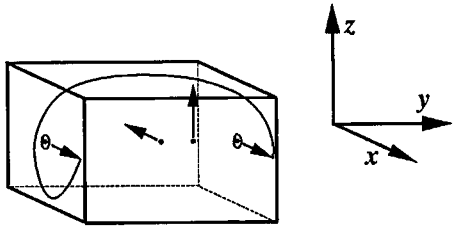
# 12

# Two-Slit Inventions

In chapter 9 we concluded that in quantal interference experiments a single atom passes through both branches of an interferometer. In chapter 10.1 we firmed up that everyday-language expression to the technical phrase "there is an amplitude for the atom to go through either branch". Exactly what do these strange statements mean? How can our minds grow familiar with a real quantal atom, which behaves so unlike a small, hard marble? To prepare for these questions, this chapter examines two variations of the quantal interference experiment. This chapter is not absolutely essential for the logical development of the book, but it dramatically underscores that quantal interference demands a total rethinking of our picture of the atom — no simple trick will suffice.

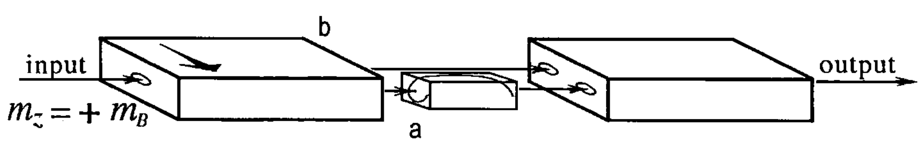
## 12.1 The Aharonov–Bohm effect

It's possible to build a box called a "corkscrew" from a uniform magnetic field twisted into one turn of a spiral (see figure below). At the left edge of the box the magnetic field points straight out of the page (that is, in the $+x$ direction). Moving towards the right the magnetic field slowly dips until it points straight down, then continues to twist until it points into the page, then straight up, until finally — at the right edge of the box — the magnetic field again points straight out of the page. (The magnetic field always points perpendicular to the $y$ direction.)



How do atoms behave when they pass through a corkscrew? Only experiment can tell for sure, but the following argument is suggestive and turns out to be correct. If an atom with $m_x = +m_B$ enters a corkscrew, it enters with its magnetic arrow pointing "more-or-less" in the same direction as the magnetic field. (The qualifier "more-or-less" is there just to remind you that atomic magnetic arrows don't point in the same definite manner that sticks do.) It seems reasonable that such an atom's arrow would be dragged around by the field as the atom passes down the center of the corkscrew, and thus that it will emerge with its magnetic arrow still pointing in the $+x$ direction, after having executed a complete flip. This expectation is confirmed by experiment: If an atom with $m_x = +m_B$ enters a corkscrew, it emerges with $m_x = +m_B$ and no experiment performed on that single atom can tell whether it passed through a corkscrew or through an empty box. As far as an atom with $m_x = +m_B$ is concerned, passing through a corkscrew is equivalent to doing nothing.

Using a corkscrew we can turn the interference experiment sketched on page 65 into something surprisingly different (see figure below). Recall from experiment 9.3 on page 66 that if an atom with $m_z = +m_B$ enters an unblocked interferometer, it leaves in the same state, namely with $m_z = +m_B$. The two halves of the interferometer can be drawn apart and experiment repeated: the results are exactly the same. Now, insert a corkscrew into branch a so that any atom passing through branch a also passes through the corkscrew. Remember that an atom passing through branch a has $m_x = +m_B$ and that for such atoms a corkscrew does nothing. Experiment reveals that after the corkscrew is added any atom entering with $m_z = +m_B$ emerges in a *different* state, namely with $m_z = -m_B$.

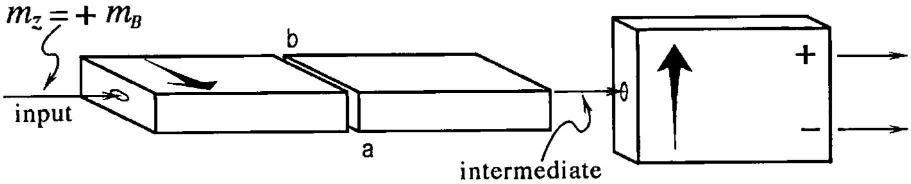



How can this be? Didn't we say, just two paragraphs ago, that "as far as an atom with $m_x = +m_B$ is concerned, passing through a corkscrew is equivalent to doing nothing"? Indeed we did. But the atom *doesn't* simply pass through a corkscrew — it passes through *both* branches.

