Macroscopic Quantum Processors Based on Stored High-Energy Polarized Beams

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Abstract. The coherent spin rotation of stored particle beams produces macroscopic states with familiar quantum properties. Because massive quantum systems with spin greater than or equal to one display instructive interference effects not accessible with spin one-half particles, we discuss the sequential rotation and decoherence of a stored polarized deuteron beam. Experimental measurements on such systems should produce unique quantum effects.

The purity and lifetime of polarized beams stored in high-energy rings have improved dramatically in recent decades as progress in polarized sources and refinements in accelerator design have been implemented. In a series of experiments based at the IUCF facility at the University of Indiana [1] a group led by Alan Krisch has systematically studied the spin manipulation of stored beams using a Siberian snake as well as various induced-resonance techniques. These experiments demonstrate conclusively that coherent spin rotation using the Froissart-Stora [2] technique of adiabatic resonance crossing can be reliably controlled with existing radio-frequency magnet technology. The resulting large-scale particle beam systems display carefully-designed quantum complexity. An explicit example of such a process involves the coherent rotation of a stored polarized deuteron beam.

The concept of intrinsic angular momentum or “spin” constitutes an intrinsically quantum-mechanical feature of matter that has no classical counterpart. The quantization of spin is built into the fabric of space-time [3]. For example, the spin-statistics theorem [4] inexorably slots particles as fermions or bosons according to the spin quantum number. While we are familiar with quantum systems at the particle or “atomic” level, most quantum effects are lost in macroscopic systems due to averaging over a very large number of possibilities. However, a beam of particles moving with spins aligned — a “polarized beam” — retains the inherently quantum-mechanical nature of the spin degree of freedom in spite of multiple random interparticle effects. The spatial rotation of the spin degree of freedom using electromagnetic fields necessarily involves highly nontrivial coherent effects. The coherence allows the quantum superposition principle to apply to large-scale quantum spin states. In a storage ring, these states return to the same location at periods controlled by the ring circulation frequency and can be studied in controlled experiments. The idea that particle beams can constitute definite quantum states is not unfamiliar [5] but it does seem to be under appreciated. At a time when the quantum nature of the spin degree of freedom is
under study for field-effect transistors and other examples of “spintronics” [6], it
seems worthwhile for accelerator physicists to consider the application of quantum
ideas to the manipulation of stored polarized beams.

The range of possible quantum effects involving polarized beams is quite large.
The opportunity for interferometry with multiple beams is worth consideration. We
would like to illustrate the basic concept with a discussion of the coherent rotation of a
polarized deuteron beam. With a beam stored in the x-y plane and the spin
quantization axis in the z direction, the most general form of a massive spin-1 density
matrix is

\[
\rho = \begin{pmatrix}
N_+ & 0 & a(N_+N_-)^{1/2} e^{i\theta} \\
0 & N_0 & 0 \\
a(N_+N_-)^{1/2} e^{-i\theta} & 0 & N_-
\end{pmatrix}
\]

The activation of a coherent Froissart-Stora spin rotation using a dipole (or a
solenoid) rf magnet directly breaks the symmetry in the x-y plane. The breaking of
the symmetry produces an explicit example of the Higgs mechanism [7] in which the
symmetry breaking couples the \( |0> \) states to the \( |+> \) and \( |-> \) quantum states. The
effect of the rotation can be illustrated by a simple example. Let \( c=\cos(\theta) \) and
\( s=\sin(\theta) \), the coherent rotation of the pure quantum state represented by the
idempotent density matrix

\[
\rho_x(0) = \begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

produces the density matrix

\[
\rho_x(\theta) = \frac{1}{4} \begin{pmatrix}
(1+c)^2 & s(1+c)\sqrt{2} & s^2 \\
s(1+c)\sqrt{2} & 2s^2 & s(1-c)\sqrt{2} \\
s^2 & s(1-c)\sqrt{2} & (1-c)^2
\end{pmatrix}
\]

The density matrix also represents a pure quantum state. If, however, the rotator
magnet is turned off after a rotation through an angle less than 180 degrees, the
coherence between the \( |0> \) states and the \( |+> \) and \( |-> \) states which had been
maintained because of the broken symmetry during the magnet operation begins to be
lost as the original symmetry is restored. The subsequent decoherence occurs with a
time scale which depends of the full set of operating parameters of the storage ring.
The decoherence may happen within a few cycles or the rotated “pure” state may
persist as a quasistable state for thousands of cycles. The diagonal elements of the
density matrix are preserved as the phase information is lost. However, a subsequent
coherent rotation can detect the amount of “depolarization.” Therefore, a systematic
set of measurements of the deuteron polarizations, \( P_z \) and \( P_{zz} \), after a set of timed
sequences involving a coherent rotation, decoherence interval, and further rotation can explore the dynamics of this simple, but interesting, quantum system in some detail. Because of the full quantum nature of the spin degree of freedom, a polarized deuteron beam can provide a quantum workbench to study the Higgs mechanism in action.

While we have chosen a simple example from a spin-1 system to illustrate a nontrivial quantum effect, it should be kept in mind that numerous examples involving spin-1/2 systems can also be formulated. This presentation has not focused on the accelerator physics techniques that allow the storage and manipulation of polarized beams. Many practical aspects are discussed in the papers cited in reference 1. Further discussion concerning the application of Froissart-Stora rotations can be found in the presentations of Vassili Morozov at this conference (7). This talk is intended to point out some of the "sophomore quantum mechanics" of polarized beams. Because these aspects of polarized beams are simple, they can often be ignored. Stored polarized beams do, however, involve some profound information about the nature of space and time so that the manipulation and measurement of the spin degree of freedom in these systems can prove to be very informative.

It is instructive to compare the properties of a stored polarized beam with the properties of other macroscopic quantum systems. Lasers provide macroscopic quantum collection of photons. The range of applications that has been found to date for lasers is enormous. However, the photons in a laser lack one aspect of control that stored particle beams possess, the charged particles in a storage ring can be manipulated by electromagnetic fields in a very controlled manner. Multiple beams or multiple bunches within the same ring can be controlled from a few simple instructions. The phase information contained in the polarized beam can be used to monitor these instructions. In this sense, a polarized beam in a storage ring can be considered a full-fledged quantum processor.

REFERENCES

7. V. Morozov, these proceedings.