Iron-cored coil system for the measurement of angular distributions of charged particles

D. Cubric, a) R. Ward, G. C. King, and F. H. Read

Department of Physics and Astronomy, Schuster Laboratory, Manchester University, Manchester M13 9PL, United Kingdom

(Received 10 February 2000; accepted for publication 17 May 2000)

A novel coil system is described that enables the magnetic angle-changing technique to be used at higher energies. The system consists of coils of wire that are combined with specially shaped iron cores in such a way as to preserve localization of the magnetic field. The system extends the operational energy range of previous systems consisting of solenoids alone by a factor of 25.

Measurements of the electron impact excitation of the $n=2$ states of helium are presented as an example of the use of the device. © 2000 American Institute of Physics.

I. INTRODUCTION

Recently a new “magnetic angle-changing technique” has been described 1,2 for measurements of the angular distributions of charged particles in atomic and molecular physics. This technique involves the production of a magnetic field, localized in the vicinity of the interaction region, that is used to change the angles of electron trajectories in a controlled manner. The technique has been successfully applied to angular distribution measurements over the full angular range for the $n=2$ excited states of He and also to measurements of photoelectron angular distributions. 3,4

The magnetic field in those experiments was produced by a set of solenoids. They had a typical radius of 15 mm. The strength of the magnetic field that could be produced by these solenoids was limited by overheating in the vacuum environment and by the physical size of the coils. This limited the angular change attainable at electron energies above about 50 eV. These limitations are overcome in the improved design described here that combines an iron core with the solenoids while still preserving magnetic field localization. The system significantly extends the range of electron energies that can be used in angle-changing experiments.

II. PRINCIPLES OF THE MAGNETIC ANGLE-CHANGING TECHNIQUE

In this technique a localized magnetic field is used to change the direction of electrons before they reach a target and to change the direction of electrons produced or scattered at the target, which has been a gas beam in the existing applications. It is necessary for the field to be localized in the region of the target in order not to disturb the action of electrostatic devices that are used for energy selection or analysis. In the previous applications of the technique 1–4 the magnetic field has been produced by concentric iron-free solenoids and the localization has been achieved by ensuring that the overall magnetic dipole moment of system is zero (see below). Because the overall magnetic quadrupole moment of a system of cylindrical solenoids is automatically zero, 1 the external magnetic field then decreases asymptotically as the inverse fifth power of the distance from the center of the system.

Another important feature of the technique is that an electron beam that is initially directed towards the central axis of the system of solenoids still passes through that axis after deflection by the field. The reason for this 1 is that for an axially symmetric field the generalized momentum $\mathbf{p}_f$ is a conserved quantity, the value of which is zero in the external region and is also zero at the axis. Similarly, electrons originating at the axis will move radially away from the axis in the external region, after deflection by the field. The presence of the localized field therefore does not require any realignment of the electron source or analyzer.

The change in direction of trajectory in going from the external region to the axis, or vice versa, clearly depends on the electron energy and the strength and shape of the magnetic field. This has been discussed by Read and Channing, 1 who have also considered the optical properties and aberrations of some particular systems.

III. PRINCIPLES OF THE DESIGN OF THE IRON-CORED SYSTEM

In an iron-free system the magnetic dipole moment for a set of circular loops or solenoids is proportional to

$$D = \sum_i I_i R_i^2,$$  (1)

where $I_i$ is the current, $R_i$ the radius of a loop or turn, and the subscript $i$ labels separate turns. The attainment of a zero magnetic dipole moment can therefore be achieved with two solenoids of different radii and appropriate currents flowing in opposite directions. For the iron-cored system that is the subject of the present study we still require a zero value for the overall magnetic dipole moment of the system. Our approach is necessarily more pragmatic, although we still expect Eq. (1) to provide an indication of the required currents.

