Temperature dependence of crystal field excitations in CuO

S Huotari\(^1\), L Simonelli\(^2\), C J Sahle\(^1\), M Moretti Sala\(^2\), R Verbeni\(^2\) and G Monaco\(^2\),\(^3\)

\(^1\) Department of Physics, University of Helsinki, PO Box 64, FI-00014, Finland
\(^2\) European Synchrotron Radiation Facility, F-38043 Grenoble cedex, BP 220, France
\(^3\) Physics Department, University of Trento, Via Sommarive 14, 38123 Povo (TN), Italy

Received 26 November 2013, revised 23 January 2014
Accepted for publication 3 February 2014
Published 1 April 2014

Abstract
We report a study on the temperature dependence of charge-neutral crystal field (dd) excitations in cupric oxide, using nonresonant inelastic x-ray scattering spectroscopy. Thanks to a very high-energy resolution (\(\Delta \varepsilon = 60\) meV), we observe thermal effects on the dd excitation spectrum fine structure between temperatures of 10–320 K. The spectra broaden considerably with increasing temperature, consistently with an enhancement of the coupling between crystal field excitations and the temperature-dependent continuum of states above the band gap. We discuss this and other mechanisms that may explain this temperature dependence.

Keywords: crystal field excitations, inelastic x-ray scattering, CuO

(Some figures may appear in colour only in the online journal)
strong electron–phonon coupling [19]. The present study is aimed at the determination of the dd spectra as a function of temperature, especially to see whether the two phase transitions or electron–phonon coupling have detectable influences on the spectral lineshape. While for example the electronic structure of CuO has recently been studied as a function of temperature [24, 25], for CuO temperature-dependent high-energy resolution studies have to our knowledge not been reported.

In this article, we report high-resolution (ΔE = 60 meV) NRIXS spectra of CuO in temperatures between 10–320 K. The observable in NRIXS is the intensity of radiation scattered via an inelastic process where both momentum ℏq and energy ℏω are transferred to the electron system [26]. In the following we assume atomic units, i.e. ℏ = 1. The probability for scattering is quantified by the doubly differential cross section, which is related to the electron dynamic structure factor [26] as

\[ \frac{d^2\sigma}{d\Omega d\omega} = \left( \frac{d\sigma}{d\Omega} \right)_T S(q, \omega), \]

where \( (d\sigma/d\Omega)_T \) is the Thomson scattering cross section, and \( S(q, \omega) \), the dynamic structure factor, contains the information on the material properties to be investigated. The same function is measured in electron energy loss spectroscopy (EELS) [6]. Both EELS and NRIXS have their advantages. In general, NRIXS has its strengths in being bulk sensitive, also yielding access to extreme sample environments such as high pressure, and having access to high momentum transfers. The \( S(q, \omega) \) can be written as

\[ S(q, \omega) = \sum_F \left( \sum_i e^{iq\cdot r_i} \right)^2 \delta(\Omega_F - \Omega_i - \omega), \]

where \( |l\rangle (\Omega_i) \) and \( |f\rangle (\Omega_F) \) are the initial and final states (energies) of the electron system, respectively, with a summation over all electrons \( j \). The dynamic structure factor is also related to the macroscopic dielectric function \( \varepsilon(q, \omega) \) as

\[ S(q, \omega) = -\frac{n}{4\pi} \text{Im}[\varepsilon^{-1}(q, \omega)]. \]

This equivalence is often used to relate optical spectra and dielectric screening to the results of an energy-loss experiment such as EELS or NRIXS [17, 27]. The theoretical framework on how NRIXS can access dipole-forbidden excitations in different systems has been laid down in, e.g., [13], [18], [28–31].

CuO has a monoclinic crystal structure (space group C2/c) [32] with eight nonequivalent Cu and O sites in the primitive unit cell [22, 23]. The lattice parameters are \( a = 4.68 \text{ Å}, b = 3.42 \text{ Å}, c = 5.13 \text{ Å}, \alpha = \beta = 90^\circ, \gamma = 99.5^\circ \). The structure of CuO can be thought to consist of two different kinds of CuO4 plaquettes that are at an angle of 77.84° with respect to each other. The orientation of the \( q \)-vector with respect to the planes is thus in general an average over the two nonequivalent planes.

