Demonstrating Magnetic Resonance Using Magnetic Torque

The following discussion was developed for a student representing TeachSpin at an APS area meeting. He had never used Magnetic Torque in his own classes and had performed the first few experiments on his own. He was struggling with demonstrating the use of the rotating magnetic field. He had never heard of a gyromagnetic ratio and had no idea what NMR entailed.

Watching the Ball Precess

When a spinning object which has a magnetic moment oriented along the spin axis is placed in a magnetic field, it precesses. When you spin the ball and turn on the vertical magnetic field, the ball very obviously precesses around the vertical axis. As you will notice, the ball precesses faster if it is spinning rather slowly or if the magnetic field B (as indicated by the current) is high. A magnet with a larger magnetic moment would also have a faster precession rate. For a given magnetic field, the precession rate depends on the ratio of the objects magnetic moment (μ) to its angular momentum, L. That ratio is so important it is called the gyromagnetic ratio and is characteristic of a particular particle. The gyromagnetic ratio is a signature of the particle as much as its charge or mass. The precession frequency for any particle in a particular magnetic field is called its Larmor Frequency.

Imagining a Signal from the Precessing Ball

Think about holding the ball so the handle would be perfectly horizontal when you started it spinning and precessing. Now, visualize placing a small loop of wire so that, in the course of its precession, the magnetic moment (here, its direction is indicated by the black handle) would sweep past the open end of the loop, One moment the handle, and thus the magnetic field, would be aimed right down the axis of the loop, the next moment the field in the loop would be decreasing as the handle swept by. Soon the "rear end" of the ball would be aligned with the axis of the loop giving a "south" magnetic field aiming down the axis of the loop. The loop would experience a sinusoidally changing magnetic field along its axis. According to Maxwell's equations, this will induce an emf and thus a voltage in that loop which also varies sinusoidally. This emf, induced in the *pickup coil* by the precessing magnet, is the beginning of NMR and MRI. (If the handle, representing the "spin," had not been perfectly horizontal, the signal would be smaller because only the component along the axis of the pickup coil will create the emf.)

Relating the spinning ball to protons in a sample

Under real conditions of Pulsed NMR, however, we are working not with one particle but with many and the pickup coil responds to the combined effect. The strength of the signal is an indication of the degree of "magnetization" of the sample and is given the symbol M. A higher magnetization means that a larger number of spins are both in the same plane and in phase. Even if we could initially get all the atoms precessing with their spins perpendicular to the reference (in our case vertical) magnetic field, the particles influence one other. The particles bump, they exchange angular momentum, they get out of phase, they become aligned with the reference field. Any of these influences decrease the magnetization and the signal from the pickup coil decreases. The changing signal is called the free induction decay, FID.

The magnetization in the x-y plane, and, therefore, the signal from the pickup coil, decays exponentially. The equation for the signal as a function of time is $M_{xy} = M_o e^{-t/T_2}$ where M_o is the magnitude of the initial signal. The capital T_2 is called the spin-spin relaxation time. It is the characteristic time it takes for the initial signal to drop to 1/e of its initial value. The characteristic time for the decay to occur tells chemists and physicists about the environment in which the particles are located. In an MRI, a computer interprets the characteristic time determined for a given spot on your body and makes the required pixel look like blood, or bone or tumor cell. This explains why an MRI takes so darned long. The machine has to look at one very small spot at a time. The finer the resolution, the longer it takes.

The next question is how, in an NMR or MRI, do we get the particles (in an MRI the particles of interest are the protons of the hydrogen molecules in your body) to be perpendicular to the reference magnetic field. So here we go!

Changing the orientation of the spinning ball

Turn off the vertical field and slide the permanent magnetic assembly over the air bearing. The magnets at either end produce a horizontal field. If you simply hold the ball with its handle toward the ceiling and let go, the ball just rotates until the handle points in the same direction as the arrow on the base of the assembly. The ball acts like a compass. You have seen a simple response to a torque. If, however, you spin the ball with its handle pointing towards the ceiling, the handle ends up pointing out between the two ends of the permanent magnet. The axis of the spin, as shown by the handle, is precessing around a horizontal field.

In NMR measurements, we need the spin to be deflected until it is perpendicular to a reference magnetic field (in this case our vertical field) and then allowed to precess. It looks as if a magnetic field perpendicular to the reference field would work.

If we now leave the horizontal field in place, turn on the coil field as high as it will go, and spin the ball, we are in for disappointment. The ball simply precesses happily around the vector sum of the fields. Now what? Somehow we need to have the ball think it is in the presence of just the horizontal field so that it will turn down, or "flip."

