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Comment on "Reduced coherence in double-slit diffraction of neutrons"

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With the present Comment, we would like to clarify several aspects and some claims recently stated by Tumulka, Viale, and Zanghì [Phys. Rev. A **75**, 055602 (2007)] in connection with a work published by Sanz, Borondo, and Bastiaans [Phys. Rev. A **71**, 042103 (2005)].

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In 1988 Zeilinger *et al.* (ZGSTM) [1] published a series of diffraction experiments of cold neutrons by different slit assemblies which nicely evidenced the wave nature of matter particles. Among the results reported, those concerning the double-slit experiment are particularly interesting because they present a noticeable attenuation of the fringe visibility. In a recent publication, Tumulka, Viale, and Zanghì (TVZ) [2] arrived at the conclusion that such an attenuation is only due to initial incoherence. This is in contrast with a previous result by Sanz, Borondo, and Bastiaans (SBB) [3], where the same effect is explained by means of a simple phenomenological model combining both incoherence and decoherence [4].

In this Comment we would like to discuss this contradiction and clarify several criticisms risen by TVZ regarding the work of SBB, which are neither justified nor correct. Moreover, some aspects related to both incoherence and decoherence in the model presented by SBB will be explained in more detail to avoid any further misunderstanding. In our discussion we will follow the same order as in the work of SBB: first the different questions related to the ZGSTM double-slit experiment and incoherence will be clarified, and then we will discuss the issue of decoherence in this experiment.

To put into context the discussion and better understand the work of SBB, first it is worth describing shortly the approach of ZGSTM. As indicated in Ref. [3] (see Sec. III), provided that the energy is low and the spin effects negligible, neutron diffraction can be accurately described by means of classical scalar optics. From this standard first-principle assumption, ZGSTM derived a theoretical formula to fit their experimental data. This formula depends, on the one hand, on the widths of the entrance, diffracting and exit or scanning slits, and also on the variation of the neutron-beam phase at the double-slit and the wavelength distribution just before the beam reaches this slit. The excellent agreement found between the theoretical curve and the experimental data (see Fig. 7 of Ref. [1]) arises after considering some of those elements as fitting free parameters. (Note that the analysis of TVZ is very similar: a fitting based on first principles is considered, but replacing the optical approach by wave-packet calculations.)

In order to understand the ZGSTM experiment strictly from first principles (i.e., with no fittings at all), SBB proposed decoherence as an additional mechanism responsible for the reduction of fringe visibility. This is not an *ad hoc* hypothesis. After a detailed optical analysis of the experiment, following the same steps as ZGSTM, SBB realized that the different incoherence sources are not sufficient to explain the experimental diffraction pattern. (As ZGSTM and TVZ, SBB also paid special attention to the attenuation associated with the averaging due to both the width of the exit or scanning slit and the nonmonochromaticity of the neutron beam.) Hence they considered that additional decoherent sources should be included in the model. It is within this context where the SBB statement "incoherence and decoherence are both needed in order to explain the loss of coherence found in the experiment" has to be interpreted, where no fittings or free (adjustable) parameters are considered. Moreover, note that this model allows one to understand the ZGSTM experiment in relation to "which-way"-information experiments: the visibility reduction arises as a consequence of the different way in which the environment couples to each possible path [5]. Recently, Villar and Lombardo [6,7] have found arguments supporting the feasibility of the SBB model by means of a rigorous theoretical quantum analysis.

The main purpose of the optical analysis of SBB was to characterize the different incoherence sources and to determine their relevance before formulating a quantum-mechanical model to describe slit-diffraction experiments. In particular, in the ZGSTM experiment, one of these sources is related to the (single-slit) diffraction effect produced by the entrance slit. This effect is very important here because it makes that the neutron beam cannot be treated as a local plane wave when it reaches the two slits. The distance between the first two minima around the central maximum of the single-slit diffraction pattern formed just before the two slits is ≈ 920 μm ($\Delta x \approx \pm 461$ μm), about six times larger than the distance covered by the double-slit assembly (≈ 150 μm). In order to approximate the incoming wave front by a plane wave, the extension of this central maximum should be much larger than the double-slit assembly. Therefore after the splitting due to the double-slit, this local curvature leads the resulting diffracted beams to move apart with slightly different divergent momenta, with $|p_z^{(i)}| \gg |p_x^{(i)}|$.

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It seems that TVZ have missed this argument when reading the work of SBB and writing in Ref. [2] that "this momentum difference was already suggested" by SBB, "but no physical explanation was given." This is not correct; as can be seen in Ref. [3], Sec. III, the physical origin for this effect is also well-explained in the SBB work. Furthermore, based on the same physical argument (the radial divergence), it is also clear the choice made by SBB of the sign associated with the average transverse momentum of each diffracted beam; since they are opposite and divergent, then $p_x^{(1)}>0$ and $p_x^{(2)}<0$.