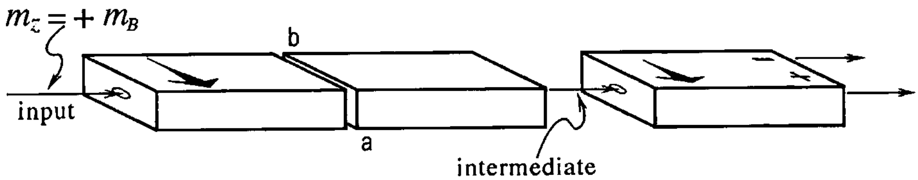
If an atom went through branch a, or through branch b, then inserting a corkscrew in branch a would have no effect on the interference experiment. The fact that the corkscrew *does* have an effect proves that a single atom goes through both branches.

## 12.2 Delayed choice experiments

In our primary quantal interference experiment (experiment 9.3 on page 66), the interferometer was horizontal and the trailing analyzer was vertical. In this situation each unwatched atom "goes through both branches" of the horizontal interferometer and emerges from the + exit of the trailing analyzer. In contrast, each watched atom goes through only one branch (whichever branch it is observed to take), and has probability $\frac{1}{2}$ of emerging from the + exit.




A variation on this experiment is to orient the trailing analyzer horizontally. In this situation both watched *and* unwatched atoms have probability $\frac{1}{2}$ of emerging from the + exit of the trailing analyzer. An atom observed to pass through branch a always emerges from the + exit, so it is tempting (although wrong) to believe that an unobserved atom found emerging from the + exit had also passed through the single branch a. Indeed, if this were the only experiment we ever performed, we would never have to deal with ideas like "a single atom goes through both branches" or "a watched atom behaves differently from an unwatched atom" — we could always be content with each atom taking a single definite path through the apparatus.




Is it possible, then, that the atom goes through both branches when the trailing analyzer is vertical but goes through a single branch when the trailing analyzer is horizontal? This possibility is called a "conspiracy theory" because the atom somehow senses the arrangement of the apparatus and behaves accordingly. (In fact, it senses the arrangement of the trailing analyzer even as it passes through the interferometer, having not yet encountered the trailing analyzer!) Quantum mechanics, in contrast, predicts that an unwatched atom goes through both branches in either case. One way to test the two alternatives is through a "delayed choice experiment". In this experiment the trailing analyzer is mounted on a pivot and can be swung from vertical to horizontal at a moment's notice.

Suppose an atom enters the interferometer while the trailing analyzer is horizontal. Then, according to the conspiracy theory, it goes through one branch or the other and emerges with $m_x = +m_B$ or with $m_x = -m_B$. Now, as the atom flies from the interferometer to the trailing analyzer, the trailing analyzer is quickly swung to the vertical position. When an atom with either $m_x = +m_B$ or $m_x = -m_B$ enters a vertical analyzer, it has probability $\frac{1}{2}$ of emerging from the $-$ exit. Thus the conspiracy theory predicts that half of such atoms will leave through the $-$ exit of the now-vertical analyzer. Quantum mechanics predicts that, regardless of the orientation of the trailing analyzer, each atom goes through both branches, each atom flying from the interferometer to the analyzer has $m_z = +m_B$, and thus all such atoms will leave through the $+$ exit of the vertical analyzer.

This conceptual experiment has been realized in several different ways — each time with somewhat different details — and quantum mechanics has been confirmed every time.

## 12.3 References

The Aharonov–Bohm effect was predicted from quantum theory in 1959 in a form and context very different from the one described here, and this prediction gave birth to a whole series of experiments and arguments. This story is told in the highly technical yet very beautiful little book

M. Peshkin and A. Tonomura, *The Aharonov–Bohm Effect* (Springer–Verlag, Berlin, 1989).

No such overview has been written for delayed choice experiments. The closest approach is

George Greenstein and A.G. Zajonc, *The Quantum Challenge* (Jones and Bartlett, Sudbury, Massachusetts, 1997), pages 37–42.

Recent developments are reported in

T. Kawai *et al.*, "Development of cold neutron pulser for delayed choice experiment", *Physica* B, **241** (1998) 133–135.