THE ATOMIC SCATTERING POWERS OF NICKEL, COPPER AND IRON FOR VARIOUS WAVE-LENGTHS

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Abstract

Atomic scattering powers are measured for the atoms in metallic nickel, copper and iron when they are reflecting the $K\alpha$ lines of molybdenum, copper, nickel and iron. These data show that the scattering power of an atom passes through a minimum at its K absorption limit and attains a maximum at, or near, its "resonance" wave-length. The atomic F-curves of the nickel atom in metallic nickel and in NiO are practically identical.

THE data of this paper consist in measurements of the scattering powers of the metals nickel, copper and iron for the $K\alpha$ lines of molybdenum, copper, nickel and iron. Previous work from this laboratory with metallic copper and iron[1] showed that the reflecting powers of an atom might be considerably different for different wave-lengths. Studies[2] of NiO have indicated that the scattering power of nickel decreases as the wave-length used approaches its K critical absorption limit from the high frequency side and that it rises again after the limit is passed. The following results[3] suggest that this variation is generally to be expected.

F-curves for metallic nickel have been measured using the $K\alpha$ lines of molybdenum, copper, nickel and iron. The previous data from metallic copper and iron have also been extended through observations with copper, nickel and iron rays. The experimental procedures and the calculations leading to absolute F-values are the same[4] as those which have already been described. The $K\alpha$ lines of molybdenum were obtained by filtering the beam from a General Electric diffraction x-ray tube through a ZrO_2 filter; all other radiations were the unfiltered output of Siemens-Phoenix tubes equipped with appropriate targets. Calculation showed, however, that none of the measured $K\alpha$ reflections was, under the conditions of the experiment, contaminated by other wave-lengths.

The specimens studied were chemically pure, powdered metals which were passed through a fine meshed sieve and formed into suitable cakes by pressure applied in an ordinary vise. The surfaces of the preparations made in this way were filed and brushed before use in order to remove any super-

[1] A. H. Armstrong, Phys. Rev. **34**, 931 (1929).
[2] R. W. G. Wyckoff, Phys. Rev. **35**, 583 (1930).
[3] cf. R. W. G. Wyckoff, Phys. Rev. **35**, 215 (1930).
[4] A. H. Compton, X-rays and Electrons (New York, 1926), Chap. V; R. W. G. Wyckoff and A. H. Armstrong, Zeits. f. Krist. **72**, 319 (1929).

ficial layer which might show a preferred orientation. Two samples each of nickel and copper, one of domestic and the other of foreign manufacture, gave concordant results. The iron used was an imported preparation of pure electrolytic metal.

The relative intensities of the various measured reflections are listed in Tables I and II together with the intensities of (220) of NaCl which has served

TABLE I. *Relative intensities of the measured powder reflections from metallic nickel.*

Plane	Relative Intensities for Mo $K-\alpha$	Cu $K-\alpha$	Ni $K-\alpha$	Fe $K-\alpha$
111	$374._6$	$431._2$	$412._4$	$226._5$
200	$181._6$	$192._1$	$185._7$	[100]
220	[100]	[100]	[100]	—
113	$102._9$	$107._4$	—	—
222	34.1	32.0	—	—
400	—	—	—	—
133	30.6	—	—	—
240	28.6	—	—	—
224	18.3	—	—	—
333, 115	18.5	—	—	—
220 of NaCl	$571._7$	$107._7$	93.3	49.1

TABLE II.

Radiation	Reflection	Intensity of reflection (220, NaCl = 100)	F for 110, Fe
Cu $K-\alpha$	110, Fe	51.9	11.48
Ni $K-\alpha$	110, Fe	37.5	9.77
Fe $K-\alpha$	110, Fe	$609._2$	13.45
Cu $K-\alpha$	220, Cu	94.2	—
Ni $K-\alpha$	220, Cu	88.4	—
Ni $K-\alpha$	200, Cu	$167._7$	—
Fe $K-\alpha$	200, Cu	$153._7$	—
Fe $K-\alpha$	111, Cu	$330._1$	—

as standard. Since the absolute reflecting power of no crystal is known for any of the wave-lengths used except Mo $K\alpha$, it has, as before, been assumed that F(220, NaCl) is independent of wave-length and equal[5] to 15.62. Though this assumption is almost certainly not strictly accurate, it probably does not depart far from the truth. When absolute F's shall have been determined for these longer wave-lengths, it will be easy to shift the present results to conform with them.

