rectly positioned or when the atomic beam does not pass along the middle of the laser beam. In general, line-shape distortions will always occur if the laser field is not symmetric about its axis of propagation or if the atomic beam density distribution is not uniform.

On the other hand, the spatial behavior of the absorption and its dependence on frequency can be exploited as a means of performing spectroscopy and also as a tool for the study of atom-field interaction. Other possibilities may also be considered such as three-dimensional visualization of the atomic beam density distribution, based on the principle of holography.[9] Finally, light diffraction by atoms may make possible the observation of the shape and size of large single stationary ions in recently developed ion traps[10] or large single neutral atoms if and when neutral traps become feasible.

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[1]M. Born and E. Wolf, *Principles of Optics* (Pergamon, New York, 1970); J. M. Cowley, *Diffraction Physics* (North-Holland, Amsterdam, 1981).

[2]P. R. Hemmer, P. W. Peuse, F. Y. Wu, J. E. Thomas, and S. Ezekiel, Opt. Lett. 6, 531 (1981).

[3]R. V. Pound, Rev. Sci. Instrum. 17, 490 (1946); G. C. Bjorklund, Opt. Lett. 5, 15 (1980); M. Prentiss, B. Peuse, G. Sanders, and S. Ezekiel, Research Laboratory of Electronics, Massachusetts Institute of Technology, Progress Report No. 123, 1981 (unpublished); J. L. Hall, L. Hollberg, T. Baer, and H. G. Robinson, Appl. Phys. Lett. 39, 680 (1981).

[4]M. Prentiss, B. W. Peuse, and S. Ezekiel, to be published.

[5]B. R. Mollow, Phys. Rev. 188, 1969 (1969).

[6]C. Cohen-Tannoudji, in *Laser Spectroscopy*, edited by S. Haroche, J. C. Pebay-Peyroula, T. W. Hänsch, and S. E. Harris (Springer-Verlag, Berlin, 1975).

[7]F. Y. Wu, R. E. Grove, and S. Ezekiel, Phys. Rev. 35, 1426 (1975).

[8]P. R. Hemmer, F. Y. Wu, and S. Ezekiel, Opt. Commun. 38, 105 (1981), and references therein.

[9]R. J. Collier, C. B. Burckhardt, and I. H. Lin, *Optical Holography* (Academic, New York, 1971).

[10]W. Neuhauser, M. Hohenstalt, P. E. Toschek, and H. Dehmelt, Phys. Rev. A 22, 1137 (1980); D. J. Windland, J. C. Berquist, W. M. Itano, and R. E. Drullinger, Opt. Lett. 5, 245 (1980).

"Perfect" Elastic e$^-$-Xe Scattering Experiment

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The complete set of observables which describe elastic electron scattering from a xenon atom has been studied at energies between 30 and 360 eV. The polarization measurements presented here in conjunction with absolute measurements of the differential cross section yield the maximum possible information on the scattering process and allow complete evaluation of the complex scattering amplitudes. The results show that a correct overall description of the scattering process by theory is still missing.

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Elastic scattering of electrons by spinless atoms is theoretically described by two complex scattering amplitudes: the direct amplitude $f = |f|\exp(i\gamma_1)$ depending primarily on the Coulomb interaction and the spin-flip amplitude $g = |g| \times\exp(i\gamma_2)$ depending on the spin-orbit interaction of the scattered electron in the atomic field. In an experiment, it is not these amplitudes that are measured. Instead one observes combinations of the amplitudes such as the differential scattering cross section,

$$d\sigma/d\Omega = |f|^2 + |g|^2, \tag{1}$$

or the Sherman function,

$$S = -2\frac{|f|\,|g|\sin(\gamma_1-\gamma_2)}{|f|^2+|g|^2}, \tag{2}$$

which describes the polarization after the scattering of an initially unpolarized electron beam. It is obvious that these observables do not give all the information hidden in the complex scattering amplitudes. For a complete experimental determination of the scattering amplitudes one has to observe in addition the quantities

$$T = \frac{|f|^2 - |g|^2}{|f|^2 + |g|^2}, \tag{3}$$

$$U = 2\,\frac{|f|\,|g|\cos(\gamma_1 - \gamma_2)}{|f|^2 + |g|^2}, \tag{4}$$

which are obtained by measuring the change of the polarization components of a polarized electron beam as caused by the scattering process. From the observables (1) to (4) one obtains $|f|$, $|g|$, and the relative phase $\gamma_1 - \gamma_2$, i.e., the maximum possible information on the scattering process. It is the purpose of the present Letter to report on such a "perfect" scattering experiment.

