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Text: Review on What Neutrons Can Do

When introducing the neutron scattering technique, we always wrote that '*the neutron diffraction probes the lattice and magnetic structure*' and '*the inelastic neutron scattering* (INS) *probes the phonon and magnon*'. Indeed, these properties already made neutron scattering irreplaceable in condensed-matter research. However, there are far more things that neutron scattering can do if we review the neutron-condensed-matter system in detail.

Viewing from the properties of neutron, things can be divided into two; **A.** Neutron interacts with the nucleus itself, as described by the Fermi pseudopotential. **B.** Neutron has a spin-1/2, and interacts with the electromagnetic potential.

Viewing from what's in the condensed-matter system, of course we have nucleus and electrons. They can be further classified as follows; **A1.** Nucleus itself, **B1.** Electron spin & electron orbit*1, **B2.** Nucleus spin, **B3.** Nucleus charge & electron charge, and interplays among them.

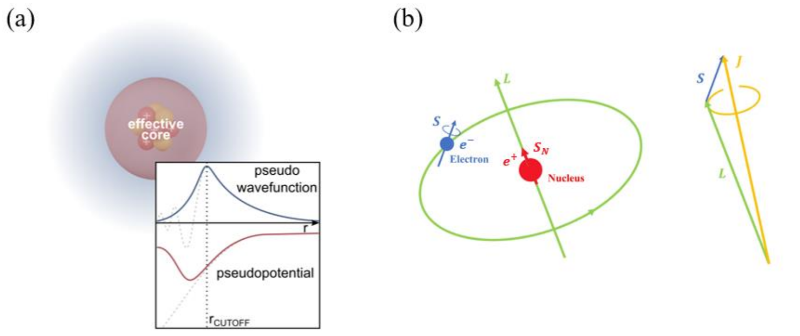

Fig.1 (a) Fermi pseudopotential, adopted from Wikipedia. (b) Schematic of electron-nucleus system.

According to these frameworks but still limited to my knowledge in this field, I list what can be detected by neutron scattering.

A1. Nuclear Bragg peak.

Phonon, Charge density wave*2.

Roton: an elementary excitation in Bose–Einstein condensates, e.g. INS on rotons in liquid helium [1].

B1. Magnetic Bragg peak.

Magnon.

Spinon: fractionalized spin excitation in 1-D Luttinger liquid and quantum spin liquid, e.g. INS on spinons in a spin-1/2 antiferromagnetic chain $CuSO_4 \cdot 5D_2O$ [2]. Magon is an excitation carrying integer magnetization S_z= +1/2 - (-1/2) = 1 in magnetic long-range order system (paramagnon if short-range order). However, spinon can be excited in either an ordered spin-1/2 antiferromagnetic chain or a disordered spin liquid, carrying a fractional magnetization S_z = 1/2.

Triplon: bound states of spinon pair, e.g. INS on spinons and triplons in frustrated triangular antiferromagnet Cs_2CuCl_4 [3].

Orbiton: an elementary excitation carries the orbital degree of freedom of electrons, e.g. orbitons in the quasi-one-dimensional antiferromagnetic chain Sr_2CuO_3 [4], though detected by resonant inelastic X-ray scattering.

Crystal electric field (CEF) excitation: excitation of the energy level of the spin-orbit states*3 due to a static electric field produced by the surrounding anion neighbors. In most magnetic materials, the ground state of magnetic ions in CEF has a nonzero spin. This kind of CEF excitations is expected to be dispersiveless in reciprocal space and well defined in both the magnetically ordered and paramagnetic states.

Magnetic exciton: When the ground state of magnetic ions in CEF is a nonmagnetic singlet and the magnetic exchange interaction is relatively large, the magnetic order appears as result of a polarization instability of the singlet state rather than the alignment of permanent moments. In this case, the magnetic excitations originate from the CEF levels are called magnetic excitons, e.g. INS on magnetic excitons in singlet-ground-state ferromagnets *fcc* Pr and Pr_3T1 [5]. They are dispersive and relate to the magnetically ordered state.

Spin-roton: an analogy of the roton in superconductors, e.g. spin-roton in cuprate superconductors [6].

B2. Disordered nucleus spins result in a part of incoherent (elastic or inelastic) neutron scattering. This is usually annoying to us but it's actually very useful, e.g. Hydrogen vibration excitations of $ZrH_{1.8}$ and $TiH_{1.84}$ [7].

Ordered nucleus spins appear in nano-Kelvin range in simple metals such as Cu, Ag, and Rh [8]. This leads to magnetic Bragg peak and theoretically observable magnon.

B3. Though the net charge of neutron is zero, neutron still weakly interacts with the electric potential of the electrons and nucleus.

When neutron moves through an electric field (of electrons and nucleus) with a finite velocity, in the frame of neutron, a magnetic field appears. The effect of this magnetic field to neutron is known as the spin-orbit interaction. Note that here the '*spin*' means a neutron spin and the '*orbit*' means a neutron momentum.

If abandon the point charge approximation, the charge distribution of neutron will give an electrostatic interaction with electrons and nucleus. This is known as the Foldy effect.

*1 Here we adopt the Born–Oppenheimer approximation, therefore no nucleus orbit.
*2 Realized as a zero-energy phonon mode.
*3 Can be considered as a *J*-multiplet state, where *J* is the total angular momentum of the ion.

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