experiments. For heavy target nuclei the situation is also complicated by a need to understand the correct way to incorporate distortion and atomic screening into the calculation.

We have shown, at least for the present typical kinematic situation, that the procedure used by many experimenters (for example Refs. 8, 21–23) to calculate the radiative tail of the elastic peak is an excellent one, producing results in good agreement with experiment. Thus, the foundation for the use of electron scattering as a probe of nuclear transition charge densities and momentum distributions appears to be sound.

ACKNOWLEDGMENTS

We thank Professor L. Wright and Professor D. Onley for useful conversations during the planning and analysis of this experiment. The experiment derives from a chance remark by Dr. L. C. Maximon to one of the present authors. Dr. Ch. Schmidt performed x-ray measurements of the target thicknesses and uniformities. We thank the staff of the Mainz linear accelerator for their help in setting up and running the experiment. The LSU members of the group thank Professor H. Ehrenberg and the Institut für Kernphysik for their hospitality during the experiment and the data analysis. The LSU group is supported in part by a grant from the U. S. National Science Foundation.

[1]R. Hofstadter, Les Prix Nobel en 1961, Nobelstiftelsen, Stockholm, 1962.
[2]J. L. Friar and J. W. Negele, Adv. Nucl. Phys. **8**, 219 (1975).
[3]W. C. Barber, Annu. Rev. Nucl. Sci. **12**, 1 (1962).
[4]J. Heisenberg and H. P. Blok, Annu. Rev. Nucl. Part. Sci. **33**, 569 (1983).
[5]Wieslaw Czyz and Kurt Gottfried, Ann. Phys. (N.Y.) **21**, 47 (1963).
[6]E. J. Moniz, Phys. Rev. **184**, 1154 (1969).
[7]Peter D. Zimmerman, C. F. Williamson, and Y. Kawazoe, Phys. Rev. C **19**, 279 (1979).
[8]M. Deady, *et al.*, Phys. Rev. C **28**, 631 (1983).
[9]L. C. Maximon, Rev. Mod. Phys. **41**, 193 (1969).
[10]J. Schwinger, Phys. Rev. **76**, 790 (1949).
[11]L. I. Schiff, Phys. Rev. **87**, 750 (1952).
[12]N. Meister and D. R. Yennie, Phys. Rev. **130**, 1210 (1963).
[13]L. C. Maximon and D. B. Isabelle, Phys. Rev. **133**, B1344 (1964).
[14]E. Borie, Lett. Nuovo Cimento, **1**, 106 (1969).
[15]Y. S. Tsai, Stanford Linear Accelerator Center Report SLAC-PUB-848, 1971; L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).
[16]H. Crannell, Phys. Rev. **148**, 1107 (1969).
[17]L. C. Maximon, National Bureau of Standard Technical Note 955, 1977, pp. 15 and 20; and private communication.
[18]H. Ehrenberg *et al.*, Nucl. Instrum. Methods **105**, 253 (1972).
[19]C. W. De jager, H. De Vries, and C. De Vries, At. Data Nucl. Data Tables **14**, 479 (1974).
[20]Y. S. Tsai, Rev. Mod. Phys. **46**, 815 (1974).
[21]P. Barreau *et al.*, Nucl. Phys. **A402**, 515 (1983).
[22]P. D. Zimmerman *et al.*, Phys. Lett. **80B**, 45 (1978).
[23]Z. E. Meziani *et al.*, Phys. Rev. Lett. **52**, 2130 (1984).