MAGNETIC TORQUE – "A NEW CLASSIC"

Magnetic Moments Interacting with Magnetic Fields

Magnetic Torque, Mτ1-A, is the first instrument specifically designed to provide science and engineering students with hands-on experiments that demonstrate the effects of a magnetic field on a magnetic dipole. Although every introductory physics textbook discusses the interactions of a current loop with magnetic fields, Mτ1-A is the first teaching apparatus capable of demonstrating and measuring such interactions.

Using small magnetized disks that act like magnetic dipoles, students measure phenomena that result from magnetic torque or force. They are able to determine the dipole moment of the disk in a variety of ways using fundamental E&M and mechanics principles. In addition, Mτ1-A can be used to demonstrate basic principles of magnetic resonance. These experiments are appropriate for freshman, sophomore, and even junior level instruction.

- **Measure Magnetic Moment Four Independent Ways**
  - ➢ Static Torque
  - ➢ Harmonic Oscillation
  - ➢ Precession
  - ➢ Magnetic Force
- **Gyromagnetic Ratio**
- **"Magnetic Resonance" Spin-Flip Analog**

Instruments Designed For Teaching

TEACH SPIN

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THE INSTRUMENT

All torque measurements are done on a cue ball which has a magnetized disk imbedded at its center. The handle is oriented along the direction of the magnetic moment. The ball floats on an ultra low-friction air bearing located at the center of the Helmholtz-like coils. The power supply has both a DC current source for the coils, and the electronics for a strobe light and frequency counter. The counter measures the rotational frequency of the spinning ball. A compressed air source for the bearing is also included.

Force measurements are carried out on a magnetized disc supported in a gimbal. The gimbal is suspended from a calibrated spring. The power supply can be switched so that the current in the two coils flows in opposite directions, creating a field gradient at the coils' center.

The spinning cue ball can be used to demonstrate a classical model of magnetic resonance. A millitesla uniform horizontal magnetic field, created by permanent magnets and iron shims, is added to the system. This unit is manually rotated at the Larmor precession frequency of the spinning sphere to visually demonstrate the "spin-flip" process.

THREE INDEPENDENT MEASURES OF μ

The magnetic moment of the magnetized disk imbedded at the center of the cue ball can be measured by the students in ***three independent ways using three different physics principles.***

I. Magnetic Torque Equals Gravitational Torque

This is a statics experiment. A gravitational torque is applied to the ball by a weight on an aluminum arm inserted in the ball's handle (Figure 1).

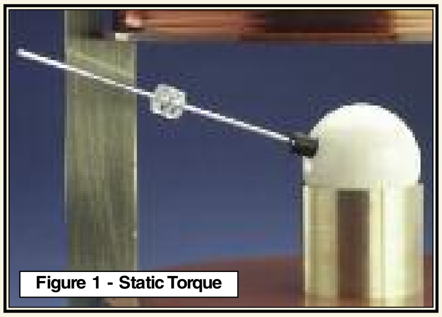

Figure 1 - Static Torque

When the magnetic torque is adjusted to equal the gravitational torque:

$$\mu \times \mathbf{B} = \mathbf{r} \times \mathbf{mg}$$

Here, r is the distance of the plastic slider mass, *m*, from the center of the ball. Since **B** and **mg** are measurable quantities, μ can be determined.

A graph of the gravitational torque, rmg, as a function of the magnetic field **B**, Figure 2, yields a straight line whose slope is the magnetic moment μ. This experiment also provides an "operational definition" of magnetic moment: a one unit magnetic moment experiences a one N-m torque in a one tesla field. Simple algebra shows N-m/tesla = amp-m^2.

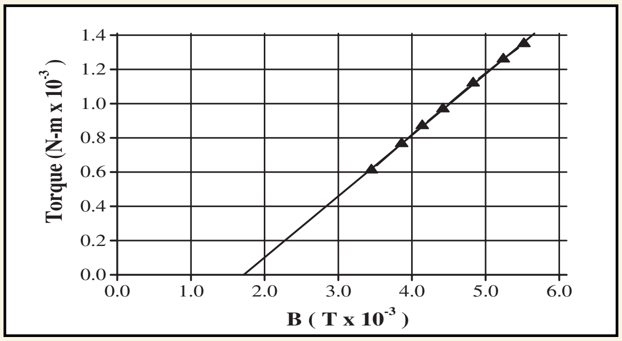

Figure 2 - Static Torque

Notice that the line does not go through (0,0) because the magnetic torque must balance the combined torque of both the mass and the aluminum arm.

