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The Scattering of Fast Argon Atoms in Argon Gas

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Apparatus is described for the production of argon atom beams of energies of 500 ev to 3500 ev and for the measurement of the elastic scattering of these beams in argon gas at rest. Differential scattering cross sections are found and from them an interaction potential over a range of 0.6 to 1.2A is determined. This is compared to the exponential repulsive term of the potential suggested by Buckingham for argon. The agreement is within the experimental error.

INTRODUCTION

ONE of the most direct ways of investigating the force of interaction between atoms is to study the elastic scattering of a beam of such atoms when it traverses a like gas. Hoyt[1] has developed for classical scattering a method by which numerical values of the potential as a function of distance may be obtained without any assumption as to the analytical form of the potential function. To observe primarily the repulsive force and to investigate the potential for close distances of approach an energetic atom beam of several hundred to several thousand electron volts is required. In this energy range much work[2] has been done on the scattering and absorption of positive ions but here charge exchange between the ion and the gas atom may introduce complicating effects. The scattering of thermal energy molecular beams which, however, lack homogeneity in energy has also been extensively investigated.[3] But very little work has been done with fast homogeneous neutral atom beams[4] with energy variable over a large range. Such beams may be produced by first forming an ion beam of the desired energy and then by means of charge exchange with gas atoms present neutralize the ions thus having a neutral atom beam with the same energy as the original ion beam. Generally here because of the higher energies usually used techniques different than those developed in molecular beam work are employed. In the work reported here homogeneous argon atom beams of energies of 500 ev to 3500 ev have been produced, allowed to traverse a region containing argon gas, and the resulting scattering measured.

EXPERIMENTAL PROCEDURE

The sectional schematic diagram of Fig. 1 illustrates the essential parts of the apparatus. The ion gun is a modification of an ion source developed by Finklestein.[5] There, ions are produced in a field free region P by bombardment of electrons from the filament F. The accelerating voltage for the electrons is generally $60\,V$ so as to produce a preponderance of singly ionized argon ions.[6] These ions are then accelerated to the desired energy by the potential difference V. The ion beam next enters a region where argon gas is present at a pressure of several microns and where a charge exchange between the ions in the beam and the gas atoms may occur. If the charge exchange collision occurs with only slight deflection the now fast atom may continue through the $\frac{3}{32}$-inch holes in the succeeding diaphragms to the scattering chamber. The diaphragm D is at a potential of 45 volts more

[1] F. C. Hoyt, Phys. Rev. **55**, 664 (1939).
[2] Some of these are: W. J. Hamm, Phys. Rev. **63**, 433 (1943); A. J. Dempster, Phil. Mag. **3**, 115 (1927); J. S. Tompson, Phys. Rev. **35**, 1196 (1930); A. G. Rouse, Phys. Rev. **52**, 1238 (1937); J. H. Simons, *et al.* J. Chem. Phys. **11**, 307 (1943).
[3] Some of these are: S. Rosin and I. I. Rabi, Phys. Rev. **48**, 373 (1935); F. Knauer, Zeits. f. Physik **90**, 559 (1934); R. M. Zabel, Phys. Rev. **46**, 411 (1934).
[4] I. Amdur and H. Pearlman, J. Chem. Phys. **9**, 503 (1941); I. Amdur, J. Chem. Phys. **11**, 157 (1943).
[5] A. T. Finklestein, Rev. Sci. Inst. **11**, 94 (1940).
[6] W. Bleakney, Phys. Rev. **36**, 1303 (1930).

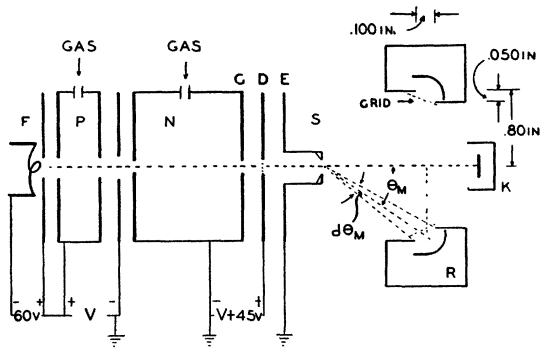

FIG. 1. Schematic diagram of apparatus.

positive than the ion accelerating electrode to remove any unneutralized particles in the beam. To assure that the entire area of the opening is at the potential of the plate a fine wire mesh was placed in the diaphragm hole.