In the following discussion we assume Cu2+ ions in a CuO4 plaquette with a \( D_{4h} \) point group symmetry. Within the crystal field model [33], the local field splits the 3d energy levels into \( a_{1g} (d_{xz}), b_{1g} (d_{yz}) \), \( b_{2g} (d_{xy}) \) and (nearly) doubly degenerate \( e_g (d_{xz}, d_{yz}) \). In the ground state, the hole occupies the \( d_{x^2-y^2} \) orbital. More refined calculations [16, 34–42] can be done in order to include Cu–O hybridization and band structure but the crystal field model is sufficient to capture the overall energy-level picture. The CuO4 plaquettes in CuO are not square, but rather almost rectangular parallelograms with side lengths of 2.62 and 2.90 Å, and exhibit two different Cu–O distances (1.95 and 1.96 Å). This lifts the degeneracy of the \( d_{xz} \) and \( d_{yz} \) orbitals, with an energy splitting that is expected to be \( \sim60 \text{ meV} \) [35]. In this work we study the dd excitations in CuO, i.e. excitations where the hole state is lifted from the ground state \( d_{x^2-y^2} \) orbital to other Cu2+ d orbitals. We denote hole excitations to the \( d_{xy}, d_{xz}, d_{yz}, d_{x^2}, d_{y^2} \) orbitals as the \( xy, x^2, y^2 \) excitations, respectively.

The experiment was performed at the beamline ID16 of the European Synchrotron Radiation Facility. The incident photon beam was monochromatized using a combination of Si(111) premonochromator and a Si(444) channel cut to a bandwidth of 40 meV. The beam was focused using a toroidal mirror to a spot size of 30 × 100 μm² (V × H) on the sample. We used a spectrometer designed for high-energy resolution NRIXS experiments [43]. It was equipped with six diced Si(444) analysers at a Bragg angle of 88.5°, observing...

---

1 In 2013, the IXS beamline ID16 was replaced by a new upgraded beamline ID20 of the European Synchrotron Radiation Laboratory.
the intensity of scattered photons with a constant energy of \( \sim 7.9 \) keV. The total energy resolution was 60 meV. The sample temperature was controlled using a miniature He-flow cryostat. The sample was a single crystal of CuO (the same as that used in [20]). The spectra were measured at a fixed momentum transfer value \( q = |\mathbf{q}| = (7.5 \pm 0.1) \) Å with the average \( \mathbf{q} \) in the direction \( \mathbf{q}||[234] \). Based on the expected angular dependence of dd excitations [18], in this geometry the \( xz/yz \) and \( z^2 \) peaks are expected to be excited most strongly, with the \( xy \) peak being weak. The spectra were measured at several temperatures between 10 and 320 K.

All the spectra collected as a function of temperature, after subtracting a sloping background due to the quasielastic line tail, are shown in figure 1. The spectra have been normalized to have the same area between 1–3 eV. The spectra can be broken into a few components: a main peak at 2 eV and a weaker peak manifesting itself as a shoulder at 1.6 eV, and an even weaker shoulder (mainly visible at the lowest temperatures) at 2.2 eV. A recent \textit{ab initio} calculation [35] predicts the excitations to be assigned as, from lowest to highest energy, \( xy, xz/yz, \) and \( z^2 \). The peak assignment can be confirmed by studying either their angular dependence [8] or their dependence on \( q \) [18]. Indeed, this assignment has recently been supported by an angle-resolved study of Wu \textit{et al} [21]. In this work, we concentrate on the overall temperature dependence of the spectra.

The main effect of increasing the temperature from \( T = 10 \) K is a clear broadening of the overall spectral shape. Due to the broadening, the low-energy shoulder seems to merge into the main peak and is nearly undetectable at room temperature. To emphasize the behaviour, a smoothed version of the spectrum recorded at \( T = 10 \) K is shown as a reference throughout. Thus, an important result is the bandwidth of the excitations: with a 60 meV energy resolution the main peak has a width of the order of 400 meV even at \( T = 10 \) K. This is partly due to the overlap of the \( xz/yz \) and \( z^2 \) excitations, but even then the individual components have a width of about \( \sim 300–400 \) eV. While in the orbital ionic picture the 3d states are expected to have a very narrow line shape, when switching on the band structure the 3d states gain non-negligible bandwidth due to the electron–ion interaction and hybridization [36, 44–46]. The observed width extrapolated to \( T = 0 \) K may thus reflect the width of the density of states of the occupied and unoccupied 3d bands [16]. Time-dependent density functional theory that takes into account band structure, realistic transition matrix elements and local field effects could possibly explain the spectral linewidth and shape in a more detailed way [47–49]. Also, the spin–orbit interaction (\( \sim 100 \) meV) should be taken into account for a full description of the spectra. Simultaneously with dd excitations, excitations of lattice vibrations, modeled by a Franck–Condon treatment, have been used to explain finite-width lineshapes of dd excitation spectra in \( \text{Ca}_2\text{Y}_2\text{Cu}_5\text{O}_{10} \) [50]. Alternatively, one can consider the coupling between the crystal field excitations and the continuum of states above the band gap, and relate the temperature dependence of dd excitations to the thermal behavior of the band gap itself. It should be noted that the dd excitations in NiO also have non-negligible bandwidth of the order of 200 meV, [51] even though the band gap is larger in NiO (\( \sim 4 \) eV in comparison to \( E_g \sim 1.35 \) eV of CuO at room temperature).

