Slow Neutron Scattering by the Titanium Isotopes

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Neutron diffraction studies are reported on isotopically enriched samples of TiO_2 from which are evaluated the coherent scattering amplitudes of the titanium isotopes. Scattering amplitudes of $+0.48$, $+0.33$, -0.58, $+0.08$, and $+0.55\times10^{-12}$ cm were established for the titanium isotopes of mass 46, 47, 48, 49, and 50, respectively. The major isotope Ti^{48} is thus responsible for the anomalous scattering amplitude, -0.34×10^{-12} cm, characteristic of the normal element. Pronounced nuclear scattering resonance effects on the observed neutron scattering are suggested to occur for most of the isotopes.

INTRODUCTION

THE element titanium is one of the few elements possessing an anomalous, negative scattering amplitude for slow neutrons as first observed by Sidhu, Winsberg, and Meneghetti[1] in transmission studies of TiC. This anomalous scattering amplitude is easily observed in neutron diffraction patterns of titanium-containing compounds since the intensity distribution is affected markedly by its presence. Elemental titanium contains five stable isotopes of mass value 46, 47, 48, 49, and 50 with the mass 48 isotope comprising 73.45% of the element and with the other masses approximately equally distributed. It was of interest to determine the individual isotopic scattering amplitudes and thereby establish which of these was responsible for the anomalous elemental scattering.

Samples of separated isotopes were obtained from the Stable Isotopes Division, Oak Ridge National Laboratory, in the oxide form, TiO_2 with the rutile crystal structure. These polycrystalline samples, varying in quantity from 1.95 to 6.64 grams, were placed in small cylindrical specimen tubes of thin-walled vanadium (which produces no extraneous coherent scattering) and neutron diffraction patterns were obtained for the innermost seven reflections ranging from (110) to (220). Most of the patterns were taken using neutron radiation of wavelength 1.218 A. Examination in the oxide form is particularly convenient because the sign of the titanium scattering amplitude can be directly established through comparison with the oxygen scattering amplitude. The oxygen scattering amplitude is known to be of value $+0.575\times10^{-12}$ cm. Moreover, since some of the reflections which were studied had crystal structure factors dependent only upon oxygen scattering, these could be used as convenient internal standards.

Two of the diffraction patterns obtained for the nominal $Ti^{48}O_2$ and $Ti^{50}O_2$ samples are illustrated in Fig. 1 and these demonstrate the pronounced dependence of the intensity upon the titanium scattering amplitude. The individual patterns were analyzed in the conventional manner and effective values for the titanium scattering amplitude were calculated for each sample. All of the intensities were placed on an absolute scale through intercomparison with the scattering by a standard nickel sample for which the coherent scattering amplitude was taken as 1.03×10^{-12} cm. Additionally, this calibration was intercompared with the pure oxygen-contributing reflection as mentioned above. In treating the intensity data it is necessary to know the oxygen position parameter in the crystal structure.

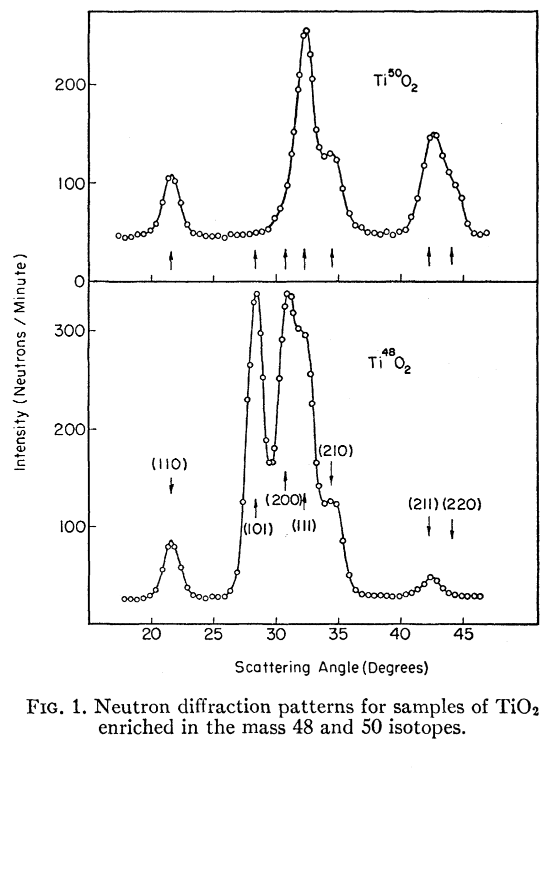

FIG. 1. Neutron diffraction patterns for samples of TiO_2 enriched in the mass 48 and 50 isotopes.

