in Eq. (11) would be to measure the ratio of g factors for two atoms with different Z. For example a measurement of the hydrogen-to-helium (singly ionized) ratio to one part in 10^8 would determine the coefficient to about 10%.

The author would like to thank Professor S. J. Brodsky and Professor D. Kleppner for early discussions which stimulated interest in this work. He would also like to acknowledge useful telephone conversations with Professor R. A. Hegstrom. Finally, the author also wishes to express his appreciation to S. McDaniel for checking one of the calculations and to Professor R. M. Herman for reading the manuscript and for making some helpful suggestions.

---

[1]W. M. Hughes and H. G. Robinson, Phys. Rev. Letters 23, 1209 (1969); D. J. Larson, P. A. Valberg, and N. F. Ramsey, Phys. Rev. Letters 23, 1369 (1969).

[2]R. A. Hegstrom, Phys. Rev. 184, 17 (1969).

[3]Z. V. Chraplyvy, Phys. Rev. 91, 388 (1953), and 92, 1310 (1953); W. A. Barker and F. N. Glover, Phys. Rev. 99, 317 (1955).

[4]The expansion referred to is essentially a two-body generalization of the Foldy-Wouthuysen expansion for a single particle. See L. L. Foldy and S. A. Wouthuysen, Phys. Rev. 78, 29 (1950).

[5]S. J. Brodsky and J. R. Primack, Ann. Phys. (N.Y.) 52, 315 (1969).

[6]E. H. Lieb, Phil. Mag. 46, 311 (1955).

[7]S. J. Brodsky and G. W. Erickson, Phys. Rev. 148, 26 (1966).

[8]According to Brodsky and Erickson (Ref. 7) [Eqs. (C1) and (C2)] and earlier work on p. 882 of N. M. Kroll and F. Pollock, Phys. Rev. 86, 876 (1952), the vacuum-polarization contribution is

$$\frac{\alpha}{2\pi}\left\langle \beta \vec{q}^2 \int_0^1 dv \frac{2v^2(1-v^2/3)}{4m^2+\vec{q}^2(1-v^2)} \vec{\gamma}\cdot\vec{A}(\vec{q}) \right\rangle .$$

For a constant magnetic field, $\vec{A}(\vec{q}) \sim \vec{H}\times\nabla_q \delta^3(\vec{q})$. Because of the presence of $\vec{q}^2$ in the numerator, terms involving $\vec{A}(\vec{q})$ give zero. The magnetic field dependence arising from the $A_0(\vec{q})$ term turns out to contribute to order $\alpha(Z\alpha)^4$. Lieb has used a different Coulomb gauge in which $A_i(\vec{q}) \sim H\delta(q_x)\delta'(q_y)\delta(q_z)\delta_{i1}$. However, it is readily seen that the above result will also be zero for this choice as well. We believe that Lieb obtained a nonzero result $[(4/15\pi)\alpha(Z\alpha)^2]$ by using Eq. (40) of Kroll and Pollock instead of the above expression. Equation (40) of the aforementioned work is an approximation which is valid for the purpose of calculating $\alpha(Z\alpha)$ corrections to the hyperfine splitting, but is not accurate enough for obtaining $\alpha(Z\alpha)^2$ corrections to the Zeeman effect.

[9]The large components are essentially unaffected. There is, however, a normalization correction linear in the magnetic field, but it does not affect the calculations done here.

[10]The $-(26/15\pi)\alpha(Z\alpha)^2$ term gives the binding correction from lowest-order radiative corrections, as calculated by Lieb. It is clear that there is a discrepancy between this number and the result of our Eq. (9), which represents the complete radiative correction as calculated here. We have discussed the origin of part of this discrepancy in footnote 8. Our results also disagree with those of Lieb for terms of type (A) discussed above (i.e., vertex corrections).

[11]R. A. Hegstrom, Phys. Rev. (Erratum, to be published).

ENERGY SPECTRA OF ELECTRONS FROM AUTOIONIZATION STATES IN HELIUM BY ELECTRON IMPACT

N. Oda, F. Nishimura, and S. Tahira*
Research Laboratory of Nuclear Reactor, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan
(Received 17 November 1969)

Energy spectra of electrons ejected from autoionization states in helium excited by electron impact have been measured at bombarding energies from 65 to 250 eV as a function of the angle to the primary electron beam.

The height of peaks of the energy spectra due to optically forbidden transitions from the ground state compared with those due to optically allowed transitions increases as the impact energy is reduced; this trend was most marked for the triplet-state $(2s2p)^3P$ excitation.

