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UNIVERSITY OF CALIFORNIA
INSTITUTE OF ENGINEERING RESEARCH
BERKELEY, CALIFORNIA

ON THE MOLECULAR INTERACTIONS BETWEEN GASES AND SOLIDS

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by

F. C. Hurlbut

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The following was prepared for presentation to the AFOSR-GE Symposium on the Dynamics of Manned Lifting Planetary Entry, Philadelphia, Pa., October, 1962, and will appear in the Proceedings of that meeting.

ABSTRACT

Problems of energy and momentum transfer between the gas particle and the surface are examined with attention given to those processes which directly influence the flow under free molecule and near free molecule conditions. A review of early and also very recent scattering studies reveals consistent trends in the reflected angular distribution in particle flux from cleaved and degassed alkali halide crystals and from certain degassed metal surfaces. These observations lend support to a dynamical model of the lattice in interaction with the gas particle. In connection with the discussion of this model three broad regimes of interaction in the presence of attractive forces are defined.

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I. INTRODUCTION

The kinetic theory of gases is no longer in its infancy, having become already wonderfully matured at the hands of Maxwell and Boltzmann by the year 1880. By the end of the first quarter of our century the formal theory of the transport properties of gases at moderate densities had been highly developed[1,2] and by the present intermolecular potentials and collision parameters had been employed in extensive correlations and predictions of coefficients of viscosity, heat conductivity, and diffusion in pure gases and mixtures.[2,3,4] Nowhere would there seem to be a more satisfying connection between microscopic behavior and the macroscopic properties of matter than between the collisional processes of gas molecules and the dynamics of gaseous flows.

However, as it is well known, these notable successes of the kinetic theory occur in regions well removed from the boundaries; well removed in terms of the number of collisions among gas molecules ordinarily occurring between the point of interest and the wall. Under other circumstances, where the gas is very rarefied on a scale fixed by a characteristic length of the body, the kinetic theory has not produced satisfactory descriptions of the macroscopic gradients of temperature, density, etc. except under severely limiting conditions;[5,6] under many circumstances the flow remains virtually undescribed. To be specific, while the elementary kinetic theory at the free-molecular flow limit is satisfactory and possesses utility, the theories of near free molecular flows and transition flows are notably incomplete. Aside from considerations of formal limitations and of approximations brought about by the complexity of the problems, the theories are incomplete to the extent that they have not employed realistic collisions either in the gas phase or at the boundary. In very rarefied flows where strong gradients of velocity and high particle energies are both possible it seems essential to consider the complete distribution of velocities and the correct description of the molecular encounters in the gas phase if the flow is to be properly described. And by the same token, and this is the principal concern of the present paper, it seems essential to incorporate a realistic treatment of the molecular collision at the wall in order that the proper distribution of velocities for the issuing molecules may be prescribed and the proper transfer of momentum and energy to the boundary obtained.

Inadequacy in this last respect is not really the fault of the kinetic theorist. He has been forced to adopt the most elementary and most convenient models (with one notable exception[7]) by the absence of clear and orderly theories of the interaction and by the presence of certain limited amounts of data of real value only in low speed, low temperature applications. However, on the basis of certain earlier work, now largely unknown to the aerodynamicist, and on the basis of quite recent studies, both theoretical and experimental, one can broaden the most elementary views somewhat and guess, as well, at trends of behavior for higher interaction energies. It is our task in the present paper to make this review and extrapolation.

II. EXPERIMENTAL OBSERVATIONS

We are concerned with the general problems of momentum and energy transfer between the gas and the surface where the interaction energies are high and where they are low. However, attention is concentrated on those processes which have the most direct influence on the character of the flow under free molecule and near free molecule conditions.

The earliest clues as to nature of molecular scattering at the surface were obtained from experiments on the damping of vanes and disks[8] in rarefied gases and in the observations of the failure of viscous flow in capillaries. By 1879 the matter had been successfully formulated by Maxwell in terms of the coefficient of momentum transfer "f", or, as it is now represented, "σ". The special interpretations of $1 - \sigma$ as the fraction of molecules specularly reflected and σ as the fraction diffusely reflected is unnecessary, although Maxwell himself viewed the matter in these terms. But it should be pointed out that Maxwell's formulation adds no new insight into our view of the reflected particle flux except where σ is found near or equal to unity. By the middle 1920's quite a number of values of σ had been compiled for various gas-surface systems, mostly by Millikan and students,[9,10,11] using rotating cylinder equipments. These values and those of more recent origin are listed in Table I. An inspection of the table reveals immediately that a great many of the values are essentially unity, giving strong support to belief in the general applicability of diffuse scattering and perfect accommodation of tangential momentum.

Analogy with the reasoning concerning momentum transfer led Smoluchowski by 1898 to look for and to observe the "temperature jump" effect, a discontinuity in gas temperature at the gas-surface interface. The magnitude of the temperature jump is determined by the degree of adjustment in energy at the surface experienced by gas molecules possessing the kinetic temperature of the gas a small distance away. The effects were formulated in terms of the "accommodation coefficient" by Knudsen[12] in 1911, where α, the energy accommodation coefficient, represents the efficiency of energy transfer between a gas and surface. Since this topic has been carefully treated in a recent paper,[13] it will not be enlarged upon further here beyond noting that a number of values of α are given in Table II of the present paper. It is important, however, to notice that the values of accommodation coefficient for energy are not invariably close to unity, and in fact for the lighter gases in clean systems, notably in recent times as shown by the excellent work of Wachman,[14] the values approach very close to zero. This point did not escape the notice of early investigators, with the result that Baule'[15] as early as 1914 had proposed a rigid sphere model of energy transfer, and had suggested in terms of surface roughness how the scattering could be diffuse while the energy accommodation remained slight.

The analogy with tangential momentum transfer was carried one step further by Schaaf,[16] who proposed a third transfer coefficient " σ' " representing the efficiency of normal momentum transfer between the gas and the surface. It should be clear that σ, σ' and α could be determined by integration over the complete distribution function at the surface, appropriately weighted, if it were known, and that in general the results would be different for each function chosen. Thus these parameters do not "characterize" the interaction between gas and surface in general, but only in the special case $f \rightarrow f_{equ}$, which implies that $T_{gas} - T_{surface} \approx 0$, and that $\bar{U}_{gas} - \bar{U}_{surface} \approx 0$. These conditions are nearly achieved in the early rotating cylinder work of Millikan, and are deliberately sought in the accommodation coefficient experiments.

The kinds of experimental work discussed to this point are macroscopic, and the values of the parameters have been inferred from measurements of the flow and the equations of motion. However, in 1911 Dunoyer[17] produced an atomic beam of Cd, and by 1915 R. W. Wood[18] using the new technique tested the cosine law of reflection for Hg and Cd on glass. Knudsen[19] verified the law with great precision at about the same time, using Hg on glass, and then Taylor,[20] scattering Li, K, and Cs from cleavage planes of NaCl and LiF crystals observed the angular distribution in scattered flux employing as a tool the surface ionization detector which bears his name. The cosine law was obeyed to better than 1 part in 10^4 in these systems.

If Taylor or Knudsen had worked with Hg on NaCl, quite another impression of general trends in scattering might have been created. By the early 1930's the molecular beam technique had been employed in the wholesale observation of scattering and diffraction at crystal surfaces, beginning with the classic observation of Knauer and Stern[21] and of Estermann and Stern[22] on the diffration of He and H_2 at the cleaved LiF surface. The work with which we are particularly concerned in this period is that of Zahl and Ellett, of Hancox, of Zabel, and of others in which beams of Hg, Cd, and noble gases were scattered from various surfaces, principally those of cleaved alkali halides. In Figure 1 we see typical results of Zahl and Ellett[23] for Hg on NaCl, and these are qualitatively similar in all respects to the results for Hg on KBr and KCl. Note the strong quasi-specular scattering at all angles of incidence, but note that the maximum is not directed along the specular ray, but lies somewhat closer to the normal. The difference in directions becomes smaller as the angle of incidence is decreased. Somewhat more detailed diagrams, Figure 2, show the influence of separately varying the temperature of beam and crystal surface. In these drawings the circles and inner lobes represent the decomposition into a diffuse component and a quasi-specular component offered in partial explanation of the curious shape of some of the functions. From the legend it may be seen that four effects of temperature variation may be distinguished: a) the positions of the maxima shift towards the specular ray with decrease in crystal temperature, and b) with an increase in beam temperature; c) the corrected quasi-specular lobe becomes narrowed with decrease in crystal temperature, while d) the relative number of atoms scattered randomly increases. Zahl and Ellett also scattered randomly increases. Zahl and Ellett also scattered beams of Hg from glass surfaces and K I crystals and observed completely diffuse scattering from each. The K I crystal was handled in the same careful way as the others.

