Inelastic Electron Scattering by Helium Atoms

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The angular distribution of electrons scattered by helium atoms when the electrons have lost 21.12 volts energy, thereby exciting the atom to the 2^1P state, has been studied for energies between 27.5 and 400 volts and over an angular range from 6° to 150° in most cases. For the higher energies the angular range over which measurements could be made was less, e.g., for 400 volt-electrons measurements could not be made beyond 22°. The higher the original energy of the electrons, the less the number of electrons scattered with a 21.12 volt energy loss, and the steeper the angular distribution curve. For the lower energies (below about 100 volts) the curves fall gently to about 60° and then become practically flat up to 150°. One curve is given for the distribution of 42 volt-electrons which have lost 22.97 volts energy (excitation to the 3^1P state) and another for 400 volt-electrons which have lost 25 volts energy (thereby ionizing the atom). Comparisons are made between the experimental results and theories proposed by Morse and by Massey and Mohr. A very direct comparison is possible with the theory of Massey and Mohr and a very satisfactory agreement is found.

INTRODUCTION

THE electrons scattered by atoms fall into two classes: Those which are scattered elastically and those which are scattered inelastically. The former all have one and the same energy, equal to that which they had before collision; the latter have lower energies distributed over a wide range. For each possible excited state of the atom there will be a correspondingly discrete energy loss; in addition there will be, in those cases where ionization occurs, a continuous distribution of energy losses depending on the way the energy left over after ionizing the atom is shared between the ionizing electron and the ejected electron. The four lowest energy losses occurring in collisions between electrons and helium atoms are the 19.77, 20.55, 21.12 and 22.97 volt losses, corresponding to excitation of the atom to the 2^3S, 2^1S, 2^1P and 3^1P states, respectively. These have been discovered in experiments designed specially to detect their existence. They are of course given by the spectral terms as well. Theoretical investigations have been made to predict the angular distribution of the electrons which have given rise to any one excited state. It is desirable to check such predictions by experiment. In experiments made to study the angular distribution of electrons after exciting the atom to one particular state, the electron thereby losing a definite amount of energy, certain factors unfortunately hamper the carrying out of systematic measurements on more than a very few energy losses. One factor is the difficulty of resolving energy losses which are separated by less than about 0.5 volt; another is the lack of intensity in the inelastically scattered electron beams. Thus even with the most probable energy loss, 21.12 volts, the number of 200 volt-electrons scattered through an angle greater than about 30° becomes too small to be measured.

Little work has been done in the field of inelastic scattering. McMillen[1] found that when 100 volt-electrons collide with helium atoms, the number of those which lost 21.12 volts energy diminished with extraordinary rapidity with increasing angle from 10° to 30°, beyond which it was too small to measure. Mohr and Nicoll[2] studied the angular distribution of 54 to 196 volt-electrons over the range 15° to 150°, after they had lost 21.12 volts energy in collision with helium atoms, thus leaving them in the 2^1P state. For those electrons which left the helium atom in the 3^1P state (energy loss, 22.97 volts) they gave

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[1] J. H. McMillen, Phys. Rev. **36**, 1034 (1930).

[2] C. B. O. Mohr and F. H. Nicoll, Proc. Roy. Soc. **A138**, 469 (1932).

the distribution between 20° and 50°, for one primary energy, 83 volts. Van Voorhis[3] has published a preliminary abstract describing results of scattering experiments in the small angle region 0° to 15°. The primary electrons had energies varying from 100 to 300 volts, and the scattered electrons selected for study were those which had lost 21.12 volts.

Apparatus and Method

The apparatus used in this investigation was that used by us[4] in a recently published article on *Elastic Scattering in Neon.* For a description of the apparatus the reader is referred to that article. The only difference was that the slit S_2 was absent, and in front of the slit S_1 there was a grid of fine wires. By placing a retarding field between the grid and S_1 it was possible to slow down the electrons passing into the analyzer and simultaneously to decrease the angle within which the scattered electrons had to be to enter the analyzing chamber. Further details concerning the use of such a field will be found in our paper on argon.[5] When the primary energies were 400 and 200 volts, the electrons were slowed down to 50 volts energy in the analyzer. For lower primary energies, this was unnecessary, as sufficient intensity could be obtained without any retarding field between the grid and analyzer.

Results and Discussion

The number of electrons scattered per unit solid angle, after losing 21.12 volts in collisions with helium atoms, is given in Table I as a function of the angle and the primary electron energy. The values are all in terms of the same arbitrary unit. It should be stated that this unit is identical with the one used in our paper on the elastic electron scattering in helium[6] and therefore it is possible to effect a quantitative comparison between the elastic and the inelastic scattering. The angular distributions of electrons which have lost 21.12 volts energy in collisions with helium atoms are shown in Figs. 1 and 2, the different curves corresponding to the various electron energies before collision. It is very evident how the scattering, especially at medium and large angles, falls off very rapidly with increasing primary energies when these exceed 50 or 100 volts. For lower energies, it is noteworthy

[3] C. C. Van Voorhis, Phys. Rev. **43**, 777 (1933).

