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COINCIDENCE STUDY OF O^+ on Kr COLLISIONS

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1. ABSTRACT AND INTRODUCTION

The reaction under study is

The incident oxygen is scattered to angle θ with charge $+m$ and the target krypton recoils to angle ϕ with charge $+n$. A coincidence apparatus is used which enables one to study simultaneously the two particles resulting from the same collision. The two charge states m and n are determined, and also the quantity $\bar{Q}_{mn}$ is found, which is the inelastic energy for the (m,n) reaction.

The study is concerned with violent large-angle collisions wherein the oxygen is scattered to angles $\theta = 10^\circ$ to 40° . The incident energy ranges from 25 to 230 keV. In the more violent collisions the oxygen is found to up to 4X ionized and the krypton up to 8X ionized. The ionization probabilities are plotted vs the average inelastic energy of the collision. The inelastic energies run from 100 eV to 960 eV.

An extensive series of similar measurements on the $Ar^+ - Ar$ collision have already been reported by the present authors in two papers.^{1,2} All the apparatus, theory, and procedure necessary here were developed in the course of the $Ar^+ - Ar$ study, which was sponsored first by the U. S. Army Research Office, Durham, and more recently by the U. S. Air Force Office of Scientific Research.

Coincidence measurements of this type are a rather recent development, besides the two papers mentioned above^{1,2} and two brief letters by our group,^{3,4} the only other somewhat similar experiment is that by Fedorenko and his group^{5,6} at Leningrad.

2. THEORY OF MEASUREMENT

The equations for the inelastic energy loss are derived classically from the laws for the conservation of energy and momentum. In Fig. 1, the incident particle of initial energy T_0 , has energy T_1 after scattering to angle θ , and the target particle has energy T_2 after recoiling to angle ϕ . Denoting the inelastic energy loss by Q and ignoring the energy and momentum carried away by the electrons and photons, the conservation equations are

$$T_0 = T_1 + T_2 + Q \quad (2)$$

$$\sqrt{m_1 T_1} = \sqrt{m_1 T_1} \cos \theta + \sqrt{m_2 T_2} \cos \phi \quad (3)$$

$$0 = \sqrt{m_1 T_1} \sin \theta - \sqrt{m_2 T_2} \sin \phi \quad (4)$$

in laboratory coordinates. Solving these equations, letting $\gamma = m_1/m_2$, and $\beta = \theta + \phi$ gives:

$$Q = T_0 - T_1 - T_2 \quad (5)$$

$$T_1 = T_0 \frac{\sin^2(\beta - \theta)}{\sin^2 \beta} \quad (6)$$

$$T_2 = \gamma T_0 \frac{\sin^2 \theta}{\sin^2 \beta} \quad (7)$$

The percentage of collisions (for a given T_0 and θ) for which the scattered oxygen ion is m times ionized while the corresponding recoil krypton ion resulting from the same collision is n times ionized is denoted by $\bar{p}_{mn}$, an experimentally determined quantity. The percentage of oxygen ions that are m times ionized, $\bar{P}'_m$, after collision is given by a summation of

FIG. 1. The collision.

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$\bar{p}_{mn}$ over all possible recoil charge states. Thus

$$\bar{P}_m' = \sum_n \bar{p}_{mn} . \quad (8)$$

Similarly the percentage of recoiling ions that are n times ionized, $\bar{P}_n''$, is given by

$$\bar{P}_n'' = \sum_m \bar{p}_{mn} . \quad (9)$$

The average charge state for the scattered oxygen ions is given by

$$\bar{m} = \sum_m m \bar{P}_m' \quad (10)$$

and, similarly for the krypton

$$\bar{n} = \sum_n n \bar{P}_n'' . \quad (11)$$

The equations of this section are taken from an earlier paper¹ and are included here for convenience and reference.

3. APPARATUS AND PROCEDURE

a) Description of Apparatus

The apparatus was designed and constructed under the sponsorship of the U. S. Air Force Office of Scientific Research and the U. S. Army Research Office, Durham, and has already been described in detail.^{1,7} The description is repeated in abridged form here.