In order to quantify the change in shape as a function of temperature, we fitted the spectra using Pearson VII functions [52]. An example of such a fit in the case of \( T = 10 \) K is shown in figure 1. Since the lowest and highest energy peaks are weak in this geometry, neither their position nor their width could be fitted very reliably, especially in the data recorded at high temperatures. However, the determination of the width of the main peak at 2.0 eV can be done with a high accuracy. The resulting fitted values for the width (full-width at half maximum, FWHM) of the 2.0 eV peak are shown in figure 2 as a function of temperature. One important result is that the peak width across different temperatures does not have a significant relation to the magnetic transitions as it does not exhibit significant changes across either transition temperature. Instead, the thermal behavior of the peak width seems to be rather smooth across the studied temperature range.

The width of the band gap of CuO has been reported to vary from \( E_g = 1.55 \) eV at \( T = 0 \) K to 1.35 eV at \( T = 300 \) K [19]. If the relatively large width of the dd excitations (\( \sim 400 \) meV) is due to interaction with continuum states owing to the presence of the band gap, the decreasing gap width with increasing temperature could explain the observed behavior. In this scenario, an increase of the density of states at, or near to, the energy of the dd excitations could increase the width of the dd peaks. The temperature dependence of the optical gap has been explained to be due to the large electron–phonon coupling [19]. Electron–phonon coupling thus seems to be a natural reason for the temperature dependence of the dd excitations as well. Also, magnetic correlations that are responsible for the magnetic transitions at \( T_{N1} \) and \( T_{N2} \) may contribute to the temperature dependence of the band gap. Their effect, though, is expected to be marginal and will be neglected here.

Using a Bose–Einstein statistical factor for phonons with average energy of \( k_B \theta \), the gap energy as a function of temperature [19] can be fitted to a form [53]...
where $E_B = 1.66$ eV, $\alpha_B = 0.1$ eV and $\theta = 196$ K. We assume a density of states above the gap of the free-electron form $\rho(E) \propto \sqrt{E - E_g}$, when $E \geq E_g$, and $\rho(E) = 0$ when $E < E_g$. Assuming a linear dependence of the $dd$ spectral linewidth $\Gamma$ on the density of states at the $dd$ excitation energy,

$$\Gamma(T) = a_B \sqrt{E_{dd} - E_g(T)} + \Gamma(0),$$

we get a good agreement with the experiment with $\Gamma(0) = 0.0569$ eV and $a_B = 0.526$ eV/12. The resulting fit is shown in figure 2. Even if the neighboring $dd$ excitations may give a non-negligible contribution to $\Gamma(0)$, the temperature dependence is the most interesting result here. The fit agreement is good, yielding insight that the interaction with the continuum states could be the underlying reason for the $dd$ excitation lineshape. The dependence of the band gap as a function of temperature has in turn been interpreted to be due to electron–phonon coupling [19].

There are also other approaches which can be used to investigate the temperature dependence of crystal field excitations. The $ab$ initio optical absorption spectrum in the range of $dd$ excitations in NiO has been calculated based on molecular dynamics simulations in finite temperature [54], but to our knowledge, such calculations do not exist for CuO. A finite distribution of Cu–O bond lengths in finite temperatures, due to thermal disorder, is expected to have an effect similar to the one observed here. This is because the $dd$ excitation energy is proportional to $a_{Cu-O}$, where $a_{Cu-O}$ is the Cu–O bond distance. Furthermore, in principle, the coupling to the lattice could possibly be quantified from phonon parameters [55, 56]. Wray et al [25] found that the temperature dependence of crystal-field excitations in CoO could be explained as anti-Stokes scattering and interatomic many-body dynamics. Providing a complete description of the coupling of vibrational and electronic excitations is a problem of high-level complexity. Approximations such as the Franck–Condon principle can be used to simplify the task. Recently, some of us have used a classical approach to explain the temperature dependence of core-electron excitations of gas-phase CO$_2$ [57]. Lee et al [50] provided a detailed analysis of the linewidth of the $dd$ excitations in Ca$_2$Y$_3$Cu$_3$O$_{10}$, based on a Franck–Condon treatment. Here, our experimental data on CuO, and the good agreement obtained by considering the evolution of the density of states at the $dd$ excitation energy, give an important benchmark for studies of the coupling of the $dd$ excitations and lattice vibrations.