With respect to the values of the transverse momentum, we would like to clarify that it is not correct to consider that the SBB use of Heisenberg's uncertainty principle is "dubious" and "based on an incomprehensible application" of this principle, as stated by TVZ in Ref. 20 of their work. This is a standard procedure in diffraction experiments to estimate the value of different magnitudes. In the case of SBB, they obtained $v_x^{(1)}\approx 0.0028$ m/s and $v_x^{(2)}\approx -0.0029$ m/s [$v_x^{(i)}=p_x^{(i)}/m$, m being the neutron mass], and a divergence rate $\Delta v=v_x^{(1)}-v_x^{(2)}=0.0057$ m/s. As noticed by TVZ, these theoretical values are in agreement with those found by them after considering a fitting procedure. Therefore we think it is important to clarify that, in their Ref. 20, TVZ might be confusing the meaning of estimate value with theoretical value (which is neither the case of SBB nor their fitted values).

Another important point to clarify is that Fig. 2 in the work of SBB is evidently totally correct and understandable, contrary to the claim of TVZ in their Ref. 16. As clearly explained, this figure refers to the case of quasiplane (hat-shaped) waves crossing the two slits, not to Gaussian-shaped ones. According to SBB (see Sec. IV A, case I, of Ref. [3]), in this case incoherence effects are negligible [see Fig. 2(a) of Ref. [3]] and only when decoherence is considered one obtains a (relative) better agreement with the experiment. This second case is also well-specified [see Fig. 2(b) of Ref. [3]] and therefore the assertion of TVZ, "may represent either incoherence or decoherence," is out of place: in the corresponding figure caption it is explicitly written that the results describe "the case of incoherence plus decoherence effects." It is interesting to note that the behavior of the diffraction pattern is very much affected by the shape of the transmitted beams, as shown in Fig. 3 of Ref. [3], where the quasiplane waves have been replaced by Gaussian wave packets (in the caption of this figure, "Gaussian slits" should be understood as "Gaussian wave packets"). In this case, in both panels the results are highly improved. We would like to stress in this regard that Gaussian wave fronts are not just an idealization to perform analytical studies [8]. When one deals with realistic potentials simulating the (scattering) interaction between the slits and the incident particle beam [9], the diffracted waves happen to be essentially Gaussian [10]. This is something that goes beyond the works of both SBB and TVZ, where Gaussian wave packets are just preassumed, with no physical reason (although experimentally absorption at the boundaries of the slits can play the role of the "shaper" of the transmitted beams).

Now, we would like to address the issue of decoherence in the ZGSTM experiment. We think that considering that neutrons do not interact much with matter, as specified by TVZ, may be vague, misleading, and, possibly, not appropriate. Note that such an assertion contrasts with the fact that low-energy neutron scattering is a well-known technique used as a tool to probe different material targets [11] (the ZGSTM experiments are just a particular application of this technique). In this technique the neutron mean-free path inside a material is often comparable with the macroscopic dimensions of the sample. When a neutron passes near a nucleus, it can be absorbed or scattered; in the latter case, the energy and direction of the incident neutron beam change ($\hbar\omega=E-E_0$ and $\mathbf{Q}=\mathbf{k}-\mathbf{k}_0$). So the experimental spectra may have to be corrected for the contribution from neutrons which have been scattered several times and for the attenuation in single scattering due to absorption and self-shielding. Thus, the energy exchange after scattering can have similar effects as a dispersion in the wavelength. In the ZGSTM experiment these energy events arise from multiple sources, such as elastic collisions with air molecules, coupling to the vibrational and rotational motions of these air molecules due to inelastic collisions, interaction with the double-slit assembly through coupling to lattice vibrations (thermal phonons), etc. The evaluation and/or estimation of the effects provoked by these possible decoherent sources was out of the scope of the work of SBB and therefore oversimplified, considering a general exponential damping for the coherence. Nonetheless, they could be tested using appropriate detailed theoretical decoherence models [6,7]. In this regard, although we acknowledge the estimate value of the decoherence time provided by TVZ, we would like to point out that it has been obtained by means of a particular decoherence model and therefore it should be considered with care. Note that, for instance, it does not include eventual lattice effects due to the coupling with the double-slit, although they are expectable; the experiment is carried out at some finite temperature (these experiments are usually performed at room temperature), which will lead to an attenuation of the fringe visibility. Decoherence by thermal fluctuations of the slits have been studied with different types of matter particles [9,12].

To conclude, we would like to express a final general thought. The main purpose of the model proposed by SBB was to provide an alternative way to look into the dynamical behavior of a neutron beam diffracted by a double-slit, analyzing the effects on the interference pattern due to different sources and avoiding the use of any fitting parameter. However, it was not the aim to provide a deep and detailed theoretical study of every source contributing to the fringe visibility. Within this phenomenological model, the average or combined effects of decoherence are treated dynamically by means of an exponential damping, as in Ref. [13]. As has been seen, there are different decoherence sources which may lead to the same effects that could also arise when considering an optical model with incoherence [1,2], in particular, the lack of visibility in the interference pattern (in the language of neutron scattering, the "broadening" of the line shape).

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