Figure 2 shows a schematic diagram of the apparatus. The magnetically analyzed ion beam from the accelerator passes through collimating holes a, b, and c into the target gas region. The scattered incident beam is defined by slits d and e and the recoil particle is defined by slits f and g.

FIG. 2. The apparatus.

After passing through slit e (or g) the scattered (or recoil) beam enters a charge state analyzer. Each electrostatic analyzer consists of two radially concentric plates with a hole bored in the positive plate, allowing for the passage of neutral particles into a detector in position "A". If both plates are grounded, the detector in position "A" records all particles passing through the collimators regardless of charge state. Position "B" of the detectors together with the proper voltages applied to the analyzer plates allows the separation and detection of differently charged ions.

The detectors are fourteen stage secondary electron multipliers. The first dynode is grounded so that there is no post-acceleration of charged ions. These detectors are operated under conditions for which they are at least 90 percent efficient regardless of the ion being detected.

b) Single Collision Conditions

Ideally, the collision products should be the result of single collisions. Avoiding a secondary collision is difficult, for charge exchange cross sections are much larger than the differential cross sections for the rare large angle scattering events being studied here. A second collision becomes likely when the path through the target gas is too long or when the target pressure is too high. On the other hand, if the target gas pressure is too low, large angle scattering events become so rare that an accurate study is all but impossible.

Figure 3 shows the effect of target gas pressure on $\bar{P}_i$, the percentage of the particles in ionization state i , for both the scattered oxygen and the recoil krypton beams under typical operating conditions. In Fig. 3a, where $\bar{P}_m^i$ is plotted against the target gas pressure, it is seen that below

FIG. 3. Pressure run for coincidence scattering of $O^+ - Kr$. (a) Oxygen and (b) Krypton charge state probabilities.

a pressure of about 0.5 micron the various $\bar{P}'_m$ remain constant. Fig. 3b shows $\bar{P}''_n$ plotted in the same way. The recoiling krypton ions, which have only about 600 eV energy, have a much higher charge exchange cross section in krypton than do the corresponding oxygen ions, which have nearly 99 keV energy. This is shown by the fact that the curves in Fig. 3b do not become level below 0.5 micron. However the error introduced into the $\bar{P}'_n$ by taking data at 0.5 micron is less than 4 percent (estimated by extrapolating curves as straight lines to zero pressure). This 4 percent error in $\bar{P}'_n$ is probably an overestimate and is less an error than would appear due to poor counting statistics at lower pressures. Fortunately, there is hardly any error in the Q-values from this cause.

At these pressures the incident ion beam was found to have a neutral component of only 2 percent.

The target gas supply was spectroscopically pure krypton. Angular resolution is such that effects due to the several isotopes of krypton have not been observed. An advantage of these coincidence measurements is that small impurities in the target gas do not effect the coincidence data. The scattered and recoil collimators are set at angles θ and ϕ that correspond and depend on the masses of oxygen and krypton. A target gas impurity with a mass differing from that of krypton would result in a different set of angles θ and ϕ and there would be no contribution to the coincidence data.

c) Time of Flight

The voltage pulses resulting from the detection of the scattered and recoil particles from a given collision are passed through a coincidence circuit to insure that the particles detected are indeed, the result of the

same collision. The particles have different velocities after collision resulting in the scattered particles being detected before the recoil particles. It is necessary to delay the scattered voltage pulse before passing it through the coincidence circuit. A magnetostrictive delay line that can be set to within 0.02 microseconds is used for this purpose. The coincidence resolving time is set for about 0.5 microseconds. This is short enough to keep random coincidences infrequent, but long enough so as not to discriminate against particles with velocities differing only slightly from the average.

d) Procedure

A data set consists of three basic measurements taken using oxygen ions with a given incident energy T_0 , scattering to a given angle θ . The first of these measurements is the average inelastic energy loss, $\bar{Q}$. The second is the average energy loss for collisions resulting in an m times ionized oxygen ion and an n times ionized krypton ion; this is denoted by $\bar{Q}_{mn}$. The third of these measurements is that of $\bar{p}_{mn}$; this is the percentage of collisions for which the scattered oxygen ion is m times ionized while the corresponding recoil krypton ion resulting from the same collision is n times ionized.