Certain autoionizing states of helium have been observed by optical absorption,[1] by electron energy-loss measurements of forward-scattered electrons,[2-4] and by energy-spectra measurements of ejected electrons from states excited by ion impact.[5,6] In this paper we show part of the observations on these states by the measurements of the energy spectra of electrons ejected after bombardment with electrons as a function of the impact energy as well as of the ejected angle.[7] Mehlhorn[8] has previously observed autoionization of helium by this electron-impact

method, but this measurement lacked the resolution necessary to identify the states and was made only at fixed and somewhat higher impact energy (4 keV) and at a fixed angle (54°). While it was shown[5,6] that some of the states which were weak or absent in the other techniques showed up clearly by the ion-impact method, results reported here also show the states as clearly as the ion-impact method.

It is especially interesting to compare the spectra by electron impact with those by molecular-ion impact, particularly for the triplet-state excitation [e.g., $(2s2p)^3P$]. A transition from the ground state (with spin zero) to the triplet state (with spin 1) can only be accomplished by interchanging an electron from an impinging particle with one of the orbital electrons of helium. For molecular-ion impact, for instance, a molecular-hydrogen ion H_2^+ can excite that state but a proton cannot, whereas an impinging electron itself can exchange with one of the bound electrons when the impact energy is close to the excitation energy of the triplet state. The most important difference between the H_2^+ impact and the electron-impact excitations is that a bound electron of H_2^+ contributing to the exchange collision has a momentum distribution and this characteristic should be observed in the energy spectra of ejected electrons.

A schematic representation of the experimental arrangement is given in Fig. 1. The equipment was designed to make measurements of the angular and energy dependence of the cross sections for ejection of electrons from gases by electron bombardment. The apparatus consists of three parts which are separately pumped by three independent diffusion-pump systems: an

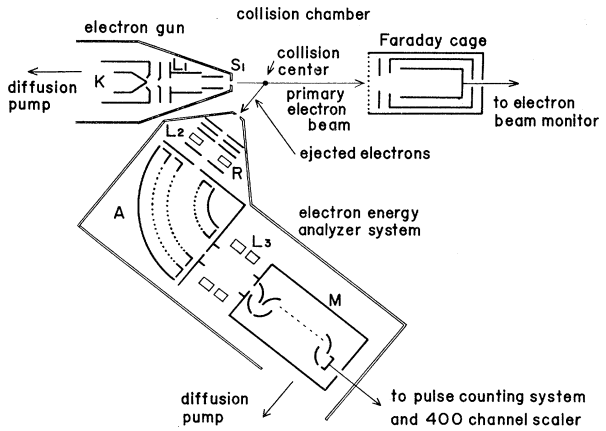

FIG. 1. Schematic diagram of the experimental arrangement. For details see text.

electron gun, a collision chamber filled with gases, and an electron energy analyzer system. Electrons from a filament K are accelerated to a definite energy, collimated by the lens system L_1 and the exit slit S_1, injected into the collision chamber, and monitored by means of a Faraday cage. After collision the ejected electrons are injected into the 90° cylindrical electrostatic energy analyzer A through a lens system L_2. Energy-selected electrons are accelerated by the lens system L_3 and are focused onto the electron multiplier M. The electron energy analyzer system can be rotated in the angular range from −90° to +140°. Individual electrons were counted and registered on the 400-channel scaler. The helium pressure in the collision chamber was about three microns Hg for the measurement reported here. The electrons were decelerated to a constant energy (11 eV) by varying the retarding field R in the lens system L_2, resulting in an energy resolution of about 0.20 eV. The energy of the peaks of energy spectra could be determined to within about 0.05 eV by this method.

As a typical example, the energy spectra of ejected electrons observed at a 140° angle with respect to the primary beam are shown in Fig. 2 for various impact energies. The energy of the ejected electrons differs from the excitation energy by the ionization potential of helium, 24.58 eV. The precise designations of the energy levels of the exicted states are rather difficult because the measured energies of the lines depended systematically on the gas pressure as well as the beam current, principally because of the space-charge effect discussed by Rudd[5,6]; furthermore, the positions of observed resonance peaks are generally shifted from the real positions of the autoionization levels due to the asymmetric line profiles for the excitation of these states[8,9] as well as because of the overlapping of the tails of neighboring peaks. Therefore, the 60.13-eV value[11] for the $(2s2p)^1P$ level measured by Madden and Codling[1] was used to calibrate one point of the energy scale and the rest of the energy scale was calibrated with the value of the retarding field R. The validity of this calibration method was carefully tested by several methods and the energies determined in this way are believed to be accurate to within about 0.05 eV. The positions of the levels identified by our measurement are marked on the graph. From this figure, one can see that the height of peaks of the energy spectra due to optically forbidden transitions from the ground state

