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COMMENT

Comment on 'Quantum entanglement and neutron scattering experiments'

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Abstract

Allegations that our theoretical description of neutron scattering by entangled spin and spatial degrees of freedom is incorrect are shown to be misplaced for the allegations are derived from a naively incomplete, quantum mechanical calculation of neutron scattering by identical nuclei.

Our comment is addressed to a paper [1] which is peppered with allegations that our theoretical description of neutron scattering by entangled, or, equivalently, quantum correlated, spin and spatial degrees of freedom is incorrect [2]. We refute all the disqualifying epithets set out in [1], and we assert that our work is technically sound and free of errors.

By studying a spin dimer, Cowley [1] argues that to observe quantum entanglement in a scattering experiment it is essential to have an energy resolution better than the exchange splitting of spin states. Experiments we aim to interpret use energetic beams of neutrons to perform Compton scattering by protons or deuterons loaded in metals, and the available energy resolution is relatively coarse and inadequate to resolve any anticipated exchange splitting. In consequence, the scattering process effectively integrates over exchange split states. We do the same in our description of the scattering event, by averaging the intensity of scattered neutrons over all initial nuclear spin states and summing over all final spin states. Cowley's charge that his finding for a spin dimer contradicts our finding, that entanglement influences Compton scattering by nuclei, thus appears to have merit at first sight. However, the charge falls flat when it is recognized that a spin dimer is an incomplete model of two nuclei, and it is not the model we use which contains both spatial and spin degrees of freedom. In other words, Cowley's spin dimer contains but half the necessary ingredients, which are all present and correct in our model. After we integrate the scattered intensity over the exchange splitting, quantum entanglement of spin and spatial degrees of freedom leaves behind an interference effect, the importance of which is independently and firmly established in collisions of like particles where it is usually called Mott scattering [3].

We calculate a homologue of the actual intensity measured in a Compton scattering experiment, which is the intensity that accumulates around the recoil energy of a struck nucleus, and the intensity in question is often called the Compton profile (Cp). If the Cp is diminished, by quantum entanglement of the relevant degrees of freedom, it cannot exhaust the f-sum rule, which is a condition on the intensity gathered in the entire spectrum of energy transfers and not just an interval of transfers that incorporates the Cp centred on the recoil energy. Cowley makes this observation, about our homologous Cp by itself not satisfying the f-sum rule, but draws the erroneous conclusion that our Cp must be incorrect.

Sum rules are correctly derived from the commutator formed out of the spatial Fourier transform of the scattering-length density, G, which depends on both the spin and spatial degrees of freedom of the nuclei, and the Hamiltonian that describes them, H. (Cowley makes the incorrect statement that sum rules are derived by constructing the commutator of the *particle density* with H, and thereby omits correlations of spin and spatial degree of freedom. In addition, his discussion omits from H both the exchange and dipole energies.) The exchange and potential energy contributions to H give a null value in $[G, H]$. On the other hand, there are non-zero contributions to $[G, H]$ from the kinetic and dipole energies in H. In the case of unpolarized neutrons, the kinetic energy contribution to the f-sum rule is equal to the product of the recoil energy and the total cross-section [1]. The corresponding contribution from the dipole energy of a dimer vanishes when it is averaged over the nuclear spin states, which is appropriate in the interpretation of the Compton scattering experiments in question. We note in passing that, in the contribution to the f-sum rule made by the dipole energy, terms for even and odd values of the total angular momentum of a dimer, J, are equal in magnitude and opposite in sign, and the relative signs of the terms are opposite for bosons (deuterons) and fermions (protons). For protons, the para (ortho) state decreases (increases) the magnitude of the f-sum rule.

Our dimer model is mathematically complete. The sum of states captured in the Cp and the states outside it exhaust exact sum rules [4]. A realistic model of the nuclei in question and their host material will have additional states. Candidates below the recoil energy include lattice vibrations and defects. Energy transfers above the recoil energy may access electronic degrees of freedom that are engaged in scattering from nuclei through corrections to the Born–Oppenheimer approximation [5].

It is a misconception on Cowley's part that an interpretation designed for a dilute concentration of protons loaded in metal hosts should apply to dense quantum systems such as fluid ^{4}He, without modification. Our argument that quantum entanglement influences the Cp relies on a very large separation of the relevant timescales; these are the duration of the Compton scattering event, and the duration of random interactions with the host material which are efficient in the destruction of the delicate quantum state. The separation of timescales must be large enough for nuclei (protons) to be oblivious of their host for the duration of the scattering event, and to react like a perfect gas of dimers. Because of the larger mass of the ^{4}He nucleus and the relatively high density of a monatomic fluid the necessary separation of timescales is not achieved with a Compton scattering event.

Further experimental and theoretical work is undoubtedly required to clarify the relation between models used for the interpretation of neutron Compton scattering by nuclei, but we reaffirm that our theory correctly contains the essential features.

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