Even more striking examples of quasi-specular scattering are given by Hancox,[24] who studied the scattering of Hg and Cd atoms from LiF, LiCl, and NaF. The LiCl crystals being very deliquescent were subject to the most careful handling, being cleaved in a dry box and always kept from the laboratory air, then pumped down and degassed. Later contamination by laboratory air resulted in diffuse scattering, although the surface could in large measure be restored by degassing for 1 hour or so at 400° C. Typical results for LiF are illustrated in Figure 3, and it may be seen that the qualitative behavior is very similar to that observed by Ellett and Zahl. Hancox also worked with K I and found quasi-specular reflection from this crystal as well. The crystal could be reversibly restored to maximum reflectivity by degassing after exposure to dry laboratory air, but was permanently damaged by exposure to damp air.

A comparison of reflection data is made in Figure 4 for the gases He, Ne, A and Hg and Cd, all on NaCl. The noble gas data were supplied to Hancox by Zabel.[25] Note that the He lobe is remarkably sharp except for the unresolved diffraction maximum and that the lobe maximum lies along the specular ray.

It is interesting to compare these findings with the much more recent work of the author[26] and the even more recent results of Datz, Moore and Taylor[27] and of Smith and Fite.[28] Figure 5 illustrates typical results of the author for argon on LiF and on liquid gallium. In both cases the surfaces were initially degassed only at slightly elevated temperatures, ~ 50° C. Prolonged degassing later produced a steady deterioration of the quasi-specular signal, presumably due to the breakdown of organic vapors at the surface. Even in the case of the gallium surface, which was noticeably filmed over in patches, the patterns are qualitatively similar in all respects to those of the earlier authors. Some care was taken with the angular resolution of the detector in these experiments, and one can see the diffuse component near the incident direction very clearly defined.

A portion of Datz's results are reproduced in Figure 6, which shows the scattering of helium atoms at source temperatures to ~ 1900° C from surfaces of platinum in the temperature range 50 to 1200 °C. The striking feature of these tests is the reversible transition from quasi-specular to entirely diffuse scattering upon passage of a broad threshold in surface temperature in the region 100 to 200 °C. The transition seems connected with the adsorption of oxygen, the conditions for monolayer formation (or desorption) being energetically correct in this neighborhood of temperature. Once again the lobe maximum is shifted toward the specular ray at high beam temperatures and in the direction of the surface normal at low beam temperatures.

Similar, but more complex observations were made by Smith and Fite on the scattering of H_2 and A from Ni surfaces. It was found that certain specimens bearing a trace of carbon produced marked specular maxima after bakeout to 600° C in the presence of H_2. The specular maxima, Figure 7, were observed only in the surface temperature range 200 to 800 °C. At lower temperatures the surface was presumed to be obscured by condensed gases but the return to diffuse scattering at temperatures higher than 800 - 1000 °C is not yet understood. It should be noted that six minutes or so were required after the surface temperature was reduced from > 800° C to 650° C before specular reflecting conditions again were evidenced. The Fite apparatus as a portion of the detector incorporates an electron-bombardment ionizer which permits, because of the dependence of the probability of ionization of a particle on the duration of its flight through the detector, a crude estimate of the adjustment in energy experienced by the particle at the surface. It is found that the portion of the reflected beam near the maximum of the quasi-specular lobe suffered almost no energy adjustment while portions in direction more nearly corresponding to the surface normal suffered much more complete adjustment. This observation is supported by similar observations of Data. The direction of the reflected maximum was shifted toward the specular ray upon an increase of beam temperature as in the other studies.

Much more precise studies of velocity distributions in reflected beams have been made by Marcus and McFee,[29] but only for potassium, and not as a function of the angular parameters. In Figure 8 we see an example of the beautiful results obtained by these investigators. The results may be summarized very briefly as follows: in every case beams of potassium reflected from tungsten or other metallic targets exhibited a velocity spectrum characteristic of the temperature of the target to target temperatures of 2135° K irrespective of the parent beam temperature in the range ~ 400 to 700 °K. The observations were made by means of a slotted wheel velocity selector and Taylor detector. Reflection from LiF gave results indicating a partial adjustment of the energy of the K atoms to that of the surface in contradiction to expectation from the work of Taylor. The results of Marcus and McFee will be considered again shortly; for the present we note that the coefficient of energy accommodation would appear to be unity in the present range of beam energies and surface temperatures for all cases of metallic surfaces in interaction with potassium atoms.

One further reference to experimental work should be introduced at this time, the normal momentum transfer studies of Stickney.[30] In these studies beams of noble gases and of N_2, CO_2 and H_2 were directed against surfaces of W, Pt, and Al in a torsion balance apparatus and the coefficient of normal momentum transfer for gas particles at normal incidence determined. The surfaces were heated at various temperatures to 600° C. The results may be summarized as follows: the transfer of normal momentum at normal incidence is about equally complete for argon and nitrogen, more complete for CO_2, and less complete for Ne, H_2 and He, in that order. If cosine reflection is assumed these results can be related to accommodation coefficients for translational energy and the values in the case of the tungsten surface are:

Gas	α_t
He	0.55
H_2	0.60
Ne	0.70
N_2	~ 1.0

No difference in behavior among the three materials tested was observed, suggesting that surface contamination played a major role in these measurements.

III. DISCUSSION

In the foregoing we have seen a representative selection of experimental results where velocity spectra or angular distributions in flux have been measured directly. In addition, certain macroscopic experiments have been mentioned where the interaction coefficients are more or less directly found but details of interaction are determined, if at all, by inference. By itself a single observation of a scattering distribution or velocity spectrum does not constitute a determination of the macroscopic interaction parameter. Observations over a sufficient number of incident angles must be made so that the results may be averaged with respect to a weighting function. The procedure has been indicated in detail by the author for the case of N_2 on glass[31] and for A on gallium.[32] In order to avoid confusion on this point it is strongly recommended that coefficients estimated from isolated observations be designated as partial.

Perhaps the most striking limitation of the data in the foregoing resume' from the contemporary view is the absence of any information at all for particle energies exceeding ~ 0.2 ev. It is true that there exist a number of neutral particle and ion beam studies of secondary electron production and of sputtering at surfaces, but the work has been done at energies beyond the range of interest for this paper, and there exist orbital decay data for the range of particle energies 4 ev to 16 ev relative to the surface. These latter data are uninterpretable in terms of the collision processes. It is hoped and expected that this deficiency will in part be corrected within the next few years, and it may be guessed that the several experimenters who are currently preparing instruments for an attack on these problems share this hope. But for the present there are only the indications from experiments of ordinary thermal order cited here, together with a very modest amount of theory.

In a paper on the deposition of atomic beams Wexler[33] attempts to correlate the sticking coefficients of atomic beams on the basis of the depth of the potential well for adsorption. The attempt is not entirely satisfactory because of the unappraisable influence of the condition of the surface in the many experiments. Nevertheless, the suggestion is a good one, and appears prominently in what follows. Most adsorption work is done under conditions of thermodynamic equilibrium and the results are expressed in terms of adsorption potentials and sitting times which apply under those conditions. Even now there are no adequate dynamical theories of adsorption which fact, perhaps, led Wexler to overlook the two other very important elements of the adsorption process, the incident particle energy and the dynamical properties of the lattice.

