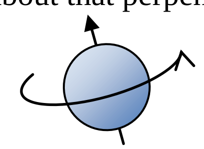
Preface

The point of Q5 was to really build the case for our needing a new kind of model to describe quantum mechanical behavior – a model that's somehow a hybrid of particles and waves. Much of the chapter focuses on the situation of electrons passing through Stern-Gerlach devices, and it reports concrete observations that we'd make if we did so – observations that will require this new kind of model to understand. So, Q5 builds up the case for Q6 – where we begin working with that new kind of model.

Here's a recap of most of what chapter 5 told us about an electron's spin. My description will be rather 'classical' so I can highlight what the classical picture can, and (more importantly) exactly what it *can't* account for.

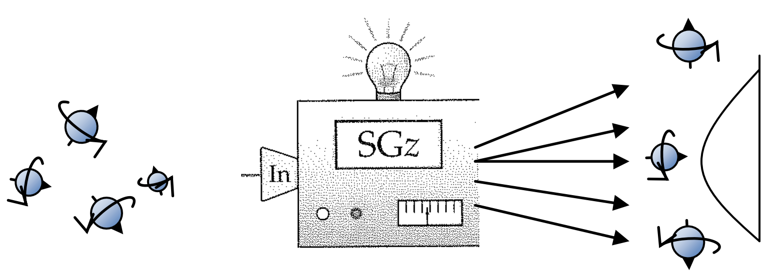
Think of the Earth spinning on its axis. By convention, to be able to quantify the spin as a single vector, we assign the vector's direction to be along the axis of spin according to the right hand rule (wrapping the fingers in the direction that the earth is spinning and pointing the thumb along the axis) so the Earth's spin vector points North (at about 23degrees off perpendicular from its orbital plane and slowly pressesing about that perpendicular.)



An electron has a similar property. Since the electron has charge, that associated charge circulation constitutes a current loop and that, of course, interacts with an externally applied magnetic field. That's at the heart of the Stern-Gerlach devices. Inside the SG device is a (diverging) magnetic field. Which way the electron gets pushed as it travels through the device depends on the electron spin's alignment with that field, so we can determine the spin alignment by seeing which way the electron's path exits the device. To learn more about *how* these devices work, see Q8.5.

What we'd expect classically

If you shot a random beam of electrons into an SG machine with, say, magnetic field pointing up, you'd find that half deflected up and half down, suggesting that there was an even distribution of electrons of both orientations. Classically, you'd expect the electrons to be able to be spinning in any old direction, so you'd get a smooth distribution of electrons coming out of the machine.



Spin completely aligned with +Z

Spin completely aligned in the x-y plane

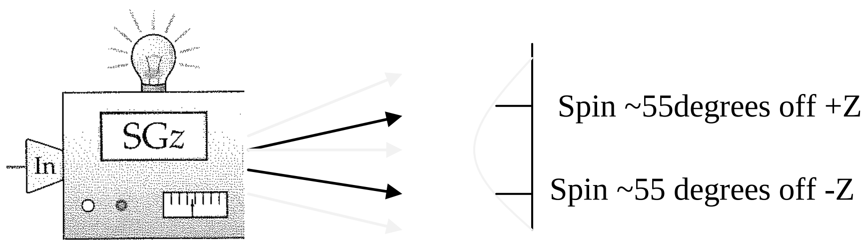
Spin completely aligned with -Z

Classically expected distribution of random electrons coming out SGz machine

Mind you, this machine only interacts with / determines the z-*component* of the spin, so, for example, you could tell if an electron's spin was 60degrees off the z-axis, but you couldn't tell in what *direction* it was 60 degrees off – toward the x axis, toward the y axis, somewhere in between…

What actually happens

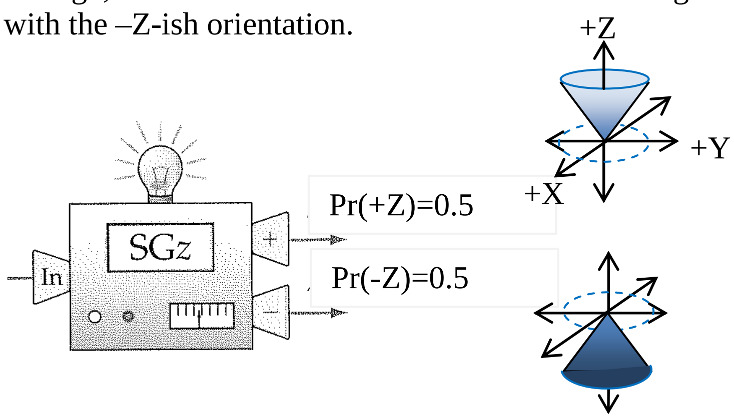
Now, when one *does* this experiment, you *don't* get a smooth distribution of electron orientations, you only get two possibilities. This is a reflection of something fundamental about quantum mechanics – observable properties can have only *specific* values, not a continuum. Moreover, the electrons come through the machine as if they were *either* aligned with the +Z axis or the –Z axis. A little more specifically, they're either 55degrees of the +z (which we'll call "aligned with +z") or 55degrees of the –z axis, and just as we'd expect classically, we have no idea if it's 55degrees off in the +x direction, the –y direction, or some direction in between.