Since the technique for measurement of $d\sigma/d\Omega$ and S may be called conventional nowadays,[1] the attention of this Letter is focused on measurement of T and U as shown in Fig. 1. The process of interest is the scattering of a polarized electron beam from xenon. The initial polarization vector $\vec{P}$ is transformed by the scattering to a vector $\vec{P}'$ which has the simple form[1]

$$\vec{P}' = S\hat{n} + T\vec{P} + U(\hat{n} \times \vec{P}), \tag{5}$$

if $\vec{P}$ lies in the scattering plane, whose normal is denoted by $\hat{n}$. If $\vec{P}$ is parallel (or antiparallel) to the scattering direction, $T\vec{P}$ and $U(\hat{n} \times \vec{P})$ are the longitudinal and transverse polarization components of the scattered beam, respectively, which are shown in the inset of Fig. 1. Measurement of these components yields the desired quantities T and U, if the initial polarization $\vec{P}$ is known.

The experiment operates as follows: The polarized electrons are produced by photoemission from a negative-electron-affinity GaAs crystal irradiated with circularly polarized light (GaAs source[2,3]). On average a polarized electron beam of 0.4 μA with a diameter of 2 mm, an angular spread of less than ±1°, and a polarization of 30% could be obtained. With the help of magnetic spin rotators in the source the primary polarization vector $\vec{P}$ was adjusted along the scattering direction. The energy was calibrated by electron impact on a mercury atomic beam with optical observation of the $6\,^1S_0 - 6\,^3P_1$ excitation function,[4] whose second pronounced maximum was set to 5.5-eV collision energy.

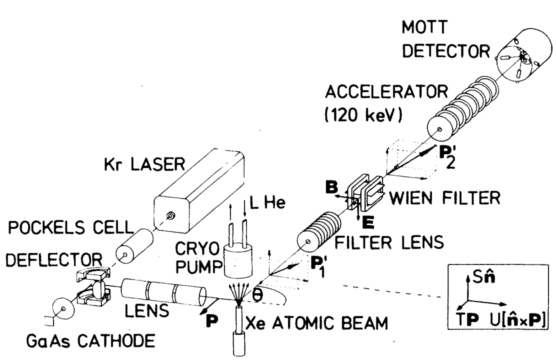

FIG. 1. Schematic diagram of the apparatus.

The electrons which are elastically scattered from the xenon target are transmitted through a filter lens[5] and a Wien filter[6] and enter a Mott detector for polarization analysis. Two pairs of counters in the Mott analyzer allow simultaneous analysis of the transverse polarization components $U(\hat{n} \times \vec{P})$ and $S\hat{n}$, if the Wien filter is switched off. If the Wien filter is on, the two polarization components perpendicular to the magnetic field $\vec{B}$ are rotated through 90° ($\vec{P}_1' \to \vec{P}_2'$) so that the longitudinal component $T\vec{P}$ can be measured also.

The experimental procedure was as follows: (i) First the primary polarization was measured by moving the atomic beam capillary into the electron beam and observing the electrons reflected by elastic scattering from its graphite-coated surface. The reflection from the capillary yielded a diffuse beam similar to that produced by scattering from the xenon target. This method could be applied because its comparison with the results obtained by using an electrostatic deflector instead of the atomic beam capillary showed that the same polarization values were obtained in both cases. Obviously, because of the low atomic number of carbon, the spin-orbit interaction is negligible in the former process so that the polarization is not affected by the deflection, if only the elastically scattered electrons are considered. Since the primary polarization was adjusted along the scattering direction the Wien filter had to be switched on to obtain a transverse polarization for measurement in the Mott detector. With the Wien filter switched off no transverse polarization component should arise. This was used to check the exact adjustment of the primary polarization.

(ii) The atomic beam capillary was removed and the electrons were scattered from the xenon target. The polarization components $T\vec{P}$ and

$U(\hat{n}\times\vec{P})$ were measured simultaneously with the Wien filter switched on. In a single counting cycle the statistical error of the measured polarization was about ±0.05 (signal counting rates between 150 and 3 s^{-1}). Twelve to twenty-five of such cycles were averaged to give the final polarization values with a statistical error of about ±0.01.