Ordinary surface roughness can be counted upon to influence the distributions of scattered particles in the direction of diffuse scattering, but since the work of Datz and of Smith and Fite it is no longer clear what surfaces are rough and under what conditions. In any case, the individual molecular encounter takes place at an element of the surface lattice which may be bare, or it may be covered in varying degree with physically or chemisorbed particles of the incident species or of contaminants. The exchanges of momentum and energy with which we are concerned are not separate processes, but are somewhat different manifestations of a single event or a discrete chain of events in which velocities are changed in directions and magnitudes, and energy is dissipated in motion of the lattice.

The interaction occurs in the presence of surface attractive forces and involves a response in the motion of the incident particle to the presence of the nearest members of the lattice or adsorbed species in all phases of the interaction. Limitations of early quantum theoretical approaches were discussed by Zwanzig[34] in 1960. He points out that the single quantum limitation imposed in this work cannot apply in an interaction involving a high energy particle. Experimental work on the deposition of atomic beams is cited to substantiate the claim. Zwanzig investigates a one-dimensional model of the surface in which the masses are linked classical oscillators and the incident particle impinges head-on at the end of the chain, where it experiences a truncated harmonic oscillator potential. This simplified classical picture cannot be expected to be quantitatively correct, but it permits large transient deformations of the lattice of the sort that occur in collisions, and through which large amounts of energy may be transferred from the gas to the solid.

The use of classical collision theory in first approximation at normal temperatures instead of quantum theory has been justified many times, for example by Zwanzig above. If the molecular wave length is small compared with distances within which the scattering potential varies appreciably, then it can be shown that the scattering follows approximately the classical laws. The general formula for molecules of molecular weight m and having energy corresponding to kinetic temperature T is $\lambda = \frac{h}{M m_o \bar{v}} = \frac{2.74 \times 10^{-7} \text{cm}}{\sqrt{M T}}$ in which m_o is the mass of a molecule with $M = 1$, h is Planck's constant, and $\bar{v}$ is the mean velocity. At 15° C λ for H_2 is 1.136×10^{-8} cm, for N_2 λ is 0.3048×10^{-8} cm, and for Hg λ is 0.1139×10^{-8} cm. Thus diffraction effects in the scattering of He and H_2 were predicted and observed[21,22] and Zabel[25] observed very weak diffraction effects in the case of Ne. In this connection the viscosity of H_2 and He exhibits quantum effects up to about room temperature, but at higher temperatures may be discussed in classical terms.[35] On the other hand, the observations of Ellett and Zahl and others using Hg and Cd were quite unexpected and remain undiscussed.

In more recent times Goodman[36] has considered the trapping of gas particles at simple cubic lattices. Only impact normal to the surface and head-on at the end of an atom chain is considered so that the other atoms feel the force of interaction indirectly. Although highly idealized, the 3-dimensional lattice possesses advantages over the 1-dimensional in that it affords more realistic rigidity and permits calculation with $\mu \geq 1$, where μ is the ratio of the incident particle mass to that of the lattice atom. The "trapping" model interaction potential adopted by Goodman, Figure 9, involves a step potential well of depth D and a linear repulsive potential of slope F which is encountered at the bottom of the potential well. The 3-dimensional lattice will completely restore itself after any collision in contrast to the one-dimensional lattice.

No convenient formulas result for the threshold of trapping nor for the energy accommodation coefficient. However, values of this coefficient have been calculated in the range 100 to 300° K for He, Ne, A, Kr, and Xe on a clean tungsten surface and compared with values of Thomas and Schofield.[37] These partial values of accommodation coefficient are very much larger in each case than those of the experimental results. However, recall that the experimental results are derived from a condition in which all incident angles are possible. At oblique incidence it seems physically plausible that conditions are less favorable for the transfer of energy than in the head-on collision of the Goodman theory. The theory shows the following things, a) particles with insufficient initial kinetic energy (somewhat less than D) may be come trapped and hence adsorbed, b) particles with sufficient initial kinetic energy escape the surface adsorptive potential and reflect, having lost some energy to the lattice, c) qualitatively correct dependence on particle masses, adsorption energies and lattice potentials is exhibited. It appears that continued investigations along similar lines should bring quantitatively useful results.

Some evidence that the lattice continues to behave along lines suggested above even to incident particle energies of several volts is supplied by an observation concerning the reflection of potassium particles from platinum surfaces. Stein and Hurlbut[38] noted in connection with studies of the sputtering of potassium using a Taylor detector that a fraction of the potassium atoms entering the detector reflected as ions even when the platinum filament of the detector was cold. Many subsequent tests have supported the hypothesis that those sputtered atoms having energies in excess of a certain amount, perhaps 3 to 5 ev, escape the adsorption potential, and so reflect without condensation. The adsorption energy for K on W is 2.5 ev, or ~ 59 kilo calories per mole. Experiments of higher precision are now in progress. At somewhat higher incident energies the lattice would be severely distorted, and at perhaps 30 ev the distortions would be so severe as to permit the sputtering or impact ejection of platinum particles.

It would seem from the foregoing that virtually all of the observations of scattering herein discussed can be understood in terms of a simple dynamical model of the lattice in interaction with a spherically symmetric gas particle. The calculative problem for oblique incidence is truly formidable if it is to be carried out with realistic interaction potentials. Consider Figure 10, which shows an obliquely incident gas particle impinging on a close packed array of lattice atoms. The circles do not indicate rigid spheres, but rather spheres of influence corresponding to the conventional molecular diameter. The trajectory is shown as it would appear in the center of mass system or in the coordinate system of a fixed scattering center. The laboratory system is nearly identical with both because of the great rigidity of the lattice. However, the struck atom is slightly displaced into the lattice, causing the deflection angle χ to be smaller than shown. On the basis of this diagram one might anticipate a lobe position somewhat closer to the surface than the specular ray. The fact that this is not the case, except possibly (reported by Hancox in contradistinction to Ellett and Zahl) at angles of incidence very close to the normal, must be attributable to the increased likelihood of a second blow upon an undisplaced member of the lattice. At higher incident energies the first struck particle suffers a negligibly greater displacement because of the rapidly rising rigidity of the lattice. A greater fraction of the momentum of the initial particle remains following this impact and is available to displace the second struck particle. The observed change in the position of the quasi-specular lobe is the natural consequence of increased displacement of the second particle.

Physisorbed and chemisorbed species modify the above picture by roughening the surface on a molecular scale or by distorting the substrate. The influence of these effects has been noted by the investigators of the present resume' with varying degrees of precision, but only in the work of Thomas, Wachman and others of the Missouri group has the deliberate and precise control of the surface contamination level been a portion of the primary effort.

It should be evident that the above discussion applies most accurately for attractive potentials small by comparison with the residual incident particle energy. Another condition, and one which may be frequently met at clean metallic surfaces, obtains when the attractive potential is high by comparison with the initial kinetic energy. Trapping is almost inevitable and the trapped particles either remain or re-evaporate, depending upon the surface temperature. The re-evaporated (scattered) particles will be distributed in space according to the cosine law.

A third and more complex regime may be defined for the condition that the initial kinetic energy and the relevant energies of chemical binding are of the same order. In this situation the lattice will be severely distorted at each impact and weakly bound adsorbed species will be desorbed by collision. At sufficiently high energies one will see the onset of sputtering.

It should be clear from available experiment and theory that below a certain energy level, undetermined but of the order of several electron volts, two factors create a tendency for diffuse scattering and efficient energy exchange. These are surface roughness, caused by gas adsorption and by substrate roughness, and adsorption potentials which attract and may trap the incident atom. At ordinary temperatures the latter play an important and perhaps dominant role; under conditions of very high incident particle energy the importance of attractive forces must be diminished. The response of the contaminated surface to the hypervelocity gas particle remains unexplored. The examinations of the many fundamental problems of surface physics associated with this general question should provide a challenge to investigators for some time to come, but the implications of what is already known should lead to renewed study of the problems of the boundary in the kinetic theory of highly rarefied gases.