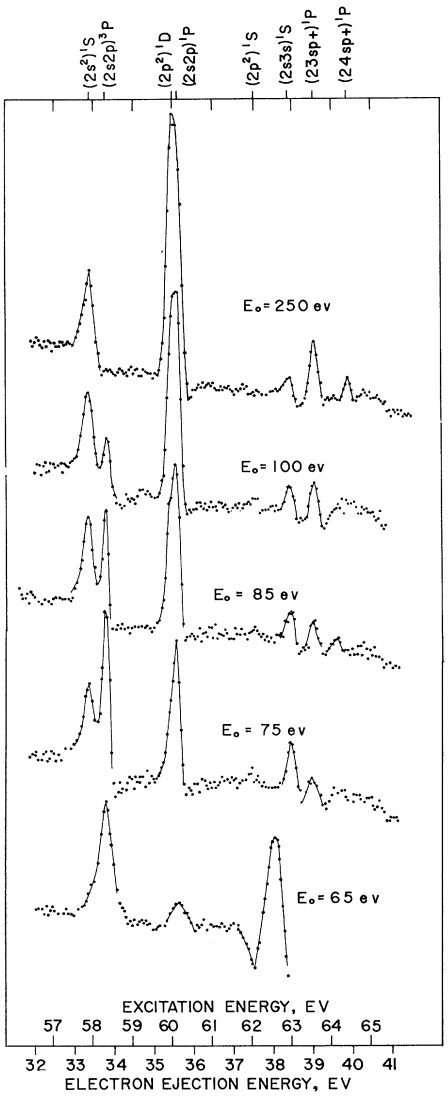

FIG. 2. Energy spectra (arbitrary units) of electrons ejected at 140° angle from helium excited by electron impact. Primary energies are shown on curves. The positions of levels identified in this measurement are marked on the graph. The primary-beam current is about 20 μA.

compared with those due to optically allowed transitions increases as the impact energy is reduced, and this trend is most marked for the triplet state $(2s2p)^3P$ excitation, as was expected. The two levels $[(2p_2)^1D$ and $(2s2p)^1P]$ in the 59.8-60.2 eV excitation-energy range cannot be visibly separated on the curves given in Fig. 2.

For the purpose of seeing the energy spectra in this range more precisely, higher-resolution energy spectra observed in the forward angle (30°) as well as in the backward angle (140°) are shown in Fig. 3. Here, the two levels mentioned

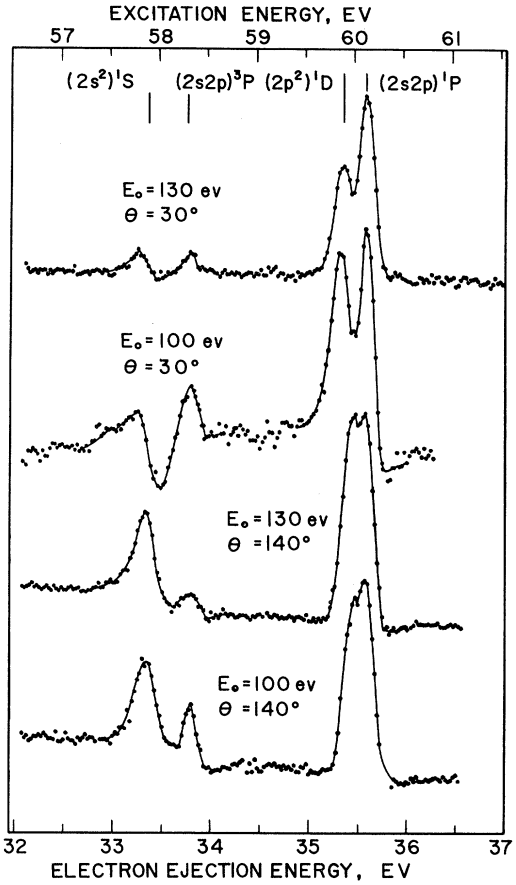

FIG. 3. Higher-resolution energy specta of electrons ejected at 30° and 140° angles from helium excited by electron impact. Primary energies are shown on curves.

above are visibly separated and the separation becomes much more marked in the forward direction than in the backward direction. The relative height of the $(2s2p)^3P$ peak compared to the $(2s2s)^1S$ peak is greater in the forward direction than in the backward direction.