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[1] S. S. Sidhu, L. Winsberg, and D. Meneghetti, Phys. Rev. **74**, 222 (1948).

TABLE I. Isotopic purity and effective neutron scattering amplitudes for isotopic titanium samples.

Isotopic composition	TiO_2	$Ti^{46}O_2$	$Ti^{47}O_2$	$Ti^{48}O_2$	$Ti^{49}O_2$	$Ti^{50}O_2$
	Nominal isotopic sample (atomic percentage)					
Ti^{46}	7.95	82.68	1.55	0.192	1.09	1.54
Ti^{47}	7.75	5.24	63.11	0.248	1.21	1.55
Ti^{48}	73.45	10.39	34.14	99.23	15.71	11.94
Ti^{49}	5.34	0.86	0.67	0.221	77.27	3.54
Ti^{50}	5.51	0.84	0.53	0.105	4.71	81.44
Mean scattering amplitude for Ti in sample	−0.34	+0.36	+0.02	−0.58	0.00	$+0.39\times10^{-12}$ cm

Wykcoff[2] has given this parameter as $u=0.31$ and from the intensities in the neutron diffraction patterns, a value of $u=0.305\pm0.003$ was obtained. For two of the isotopically enriched samples the titanium scattering amplitude was very low and hence the observed intensity was strongly dependent upon the oxygen scattering and this in turn depends upon the oxygen positional parameter. This value for the oxygen positional parameter compares very favorably with the value $u=0.305\pm0.001$ obtained by Baur[3] in an x-ray diffraction study.

NEUTRON SCATTERING AMPLITUDES

Table I summarizes the results obtained for the effective titanium scattering amplitude along with other pertinent information for the isotopically enriched samples. Wide variations in this scattering amplitude are to be noticed. Since none of the samples was isotopically pure, the titanium scattering amplitude represents a weighted average of the pure isotopic scattering amplitudes. By an iterative procedure, the observed amplitudes have been combined to yield the isotopically-pure scattering amplitudes and these values are listed in Table II. An assessment of the various factors that can contribute to the accuracy of these values leads to an uncertainty of $\pm0.02\times10^{-12}$ in the value of the isotopic scattering amplitudes.

TABLE II. Neutron scattering data for the titanium isotopes.

	b_{coh} (10^{-12} cm)	σ_{coh} (barns)	$\sigma_{tot.\ scatt.}$ (barns)
Ti^{46}	+0.48	2.90	2.1
Ti^{47}	+0.33	1.37	1.3
Ti^{48}	−0.58	4.23	3.7
Ti^{49}	+0.08	0.08	<1
Ti^{50}	+0.55	3.80	3.5
Ti (element)	−0.34	1.45	4.0

It is seen from the isotopic scattering results given in Table II that the anomalous scattering by the element is the result of the negative scattering amplitude characteristic of the isotope Ti^{48}. All of the other isotopes exhibit conventional positive scattering amplitudes, but there is considerable variation in their magnitude. Among the isotopes, only Ti^{50} possesses a scattering cross section identifiable with nuclear potential scattering which should be about 3.5 barns for nuclei of these masses. The other values are all smaller than pure potential scattering or the scattering amplitude is anomalously negative, and these data suggest the presence of resonance scattering at energies not too far removed from the neutron energy of about 0.07 ev used in obtaining the present data. Unfortunately, there are no data available on the energy dependence of the cross section.

In addition to the diffraction pattern analysis yielding the coherent scattering amplitudes, the transmission cross-section characteristic of the various isotopic samples was analyzed to furnish values for the total scattering cross section. In first approximation the total cross section should be the sum of the isotopic capture and scattering cross sections plus the oxygen scattering cross section (taken to be 4.24 barns). Isotopic capture cross sections have been given by Pomerance[4] and after correcting these to the present neutron energy assuming an inverse velocity dependence, the total scattering cross sections for the various isotopes have been determined and these are listed in Table II. Because of the approximate validity of this subtractive method, the values for the total scattering cross section are much less accurate than those characterizing the coherent scattering. Comparison of the two scattering cross sections for the even-odd isotopes Ti^{47} and Ti^{49} suggests that there is little spin-dependent scattering for these nuclei.

[2] R. W. G. Wyckoff, *Crystal Structures* (Interscience Publishers, Inc., New York, 1948), Vol. 1.
[3] W. H. Baur, Acta Cryst. **9**, 515 (1956).
[4] H. Pomerance, Phys. Rev. **88**, 412 (1952).