TABLE I

TANGENTIAL MOMENTUM TRANSFER COEFFICIENT σ

GAS	SURFACE	σ	REFERENCE
air	machined brass	1.00	9
CO_2	machined brass	1.00	9
air	old shellac	1.00	9
CO_2	old shellac	1.00	9
air	Hg	1.00	9
air	oil	0.90	9
CO_2	oil	0.92	9
H_2	oil	0.93	9
air	glass	0.89	9
He	oil	0.87	9
air	fresh shellac	0.79	9
air	Ag_2O	0.98	10
He	Ag_2O	1.00	10
H_2	Ag_2O	1.00	10
O_2	Ag_2O	0.99	10
air	oil on machined aluminum	0.90	39
N_2	glass	0.93 - 0.97	31
A	gallium	0.75	32
A	oil vapor on Al	0.60 - 0.90	40
air	oil vapor on Al	0.60 - 0.90	41

TABLE II

THERMAL ACCOMMODATION COEFFICIENTS

GAS	SURFACE	α	REFERENCE
H_2	Pt, Bright	0.32	42
H_2	Pt, Black	0.74	42
O_2	Pt, Bright	0.81	42
O_2	Pt, Black	0.83	42
N_2	Pt	0.50	43
N_2	W	0.35	43
Air	Flat lacquer on Bronze	0.88 - 0.89	44
Air	Polished Bronze	0.91 - 0.94	44
Air	Machined Bronze	0.89 - 0.93	44
Air	Etched Bronze	0.93 - 0.95	44
Air	Polished Cast Iron	0.87 - 0.93	44
Air	Machined Cast Iron	0.87 - 0.88	44
Air	Etched Cast Iron	0.87 - 0.96	44
Air	Polished Aluminum	0.87 - 0.95	44
Air	Machined Aluminum	0.95 - 0.97	44
Air	Etched Aluminum	0.89 - 0.97	44
He	W	0.025 - 0.057	45
He	Ni, Not Flashed	0.20	45
He	Ni, Flashed	0.085	45
He	W, Flashed	0.17	46
He	W, Flashed	0.12	43
He	W, Not Flashed	0.53	46
A	W, Flashed	0.82	46
A	W, Flashed	0.46	46
A	W, Not Flashed	1.00	46
Contemporary Work			
He	H_2 adsorbed on W	0.041	14
He	N_2 adsorbed on W	0.064	14
He	W, clean system	0.02	14
A	Al coated W	0.465	47
A	W, clean system	0.397	47
Ne	W, clean	0.08	48
Ne	Pt	0.296	48

NOTE: The table is not exhaustive, and in particular, does not contain many of the values or ranges of Reference 13.

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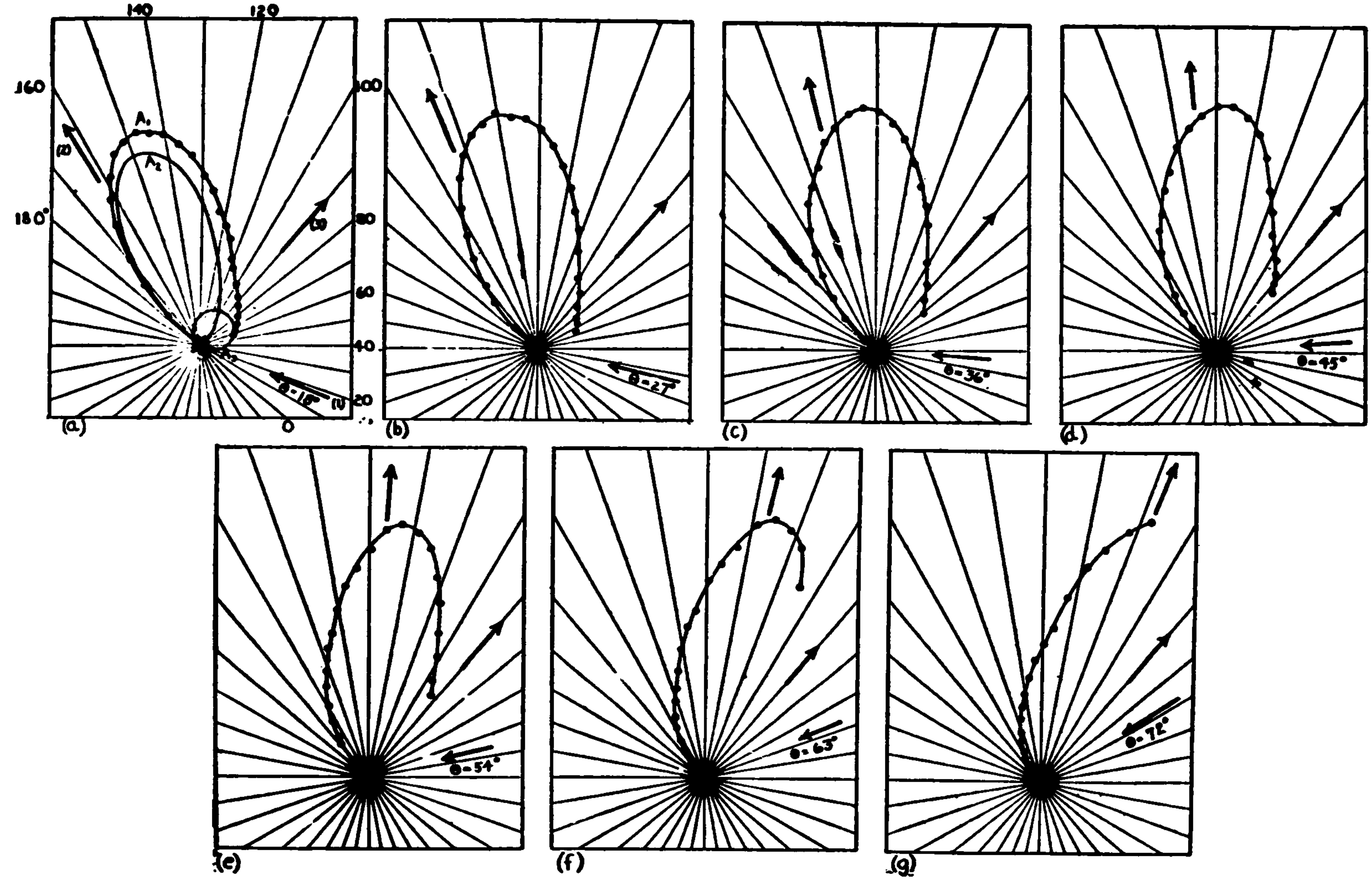


