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On how classical uncertainties might affect the coherence properties of collisions processes, and how to control them

R O Barrachina[1,2], **F Navarrete**[3] **and M F Ciappina**[4 *]

[1]Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica (CNEA) and Universidad Nacional de Cuyo, Av. Bustillo 9500, 8400 Bariloche, Argentina
[2]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[3]Department of Physics, Kansas State University, Manhattan, Kansas 66506, USA
[4]Institute of Physics of the ASCR, ELI-Beamlines, Na Slovance 2, 182 21 Prague, Czech Republic

Synopsis In principle, the quantum coherence properties of any collision experiment should be affected by unavoidable classical uncertainties. However, they seem to produce no observable effect. This mystery can be solved by introducing the concept of "coherence length" which, in addition, provides a way to control and modify the aforementioned quantum properties. Finally, we discuss different methods to achieve a transition between coherent and incoherent collisions, evaluating their strengths and weaknesses.

No matter how much we struggle to reduce the classical uncertainties in a collision experiment, we could never suppose them null. In other words, it would never be possible to describe all the different scattering events by a single and unique wave function. However, this is what we actually do in the standard scattering theory, and even assume that this wave function can be represented by a plane wave [1].

A key element for unravelling this conundrum is the coherence length ℓ [2]. The standard "fully coherent" scattering theory applies whenever ℓ is much larger than any characteristic size of the scattering event. Otherwise, a partially coherent (or even incoherent) calculation is mandatory.

In recent years, a series of experiments have explored this transition between coherent and incoherent collisions (see, e.g. [3]). Lacking a proper quantum mechanical definition of ℓ, it has been a common practice to borrow it from Optics. Thus, some authors [4] have modified the angle $\theta_L = \Delta R/L$ subtended by the collimator of aperture ΔR as seen from the target at a distance L , i.e. by assuming $\ell_L \propto \lambda/\theta_L$, with $\lambda = h/P$ the wavelength of the projectile of momentum P; while others [5, 6] have tried to set the focusing of the projectile's beam, as characterized by its angular dispersion θ_P, i.e. by defining $\ell_P \propto \lambda/\theta_P$. However, it is legitimate to question the validity of each approach, and the appropriateness to use them indistinctly. To answer these questions, we developed in a previous work a full quantum mechanical definition of ℓ [2, 7, 8], proving that $\ell \propto \lambda/\theta_L$ whenever $\theta_P \approx 0$. This result validates the first strategy, but a complete analysis incorporating both effects was still lacking. In the present communication we present this full and comprehensive study for the first time, which leads to the following expression:

$$\ell \propto \lambda \sqrt{\frac{1}{(\Delta p/P)^2 + \theta_P^2} + \frac{1}{(\Delta r/L)^2 + \theta_L^2}} \, ,$$

where $(\Delta r, \Delta p)$ are the quantum uncertainties in position and momentum of the projectile, respectively. This result shows that both strategies, i.e. modifying θ_L or θ_P, do not lead to similar results. In particular, it can be demonstrated that while modifying θ_L is an effective method for exploring the aforementioned coherent–incoherent transition, the variation of θ_P might become inconsequential in most experimental set-ups.

*E-mail: marcelo.ciappina@eli-beams.eu

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