The average inelastic energy loss, $\bar{Q}$ is determined by placing the detector in position "A" as shown in Fig. 2. In this position particles passing through the collimator are detected regardless of their charge. With the scattered incident particles being detected at an angle θ , the angle β is varied until the angle $\bar{\beta}$, the average angle for which the recoil particles are found in coincidence with the scattered particles is determined. This value of $\bar{\beta}$ is substituted into Eq. (5)-(7), thus

determining $\bar{Q}$. The inelastic energy loss $\bar{Q}_{mn}$ is determined in the same way except the charge analyzers are set so that only the particles with the desired charge states reach the detectors.

The percentages $\bar{p}_{mn}$ are determined by adjusting the charge state analyzers to accept the (m,n) type reactions and then counting the number of coincidences, N_{mn} , detected in a given length of time. This is done for all possible (m,n) combinations; then

$$\bar{p}_{mn} = N_{mn} / \sum_{m,n} N_{mn} \quad (12)$$

The angle β must be set at $\bar{\beta}_{mn}$ while determining the number N_{mn} . Direct determination of the angle $\bar{\beta}_{mn}$ may be made only for common (m,n) events. Plotting these values of $\bar{\beta}_{mn}$ versus $m + n - 1$ results in a smooth curve from which the remaining $\bar{\beta}_{mn}$ may be extrapolated.

4. DATA

Collision of singly charged oxygen ions with energies ranging from 25 keV to 230 keV, scattering from 10° to 40° are studied.

Table I gives the values of the inelastic energy loss for the combinations studied. The average inelastic energy loss values $\bar{Q}$ are the first entry in each data set and are denoted by the notation (T,T). That is, $\bar{Q} \equiv \bar{Q}_{TT}$. The average inelastic energy loss $\bar{Q}_{mn}$ for collisions resulting in an m times ionized oxygen ion together with an n times ionized krypton ion are denoted (m,n). The plus and minus values are used to indicate that when the measurement is repeated, in ninety percent of the cases it will fall within the extremes. Table II gives the $\bar{p}_{mn}$ values as calculated by Eq. (12).

Table III gives the $\bar{P}_m'$, $\bar{P}_n''$, $\bar{m}$, and $\bar{n}$ as calculated by Eqs. (8)-(11).

5. DISCUSSION

The data in Tables I - III may be plotted in a number of informative ways. First the inelastic energy loss and then the charge analysis is dealt with.

a) Inelastic Energy Loss

Fig. 4(a) shows the average inelastic energy loss plotted against the incident ion energy with contours of constant θ . It is seen that $\bar{Q}$ ranges from a value of about 100 eV to 960 eV. There appears to be a slight leveling off in the inelastic energy loss at higher energies. Fig. 4(b) plots the average inelastic energy loss $\bar{Q}$ versus the distance of closest approach, r_0 . Details of the calculation for r_0 have appeared in a paper by Everhart, et. al.⁸ Contours of constant energy T_0 are shown by the solid lines; contours of constant scattering angle θ are shown by the dashed lines.

b) Charge Analysis

Fig. 5 plots the ionization probabilities found in Table III against the average inelastic energy loss $\bar{Q}$. All these data were taken for $\theta = 10^\circ$ scattering. Figure 5a shows the various charge states for the oxygen ion, Fig. 5b for the krypton ion. It is seen that the probabilities vary smoothly with changes in the inelastic energy loss. There is some neutralization of the incident oxygen ion for the more gentle collisions.