FIG. 1. SCATTERING OF Hg AT THE NaCl SURFACE -- DEPENDENCE ON INCIDENT ANGLE

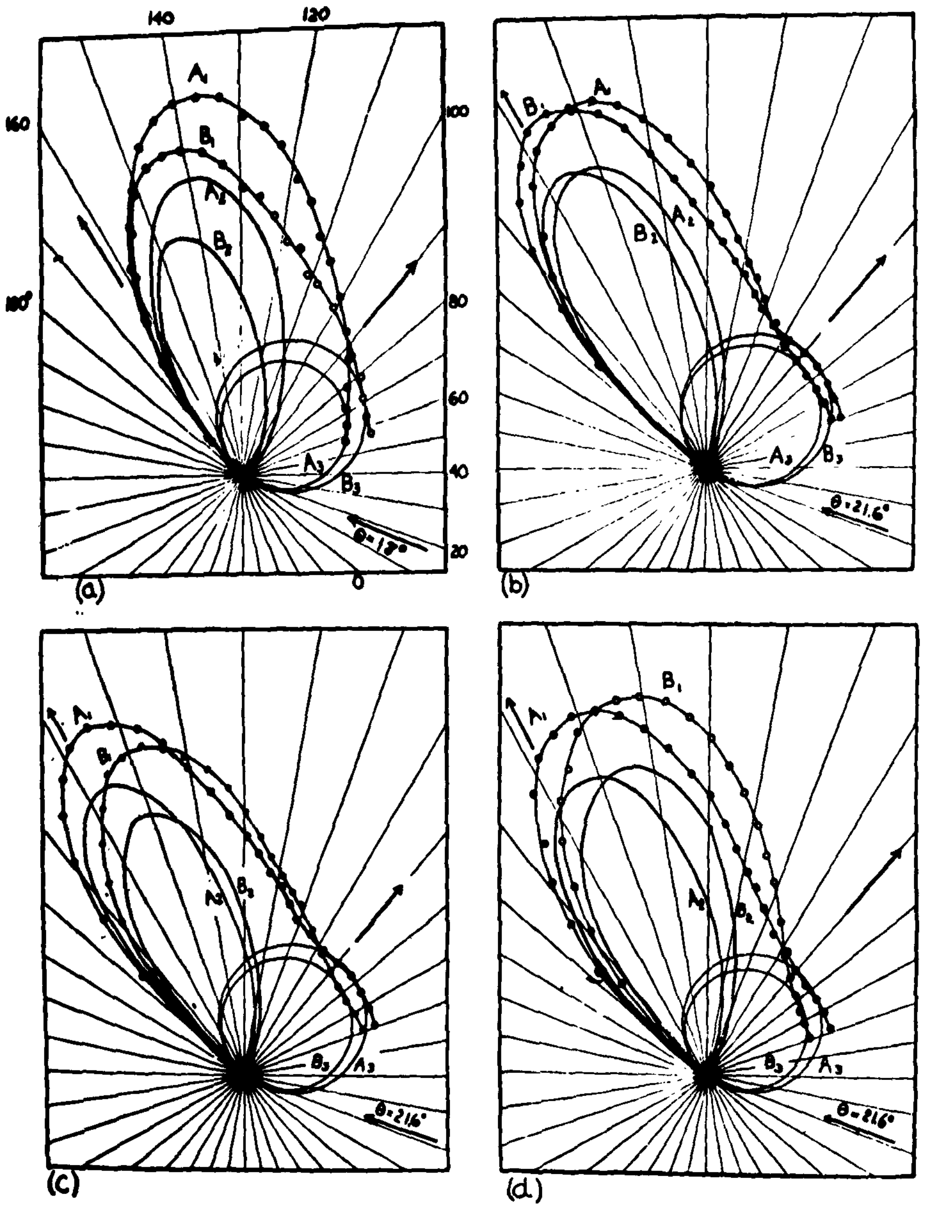


FIG. 2. SCATTERING OF Hg AT THE NaCl SURFACE -- DEPENDENCE ON BEAM AND SURFACE TEMPERATURES

a) A_1 Beam 170° C, Crystal 350° C
B_1 Beam 170° C, Crystal 50° C

b) A_1 Beam 500° C, Crystal 350° C
B_1 Beam 500° C, Crystal 50° C

c) A_1 Beam 500° C, Crystal 50° C
B_1 Beam 170° C, Crystal 50° C

d) A_1 Beam 500° C, Crystal 350° C
B_1 Beam 170° C, Crystal 350° C

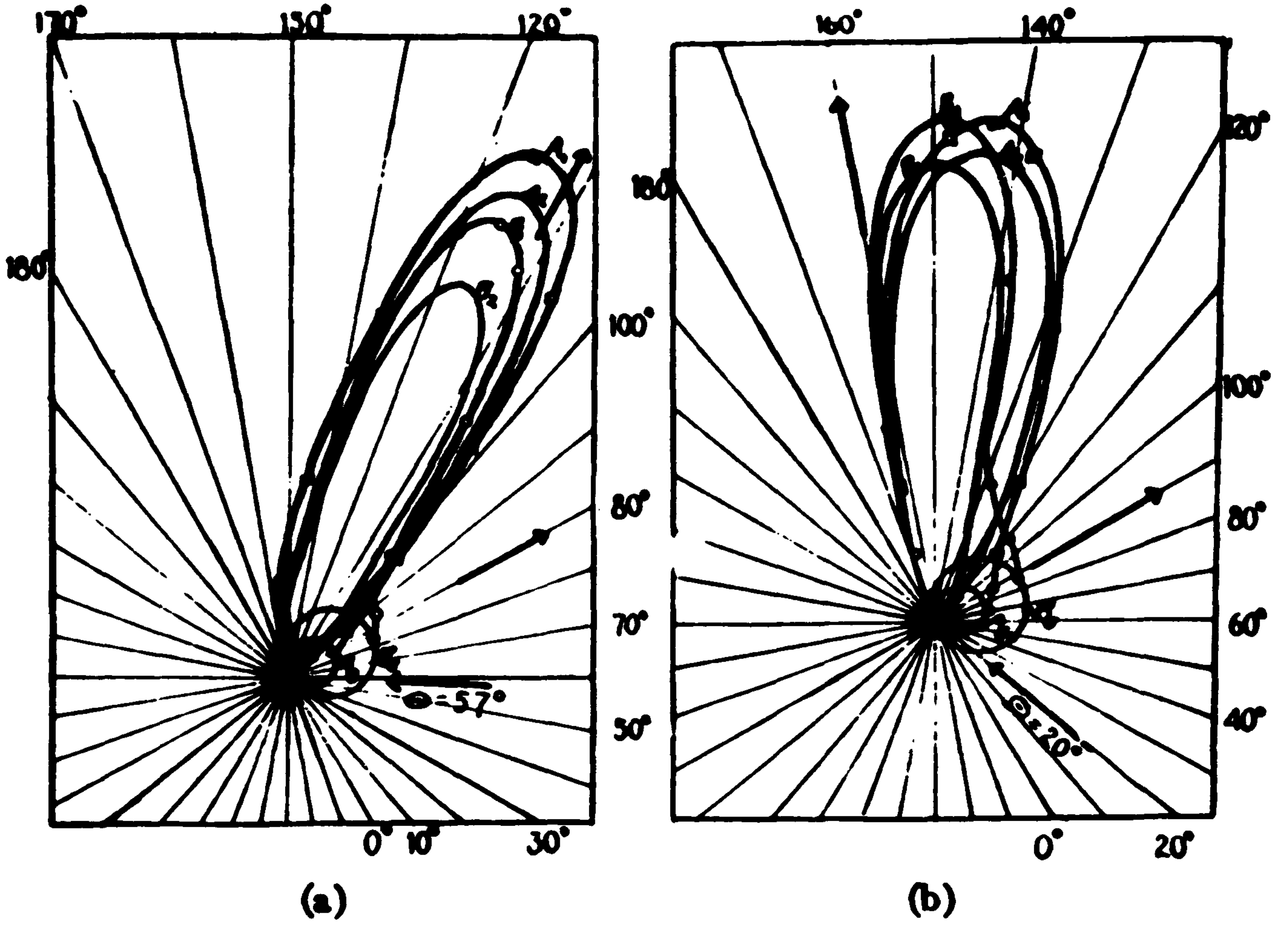


FIG. 3. SCATTERING OF Hg FROM LiCl (Hancox)