The values of the peaks observed and identified in this measurement are as follows: $(2s^2)^1S$, 57.9 eV; $(2s2p)^3P$, 58.3 eV; $(2p^2)^1D$, 59.9 eV; $(2s2p)^1P$, 60.13 eV (taken from Madden and Codling[1]); $(2s3s)^1S$, 62.8 eV; $23sp+$, 63.5 eV; $24sp+$, 64.4 eV.

---

*On leave from Department of Physics, Kyoto University, Kyoto, Japan.

[1]R. P. Madden and K. Codling, Astrophys. J. 141, 364 (1965).

[2]J. Arol Simpson, S. R. Mielczarek, and J. Cooper, J. Opt. Soc. Am. 54, 269 (1964).

[3]S. M. Silverman and E. N. Lassettre, J. Chem. Phys. 40, 1265 (1964).

[4]J. Arol Simpson, G. E. Chamberlain, and S. R. Mielczarek, Phys. Rev. 139, A1039 (1965).
[5]M. E. Rudd, Phys. Rev. Letters 13, 503 (1964), and 15, 580 (1965).
[6]M. E. Rudd and D. V. Lang, in Abstracts of the Fifth International Conference on the Physics of Electronic and Atomic Collisions (Science Bookcrafters, Inc., Hastings-on-Hudson, New York, 1965), p. 153.
[7]Experimental details and full results on the energy and angular spectra of ejected electrons will be given in a forthcoming paper.
[8]W. Mehlhorn, Phys. Letters 21, 155 (1966).
[9]U. Fano, Phys. Rev. 124, 1866 (1961).
[10]U. Fano and J. W. Cooper, Phys. Rev. 137, A1364 (1965).
[11]A. K. Bhatia and A. Temkin, Phys. Rev. 182, 15 (1969). See Table V of this paper for the derivation of the theoretical resonance position from the position of the maximum of the absorption curves given by Madden and Codling.

RAMSAUER EFFECT AS A RESULT OF THE DYNAMIC STRUCTURE OF THE ATOMIC SHELL

Michał Gryziński
Institute of Nuclear Research, Świerk k.Otwocka, Poland
(Received 28 July 1969)

We show a way of attacking elastic atomic collisions on the grounds of classical physics.

The Ramsauer effect is commonly recognized as inherently connected with the "wave" properties of matter and as constituting a conspicuous example of the uselessness of the deterministic concepts of classical physics as regards microcosmic phenomena.[1] Attempts undertaken in the twenties to explain this effect and, moreover, to construct a classical theory of elastic low-energy atomic collisions have, despite the discovery of certain regularities, entirely failed. It now appears that this failure was the result of inconsistencies committed within the framework of classical physics itself.

It is evident that the conglomerate of charges formed by a positively charged nucleus (nuclei) and electrons can, according to Coulomb's law and Newtonian dynamics, remain in a state of dynamic equilibrium only. The resulting time-varying field of such a conglomerate, if expanded as a power series in terms of the distance from the system, can be completely described by a set of coefficients, both independent and varying with time, which are closely related to the multipole moments of the system. Using the results of the potential theory and Fourier analysis, the series determining the field of such a system can be expressed in the form

$$\varphi(r,\theta,\phi,t)=\sum_k\sum_n \frac{A_{nk}(\theta,\phi)}{r^n}e^{-i\omega_k t}, \tag{1}$$

where A_{nk} represents the component corresponding to the frequency ω_k in the Fourier expansion of a multipole moment of the nth order.

Approximate analysis of the scattering problem, performed on the basis of classical small-angle deflection theory,[2] leads to the following expression for the scattering angle Θ arising from the presence of the term A_{nk}:

$$\tan\Theta \propto \frac{A_{nk}}{D^{n+1}v^2}e^{-\omega_k D/v}, \tag{2}$$

where D is the collision parameter, and v is the scattered particle velocity. It is evident from the above that, irrespective of the multipole order involved, there exists a limit to the interaction range of the scattering. This limit is determined by the frequency of the system. It is easy to show on the basis of the small-angle approximation that the results of scattering on a dynamic system are formally the same as in the case of a system with a potential

$$\varphi \propto \frac{1}{r^n}e^{-r/r_0} \tag{3}$$

with r_0 being dependent on v. This allows one to suppose that the short range interactions – that is, interactions diminishing exponentially with distance – reflect the dynamic, periodic in time, structure of scattering objects.

Having the relation between the angle Θ and the collision parameter D as given by Eq. (2), one can easily derive a formula for the elastic-scattering cross section:

$$Q_{sc} \propto 1/v^{4/(n+1)} \text{ for } v > v_1,$$
$$\propto v^2 \text{ for } v < v_1, \tag{4}$$

where the boundary velocity v_1 depends on the frequency of the system,

$$v_1 \propto \omega_k.$$