The neutral argon beam of energy equal to that of the original ion beam now enters the scattering chamber S where argon gas is present at a pressure of 1.6 microns. To facilitate the measurement of the scattered atoms the collector was made to receive the full azimuthal angle. As shown in Fig. 1 scattered atoms from the axis of the system can enter the collector if scattered at the proper angle from different positions along the axis. Behind the receiver slit is a tantalum sheet so shaped that atoms entering through the center of the slit will strike it normally. If the electrode is slightly negative secondary electrons will be removed and thus be a measure of the number of scattered atoms entering the collector. A slightly positive grid at the entrance slit prevented the field for removing secondaries from extending out into the space about the slit and pulling stray positive ions to the collector. The collector is movable along the axis of the system by means of a mounting in a Wilson seal. A smaller concentric cylinder contained another tantalum strip which could be bombarded by the unscattered beam. When this cylinder is placed just beyond the entrance hole in E, the secondary electron current from K is a measure of the unscattered beam size. Also since this inner cylinder when pushed in would block the cone of scattered atoms to the collector, it could be used to check for spurious or background currents that might be collected by the electrodes and leads. This secondary electron current produced by bombardment of collector surface by the scattered atoms was of the order of 10^{-11} to 10^{-12} ampere and was measured by an FP-54 circuit in conjunction with a galvanometer. The secondary electron current produced by the unscattered beam on electrode K was well within galvanometer range.

TABLE I. Values of the cross section for attenuation of the beam for various beam energies in electron volts.

Energy (ev)	500	1000	1500	2000	2500	3000	3500
$\sigma_A \times 10^{16}$ cm^2	4.0	2.2	1.7	1.5	1.3	1.2	1.1

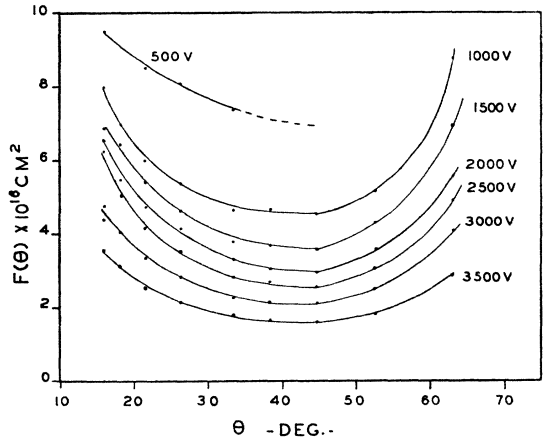

FIG. 2. Polar scattering coefficient for argon in argon as a function of the angle in laboratory coordinates.

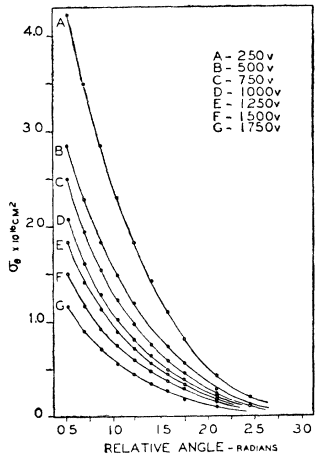

FIG. 3. Cross section for scattering outside θ as a function of θ in center of mass coordinates.