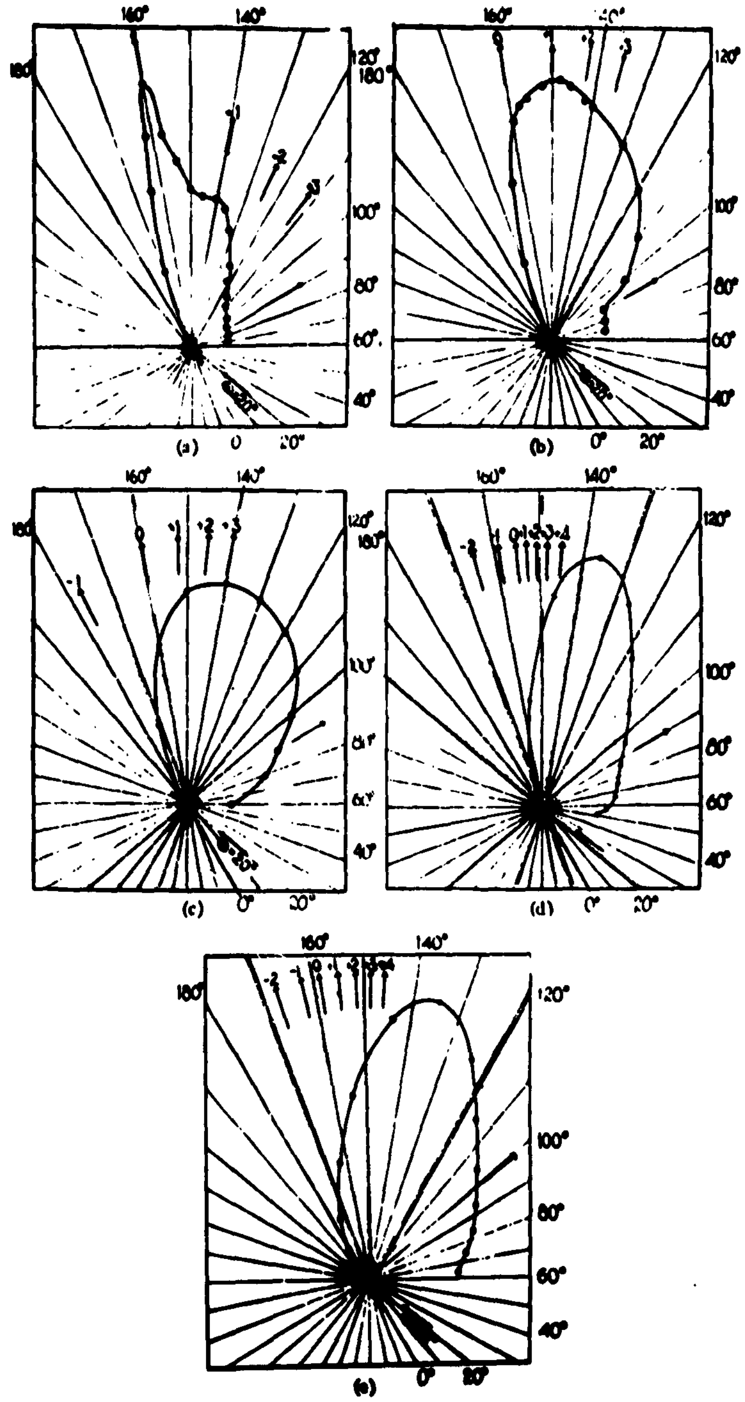


FIG. 4. SCATTERING OF VARIOUS GASES FROM NaCl (Hancox, Zabel)
(a) He; (b) Ne; (c) A; (d) Hg; (e) Cd.

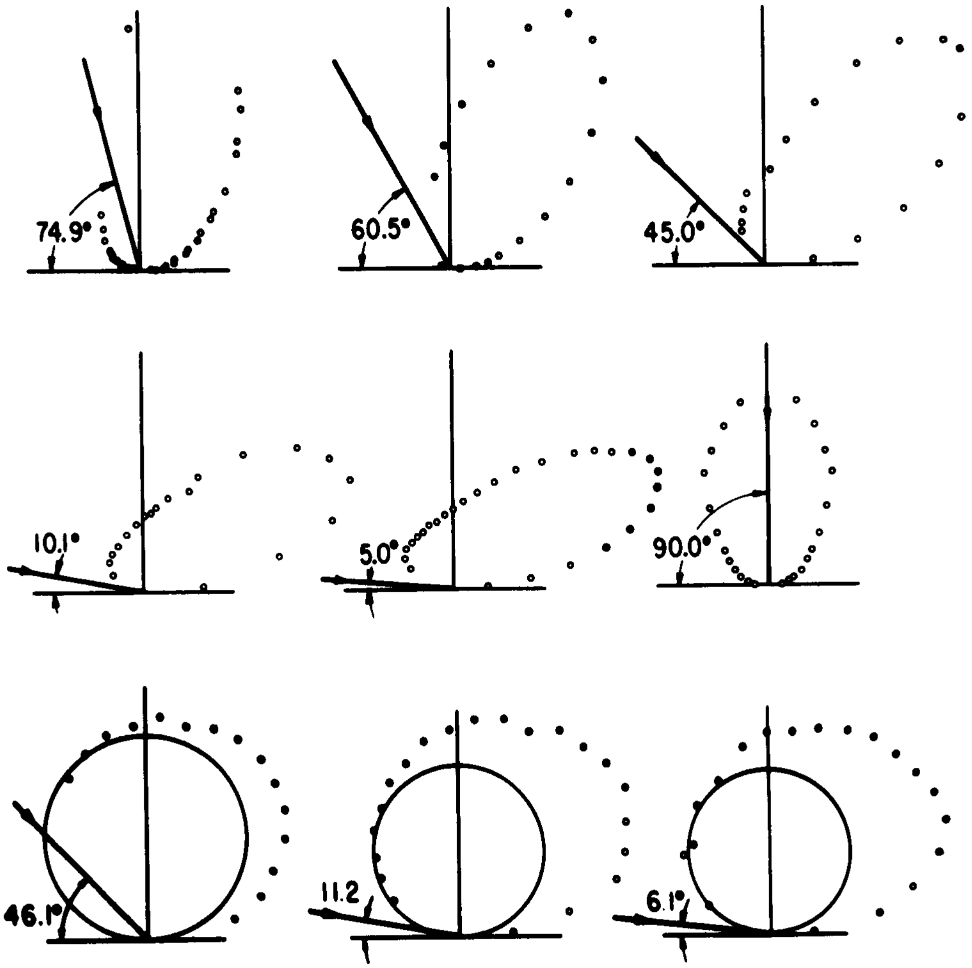


FIG. 5.

SCATTERING OF A FROM LiF (First two Rows), and FROM LIQUID Ga (Third Row)

(Hurlbut)