(iii) In order to check the stability of the source the primary polarization was remeasured at the end of the procedure.

For elimination of instrumental asymmetries, the primary polarization $\vec{P}$ has been reversed in each counting cycle by using left- and right-circularly polarized light striking the GaAs crystal. As the instrumental asymmetry for the component $S\hat{n}$ cannot be eliminated in this way [cf. Eq. (5)], the Sherman function S has been measured in the conventional way by double scattering of unpolarized electrons.[1]

The results for S, T, and U are shown in Fig. 2 at a scattering angle $\theta = 60°$ in comparison with the best theoretical results presently available for heavy atoms. They are based upon Walkers's[7]

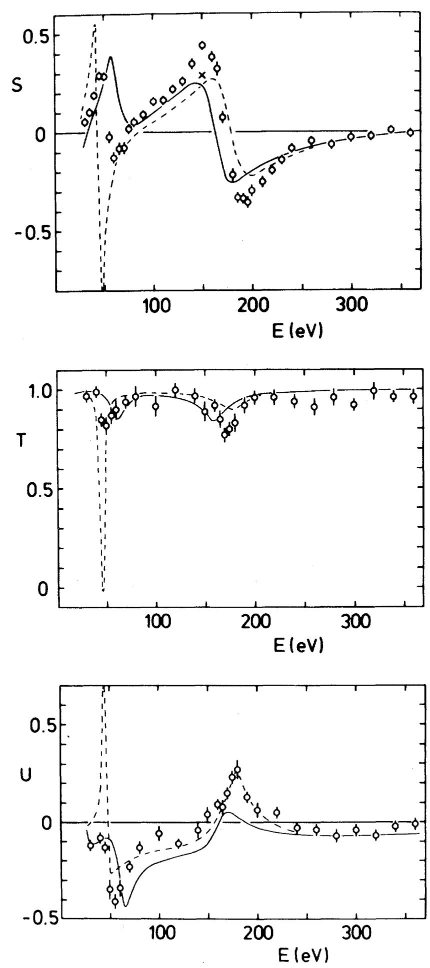

FIG. 2. Energy dependence of the parameters S, T, and U at the scattering angle $\theta = 60°$. Experimental points with single statistical error. Theoretical curves: relativistic calculations (Ref. 7) including exchange (solid curve) and charge-cloud polarization plus exchange (dashed curve).

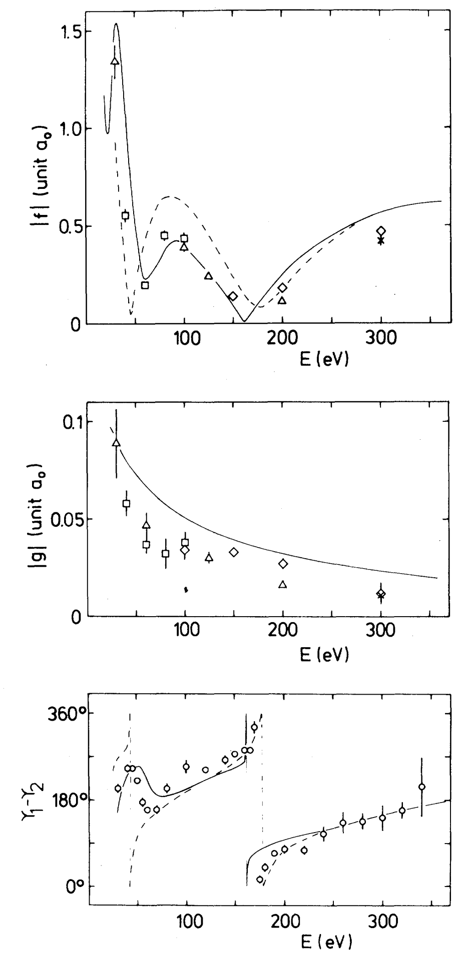

FIG. 3. Evaluation of the complex scattering amplitudes for $\theta = 60°$. The error bars give the single statistical error (where no error bars are given they are, according to the authors, smaller than the size of the symbols denoting the experimental points). The following cross sections have been used for the evaluation: crosses, Jost, Fink, and Herrmann (Ref. 12) normalized to Bromberg (Ref. 8); triangles, Williams and Crowe (Ref. 9); diamonds, Jost, Fink, and Herrmann (Ref. 12) normalized to Jansen and de Heer (Ref. 10); squares, Holtkamp (Ref. 11). In the diagram of $|g|$ both theoretical curves agree nearly within the line width.