In Fig. 6 the average number of electrons lost is plotted against the inelastic energy loss, $\bar{Q}$. Here are shown curves for the average number of

FIG. 4. (a) Inelastic energy $\bar{Q}$ vs distance of closest approach r_0 for $O^+ - Kr$ collision at angles and energies specified.
 (b) Inelastic energy $\bar{Q}$ vs incident energy T_0 for $O^+ - Kr$ collision at angles θ specified.

FIG. 5. Charge state probabilities for $O^+ - Kr$ collisions vs overall average ineladitic energy Q . (a) Oxygen; (b) Krypton.

FIG. 6. Number of electrons lost in $O^+ - Kr$ collisions.

electrons lost from each atom, $\bar{m} - 1$ for oxygen and $\bar{n}$ for krypton, as well as $\bar{m} + \bar{n} - 1$, the number lost for the collision as a whole.

It had been thought that the $O^+ - Kr$ system would show structure in the Q-values related to shell-structure in the krypton. In fact, structure is indeed seen in $Ar^+ - Ar$ collisions and this appears to arise from intersections of the two L-shells of the argons. In like manner one might have expected that as the oxygen penetrates the outer or N-shell of krypton one would find a low Q-value, and then, with increased violence of collision, as the N-shell and (and later the L-shell) of krypton is penetrated one would find successively higher steps in the Q-values. Apparently this does not happen, at least such effects are not seen in the 25 keV to 230 keV energy range with the resolution used in this study. The Q-values appear to increase smoothly and continuously with increased violence of the collision.

Before one can decide how much of the $\bar{Q}$ value is absorbed by the oxygen atomic system and how much by the krypton atomic system, it would be necessary to make a complete study of the $Kr^+ - Kr$ systems.

Table I. Inelastic energy loss values $\bar{Q}_{mn}$ for $O^+ - Kr$ collisions where charge states m and n after collision are both specified. Here $\bar{Q}_{TT} = \bar{Q}$. For each data set incident energy T_0 and angles θ are specified.

T_0, θ	m, n	$\bar{Q}_{mn}$ (eV)	m, n	$\bar{Q}_{mn}$ (eV)
25 keV, 10°	T,T	105 ± 30	1,2	115 ± 15
	1,3	145 ± 15	2,3	190 ± 30
25 keV, 20°	T,T	180 ± 10		
25 keV, 40°	T,T	270 ± 20		
34 25 keV, 10°	T,T	200 ± 8		
50 keV, 10°	T,T	305 ± 15	2,4	290 ± 15
	2,5	380 ± 35	2,3	250 ± 20
	1,3	200 ± 20		
50 keV, 20°	T,T	375 ± 25		
50 keV, 40°	T,T	425 ± 50		
70 keV, 10°	T,T	445 ± 15		
100 keV, 10°	T,T	570 ± 30	3,6	725 ± 40
	2,5	540 ± 30	3,5	605 ± 30
	2,4	470 ± 40	3,4	510 ± 90
	2,6	630 ± 40		
100 keV, 20°	T,T	650 ± 50		
100 keV, 40°	T,T	660 ± 90		
140 keV, 10°	T,T	760 ± 35		
150 keV, 10°	T,T	800 ± 70		
150 keV, 20°	T,T	880 ± 100		
150 keV, 40°	T,T	850 ± 140		
200 keV, 10°	T,T	910 ± 50	3,5	780 ± 80
	3,6	880 ± 50	2,6	800 ± 80
	3,7	1030 ± 80	2,7	970 ± 80
200 keV, 20°	T,T	990 ± 150		
230 keV, 10°	T,T	960 ± 60		

Table II. These data are for $O^+ - Kr$ collisions. The relative probability of $\bar{p}_{mn}$ of the (m,n) event is given for data sets wherein the incident energy T_0 and angle θ are specified.