II. Harmonic Oscillation

The cue ball, supported in a uniform magnetic field by the air bearing, can function as a spherical physical pendulum. Its oscillations are described by:

$$-|\mu \times \mathbf{B}| = \mathbf{I}\frac{d^2\theta}{dt^2}$$

where I is the moment of inertia and θ is the angular displacement. For small θ, the motion is simple harmonic with a period of T given by

$$T^2 = \frac{4\pi^2 I}{\mu B}$$

Sample student data is shown in Figure 3. The magnitude of the magnetic moment can be calculated from the slope of this line.

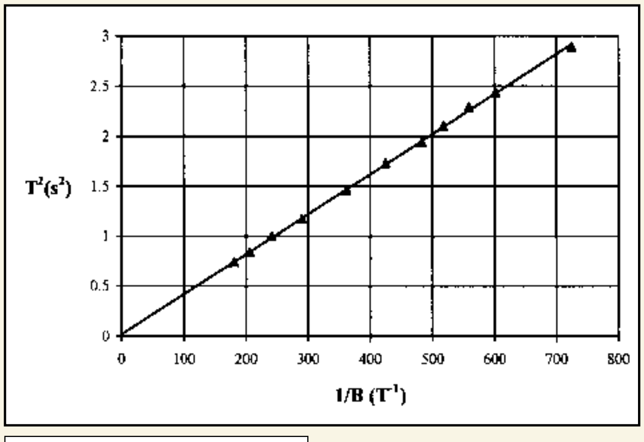

Figure 3 - Harmonic Oscillation

III. Precessional Motion

Spinning the ball gives it angular momentum L. This can be determined by measuring the ball's rotational frequency using the built-in strobe light and counter. In a uniform magnetic field **B**, the precessional motion of the spinning ball, with its "intrinsic" magnetic moment μ, is described by the differential equation:

$$\boldsymbol{\mu} \times \mathbf{B} = \frac{d\mathbf{L}}{dt}$$

The solution for the precessional frequency is:

$$\Omega_p = \frac{\mu B}{|L|}$$

One way to extract the magnetic moment from this relationship is to measure the precessional frequency as a function of magnetic field for a given angular momentum. Student data for this measurement is shown in Figure 4. The straight line behavior confirms the theory and the slope gives the third independent measurement of μ.

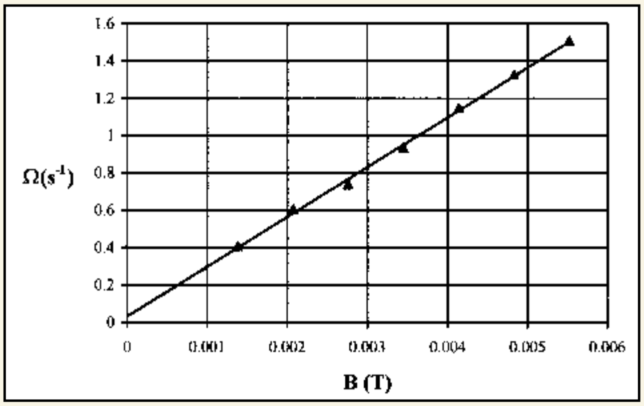

Figure 4 - Precessional Motion

GRAVITATIONAL PRECESSION

Using the short torque arm, students can observe the precessional motion of a spinning sphere due only to gravitational torque. Using the built in strobe, the dependence of precessional frequency on the sphere's angular momentum can be examined quantitatively. It is also possible to study the effect of varying gravitational torque on precessional motion by changing the location of the mass on the aluminum arm. It is even possible to study precessional motion with a combination of gravitational and magnetic torque applied.

