Aharonov and Reznik Reply: The two main claims raised by Hyllus and Sjöqvist [1] (HS) are that: (a) The local effect on the magnetic moment and the nonlocal phase shift are attributed to a single degree of freedom, and therefore such complementarity [2] cannot exist. (b) To demonstrate this, they argue that a verification measurement of the local effect does not destroy the interference. While we cannot agree with the first claim, we agree that under certain circumstances (which we discuss), a verification measurement is possible. We argue that this does not void the suggested concept of complementarity, but does require a more careful definition of the complementarity. To clarify these issues, it will be helpful to consider first the complementarity for the case of the Aharonov-Bohm (AB) [3] effect.

Consider the AB interference experiment in a two-dimensional setup. An electron moves along two circular paths around a fluxon whose magnetic field is oriented in a direction orthogonal to the plane of motion. Suppose that the fluxon is generated by a spin carrying a magnetic moment. Now the moving electron generates a magnetic field $\pm B_z$ at the location of the spin, where the $\pm$ depends on its trajectory. In order to distinguish between "right" and "left" trajectories, one can measure the magnetic field by observing the precession of the spin. But standard wave-particle complementarity tells us that such a measurement must destroy the interference. This shows how the local and nonlocal complementarity is manifested in the AB effect. The local effect on the spin is complementary to the interference effect of the charge. By interchanging the roles of the electron and the spin, this problem is mapped to the Aharonov-Casher (AC) [4] setup. The relative velocities are unchanged by this transformation, and therefore, the local spin precession as well as the accumulated relative phase are identical.

In both cases, of the AB and AC effects, we must in addition to the spin precession consider the spatial degrees of freedom of the interfering particle, i.e., the position, on a quantum mechanical level. Otherwise, no interference effect can be observed at all. The motion of the center of mass of the interfering particle is identical in both effects, and the accumulated phase can be derived from an operator depending on the spatial degrees of freedom alone. For instance, we can consider the expectation value of the modular velocity operator $\cos(mvL/\hbar)$, with $v = (p - A)/m$ the velocity perpendicular to the direction of motion and L the distance between the trajectories. It yields the cosine of the AB or AC phases. This modular operator dependents on the position degree of freedom. Hence, we argue that, in both cases, the interference effect cannot be an attribute of spin alone.

Next, consider the second claim of HS. A measurement of the precession alone can distinguish which path the interfering particle follows and, hence, destroys the interference. But one can consider a measurement involving *both* the position and the spin that nevertheless does not distinguish between the paths [5]. In the AB case, consider a "controlled" measurement: only if the electron follows the right path we measure $U_R^\dagger(T)\sigma_x(0)U_R(T) - \sigma_x(0)$ where $U_R(T)$ generates the rotation during the time interval T, when the electron is at the right path. For that we employ a von-Neumann coupling twice: at $t = 0$ we couple to the spin $\sigma_x(0)$, and later at time $t = T$ we couple to the rotated spin $U_R^\dagger(T)\sigma_x U_R(T)$. The outcome is recorded at time $t > T$. A straightforward computation yields for this outcome zero, whether or not the electron is on the right side. Furthermore, at $t > T$ the system returns to its unperturbed state. Hence, the verification measurement does not destroy the interference. In the AB case such a measurement requires a nonlocal coupling. In the AC effect the spin degree of freedom is carried by an interfering particle. Hence, the later "null" measurement may be performed locally along one of the interference arms.

If the location of the trajectory (in the AB effect) or the location of the charged source (AC effect) is fixed, we know in advance the conditional precession effect on the spin. Hence, a null verification experiment is possible. The possibility of a verification experiment still does not void the idea of complementarity, because in the general case, one would like to use either the interference effect or the local precession in order to measure an *unknown* topological phase. For example, suppose that the value of the source or that the precise location of the charged source are not known. For these cases, the value of the local electric field in the AC effect (or the induced magnetic field in the AB effect) are not fixed, and a nondisturbing null verification experiment is not possible.

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