25 keV, 10^0 , total events = 285

m =	0	1	2
n = 1	0.007	0.063	0.018
n = 2	0.039	0.253	0.056
n = 3	0.119	0.333	0.056
n = 4	0.018	0.035	0.004

35 keV, 10^0 , total events = 626

m =	0	1	2	3
n = 1	0.000	0.006	0.011	0.000
n = 2	0.006	0.058	0.050	0.008
n = 3	0.045	0.276	0.225	0.019
n = 4	0.026	0.147	0.080	0.011
n = 5	0.003	0.021	0.008	0.000

50 keV, 10^0 , total events = 797

m =	1	2	3
n = 1	0.000	0.001	0.003
n = 2	0.003	0.014	0.006
n = 3	0.036	0.131	0.069
n = 4	0.121	0.248	0.068
n = 5	0.083	0.146	0.029
n = 6	0.020	0.021	0.003

70 keV, 10^0 , total events = 686

m =	1	2	3	4
n = 3	0.008	0.057	0.060	0.009
n = 4	0.032	0.181	0.140	0.009
n = 5	0.031	0.182	0.105	0.003
n = 6	0.031	0.089	0.039	0.001
n = 7	0.009	0.009	0.004	0.001

100 keV, 10^0 , total events = 500

m =	1	2	3	4
n = 3	0.004	0.018	0.028	0.006
n = 4	0.006	0.064	0.092	0.010
n = 5	0.022	0.126	0.120	0.018
n = 6	0.050	0.160	0.122	0.010
n = 7	0.022	0.062	0.034	0.002
n = 8	0.008	0.010	0.006	0.000

140 keV, 10^0 , total events = 360 (This set does not include $m = 1$ cases, estimated at 5%)

m =	2	3	4
n = 3	0.008	0.017	0.006
n = 4	0.022	0.047	0.008
n = 5	0.086	0.097	0.042
n = 6	0.144	0.169	0.017
n = 7	0.128	0.103	0.025
n = 8	0.033	0.042	0.006

200 keV, 10^0 , total events = 446 (This set does not include $m = 1$ cases, estimated at 3%)

m =	2	3	4
n = 3	0.002	0.002	0.002
n = 4	0.005	0.015	0.002
n = 5	0.036	0.074	0.022
n = 6	0.112	0.130	0.036
n = 7	0.132	0.170	0.054
n = 8	0.101	0.074	0.029

Table III. These data are for $O^+ - Kr$ collisions at the incident energies T_0 and angles θ specified. The ionization probabilities $\bar{P}_m^i$ and the average ionization state $\bar{m}$ of the scattered oxygen are given. Similarly $\bar{P}_n^i$ and $\bar{n}$ refer to the recoil krypton. Here $\bar{Q}$ is the average inelastic energy for the data set.

T_0 keV	θ deg	$\bar{Q}$ eV	$\bar{m}$	m	$\bar{P}_m^i$	$\bar{n}$	n	$\bar{P}_n^i$
25	10°	103	0.94	0	0.18	2.56	1	0.09
				1	0.68		2	0.35
				2	0.13		3	0.51
							4	0.06
35	10°	196	1.37	0	0.08	3.17	1	0.02
				1	0.51		2	0.12
				2	0.37		3	0.57
				3	0.04		4	0.26
							5	0.03
50	10°	300	1.91	0	0.00	4.05	1	0.00
				1	0.26		2	0.02
				2	0.56		3	0.24
				3	0.18		4	0.44
							5	0.26
							6	0.04
70	10°	434	2.28	1	0.11	4.58	3	0.13
				2	0.52		4	0.36
				3	0.35		5	0.32
				4	0.02		6	0.16
							7	0.02
100	10°	557	2.38	1	0.11	5.37	3	0.06
				2	0.44		4	0.17
				3	0.40		5	0.29
				4	0.05		6	0.34
							7	0.12
							8	0.02
140	10°	740	2.61	1	(0.05)	5.96	3	0.03
				2	0.40		4	0.08
				3	0.45		5	0.23
				4	0.10		6	0.33
							7	0.26
							8	0.08
200	10°	886	2.70	1	(0.03)	6.56	3	0.01
				2	0.38		4	0.02
				3	0.45		5	0.13
				4	0.14		6	0.28
							7	0.36
							8	0.20

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