MAGNETIC FORCE MEASUREMENTS

Magnetic force experiments are done using the plastic tower assembly shown in Figure 6. A magnet, just like the one inside the ball, is set into a gimbal (a plastic holder free to rotate) and hung from a spring. The spring can be calibrated using one gram steel spheres (provided) which will adhere to the magnet. The three main objectives of these experiments are:

A. To demonstrate that there is **no net force** on a magnetic dipole in a uniform magnetic field, only a **net torque.**
B. To recognize that there is a net force on a magnetic dipole in the presence of a **magnetic field gradient.**
C. To measure the magnetic moment of the dipole using the relation:

$$F_{magnetic} = \mu_z \frac{dB}{dz}$$

Student data for magnetic force is shown in Figure 5. The magnitude of this dipole moment will be close to those found for the dipole imbedded in the cue ball.

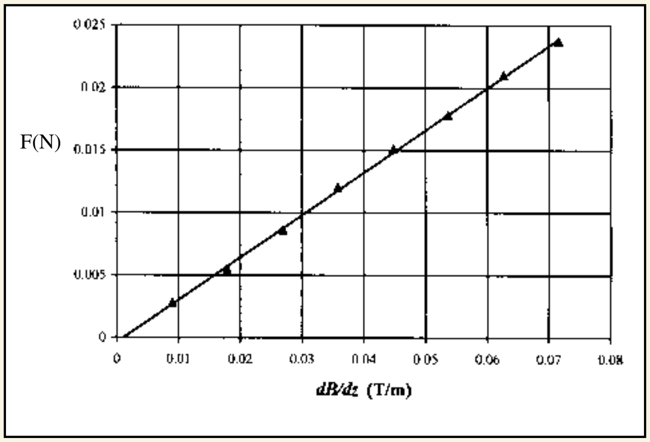

Figure 5 - Magnetic Force

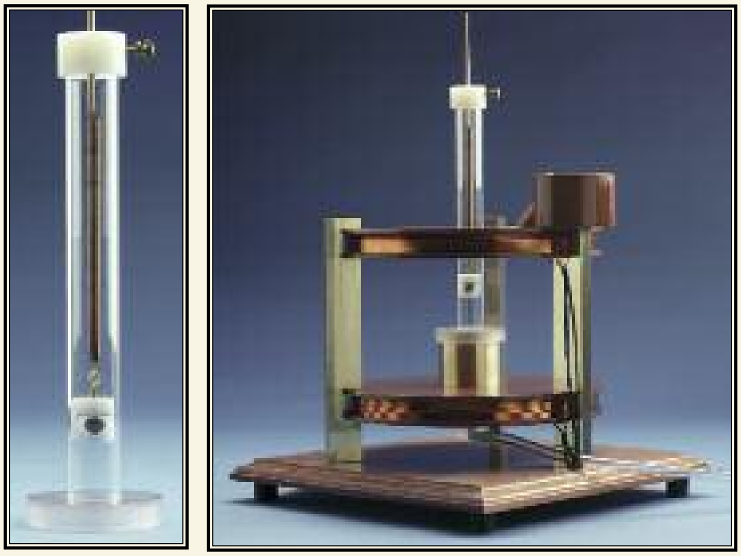

Figure 6 - Magnetic Force Apparatus with Detail of Gimbal and Calibrated Spring

A FOURTH MEASUREMENT OF μ

Another measure of the magnetic moment of the imbedded dipole can be made using a sensitive Hall-Effect Probe such as Teachspin's HE1-A.

Under the far field condition, the field of a dipole as a function of distance along its axis becomes:

$$B = \frac{\mu_o \mu}{2z^3}$$

The magnetic moment is easily calculated from a graph of B vs. $1/z^3$ as shown in Figure 7.

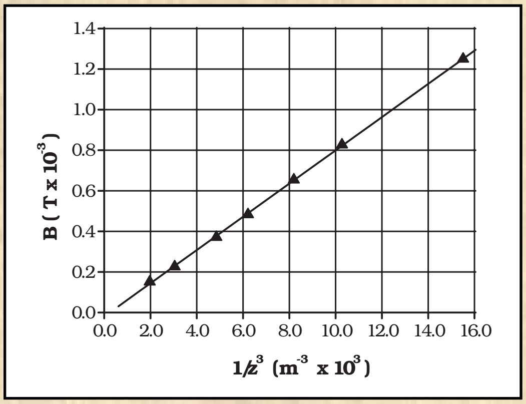

Figure 7

MAGNETIC RESONANCE ANALOG

With the addition of a horizontal, uniform, rotating magnetic field (Figure 8), the Mτ1-A becomes an instrument to demonstrate a classical analog for magnetic resonance.

