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PHASE OF NEUTRON SCATTERING

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PHASE OF NEUTRON SCATTERING
by E. Fermi and L. Marshall

A neutron wave may be scattered with a change in phase of either 0° or 180° . By studying the intensities of the orders of Bragg reflection for neutrons, one can compare the phase of neutron scattering of the different nuclei which compose a crystal.

A beam of thermal neutrons from the Argonne heavy water pile was monochromatized by Bragg reflection from the 100 face of CaF_2 . From a second crystal in the monoenergetic beam Bragg reflections of various orders were obtained.

The form factors were calculated from the positions and scattering cross sections of the atoms in the unit cell, and were compared with the observed variation of intensities of orders in several crystals. From the fact that carbon totally reflects neutrons, ^{as} found by Fermi and Zinn, it follows that the phase change for carbon is 180° . ¶ The present investigation shows that O, Ca, Fe, S, Pb, F and tentatively C scatter with the same phase shift, and that the phase shift for Mn is opposite. Consequently, the phase shift for the group may be tentatively identified as 180° , and that for Mn tentatively identified as 0° .

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PHASE OF NEUTRON SCATTERING

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Bragg scattering of neutrons is analogous to that of x-ray scattering except in one respect. X-rays are always scattered in the same phase, but for neutrons the possibility exists that they may be scattered in the same phase or in opposite phase. The purpose of this investigation was to examine the phase of neutron scattering of various nuclei.

A beam of thermal neutrons from the Argonne pile was made monoenergetic by Bragg reflection from the 100 face of a fluorite crystal at an angle of about 15° . By retarding a second crystal in the monoenergetic beam, Bragg reflections of various orders were obtained. A study of the relative intensities of the orders allow one to compare the phase of neutron scattering of the different nuclei which compose the second crystal.

The simplest case is that of a crystal in which the planes are equidistant and consist alternately of two kinds of atoms. Such is the case for instance for the 1,1,1 planes of NaCl. These planes are equidistant and contain alternately sodium and chlorine. In the first order Bragg reflection, the optical path for reflection from sodium planes differs from that for reflection from chlorine planes by $\lambda/2$. Consequently, if sodium and chlorine scatter in the same phase their contributions will subtract and the order will have low intensity. If they scatter in opposite phase the order will have high intensity.

The situation is different for the second order. In this case the difference in optical path for reflection from the two kinds of planes is λ . Consequently, if sodium and chlorine scatter in the same phase, the order will have high intensity; and, if an opposite phase, low intensity. By analogous reasoning it follows that if the two types of nuclei scatter in the same phase the odd orders will be weak and the even orders will be strong. Conversely if they scatter in opposite phase the odd orders will be strong and even orders weak.

Analogously to x-ray scattering, there is superimposed upon this effect a continuous decrease from order to order due to geometrical factors, to thermal agitation, and to imperfections of the crystal.

Aside from this regular decrease the intensity of the various orders is determined by the form factor.

$$F = \left| \sum_j \pm \sqrt{\sigma_j} \exp(2\pi i n S_j/d) \right|$$

where $\sqrt{\sigma_j}$ is the square root of the scattering cross section, d is the spacing of the lattice planes, n is the order of the Bragg reflections, S_j is the perpendicular distance from the j^{th} atom to the plane of reflection. The $+$ sign is used if the neutrons are scattered in phase and conversely the $-$ sign is used if the neutrons are scattered in opposite phase. In the case that an element has more than one isotopes, the weighted average of the square roots of the isotopic scattering cross-sections is used.

The observed intensities of Bragg reflections from various crystals are given in the table below. They have not been corrected

TABLE I

Crystal	Plane	Order	Max. Intensity e/m	Theoretical form Factor
Na Cl	111	1	2376	Na - Cl
		2	2750	Na / Cl
Na Cl	100	1	8200	Na / Cl
		2	2960	Na / Cl
		3	680	Na / Cl
Pbs	111	1	7280	Fb - 2
		2	10700	Pb / s
		3	808	Pb - s
		4	750	Pb / s
PbS	100	1	6893	Pb / S
		2	1354	Pb / S
		3	726	Pb / S
Ca F ₂	100	1	16400	Ca - 2F
		2	20400	Ca / 2F
		3	1287	Ca - 2F
FeS ₂ (Pyrite)	100	1	6393	Fe / 0.68
		2	1354	Fe - 1.68
		3	726	Fe - 1.63
Mn S ₂	111	1	7930	Mn - 1.06S
		2	2360	Mn / .06S
		3	670	Mn / .068
Fe ₃ O ₄	111	1	13000	2.3 Fe / 1.2 Ox
		2	12600	16.0 Fe - 31.9 Ox
		3	13800	13.7 Fe - 3.5 Ox
		4	21000	8.0 Fe / 31.5 Ox
		5	5100	13.7 Fe / 5.9 Ox
Ca CO ₃ (Calcite)	111	1	2820	Ca - CO ₃
		2	2000	Ca / OO ₃
		3	1060	Ca - Co ₃
Ca CO ₃ (Calcite)	211	1	10900	Ca / C / 0.9 Ox
		2	3360	Ca / C - 1.0 Ox
		3	2400	Ca / C / 1.3 Ox

