Phonon spectroscopy in solid helium using x-rays

C. Seyfert[a,b], D. A. Arms[c], H. Sinn[b], R. O. Simmons[c], and E. Burkel[b]

[a] Institut für Angewandte Physik, FAU Erlangen, Bismarckstr.10, 91054 Erlangen, Germany
[b] FB Physik der Universität Rostock, August-Bebel-Str.55, 18051 Rostock, Germany
[c] Physics Department, University of Illinois at Urbana-Champaign, IL 61801 USA

New data on the phonon dispersion of helium under high pressure was obtained using inelastic x-ray scattering with an energy resolution of several meV. At 9 K and a pressure of 70 MPa a single crystal of hcp ^{4}He with a molar volume of 13.3(1) cm^3 was grown in situ. The high lying longitudinal phonon branch along the $(00q)$ direction was measured. These investigations are the beginning of a new series of studies on the excitations in helium of both isotopes, ^{3}He and ^{4}He.

1. INTRODUCTION

For decades inelastic neutron scattering has been the method of choice to measure phonon excitations in solids. However, some systems are not readily accessible by this technique. For example, a high neutron absorption cross section of the sample or extreme sample conditions can practically inhibit the investigation of certain systems by neutron scattering. Crystalline helium of the isotope ^{3}He is such a system.

Considerable knowledge of the lattice dynamics has been gained for the isotope ^{4}He in its bcc, hcp and fcc modifications [1]. However, very little is known about the dynamics in solid ^{3}He. The reason for this almost complete lack of experimental data lies in the very high absorption cross section for this isotope. Besides, as for ^{4}He, the necessary high pressure and low temperature environment is an additional obstacle, limiting the possible sample size. But even for solid ^{4}He, the available data is far from complete. In the higher energy parts of the phonon branches the observed neutron groups are anomalous and weak, and there is a considerable uncertainty in their excitation energies[6].

The technique of high energy resolution inelastic x-ray scattering at modern synchrotrons offers the possibility to address these questions. No isotope dependance and a very well focused beam allows the addition of experimental evidence on the dynamics of these quantum solids, complementary to inelastic neutron scattering. The experimental method and phonon data obtained on hcp ^{4}He are reported here.

2. EXPERIMENTAL METHOD

Our investigations into the lattice dynamics of solid helium have been the first to use very high energy resolution inelastic x-ray scattering in the field of low temperature physics. Therefore, the experimental aspects will be discussed in more detail. The basic idea for an inelastic scattering instrument is the same for x-ray and for neutron scattering. A well defined monochromatic beam from a monochromator crystal hits the sample and undergoes an inelastic process. Afterwards, the energy and momentum transfer to the sample is determined by elastic scattering from the analyzer crystal. For x-rays an energy resolution of the order 10 meV corresponds to a relative resolution of about 5×10^{-7}. This can only be obtained if high order reflections from perfect silicon crystals are used as momochromator and analyzer crystals in backscattering geometry. This principle lead to the development of the first x-ray spectrometer with an energy resolution of about 10 meV: INELAX at HASYLAB [2]. At this instrument measurements of longitudinal phonon groups in hcp ^{4}He (at 61 MPa and 4.3 K) succeeded [3].

The data presented here were measured at the new very high energy resolution inelastic x-ray scattering beamline (BL21-ID16) at the European Synchrotron Radiation Facility (ESRF) [4]. With the new third generation undulator source and improved x-ray optics, there is a gain of more than two orders of magnitude in intensity compared to the spectrometer INELAX.

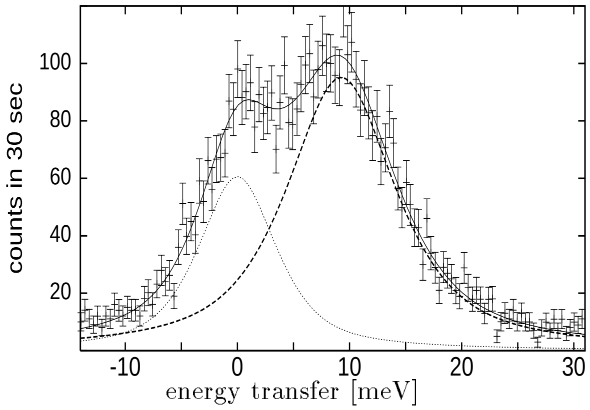

Figure 1: Energy scan at $(00q)$, q=1.2 corresponding to a momentum transfer of 1.47 Å^{-1}

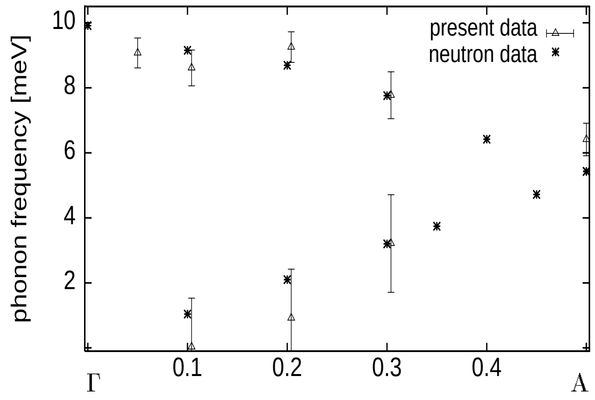

Figure 2: Longitudinal phonon dispersion relation along the c-direction in hcp ^{4}He

3. EXPERIMENTAL DETAILS

The helium crystals were grown in situ within the pressure cell that consists of polycrystalline beryllium [5], located inside a closed cycle refrigerator. The best single crystal of hcp ^{4}He was obtained at a temperature of 9 K and a pressure of 70 MPa. Its molar volume was determined to be 13.3(1) cm^3.

After the orientation of the crystal, energy scans at fixed momentum transfer were performed. The variation of the energy transfer is achieved by changing the lattice parameter of the monochromator crystal[2]. To do so, the relative temperature between the analyzer and the monochromator crystal was varied in steps of 0.01 K, corresponding to an energy step of 0.35 meV. The energy resolution (FWHM) for our experiment was 10 meV at a photon energy of 13.84 keV, using Si(777)-reflections. The momentum transfer was selected by choosing the scattering angle. Measurements were performed between 1.3 Å^{-1} and 2.3 Å^{-1}, with a resolution of 0.2 Å^{-1}.

4. RESULTS

Longitudinal phonons in hcp ^{4}He were observed. The preliminary data analysis was done describing the spectra with Voigt profiles. The contributions of the sample environment for different momentum transfers were identified by empty cell scans. These elastic contributions were used to determine the energy zero of the instrument and to unfold the spectra (figure 1). The obtained dispersion relation along the $(00q)$-direction is shown in figure 2. For comparison, the closest relevant neutron data [6], measured at a different molar volume (16.0 cm^3), have been included in the figure. They have been scaled using a formula suggested by [6]. The agreement is quite remarkable. However, further investigations on low lying excitations will benefit by an improved energy resolution and a better energy zero stability.

5. CONCLUSION

The first solid helium measurement at the new instrument was performed on the isotope ^{4}He. It demonstrated the applicability of inelastic x-ray scattering at intense sources for investigations into the lattice dynamics of helium. Studies on ^{3}He are to follow.

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