The F-values calculated from the intensity data of Tables I and II are dependent upon the absorption coefficients that are used. Experimental values exist for most of these coefficients. Except for metallic copper when absorbing Cu $K\alpha$ and metallic iron when absorbing Ni $K\alpha$ radiations, they are in satisfactory agreement with the values calculated by Jönsson's general formula.[6] Even in the most unfavorable case, the choice of extreme values of absorption coefficients makes a difference of only 0.4 of an absolute F-unit.

[5] R. W. James and E. M. Firth, Proc. Roy. Soc. **117A,** 62 (1927).
[6] E. Jönsson, Uppsala Univers. Arsskrift (1928).

For the sake of uniformity and completeness, calculated μ/ρ's as shown in Table III, have been employed throughout.

The resultant reflection F's are recorded in Tables II, IV and V and in Figure 1. Several comparisons are possible between these data and the

TABLE III. *Absorption coefficients used in calculating F-values.*

Absorber	Density	*Absorbed Wave-length* Mo $K-\alpha$	Cu $K-\alpha$	Ni $K-\alpha$	Fe $K-\alpha$
Nickel	8.90	423	432	549	825
Copper	8.95	—	468	586	886
Iron	7.92	—	2556	3124	570
NaCl	2.16	18.0_1	$161._2$	$196._2$	$306._8$

TABLE IV. *Absolute F-values of the nickel atom in metallic nickel.*

Plane	sin θ/λ	*Radiation* Mo $K-\alpha$ (0.710 A)	Cu $K-\alpha$ (1.537 A)	Ni $K-\alpha$ (1.655 A)	Fe $K-\alpha$ (1.932 A)
111	0.246	18.06	14.94	15.92	16.05
200	.284	16.89	13.70	14.71	14.69
220	.402	12.91	10.57	11.29	—
113	.471	11.10	8.73	—	—
222	.492	11.64	8.32	—	—
400	—	—	—	—	—
133	.619	8.37	—	—	—
240	.635	8.36	—	—	—
224	.696	7.48	—	—	—
333, 115	.738	7.01	—	—	—

TABLE V. *Absolute F-values of the copper atom in metallic copper.*

Plane	sin θ/λ	Cu $K-\alpha$ (1.537 A)	*Radiation* Ni $K-\alpha$ (1.655 A)	Fe $K-\alpha$ (1.932 A)
111	0.241	16.60	—	14.59
200	.278	14.90	14.57	13.72
220	.392	11.53	11.18	—
113	.461	9.56	—	—
222	.481	9.10*	—	—

* The relative intensities of the reflections in this column (compared with 220) are those found by A. H. Armstrong (reference 1).

results of previous measurements. The F(220, Cu) for Cu $K\alpha$ is in fairly good agreement with existing information, but F(110, Fe) for the same radiation fails considerably below the published[7] value. Additional observations with iron powder from the source which supplied the earlier experiments make it seem probable that there was some preferential orientation in the previous powder cake. Of interest is the comparison that can be made between the F-curves of metallic nickel and of the nickel ion[8] in NiO. This comparison

[7] A. H. Armstrong, reference 1.

[8] R. W. G. Wyckoff, Phys. Rev. **35**, 583 (1930).

is shown graphically in Figure 2 for Mo $K\alpha$, Cu $K\alpha$ and Ni $K\alpha$ rays. The agreement is especially close for the Mo $K\alpha$ and Cu $K\alpha$ curves.

