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Measurement of the mass attenuation coefficients and electron densities for BiPbSrCaCuO superconductor at different energies

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Abstract

The mass attenuation coefficients for Bi, Pb, Sr, Ca, Cu metals, Bi_2O_3, PbO, $SrCO_3$, CaO, CuO compounds and solid-state forms of $Bi_{1.7}Pb_{0.3}Sr_2Ca_2Cu_3O_{10}$ superconductor were determined at 57.5, 65.2, 77.1, 87.3, 94.6, 122 and 136 keV energies. The samples were irradiated using a ^{57}Co point source emitted 122 and 136 keV γ-ray energies. The X-ray energies were obtained using secondary targets such as Ta, Bi_2O_3 and $(CH_3COO)_2UO_2 2H_2O$. The γ- and X-rays were counted by a Si(Li) detector with a resolution of 0.16 keV at 5.9 keV. The effect of absorption edges on electron density, effective atomic numbers and their variation with photon energy in composite superconductor samples was discussed. Obtained values were compared with theoretical values.

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Keywords: BiPbSrCaCuO; Mass attenuation coefficient; Effective atomic number; Electron densities

1. Introduction

Superconductivity will, without doubt, become one of the key technologies of the 21st century. Superconductor electronics, which in the future are expected to play an important role in areas, where traditional semiconductor electronics have reached its performance limit. Today superconducting materials are routinely used in science, research and technological development and in medical diagnosis, using Magnetic Resonance Imaging (MRI), nuclear reactors, satellites, nuclear weapons, etc. Some of these materials may be exposed to radiation. One of the materials showing superconductive properties is BiPbSrCaCuO.

The total attenuation cross-section, effective atomic number and electron density are basic quantities required in determining the penetration of X-ray and γ-photons in matter. Experimental measurements of the mass attenuation coefficients have been performed since the early days of γ- and X-ray studies and an almost complete collection, including also a comparison with theoretical predictions was reported by several authors [1,3,13].

The scattering and absorption of X-rays or γ-radiations are related to the density and atomic number of an element. In composite materials it is related to density and effective atomic number. A single number therefore cannot represent the atomic number uniquely across the entire energy range, as the partial interaction cross-sections have different elemental number dependence. This number for composite materials is called the effective atomic number and varies with the energy. Many attempts have been made to find a rule to calculate effective atomic numbers of composite materials [8,11,12]. Some formulas empirically deduced have been reported in the literature [10], but their validity is limited to the experimental conditions used in the particular work. In recent years, there has been renewed interest in the measurement of photon interaction

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cross-section at different energies, especially close to absorption edges of elements [4,9,14].

In this paper, the results of the measurements of the mass attenuation coefficients for $Bi_{1.7}Pb_{0.3}Sr_2Ca_2Cu_3O_{10}$ superconductors are reported. The effective atomic number (Z_{eff}) and electron number densities (N_{el}) have been determined experimentally and calculated theoretically.

2. Theory

A parallel beam of monoenergetic γ- or X-ray photons is attenuated in matter according to the Beer–Lambert's law,

$$I = I_0 e^{-\mu x} = I_0 e^{-(\mu/\rho)d}, \tag{1}$$

where I_0 and I are the unattenuated and attenuated photon intensities, d is the mass per unit area, μ/ρ is the mass attenuation coefficient.

The mass attenuation coefficient $(\mu/\rho)_c$ for any chemical compound or mixture of elements is given by

$$(\mu/\rho)_c = \sum_i w_i (\mu/\rho)_i, \tag{2}$$

where ρ is the mass density of the sample and w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the ith constituent element, respectively.

For a chemical compound the fraction by weight is given by

$$w_i = \frac{a_i A_i}{\sum_j a_j A_j}, \tag{3}$$

where A_i is the atomic weight of the ith element, and a_i is the number of formula units.

Theoretical values for the mass attenuation coefficients were calculated by XCOM program which was developed by Berger and Hubbell [6] for calculating mass attenuation coefficients or photon interaction cross-section for any element, compound or mixture at energies 1 keV to 100 GeV.

Values of mass attenuation coefficients were then used to determine the total molecular cross-section $\sigma_{t,m}$ by the following relation:

$$\sigma_{t,m} = \left(\frac{\mu}{\rho}\right)_c \frac{M}{N_A}, \tag{4}$$

where $M = \sum n_i A_i$ is the molecular weight, N_A is the Avogadro's number and n_i and A_i are the number of formula units and the atomic weight, respectively, of the constituent element i.

The total atomic cross-section $\sigma_{t,a}$ can be easily determined from the following equation:

$$\sigma_{t,a} = \frac{1}{N_A} \sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_{t,m}}{\sum_i n_i}, \tag{5}$$

where $f_i = n_i / \sum_j n_j$ is the fractional abundance of element i with respect to number of atoms.

Also the total electronic cross-section $\sigma_{t,el}$ for the individual element is expressed by the following formula:

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_{t,a}}{Z_{eff}}. \tag{6}$$

The total atomic and electronic cross-sections are related to the effective atomic number (Z_{eff}) through the following relation [12]:

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}}. \tag{7}$$

The effective electron number or electron density, N_{el} (number of electrons per unit mass) can be derived from [7]:

$$N_{el} = \frac{(\mu/\rho)_c}{\sigma_{el}} = \frac{N_A}{M} Z_{eff} \sum_i n_i. \tag{8}$$

3. Experiment

The mass attenuation coefficients were determined by performing transmission experiment in narrow beam geometry. The measurements were performed by using a collimated γ- and X-ray beam as shown in Fig. 1. The collimator is a 10 mm thick lead cylinder that surrounds the detector. As shown in Fig. 1, three lead absorbers with a hole of 4 mm diameter each were used between the source and detector to collimate the γ- and X-ray beam. The distance between the source and the Beryllium window was 81 mm.

The method of preparation and annealing technique are very important in determining the superconducting properties of copper oxide. Using a solid-state reaction technique, samples having the composition of $Bi_{1.7}Pb_{0.3}Sr_2Ca_2Cu_3O_{10}$ have been prepared. The starting materials used are Bi_2O_3, PbO, $SrCO_3$, CaO and CuO, with 99.99% purity. The preparation procedure contains four main steps.

(1) The starting materials Bi_2O_3, PbO, $SrCO_3$, CaO and CuO were mixed in proper ratios and ground in an agate mortar for 8 h to achieve perfect homogeneity. For calcinations, the powder was then heated at 840 °C for 24 h in air and left to cool down to room temperature a cooling rate of 5 °C/min. The density of mixture BiPbSrCaCuO pellets changes from 4.29 to 4.33 g cm^{-3}.
(2) The reacted product was again reground for 7 h. The resulting samples were then pressed into pellets with radius of 13 mm and thickness from 2.13 mm to 4.21 mm, under a pressure of 3 ton cm^{-2}. The density of calcined BiPbSrCaCuO pellets changes from 4.67 to 5.05 g cm^{-3}.
(3) These pellets were sintered at 845 °C in flowing oxygen for 50 h and then left to cool down to room temperature at a cooling rate of 3 °C/min. The density of sintered BiPbSrCaCuO pellets changes from 5.15 to 5.23 g cm^{-3}.
(4) The single-phase structure of the pellet was previously tested by x-ray diffraction analysis for mixture, calcined- and, sintered-state, shown in Fig. 2(a)–(c), respectively.