Actual distribution of random electrons coming out SGz machine

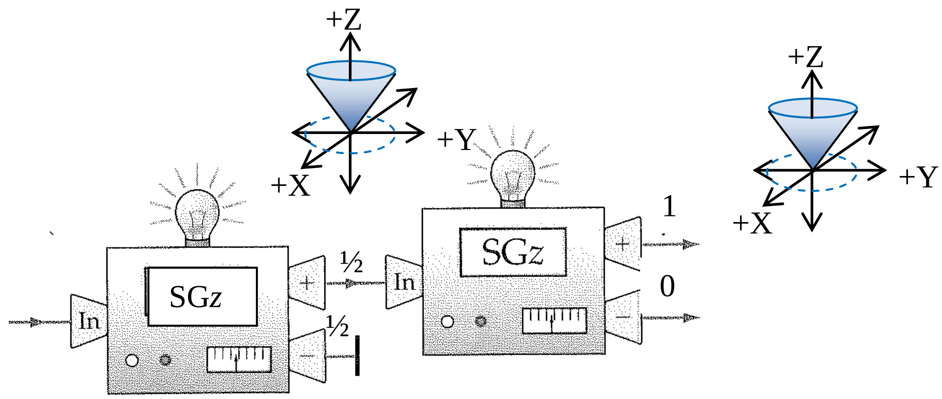
For those of us used to thinking classically, that's pretty odd. As we get deeper into Q.M, we'll see a little more of an explanation in terms of boundary conditions on the electron's wave function, but for now, we'll just go with it.

So, if you set up a detector at the output of the SGz machine and shoot a beam of electrons through, half of the electrons will be detected coming out with the +Z-ish orientation and half with the –Z-ish orientation.

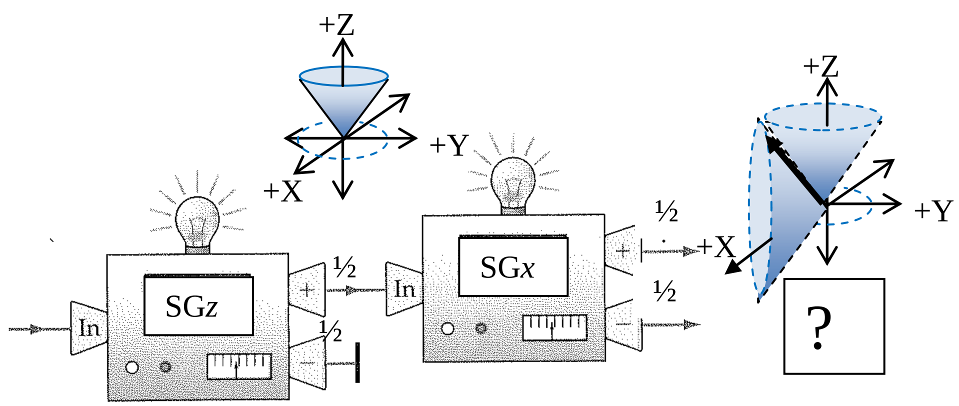


Now, pause and visualize what we know about the orientation of the spin for electrons coming out the +Z exit. It's *somewhere* in the cone centered on the +Z axis, but we can't say where; the best we *can* say is that it's is confined to the cone. Of course, the cones are symmetric along the x axis and along the y axis.