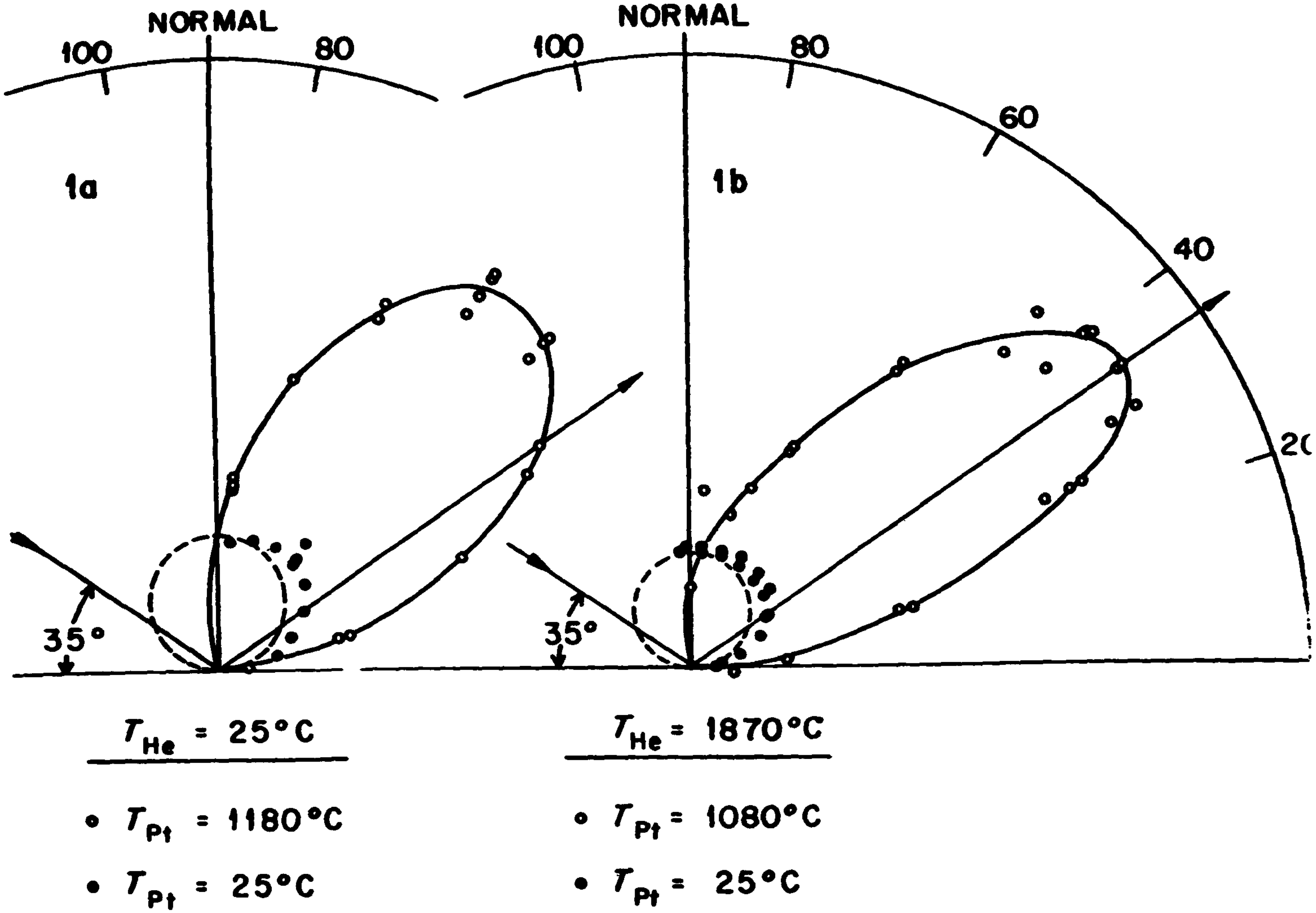


FIG. 6. SCATTERING OF He FROM Pt (Datz)

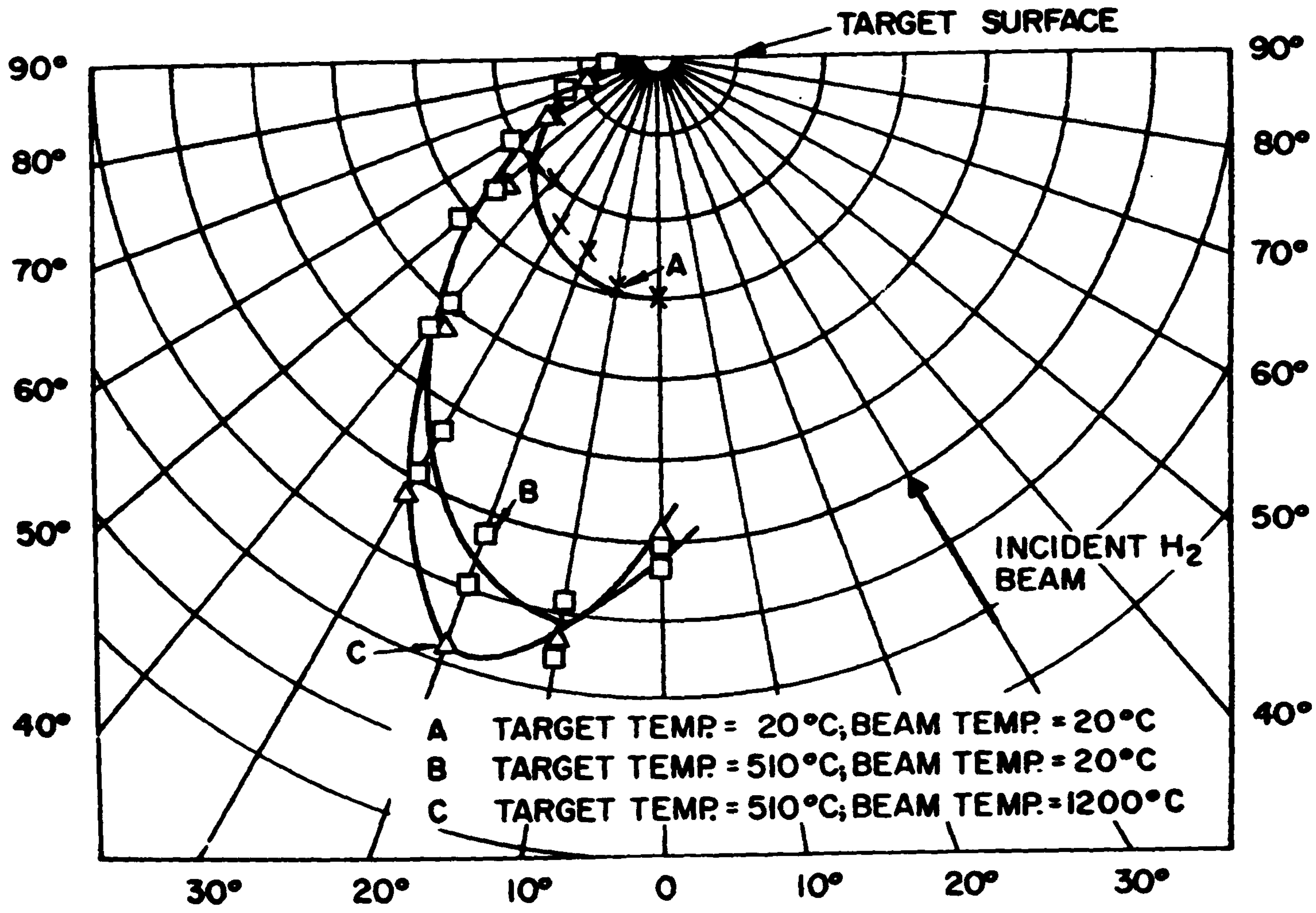


FIG. 7. SCATTERING OF H_2 FROM W (Smith and Fite)