As the collector R is moved away from the entrance hole the angular range of scattered atoms directed to the collector is increased with the smallest angle of scattering collected occuring for the element of path just inside the scattering chamber. This increase in the secondary electron current caused by moving the collector a distance dx from the entrance aperture can be written in terms of the polar scattering coefficient $f(\theta)$ as,

$$dS = \kappa_\theta I N \{f(\theta_m) + f(90° - \theta_m)\} d\theta_m dx - N\sigma_A S dx,$$

where the first term represents the increase in the collector current S caused by the additional scattering path dx. And the second term represents the

decrease in S that results from the further attenuation of the unscattered beam by the introduction of this additional path dx. In the equation, S = secondary electron current in the collector, κ_θ = number of secondary electrons removed per neutral particle[7,8] with energy characteristic of θ_m, I = unscattered beam intensity, N = number of scattering atoms per cm^3, $f(\theta)$ = polar scattering coefficient for beam atoms, $f(90°-\theta)$ = polar scattering coefficient for knocked on atoms since the particles are of equal mass, $d\theta_m$ = angle subtended by collector slit at the center of the element of path dx at entrance aperture, and σ_A = cross section for attenuation of unscattered beam. This equation may be solved for $F(\theta_m)=f(\theta_m)+f(90°-\theta_m)$,

$$F(\theta_m)=[ds/dx+N\sigma_A S]/\kappa_\theta I N d\theta_m.$$

Since the atoms scattered from the element dx at the entrance hole into the collector may undergo additional scattering, the $F(\theta)$ obtained above is divided by $e^{-N\sigma_A d}$, where d is the distance from dx to the collector slit. Actually the cross section for this process will depend upon the angle subtended by the collector slit at the scattering point. For, the particle is lost to the scattering cone only if it is again scattered outside of this angle. Since the average angle subtended by the slit is small, the same cross section is used as for the beam attenuation.

To determine S as a function of x the collector is moved back in 5-mm steps starting at the entrance hole. Each reading was corrected for background currents by intercepting the scattered atom cone with the inner cylinder. From a curve of S *vs.* x the slope dS/dx for various angles θ_m is obtained and $F(\theta)$ calculated.

Since the corrections involving σ_A are small (a few percent except for the 500-ev scattering where a maximum correction of 15 percent was applied) only a rough value of σ_A was determined. A diaphragm with a small hole is placed in the front of the collector assembly such that the collector can receive atoms scattered only from about 35° to 90° no matter what its position. Consequently if the scattered current is measured for two positions l cm apart, the ratio of the currents $=e^{-N\sigma_A l}$ from which σ_A may be determined for the different beam energies. These are given in Table I.

RESULTS

The curves of $F(\theta)$ obtained as a result of the treatment outlined above are shown in Fig. 2. As would be expected the curves have a minimum at 45°, but are not symmetrical about this minimum. Since the larger angles correspond to small x and small S, there exists for these a greater error in measurement. A small error in x or alignment of the apparatus will produce sizable errors in the calculation of the angle θ_m for large values of θ, producing little error for angles less than 45°. Also, the values of κ_θ used for the large angles (low energies) were found by extrapolation of the curves given in reference 7, following the trend indicated in reference 8. This too may be a source of large error. Consequently, only the part of the curve from 15° to 45° was used in determining the polar scattering coefficient $f(\theta)$. To find this, the following approximate graphical method is used. A curve is drawn such that

$$\begin{aligned} f(\theta)&=\tfrac{1}{2}F(\theta) \quad \text{at } \theta=45° \\ f(\theta)&=0 \quad \text{at } \theta=90° \\ f(\theta)&\to F(\theta) \quad \text{as } \theta\to 0° \end{aligned}$$

and such that the sum of $f(\theta)$ and $f(90°-\theta)$ equals $F(\theta)$ for intervening points. For the method of analysis used here the cross section for scattering outside of the angle θ is needed. So the $f(\theta)$ curves were integrated graphically to give the curves shown in Fig. 3, where

$$\sigma_{\theta'}=\int_{\pi}^{\theta'} f(\theta')d\theta',$$

θ' = relative angle of scattering and $\theta'=2\theta$(laboratory coordinates). The energies shown for the curves are also those in the center of mass system.

