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INELASTIC NEUTRON SCATTERING: INTRODUCTION

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1. INTERACTION OF NEUTRONS WITH MATTER

Thermal neutrons are often praised as the (nearly) ideal probe to inform us about structure and motion on an atomic scale. Indeed, their wavelengths, similar to X-rays, fit perfectly interatomic distances and their energies in the range 1 meV to ~1 eV match excitation energies typical for atomic or molecular oscillations. However, neutrons are only nearly perfect because there are so few of them. Starting from a high vacuum corresponding to 10^{-7} mbar inside a reactor (or spallation target), a beam of say 10^8 n cm^{-2} s^{-1} is scattered by a cm^3-sized sample. Often, only a few neutrons arrive in the detector after angular and energy analysis. This is why instrument design is so important. Use X-rays first! Formulate precise questions and optimize the experiment accordingly. Then inelastic neutron scattering becomes a powerful tool to supplement what you already know. For studies of condensed matter with neutrons, it is useful to distinguish between three cases, which provide different information on the sample properties.

- **Nuclear scattering** - Neutrons interact with nuclei *via* the very short-range nuclear force. With its wavelength λ of a few Å (10^{-10} m), a thermal neutron cannot "see" the internal structure of the nucleus, hence the scattering is isotropic (independent of angle). The fancy name for this is *s*-wave scattering. Therefore, the interaction is characterized by a scattering length ***b***, which is of the order of the size of the nucleus, i.e. fm (10^{-15} m). X-ray scattering, on the other hand, is not isotropic (it depends on angle) and is characterized by a form factor, $f(Q)$, since the photons are scattered from all the electrons of an atom. Coherent nuclear scattering probes density correlations.

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- **Spin-dependent nuclear scattering** - The neutron-nucleus interaction depends actually on the total spin of the compound nucleus formed during the scattering event between the neutron (spin 1/2) and the nucleus (spin I). To the two possible states, ($I + 1/2$ and $I - 1/2$), correspond two different scattering lengths (b_+ and b_-) respectively. This spin dependence gives rise to incoherent scattering, which probes single-particle motion (see section 5). It also allows to study the ordering of nuclear spins at ultra-low temperatures, $\sim \mu K$.
- **The magnetic dipole moment** of the neutron senses the dipolar field from unpaired electrons. It is thus the total magnetic moment of the sample, i.e. spin S plus orbital L, which is probed. The magnetic scattering length from one electron is $b_m = \gamma r_0 = 1.348$ fm, i.e. of the same order of magnitude as the nuclear scattering length. Because of the dipole-dipole character of the interaction, the scattering is not isotropic, and only magnetic moments $\boldsymbol{M}_\perp$(or moment fluctuations) perpendicular to the wave vector transfer $\boldsymbol{Q}$ are observed. As the extension of the wave function of the unpaired electrons is of the same order as the neutron wavelength, there is a magnetic form factor $f(Q)$, similar to the case of X-ray scattering.

In addition to the useful interactions discussed above, there are so-called "nuisance" interactions, which provide no useful information about the system [1]. They are small, but might need to be corrected for. Corrections to the neutron dipole interaction include spin-orbit effects (Schwinger term), relativistic quantum effects (Foldy interaction), and nuclear dipole moments. The internal structure of the neutron gives also rise to electrostatic and electric polarizability terms. One should also keep in mind that the weak interaction limits the life time of a free neutron to some odd 10 minutes while gravity causes cold neutrons to fall as fast as Newton's apple.

2. KINEMATICS

2.1. ENERGY AND MOMENTUM CONSERVATION

A neutron is characterized by its wave vector $\boldsymbol{k}$ and its spin state σ. From $\boldsymbol{k}$ we can calculate its momentum $\boldsymbol{p}$ and velocity $\boldsymbol{v}$ *via* $\boldsymbol{p} = \hbar\boldsymbol{k} = m\boldsymbol{v}$ and also the kinetic energy, $E = p^2/2m = \hbar^2k^2/2m = mv^2/2$, where m is the neutron mass. In cases where one deals with unpolarized neutrons, one can forget the neutron spin state σ, and the neutron state is thus fully characterized by $\boldsymbol{k}$.