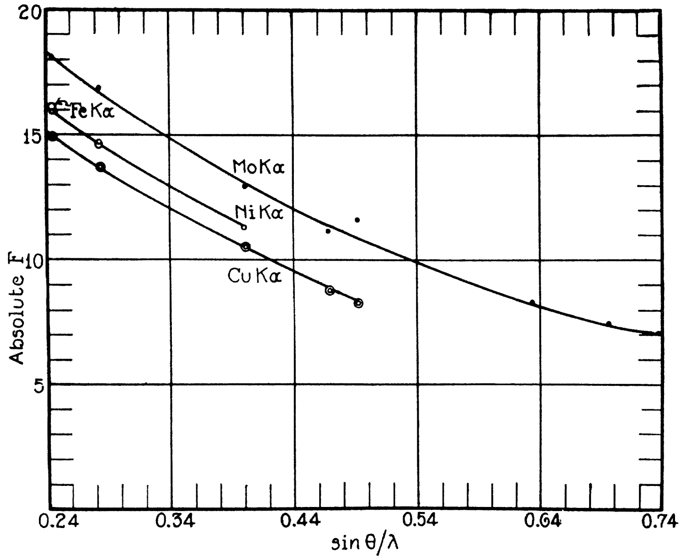

Fig. 1. The experimentally determined F-curves of metallic nickel for Mo $K\alpha$, Ni $K\alpha$ and Cu $K\alpha$ radiations. The two observed points for Fe $K\alpha$ rays are shown as large open circles.

Points on the F-curve for nickel with molybdenum radiation could be measured for reflections more complicated than (333; 115). Such reflections would be hard to determine with accuracy, however, because they are insignificant compared with the background of secondary nickel radiation

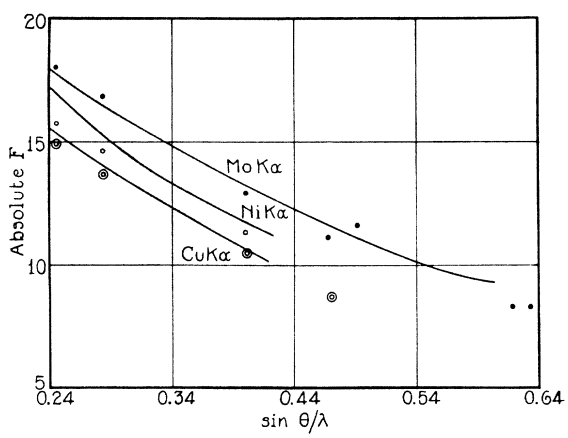

Fig. 2. The F-curves for the nickel atoms in NiO crystals are shown as full lines. Observed points for nickel atoms in metallic nickel appear as black circles (for Mo $K\alpha$), open circles (for Ni$K\alpha$) and ringed circles (for Cu $K\alpha$).

excited by the Mo $K\alpha$ lines. The first, (111), reflection of nickel occurs at so great an angle ($\sin \theta/\lambda = 0.246$) that much of the complete F-curve of metallic nickel is of necessity extrapolated. This fact seems to prevent any important physical significance being attached to the electron-distribution curves that are calculated by Fourier analysis from the extrapolated forms of this *F*-curve.

The *F*-values of this paper show clearly the way in which the reflecting power of an atom varies with the wave-length of the x-rays scattered. The phenomena are illustrated by the (200) reflections of nickel as plotted in Figure 3. All of the other data of the present paper as well as those from NiO

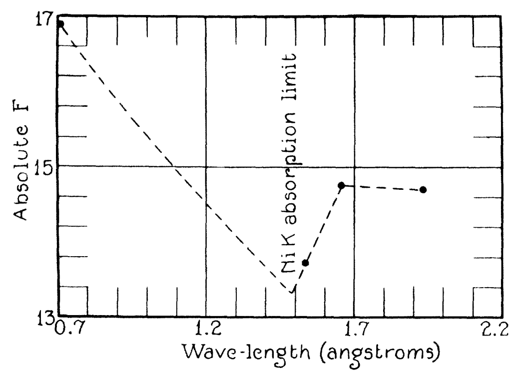

Fig. 3. The dotted curve indicates the variation of the scattering power of nickel with wave-length. The full circles are the measured values of the (200) reflection of metallic nickel.

agree with this figure in showing that the scattering power of an atom is at a minimum close to its *K* critical absorption limit, that it attains a maximum at, or near, its "resonance" wave-length, but that the reflecting power falls off only slowly on the long wave-length side of this frequency. The photographs made by Mark and Szilard[9] of RbBr using strontium and bromine radiations are obviously an expression of the same variation.

It is hoped through additional experiments to put these scattering powers for long wave-lengths upon an accurate absolute scale.

[9] H. Mark and L. Szilard, Zeits. f. Physik **33**, 688 (1925).