As described by Hoyt,[1] the method for deducing the interaction potential from the scattering cross section is as follows. The equation for the angle of deflection θ can be rewritten in terms of a deflection parameter, $\rho=\pi/2-\theta/2$, and with angular momentum L = constant. The equation for ρ will contain the energy E of the particle as a parameter and can be rewritten so as to have the form of an Abelian integral equation. This can be solved for a known function of r, the distance between atom

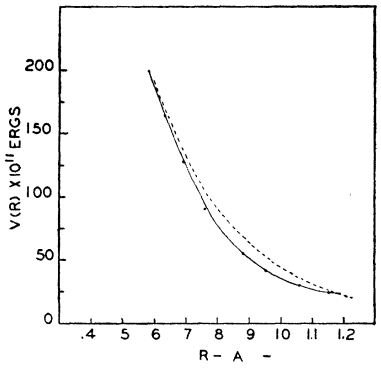

FIG. 4. Interaction potential for argon from experimental results (solid line). Repulsive term of Buckingham's potential function for argon (dashed line).

[7] H. W. Berry, Phys. Rev. **74**, 848 (1948).
[8] A. Rostagni, Zeits. f. Physik **88**, 55 (1934).

centers, in terms of an integral over the energy. Choosing a value of angular momentum within the experimental range, values of σ_θ are obtained for the values of E used in the experiment from the equation

$$\sigma_\theta = \pi L^2/2mE,$$

where m = reduced mass.

From the experimental curves of σ_θ *vs.* θ, θ may be found for a given L and E, and consequently $\rho(E)$. From these values the integral

$$\frac{1}{r} = \frac{(2m)^{\frac{1}{2}}}{\pi L} \int_0^U \frac{\rho(E)dE}{(U-E)^{\frac{1}{2}}}$$

can be found graphically where

$$U = V(r) + L^2/2mr^2$$

and $V(r)$ the interaction potential deduced.

The potential curve so determined with $L = 15 \times 10^{-25}$ g-cm^2/sec. is shown in Fig. 4. If a different L is chosen, say $L = 20 \times 10^{-25}$ g-cm^2/sec., which is about the upper value that may be used with this data a slightly different $V(r)$ is obtained, fitting closely the curve shown from 0.8 to 1.2A and about 10 percent lower for smaller values of r. If $L = 10 \times 10^{-25}$ g-cm^2/sec., again the values for $V(r)$ fit the curve in Fig. 4 from 0.8 to 1.2A but are about 10 percent higher for smaller r.

Also plotted in Fig. 4 as the dashed line is the repulsive term from Buckingham's[9] potential function for argon atoms. This is $V(r) = 1690e^{-(r/0.273)} \times 10^{-11}$ ergs with r in A. The fit is surprisingly good in view of the much higher interaction energies used here in comparison with the thermal energies for which range the potential function was determined. An exponential term of this type has also been suggested by calculations of Bleich and Mayer[10] for neon and Slater and Kirkwood[11] for helium.

[9] R. A. Buckingham, Proc. Roy. Soc. **A168**, 264 (1938).

PRESENCE OF POSITIVE IONS

When the collector electrode is made positive with respect to the grid, secondary electrons will be held and the current measured would be that of the charged particles striking the surface. For the higher energy beams there occurred under these circumstances a small positive current indicating positive ions directed to the collector. This positive ion current increased as the angular range of acceptance increased from 90° to 65° or 70°. Beyond this it remained about constant and was about 5 percent of the secondary current produced by incoming neutrals at 15°. This might indicate a preponderance of positive ions produced by inelastic scattering at the larger angles, but because of the large cross section for neutralization[7,12] of an ion in its own gas, this is very uncertain.

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[10] W. E. Bleich and J. E. Mayer, J. Chem. Phys. **2**, 252 (1934).

[11] J. C. Slater and J. G. Kirkwood, Phys. Rev. **37**, 682 (1931).

[12] B. Rosen and H. Kallmann, Zeits. f. Physik **61**, 61 (1930).