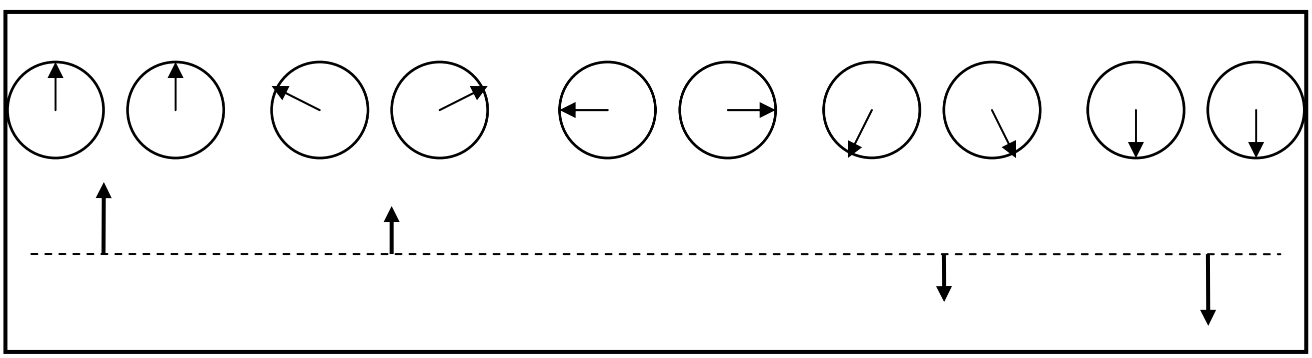
Think about watching the ball precess with just the vertical field on. Imagine yourself on a merry-go-round at the base of the air bearing. The merry-go-round is turning so that the handle of the ball is always exactly over your head. In your "rotating frame of reference" you would see the ball, with its imbedded magnet, spinning but not moving. Standing down there, looking up at the handle of the spinning ball always staying just above your head, you would be convinced that there was no vertical field. In the presence of a magnetic field, you know that a spinning ball will precess and the axis of your ball is standing still! Now, if someone were to install a horizontal field right across in front of you, I hope you would have the sense to duck because, of course, that black handle will come right down on your head.

What we do is, in a sense, trick the ball into thinking that there is no vertical field by creating a rotating reference frame for that ball, a reference frame in which there is a nice stationary horizontal field for it to precess around. To do this, you spin the ball quite close to vertical. Watch it precess for a few moments and then, when the handle is as close as possible to midway between the two ends, start rotating the horizontal field assembly so that the handle stays in the same plane. If you are moving at the right rate, the handle will rotate down just the way it did when the vertical field was off and the system was truly at rest. I hope you noticed that if you are way off ideal rotation rate, nothing much happens. If you go in the wrong direction, rotating backward, absolutely nothing happens. To use our imaginary pickup coil we would now have to get the horizontal field out of the way somehow.

Using rf to "tip the spins"

In real NMR they use an rf or radio frequency (sinusoidal) magnetic field to "tip the spins." If we think a minute, you can connect this to the rotating magnetic field. You already noticed that the backward rotation was completely ignored by the spinning ball. What would happen if we could use two rotating magnetic fields at once, one going the right way and one backward, but both at the same correct frequency. If you break your circular motions into components, you will see that while one pair of components cancel, the other pair combines into a sinusoidally changing single magnitude. With a little anthropomorphizing, we can say that protons are so "smart" that when you give them a sinusoidal magnetic field, they simply treat it as two individual rotating magnetic fields, one of which is going the wrong way and is ignored while the other creates the rotating reference frame! The rf is turned on just long enough to tip the spin by the desired amount.

This set of pictures shows how two counter-rotating magnetic fields produce a sinusoidal signal. The arrows in the circles represent the magnetic fields created by the two rotating systems. The single arrow below them represents the combined field. I hope you can see that the combined signal shown is the first half of a cosine curve.



In a pulsed NMR the rf frequency used is the same the frequency at which you are rotating the horizontal magnetic field. It is called the Larmor frequency. The time for which you rotate the horizontal field in order to get the desired change in the angle of the handle is called the pulse width. If the handle rotates by 90°, we say you have applied a 90° pulse. If, in an NMR, you have started with the spins at "thermal equilibrium" which means that the net magnetization will be along the primary field, then using a 90° pulse is like making our ball turn until the handle is horizontal. If the horizontal field is then turned off, the pick up coil will show its maximum initial signal. For pulses more or less than 90 degrees the signal will be smaller because only the component of the magnetic field of the ball which is aimed along the axis of the pickup coil will produce the emf we are monitoring. Why the signal dies out is a story for another session.