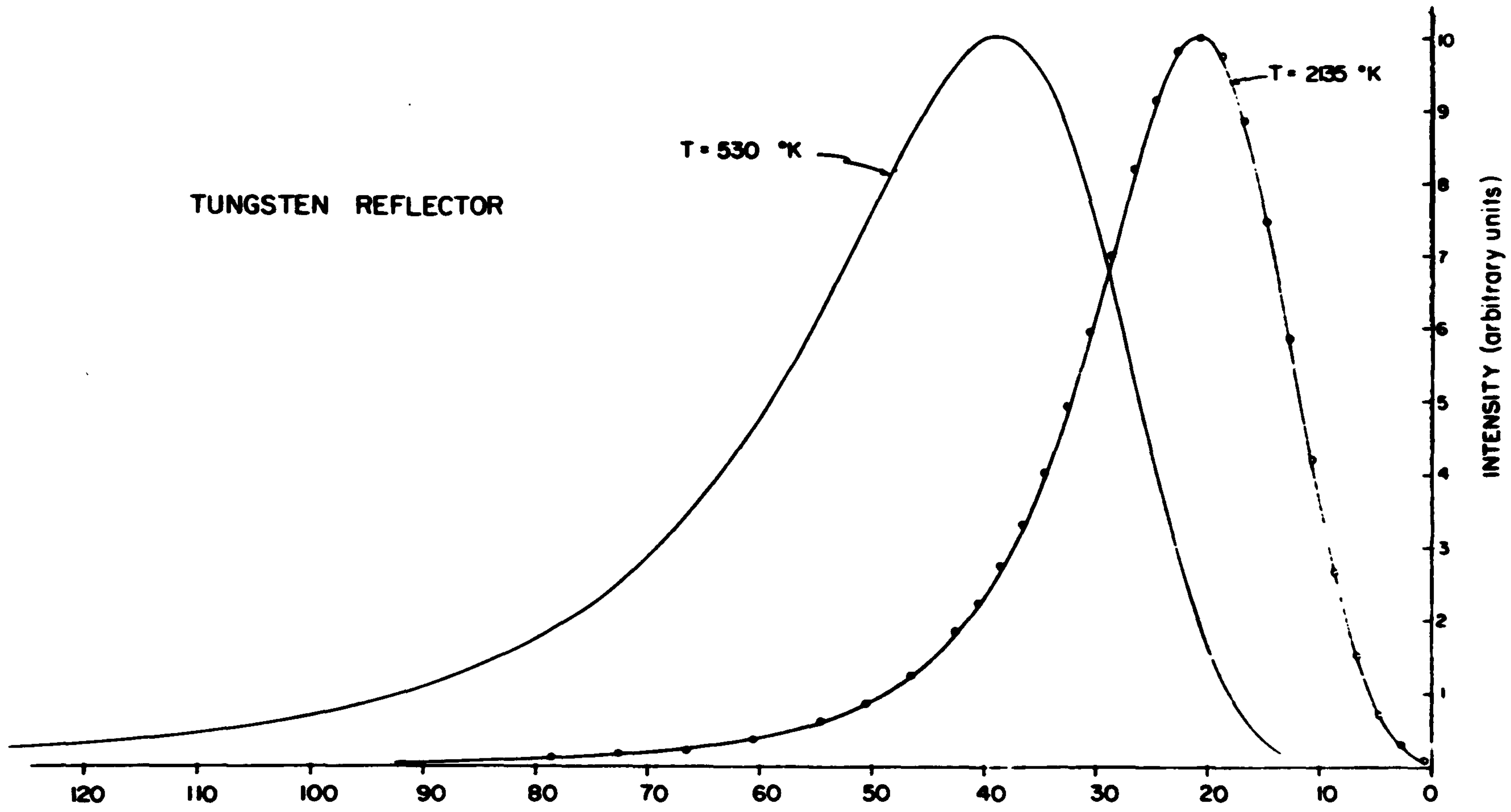
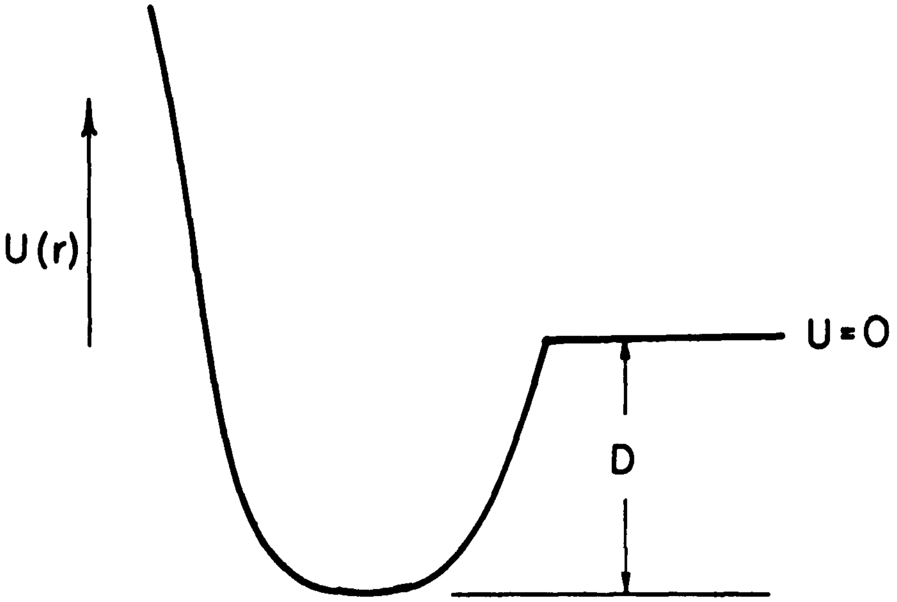
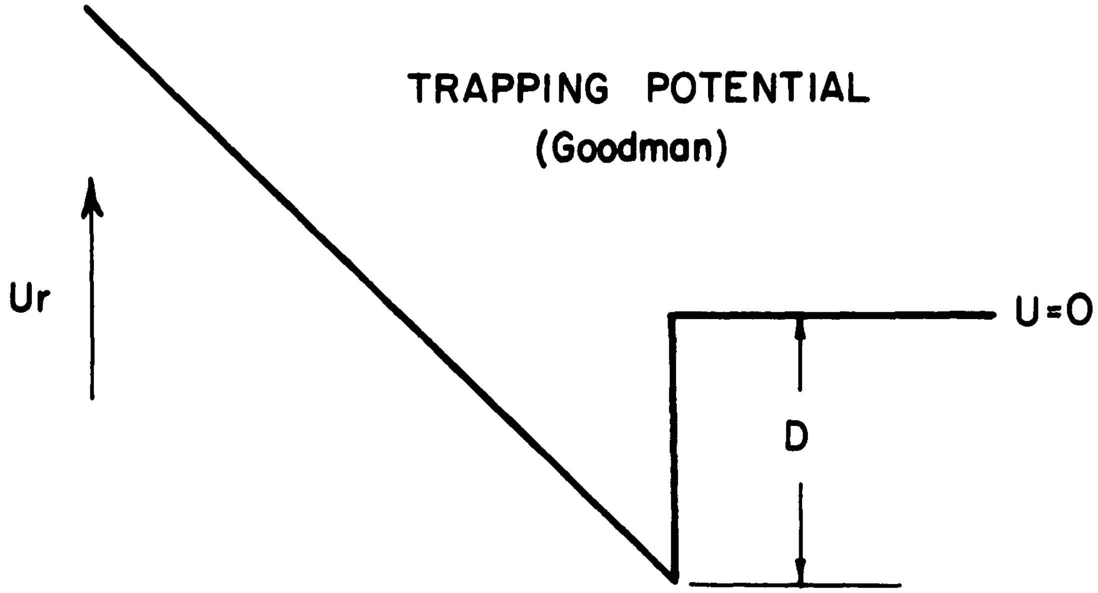


FIG. 8. PHASE SHIFT (VELOCITY) SPECTRUM FOR K BEAM (530° K)
FROM W REFLECTOR AT 2135° K (Marcus and McFee)

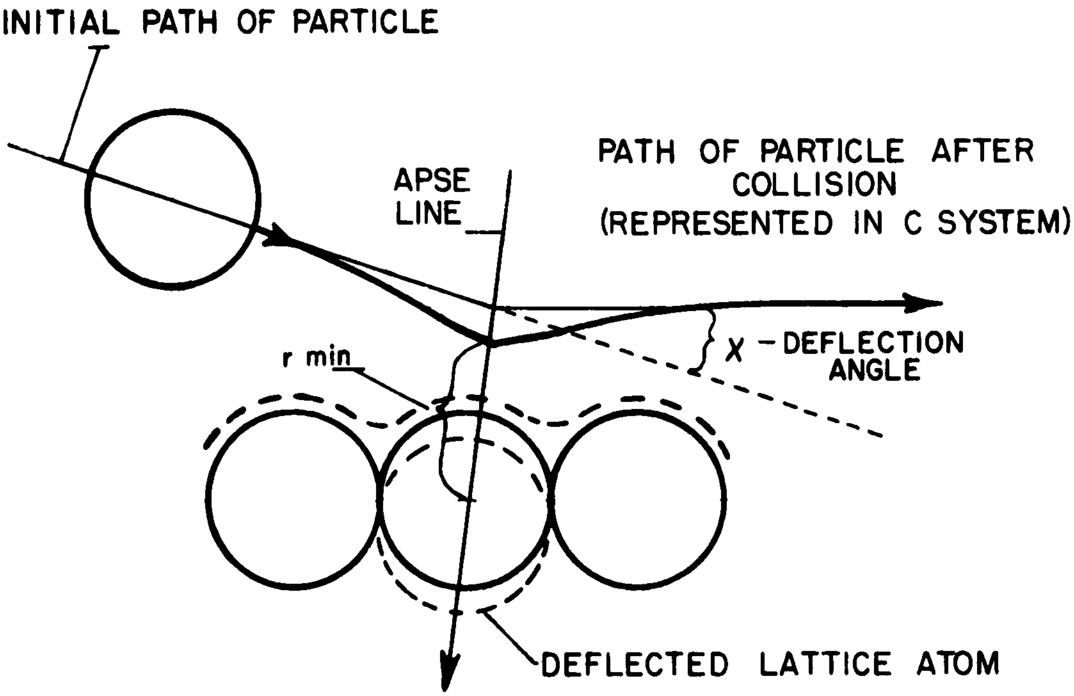


TRUNCATED HARMONIC OSCILLATOR POTENTIAL
(Zwanzig)


TRAPPING POTENTIAL
(Goodman)

TRAPPING POTENTIALS FOR INTERACTION OF A HOT GAS ATOM WITH A COLD SURFACE

FIG. 9.



COLLISION OF A GAS ATOM WITH A SOLID SURFACE

FIG. 10.

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