[4] A. L. Hughes and J. H. McMillen, Phys. Rev. **43**, 875 (1933).

[5] A. L. Hughes and J. H. McMillen, Phys. Rev. **39**, 585 (1932).

[6] A. L. Hughes, J. H. McMillen and G. M. Webb, Phys. Rev. **41**, 154 (1932).

Table I. *Angular distribution of scattered electrons which have lost 21.12 volts energy.*

$\theta°$ \ V	27.5	30	35	42	50
6°	....	(129.0)	(140.0)	....	....
8°	204.0	113.8	128.5	131.0	222.0
10°	183.2	105.2	118.0	122.0	195.8
12.5°	150.1	97.5	105.0	109.0	162.8
15°	127.0	89.0	92.2	96.2	126.5
20°	106.0	77.0	73.2	67.9	79.0
25°	95.5	66.8	53.3	48.2	48.9
30°	87.0	55.7	41.2	32.8	32.0
35°	79.0	46.5	33.5	26.0	22.6
40°	72.7	40.5	28.2	21.1	16.2
45°	66.3	37.1	24.2	17.8	13.4
50°	63.2	35.3	20.9	15.7	11.7
60°	56.8	33.8	17.7	13.1	9.6
70°	56.3	33.0	15.6	11.2	7.8
80°	56.2	32.5	15.0	10.2	6.4
90°	56.2	31.4	14.9	9.72	5.83
100°	55.3	30.7	14.5	9.48	5.83
110°	55.3	30.7	14.1	9.40	5.83
120°	55.3	30.7	13.6	9.37	5.83
130°	55.3	30.0	13.1	9.13	6.02
140°	55.3	28.0	12.1	9.02	6.12
150°	55.3	24.6	11.6	8.90	5.64

$\theta°$ \ V	100	200	400
6°	238.0	140.5	40.00
8°	164.0	100.0	25.6
10°	107.5	58.5	15.4
12°	71.2	29.9	9.50
14°	51.9	16.4	5.08
16°	35.7	8.97	2.68
18°	27.8	5.46	1.60
20°	21.1	3.43	0.80
22°	....	2.21	0.28
24°	....	1.30	
25°	8.45		
30°	4.57		
35°	3.17		
40°	2.36		
45°	1.76		
50°	1.41		
55°	1.21		

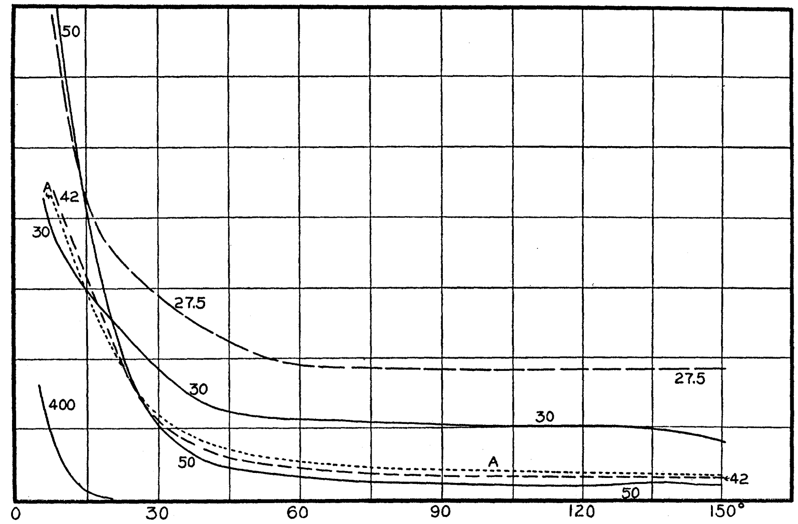

FIG. 1. Angular distribution curves for electrons losing 21.12 volts energy. Electron energy (before collision) indicated on each curve. Curve A is for 42 volt-electrons losing 22.94 volts at collision. Scale for ordinates of curve A is $\frac{1}{3}$ that of other curves.

that the scattering becomes almost independent of the angle in the middle range, 50° to 150°. In Fig. 1, curve A is the angular distribution curve for 42 volt-electrons, which, on colliding with the helium atoms, excite them to the 3^1P state, (thereby losing 22.94 volts energy). It should be noted that the units for the ordinates for curve A are three times smaller than those for the other curves. In Fig. 2 we have plotted as a dotted line the angular distribution of 400 volt-electrons which have lost 25 volts energy in collisions with atoms, thereby ionizing them. It will be noticed that this angular distribution curve is considerably less steep than the corresponding one for the 21.12 volt loss. This characteristic is in agreement with that found under similar circumstances in argon.