Magnetic resonance is observed on atomic size particles that have both intrinsic magnetic moments and angular momentum. The spinning cue ball mimics these atomic particles. And, just like these particles, the ball's angular momentum and its "intrinsic" magnetic moment, are co-linear.

The horizontal magnetic field is manually rotated by the demonstrator at the Larmor precession frequency for the ball's angular momentum. A 90˚ or 180˚ nutation (spin-flip) can easily be produced. Given the approximate magnitude of the rotating field, students can even estimate the time necessary to nutate the cue ball by 90˚. Such demonstrations significantly enhance a student's understanding of the complexities of rotating coordinate systems, effective fields, and spin nutation that are fundamental to mastering the principles of magnetic resonance.

SPECIFICATIONS

Coils: 195 turns; #18 gauge
Inner radius 10 cm
Outer radius 11.4 cm
Separation 12.4 cm

Current: 0-4 Amps

Electromagnetic field: 0-5 mT

Magnetic Moments ≈ 0.4 A-m^2

Cue Ball: Mass ≈ 140 g
Radius ≈ 2.70 cm

Strobe Frequency: 3-9 Hertz

Spring Constant ≈ 1.0 N/m

Rotating Magnetic Field ≈ 1.4 mT

Accessory: Additional Spheres

Warranty:
Two Years, parts and labor
Extended warranty available

Patent Number 5,846,088

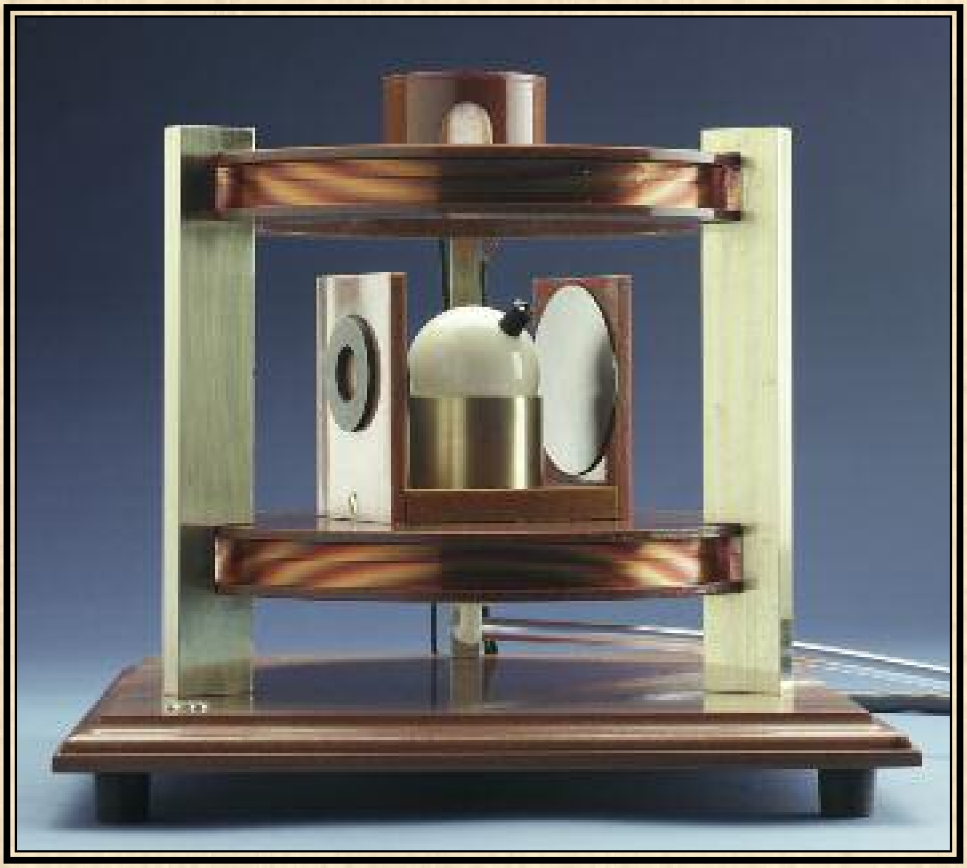

Figure 8 - Magnetic Torque with Rotating Field Attachment

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