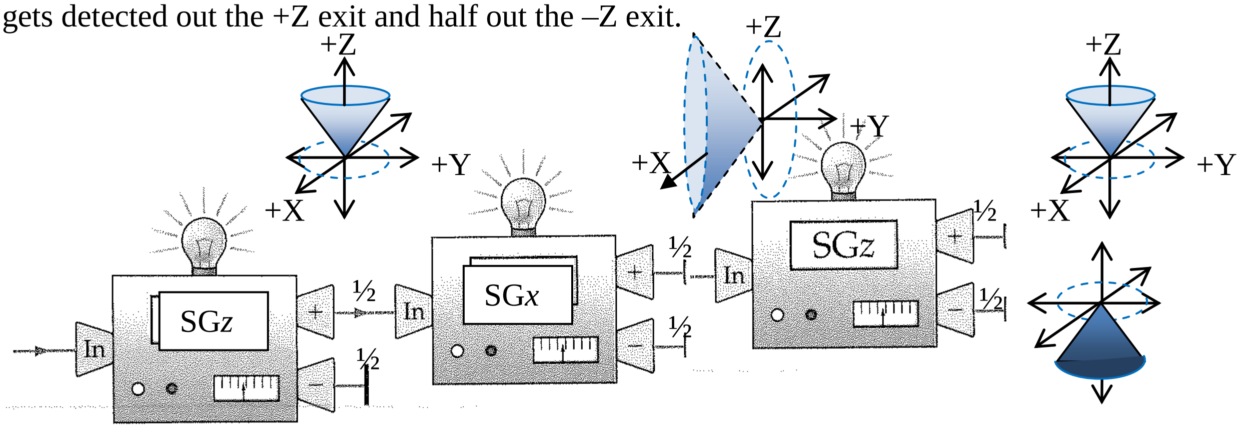
Not surprisingly, if you pass the beam of +Z oriented electrons through another SGz machine, they'll all come out the second machine's +Z output.



Now, if instead, you put an SGx machine after the first SGz machine, since the cone of possible spins is symmetric along the +X and –X axis, you'd expect to detect just as many being mostly +X aligned as mostly –X aligned. That is indeed what you get. Now, classically, one would have again expected a smooth distribution over the possibilities, but yet again you get just two instead: 55degrees off +X and 55degrees of –X. Based on this, it would be tempting to predict 'great, since I *already* know the electrons are 55degrees off the +Z axis, and *also* know that they're 55degrees of the +X axis (if they come out in that beam), then I know the exact orientation of the spin!



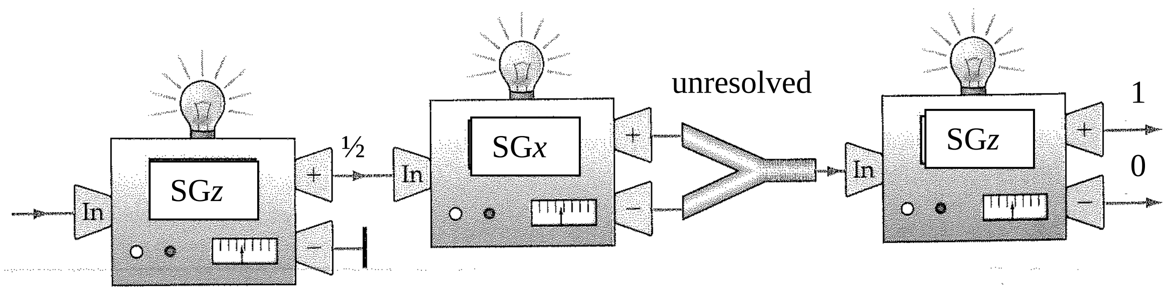
A test of that prediction would be passing the beam through *another* SGz. Alas! Half the beams gets detected out the +Z exit and half out the –Z exit.



That's consistent with saying that *measuring* the x-component / forcing the electrons to choose, scrambles the z-component. You can imagine the electrons headed into the SGx machine have spins on the cone around the +z axis; given the symmetry of the cone, when they encounter the magnetic field in the x direction, there's a 50/50 chance that they'll be pointing left-ish or right-ish, and the interaction with the field nudges them onto the +x or –x cone depending. Then a similar thing happens when the electrons encounter the z magnetic field in the second SGz. That's what the measurements at the SG machines' exits seem to imply.

Of course, if *that* were the case, the same thing should be happening for electrons coming out of the –x end of the SGx machine, and as the electrons through both exits now have spins on cones around the +x and –x axis, both of which are symmetric in the +z and –z direction. So far, so good; that is what happens.

Now, one would expect that if we then recombined the beams and then sent them through the second SGz machine, we'd see half coming out with +z orientation and half with –z orientation. Here comes another oddity of Quantum Mechanics, if you could build an ideal SGx machine, one that gives the electron both exit *options* but doesn't itself *detect* which choice the electron made (like a double slit experiment with no sensors at the slits), and then these fed into another SGz machine, then the electrons emerge from the final machine *retaining* the initial +z orientation! It's only in the interaction of *measuring* spin orientation that we influence the spin orientation.



So, our classical picture fails to explain why, should we measure the spin along a given axis, we find only two possibilities. It also fails to explain why, should we present the electron with two options but not perform an experiment to nail down which option it too, it'll continue on as if having taken both. We need a new kind of model to account for both of these observations.