TABLE I (Continued)

Crystal	Plane	Order	Max. Intensity c/m	Theoretical form Factor
K Br	111	1	1545	K - Br
		2	2853	E / Br
		3	19	K - Br
		4	~ 0	K / Br
Mg O	111	1	764	Mg - O
		2	14175	Mg / O
		3	132	Mg - O
Mg O	100	1	10352	Mg / O
		2	6258	Mg / O
Li F	100	1	740	Li / F
		2	236	Li / F
Li F	111	1	10080	Li - F
		2	~ 13	Li / F
		3	382	Li - F
Ba SO ₄	011	1	1018	-3.4 Ba / 3.8 S / 4.7 Ox
		2	1632	/1.9 Ba / 3.1 S - 9.6 Ox
		3	651	/ .4 Ba / 2.0 S - 7.9 Ox
		4	36	-2.5 Ba / .8 S - 2.2 Ox
		5	~ 0	/3.8 Ba - .6 S / .9 Ox
	010	1	3606	4 (Ba / S) / .4 Ox
		2	4837	4 (Ba / S) / 14.6 Ox
		3	756	4 (Ba / S) / 3.1 Ox
	101	1	737	.9 Ba - 1.2. S - 1.5 Ox
		2	1946	1.1 Ba - 2.0 S - 4.6 Ox
		3	1477	3.8 Ba / 1.0 S / 2.6 Ox
4		~ 0	.3 Ba - .1 S / 2.1 Ox	
5		587	1.0 Ba / 2.1 S -10.4 Ox	

for the continuous decrease of intensity with order because this correction is different for various crystals. The theoretical form factors calculated from the above expression assuming that all elements scatter in the same phase, and therefore, using always the $\sqrt{}$ sign are given also. The square root of the scattering cross-section of an atom taken with the proper sign is represented in the form factor by the chemical symbol for the atom itself.

It is at once evident that the components of the pairs, Na and Cl, Ca and F, Pb and S, Fe and S, K and Dr, Mg and O, Fe and O, scatter with the same sign. Furthermore Li and F scatter neutrons with opposite phases. The measurements of Mn S₂ do not allow a unique interpretation although they indicate more probably that Mn and S scatter with opposite phases.

Independent evidences to be discussed on another occasion shows that Be and O, scatter with opposite phases, and that the same is true also of C and O.

Assuming this last fact to be true, it follows from the measurements on calcite that Ca and C scatter with the same phase. The analysis of the measurements on Ba SO₄ is facilitated by using the fact that S and O scatter with the same phase since the measurements on pyrite and magnetite proves that both are like iron. With this assumption one finds that Be also has the same phase as O.

From these data it follows that O, Fe, Mg, Ba, Ca, S, F, and Pb all scatter neutrons in the same phase. Be, Li, C and probably Mn scatter

in the opposite phase. Na and Cl scatter with like sign, as do K and Br but are as yet unrelated to the others.

The fact that mirrors of Bo and C show total reflection for neutrons (See abstract by Fermi and inn) indicates that both elements change the phase of the scattered neutron wave by 180° , (negative phase). This permits the assignment of positive phase to O, Fe, Mg, Ba, Cs, S, F, and Pb, and negative phase to Li and probably to Mn. Theoretical results lead to the expectation that also hydrogen scatters with negative phase.

In Table II the attempt has been made to give a set of values of $\sqrt{\sigma}$ that is consistent with the observed intensities.

TABLE II

Element	$\sqrt{\sigma} \times 10^{12}$ cm	Element	$\sqrt{\sigma} \times 10^{12}$ cm
O	2.15	Ca	2.8
Fe	2.9	Be	-2.7
S	1.0	F	2.1
Pb	1.7	Li	2.1
G	-2.4	Ba	2.8
		Mg	2.0

From this table it appears that most elements of the group investigated scatter with positive phase. This is somewhat puzzling since it is contrary to the theoretical expectation. We propose to carry out in the future some check especially on the points on which this conclusion mainly rests.