Mohr and Nicoll[2] find a maximum at 60° for 54 volt-electrons. There is no indication of a maximum in our corresponding curve. There is fair agreement between their curves and ours for electrons of higher energies, except at small angles where the differences between the curves become larger.

Morse[7] has studied electron scattering from a theoretical standpoint, and has obtained an expression

$$\alpha_i(\mu) = \frac{e^4 m}{4h^2}\left[\frac{1}{Z}\left(1-\frac{F^2}{Z^2}\right)\right]\frac{Z^2}{\mu^4} \qquad (1)$$

for the *total* inelastic electron scattering, where e

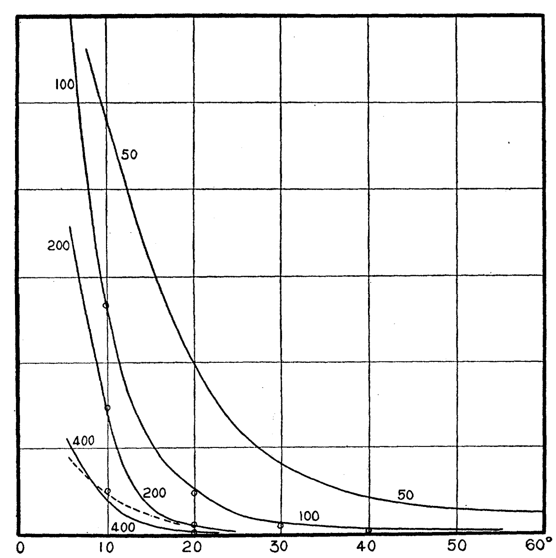

FIG. 2. Angular distribution curves for electrons losing 21.12 volts energy. Electron energy (before collision) indicated on each curve. Dotted curve is for 400 volt-electrons which have ionized the atom. Circles denote Massey and Mohr's computed values for the 400, 200 and 100 volt curves.

[7] P. M. Morse, Phys. Zeits. **33**, 443 (1932); Rev. Mod. Phys. **4**, 610 (1932).

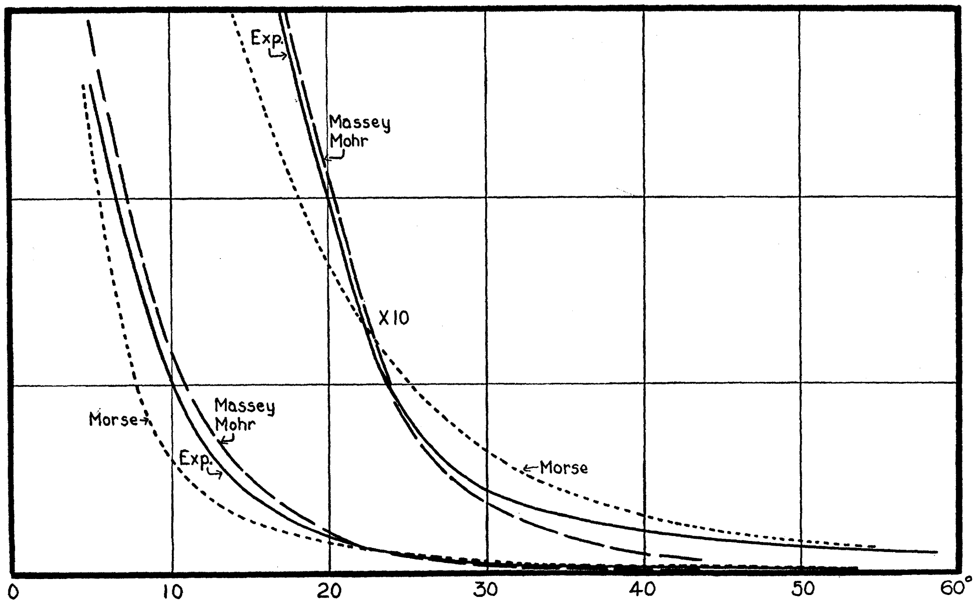

FIG. 3. Comparison of experimental and theoretical scattering curves. Unbroken line, experimental curve. Dotted line, Morse's theory. Broken line, Massey and Mohr's theory. Energy before collision, 100 volts. Energy lost at collision, 21.12 volts.

and m refer to the electron, h is Planck's constant, $Z=2$ for helium, F the form factor for helium and $\mu=\sin(\theta/2)/\lambda$ where λ is equal to the electron wave-length. The approximations made in deriving this equation are such that it is expected to hold only when the electron energy exceeds $50Z^2$ (= 200 volts for helium). Although the electrons losing 21.12 volts energy form only a part of all the electrons scattered inelastically, it may be instructive to compare our experimental results with Morse's formula. In Fig. 3, the theoretical $\alpha_i(\mu)$ and the experimental $\alpha_i'(\mu)$ for 100 volt-electrons are plotted together. A more stringent test of Eq. (1) is afforded by plotting $\alpha_i'(\mu)\cdot\mu^4$ against μ, which should give a curve proportional to $(1-F^2/Z^2)$. This is done in Fig. 4. It is clear that, even at 400 volts, there is no approach to agreement.

