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A mechanical analog of Nuclear Magnetic Resonance

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Figuring out Nuclear Magnetic Resonance: A Macroscopic Approach

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Wishful thinking

A long time ago, in a galaxy far far away, nuclei were invented. At some point between then and now, a technique called NMR spectroscopy was developed, and at present, most college students in chemistry are able to successfully "turn the crank" and use the device; however, the models generally presented for the functioning of NMR are really confusing!

Laboratory Structure

Our Modern Physics Laboratory is structured such that students can build physical understanding of the investigations. In the case of NMR, the students examine a number of different resonance investigations: Mechanical driven oscillator, RLC circuit, Mechanical model of NMR, and then onto NMR.

Deciphering NMR through basic theory

There are different "styles" of NMR spectroscopy: the external field can be swept; the frequency of a driving RF wave can be swept; or the driving RF wave can be pulsed pulsed. Either method causes certain particles to resonate at characteristic fields / frequencies, allowing for characterization of materials.

The complexities of NMR can be understood by first understanding precession of a magnetic moment under a magnetic field. The field provides a torque τ on the magnetic moment μ in order to line the particle's angular momentum **L** up with $\mathbf{B}_{ext}$.

$$\vec{\tau} = \vec{\mu} \times \vec{\boldsymbol{B}} = \gamma \vec{\boldsymbol{L}} \times \vec{\boldsymbol{B}}$$

The torque is equal to a change in angular momentum over change in time, and the change in angular momentum can be rewritten to give the following:

$$|\vec{\tau}| = \left|\frac{\Delta \vec{L}}{\Delta t}\right| = \frac{L \sin\theta\, \Delta\phi}{\Delta t} = \frac{I\omega \sin\theta\, \Delta\phi}{\Delta t} = \mu B \sin(\theta)$$

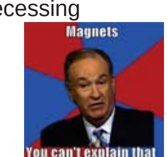
Finally, we get the **Larmor frequency**.

$$\vec{\omega}_L = \frac{\Delta\phi}{\Delta t} = \frac{\mu B}{I\omega}$$

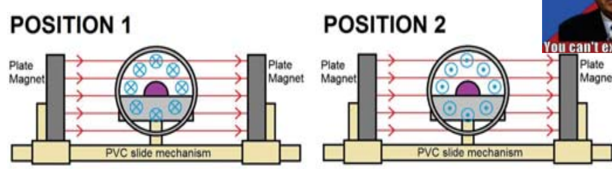
This frequency is the frequency at which the particle's angular momentum precesses about the external field and is the resonant frequency.

Where do we get a nucleus and how do we see it resonate?

Although the theory is sound, visualization of resonance behavior is an entirely different story. To replicate the intrinsic spin of a particle, a neodymium magnet, meant to emulate a proton, was placed inside of a spherical air bearing. Turbine torque causes the magnet to spin. Two plate magnets were used for production of a uniform external field. A Helmholtz coil is used for driving the oscillations. A Hall sensor is used to detect the precessing magnetic moment of the sphere.

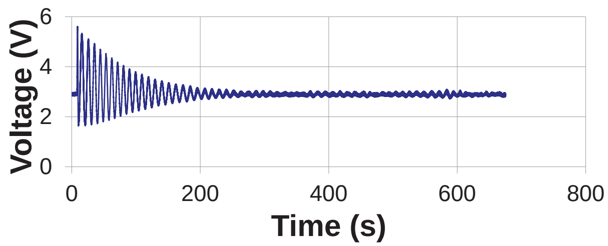


Side View of Apparatus

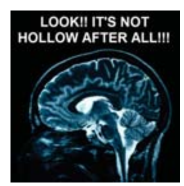


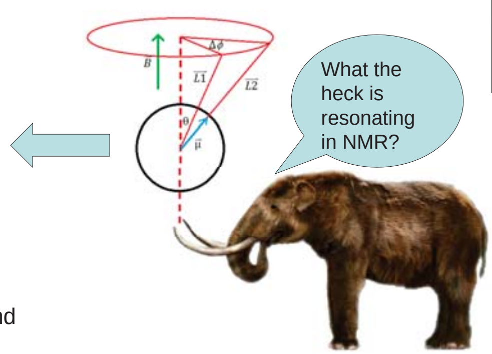
Pulse Data

Initial experiments were conducted to observe the Free-Induction Decay of our model after a single pulse.



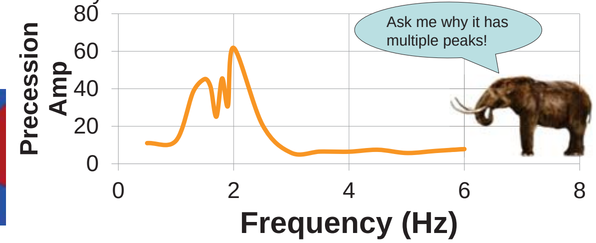
Trial Specifications: f-rotation = 125 Hz, 2.2 s pulse length, 2 psi air pressure, inner Helmholtz coil potential = 7V





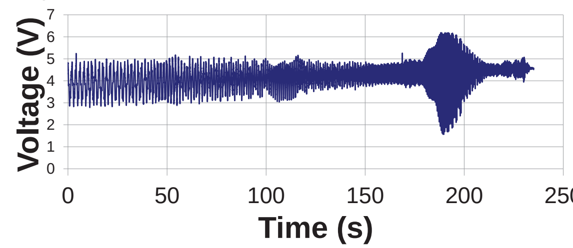
Swept Frequency Data

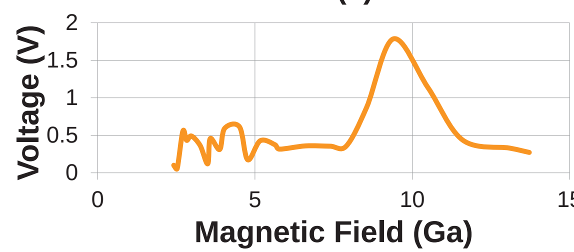
Sweeping the frequency of the inner coil with a **constant external B** resulted in resonance behavior of the neodymium magnet at certain frequencies of inner field oscillation. More specifically, when the driving frequency matched that of the Larmor frequency resonance could be visibly observed.



Swept Magnetic Field

Magnetic field sweeping, **maintaining** ω, also allowed for an impressive display of resonance behavior. The plate magnets were moved 1cm/10s.





Conclusion

Like many things in life, NMR Spectroscopy is presented to most students on a silver platter, and the actuality of what is happening is usually an afterthought; however, our relatively simple model was able to give a clear, macroscopic picture of what is happening in the mysterious technique known as NMR spectroscopy. It's really not all that complicated! The usefulness of this model does not stop here. Further research is being planned to make use of this setup in understanding Magnetic Resonance Imaging (MRI) as well as resonance in different atomic environments (with other structures). Future research will give students a more in depth vision of these chemical and medical (but inherently physical) techniques.