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

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We reply to the comment by Sanz and Borondo [Phys. Rev. A **77**, 057601 (2008)] on our paper [Tumulka *et al.*, Phys. Rev. A **75**, 055602 (2007)] concerning the double-slit diffraction experiment with neutrons published in Zeilinger *et al.* [Rev. Mod. Phys. **60**, 1067 (1988)]. We argue in particular that Sanz and Borondo's new arguments for the presence of significant decoherence in that experiment are unconvincing.

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Sanz and Borondo (SB) have written a comment [1] on our (TVZ) paper [2], connected to our criticisms of the paper [3] by Sanz, Borondo, and Bastiaans (SBB). Both SBB and TVZ have analyzed the double-slit diffraction experiment of Zeilinger *et al.* (ZGSTM) [4], focusing in particular on the reduced fringe visibility of the measured intensity pattern and on the transversal spread involving the diffractive envelope of secondary minima and maxima. SBB and TVZ have provided different explanations of these phenomena, through different arguments and methods. In the TVZ paper, we have underlined this difference and put forward some criticisms of the work of SBB.

The main issue between SB and us is whether or not a noticeable degree of decoherence occurred in the neutron interference experiment reported by ZGSTM. SBB concluded yes, TVZ no. Our conclusion was based on a calculation of the strength of decoherence (expressed as the reciprocal *coherence time*) due to elastic collisions of the neutron with air molecules, which turned out too small to be relevant. SB object that maybe inelastic collisions with air molecules might be relevant, or maybe interaction with the lattice of the double-slit apparatus. However, it is likely that these phenomena do not play any significant role in the ZGSTM experiment. Regarding the inelastic collision with air, such a mechanism is surely weaker than the elastic channel: as shown in the nonperturbative treatment of scattering processes of Ref. [5], even for inelastic collisions an upper bound on decoherence is given by the total scattering cross section, which is very small in this case. Regarding the effects of the lattice on the coherence property, neutrons are mainly subject to collisions with the atomic nuclei of the grating, couplings with thermal phonons, and (classical) vibrations of the grating due to thermal and acoustic motions. Since the interaction of neutrons with matter is very short ranged and the outer edges of the double slit are made of absorbing glass, the number of neutrons which are scattered off by the lattice should be negligible. Moreover, such neutrons would be "refracted far out of the diffraction pattern" [4]. Also the scattering with thermal phonons seems unlikely, since the slit consists of amorphous Gd [4], so that no lattice vibration could act on the neutron. Likewise, classical vibrations of the slit, typically with nanometer amplitudes, should be negligible in a situation in which the slit is 10 000 times larger.

Let us look at the two considerations on which SBB based their conclusion that decoherence is necessary to explain the data. The first consists of several model calculations of the intensity pattern in the absence of decoherence, and the fact that none of these satisfactorily reproduces the data. While SBB blame the failure on the absence of decoherence, we think that the models were too idealized with respect to the transition, at the double-slit, from the incoming wave function to the outgoing one: namely, the transition was represented as multiplication by a modulating function. Our numerical simulations suggest that the transition can be quite complicated; and indeed, in the TVZ paper we obtained a perfect fit with the data without decoherence by assuming that the outgoing wave function is the sum of two Gaussians, with a transverse momentum fitted to the data. Thus if the transition leads to such a wave function (which seems not unreasonable), an explanation of the data without decoherence is very well possible. The second consideration that led SBB to conclude the presence of decoherence is that, in another model calculation of the intensity pattern, this time including decoherence, they obtained a formula [Eq. (27) of SBB] involving a decoherence parameter Λ_t; when that parameter is fitted to the data it is significantly nonzero. However, the same type of formula can be obtained [6] in a model without decoherence, in which Λ_t quantifies the *incoherence*, see Eq. (47) in Ref. [6] and set equal to zero the parameter Λ therein present, via Eq. (39), which represents the coupling with the environment. Thus nonzero Λ_t in Eq. (27) of SBB does not mean nonzero decoherence. Note also that, while SBB *fitted* the decoherence strength, TVZ *estimated* it, which means that the TVZ value does not depend on the applicability of any particular model (but only on the negligibility of other sources of decoherence, as considered above).

Finally, another issue concerns the difference $p_x^{(2)} - p_x^{(1)}$ in mean momentum (in the transverse x direction parallel to the double-slit) between the two wave packets emanating from the double-slit. In the TVZ paper we incorrectly wrote that

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no physical explanation was given by SBB for this momentum difference; we apologize for that. Concerning the estimation of $p_x^{(i)}$, we disagree with the SBB formula $p_x^{(i)} \sim \pm\hbar/a_i$, where a_i is the width of the ith slit (and the minus sign applies only to the left slit), and argue instead for $p_x^{(i)} \sim \pm\hbar/w$, where w is the width of the entrance slit, as follows. After passing through the entrance slit, the momentum spread of the wave packet will be, according to the Heisenberg uncertainty principle, of order $\hbar/w$. Assume for simplicity that the mean momentum is zero. Roughly, the largest momenta will reach the right slit of the double slit, and the smallest momenta the left slit, so that the packet passing through the right slit will have mean momentum $p_x^{(2)} \sim \hbar/w$, and the packet through the left slit $p_x^{(1)} \sim -\hbar/w$. Of course, the values estimated by SBB are correct because, as it happens, in the ZGSTM experiment w and a_i are of the same order of magnitude [4].

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[1] A. S. Sanz and F. Borondo, preceding Comment, Phys. Rev. A **77**, 057601 (2008).
[2] R. Tumulka, A. Viale, and N. Zanghì, Phys. Rev. A **75**, 055602 (2007).
[3] A. S. Sanz, F. Borondo, and M. J. Bastiaans, Phys. Rev. A **71**, 042103 (2005).
[4] A. Zeilinger, R. Gähler, C. G. Shull, W. Treimer, and W. Mampe, Rev. Mod. Phys. **60**, 1067 (1988).
[5] K. Hornberger and J. E. Sipe, Phys. Rev. A **68**, 012105 (2003).
[6] A. Viale, M. Vicari, and N. Zanghì, Phys. Rev. A **68**, 063610 (2003).