a)Electronic mail: dane.cubric@srlab.ac.uk

0034-6748/2000/71(9)/3323/3/$17.00 3323 © 2000 American Institute of Physics

Downloaded 09 Oct 2002 to 130.88.237.145. Redistribution subject to AIP license or copyright, see http://ojps.aip.org/rsio/rsicr.jsp
Figure 1 shows a cross section through the present iron-cored coil system: only a quarter of the system is presented for the sake of clarity. The outer radius is 15 mm and the length of each section is approximately 12 mm. It is reasonable to make the coils shorter than their radius as the magnetic field in the small gap between the coils is not increased significantly by making the coils longer. The axial component $B_z$ of the magnetic field of the basic building element of the coil system, a single circular loop, is given by

$$B_z(z, \rho, R, I) = \frac{\mu_0 I}{4\pi} \int_0^{2\pi} \frac{R^2 - \rho R \cos(\varphi)}{[\rho^2 + z^2 + R^2 - 2\rho R \cos(\varphi)]^{3/2}} d\varphi,$$

where $R$ is the radius of the loop and $z$ and $\rho$ are cylindrical coordinates representing, respectively, the axial and radial distances to the center of the loop.

The dashed line in Fig. 2 shows the axial component of the magnetic field across the gap for our system calculated using Eq. (2) and summing over the separate turns of the solenoids. The positions of the two solenoids are also represented at the top of Fig. 2 and the directions of the electric currents are indicated. The magnetic field (multiplied by a factor of 5, for further comparison) is plotted for a current of 1 A through the inner solenoid and a current of $-0.772$ A through the outer solenoid. This ratio of currents together with the given geometry satisfies the condition, Eq. (1). The field is seen to be well localized and has a positive direction close to the central axis and a negative direction at a distance of about 12 mm from the axis.

The material used to increase the magnetic field is soft iron with a magnetic permeability of about 1000. The magnetic hysteresis curve for soft iron is very narrow and therefore it can be considered as a linear magnetic material. Figure 2 also shows the magnetic field obtained with the complete system consisting of coils and iron cores. The positions of the iron cores are shown at the top of the diagram by gray rectangles. The current through the coil was set the same as above and the magnetic field in the gap was measured using a small magnetometer probe.

The variation of the magnetic field with radial distance is similar for the two configurations. Essentially the use of the iron in this configuration has multiplied the magnetic field by a factor of 5 while preserving field localization. The curvature of the trajectory of a charged particle of kinetic energy $E$ depends on the magnetic field $B$ it experiences as $B^2/E$. This means the present system is capable of handling electron energies 25 times larger than a similar system without the iron cores. This increases the maximum electron energy of the present device to a few keV, depending on the magnitude of the desired change in angle.

IV. DISCUSSION

The performance of the coils has been tested by making electron impact studies of the $n = 2$ states of helium. Figure 3 shows two energy loss spectra for scattering angles of 0° and 180° at incident electron energy of 120 eV. The electron detector was kept at 90° with respect to the incident beam direction and an angular shift of ±90° was introduced using the coils.
plied to the inner solenoid to produce an angular shift in the scattering angle of ±90°. The currents used to obtain the spectra were well below the 5 A current limit imposed to prevent the solenoids overheating. The localization of the magnetic field is confirmed by the fact that activation of the target field did not affect the operation of the energy selector and analyzer.

The apparatus was also used to obtain excitation functions for the 23S and 21S states of helium. This involved scanning the incident and collection energies of the spectrometer. Figure 4 shows the results obtained. Excitation functions for the 23S and 21S states are shown in the region between 56 and 59 eV at angles of 0°, 90°, and 180°. The electric current required to obtain a 90° angular shift at the given incident energies was only 0.29 A. Prominent structures in the excitation function spectra correspond to the triply excited negative He resonances 2s2p2P and 2s2p22D. These are the first measurements of these resonances in a backward direction of 180°. Details of theoretical and experimental work dealing with the He− resonances can be found in recent publications.5,6

The results obtained using a novel iron-cored system for electron angular distribution measurements show that this system significantly extends the electron energy range of the magnetic angle-changing technique. The device is made using specially shaped iron cores and solenoids combined in such a way as to preserve good magnetic field localization. The performance of the system has been tested by measuring electron impact excitation of the helium n = 2 states. The coil system allows measurements in the full angular range from 0° to 180° for electron energies up to a few keV.

ACKNOWLEDGMENT

The authors thank the UK Engineering and Physical Sciences Research Council for financial support for these studies.


FIG. 4. Excitation functions for the 23S and 21S states in the 56–59 eV energy range at 0°, 90°, and 180°. Prominent structures in the excitation function spectra correspond to the triply excited negative He resonances 2s2p2P and 2s2p22D. The background signal has been subtracted but the relative strength of the resonance features has been preserved for comparison.