relativistic scattering calculations taking account of exchange interaction between the scattered electron and the atomic electrons. The dashed curve includes additionally charge-cloud polarization of the atom by the scattered electron. The theoretical curves have been convoluted with the angular resolution $\Delta\theta = \pm 2^\circ$ of our apparatus. When comparing experimental and theoretical results, it should be taken into account that the peaks of the curves between 130 and 200 eV are strongly affected by the convolution.

It is seen that the qualitative agreement between the theoretical and experimental data is generally good though, quantitatively, there are significant discrepancies, especially in the low-energy range.

Figure 3 gives the results of the evaluation of the scattering amplitudes for the scattering angle of 60°, obtained from Eqs. (1) to (4). Evaluation of $|f|$ and $|g|$ requires knowledge of the absolute cross section $d\sigma/d\Omega(60^\circ)$ [cf. Eq. (1)] which has been measured by different groups. Of the absolute cross-section measurements that have been used for the evaluation,[8-11] two (Refs. 8 and 10) do not comprehend the scattering angle studied here. The cross sections of these authors have been completed by normalizing relative cross sections $d\sigma/d\Omega(\theta)$ measured by our group (Jost, Fink, and Herrman[12]) to their values so as to extend them to $\theta = 60^\circ$. Because experimental cross sections are available only at a limited number of energies, the number of experimental data is smaller in the diagrams of $|f|$ and $|g|$ than in the $\gamma_1 - \gamma_2$ diagram in which not the differential cross section but only the ratio of S and U is involved [cf. Eqs. (2) and (4)]. The theoretical $\gamma_1 - \gamma_2$ curves have been calculated from the S and U curves after convolution with $\Delta\theta = \pm 2^\circ$ whereas the curves of $|f|$ and $|g|$ have not been convoluted because the various authors had different angular resolutions in their cross-section measurements. Similar measurements and evaluations have been made at $\theta = 80^\circ$.

Now that the maximum possible information on elastic electron scattering from the xenon atom has been obtained, it turns out that present theories describe only certain aspects of the scattering process (like the energy dependence in a certain range) satisfactorily. While scattering calculations for simpler atoms, such as helium, are feasible today on the basis of sophisticated theoretical models, the procedure which properly reproduces all the observables of the scattering process of heavy atoms like xenon is still to be developed.

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[1]J. Kessler, *Polarized Electrons* (Springer, Berlin, 1976).

[2]R. J. Celotta and D. T. Pierce, Adv. At. Mol. Phys. 16, 101 (1980).

[3]K. Bartschat, G. F. Hanne, and A. Wolcke, Z. Phys. A 304, 89 (1982).

[4]T. W. Ottley and H. Kleinpoppen, J. Phys. B 8, 621 (1975).

[5]H. D. Zeman, K. Jost, and S. Gilad, Rev. Sci. Instrum. 42, 485 (1971).

[6]N. Hebing, Diplomarbeit, Universität Münster, 1981 (unpublished).

[7]D. W. Walker, Adv. Phys. 20, 257 (1971), and private communication. Calculations in which exchange and charge-cloud polarization are not included [see, e.g., M. Fink and A. C. Yates, At. Data 1, 385 (1970)] are not considered here because they do not fit the experimental data below 100 eV.

[8]J. P. Bromberg, J. Chem. Phys. 61, 963 (1974).

[9]J. F. Williams and A. Crowe, J. Phys. B 8, 2233 (1975).

[10]R. H. J. Jansen and F. J. de Heer, J. Phys. B 9, 213 (1976).

[11]G. Holtkamp, Diplomarbeit, Universität Münster, 1981 (unpublished).

[12]K. Jost, M. Fink, and P. Herrmann, in *Proceedings of the Eighth International Conference on the Physics of Electronic and Atomic Collisions, Belgrade, Yugoslavia, 1973, Abstracts of Papers*, edited by B. C. Cobic and M. V. Kurepa (Institute of Physics, Belgrade, Yugoslavia, 1973), p. 277.