In a recent paper Massey and Mohr[8] have developed a theory which takes into account the effect of distortion of both the incident and scattered electron waves by the static field of the atom, together with the effect of electron exchange. They publish angular distribution curves for electrons which have excited the 2^1P state (21.12 volts energy loss). The computed curve for 33 volt-electrons may be described as a curve which falls off steeply all the way from 0° to 180° on which is superposed a pronounced hump between 60° and 120°. Our experimental curve for 30 volt-electrons (Fig. 1) has quite different characteristics. In a more recent unpublished investigation,[9] Massey and Mohr, following the

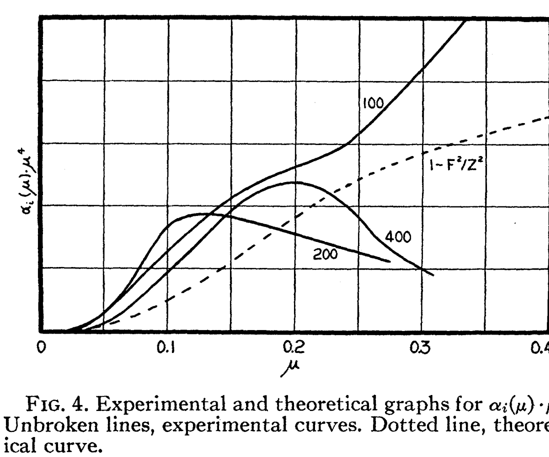

FIG. 4. Experimental and theoretical graphs for $\alpha_i(\mu)\cdot\mu^4$. Unbroken lines, experimental curves. Dotted line, theoretical curve.

[8] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. **A139**, 187 (1933).

[9] We are glad to thank Messrs. Massey and Mohr for sending us a copy of the unpublished paper.

same methods, extend their computations to the case of electrons having 100, 200 and 400 volt energies and cover the range 0° to 40°. A comparison of their results with ours is shown in Fig. 3. It will be seen that the agreement is quite satisfactory except possibly in the vicinity of 40°. In Fig. 2 we have denoted Massey and Mohr's values by circles. It will be seen that they fit our curves remarkably well. (It is unfortunate that the intensities of the 200 and 400 volt-electrons scattered in our experiments were so small, that we could not make measurements at angles greater than about 20°.) It should be pointed out that the circles representing Massey and Mohr's results were not fitted arbitrarily to *each* of our curves; their results were fitted to ours at *one* voltage and at *one* angle only. The agreement shown is therefore a much more stringent test of their theory than it would have been had the check been made for each voltage independently of the others.

It is possible to calculate the cross section of the helium atom for electron collisions which have led to excitation to the 2^1P state, or alternatively to a 21.12 volt energy loss, by multiplying each scattering coefficient given in Table I by sin θ and then integrating from 0° to 180°. Some extrapolation is necessary at the small angle end as the smallest angle at which we could take observations was about 6°. The scattering at the larger angles is so small that no appreciable error is introduced by the absence of data above 150° for the slow electron, or even above 25° for 400 volt-electrons. The 2^1P cross sections, as they may be conveniently designated, are plotted in Fig. 5 as a function of the energy of the electrons before collision. The dotted curve is the 2^1P cross section computed by Massey and Mohr.[10] It will be seen that the agreement is poor.

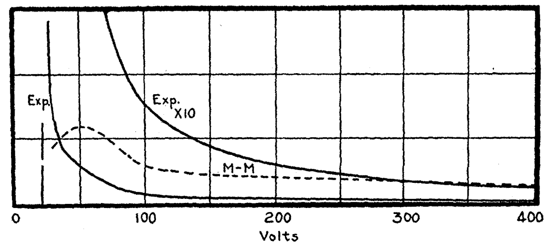

FIG. 5. The 2^1P atomic cross section. Unbroken line, experimental values. Dotted line, Massey and Mohr's theory. Broken line, conjectured course just above threshold, 21.12 volts.

[10] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. **A33**, 198 (1933). We fitted the data given here over the range 30 to 100 volts, to the data given in the unpublished paper, already referred to, over the range of 100 to 400 volts.