In conclusion, we have measured the $dd$ excitation spectra of bulk CuO with non-resonant IXS with high-energy resolution as a function of temperature. Most importantly, the study reveals the coupling of orbital excitations to other electron states via the temperature dependence of their spectral shape. We discuss different approaches that can explain this behavior. Empirically, we show that the results are compatible with a relation of the band gap and the bandwidth of $dd$ excitations, thus highlighting the crystal field level coupling to the continuum of states above the band gap. The presented data on the temperature dependence of the $dd$ excitations are an important benchmark for understanding the coupling of orbital and other degrees of freedom in CuO.

Acknowledgments

Beamtime was granted by the European Synchrotron Radiation Facility. Funding was provided by the Academy of Finland (grants 1256211, 1127462 and 1259526) and University of Helsinki Research Funds (grant 490076). The chemical purity and stoichiometry of the CuO crystal was confirmed by standardless energy dispersive spectrometry using a Jeol JXA-8600 electron probe microanalyzer at the Department of Geosciences and Geography, University of Helsinki. We are grateful to C Henriquet, M-C Lagier and the whole beamline ID16 team and support groups for expert assistance, advice, and encouragement in the experiment. We would like to thank M W Haverkort, M Hakala, M Gatti and C Rödl for fruitful discussions, as well as C Sternemann and W Schülke for lending the sample.

References

[1] Tokura Y and Nagaosa N 2000 Science 288 462
[2] Kimura T, Sekio Y, Nakamura H, Siegrist T and Ramirez A P 2008 Nature Mater 7 291
[3] Zheng X G, Xu C N, Tomokiyo Y, Tanaka E, Yamada H and Soejima Y 2000 Phys. Rev. Lett. 85 5170
[4] Chen X K, Irwin J C and Franck J P 1995 Phys. Rev. B 52 R13130
[5] Rückamp R et al 2005 New J. Phys. 7 144
[6] Fromme B 2011 dd Excitations in Transition Metal Oxides (Berlin: Springer)
[7] Ament L J P, van Veenendaal M, Devereaux T P, Hill J P and van den Brink J 2011 Rev. Mod. Phys. 83 705
[8] Moretti Sala M et al 2011 New J. Phys. 13 043026
[9] Ghiringhelli G et al 2004 Phys. Rev. Lett. 92 117406
[10] Ghiringhelli G et al 2009 Eur. Phys. J. Spec. Top. 169 199
[11] Schlappe J et al 2012 Nature 485 82
[12] Larson B C, Ku W, Tischler J Z, Lee C-C, Restrepo O D, Eguiluz A G, Zschack P and Finkelstein K D 2007 Phys. Rev. Lett. 99 026401
[13] Haverkort M W, Tanaka A, Tjeng L H and Sawatzky G A 2007 Phys. Rev. Lett. 99 257401
[14] Hiraoka N, Okamura H, Ishii H, Jarrige I, Tsuei K D and Cai Y Q 2009 Eur. Phys. J. B 70 157
[15] Hiraoka N, Suzuki M, Tsuei K D, Ishii H, Cai Y Q, Haverkort M W, Lee C C and Ku W 2011 EPL 96 37007
[16] Iori F, Rodolakis F, Gatti M, Reining L, Upton M, Shvyd’ko Y, Rueff J-P and Marsi M 2012 Phys. Rev. B 86 205132
[17] Huotari S, Soininen J A, Vankó G, Monaco G and Olevano V 2010 Phys. Rev. B 82 064514
[18] van Veenendaal M and Haverkort M W 2008 Phys. Rev. B 77 224107
[19] Marabelli F, Parravicini G B and Salghetti-Drioli F 1995 Phys. Rev. B 52 1433
[20] Döring G et al 2004 Phys. Rev. B 70 085115
[21] Wu W B, Hiraoka N, Huang D J, Huang S W, Tsuei K D, van Veenendaal M, van der Brink J, Sekio Y and Kimura T 2013 Phys. Rev. B 88 205129
[22] Forsyth J B, Brown P J and Wanklyn B M 1998 J. Phys. C: Solid State Phys. 21 2917
[23] Yang B X et al 1989 Phys. Rev. B 39 4343
