9 Nuclear magnetic resonance (NMR) is a phenomenon which soon after its discovery in 1946 became a powerful research tool in a variety of fields from physics to chemistry and biochemistry. It is also an important medical imaging technique.

When atoms are placed in a magnetic field, atomic energy levels split into several closely spaced levels. Nuclei, such as the hydrogen nuclei, also exhibit these magnetic properties. This is useful for medical imaging. The hydrogen nucleus consists only of a single proton. A physical property of nuclei is known as the spin angular momentum. It can take on only two values when placed in a magnetic field: we call these "spin up" (parallel to the field) and "spin down" (antiparallel to the field), as illustrated in Fig. 9.1.

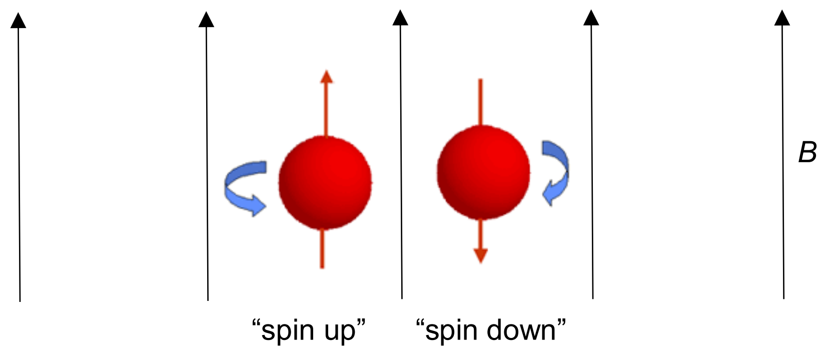

Fig. 9.1

When a magnetic field is present, the energy of the nucleus splits into two levels as shown in Fig. 9.2, with the spin up (parallel to field) having the lower energy.

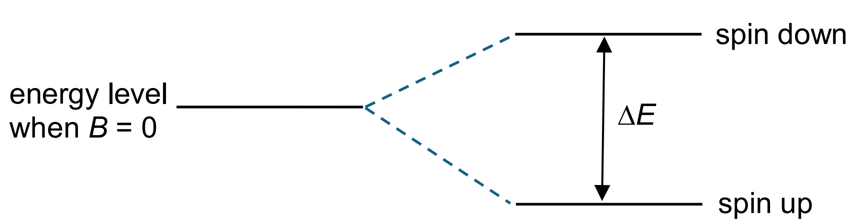

Fig. 9.2

The difference in energy ΔE between these two levels is proportional to the magnetic flux density B applied at the nucleus:

$$\Delta E = kB$$

where k is a proportionality constant that is different for different nuclides.

In a standard nuclear magnetic resonance (NMR) setup, the sample to be examined is placed in a static magnetic field. A radiofrequency (RF) pulse of electromagnetic radiation (that is, photons) is applied to the sample. If the energy of this photon matches the energy difference between the two energy levels ΔE in Fig. 9.2, then the photons of the RF beam will be absorbed, exciting many of the nuclei from the lower state to the upper state. For a free unbounded hydrogen nucleus, the frequency is 42.58 MHz for a magnetic flux density of $B = 1.00$ T.

For producing medically useful NMR images - now commonly called MRI, or magnetic resonance imaging - the element most used is hydrogen since it is the commonest element in the human body and gives the strongest NMR signals.

The experimental apparatus is shown in Fig. 9.3. The large magnetic field coils set up the static magnetic field, and the RF coils produce the RF pulse of electromagnetic waves (photons) that cause the nuclei to jump from the lower state to the upper one. Another coil detects the emitted radiation when the nuclei jump back down to the lower state.

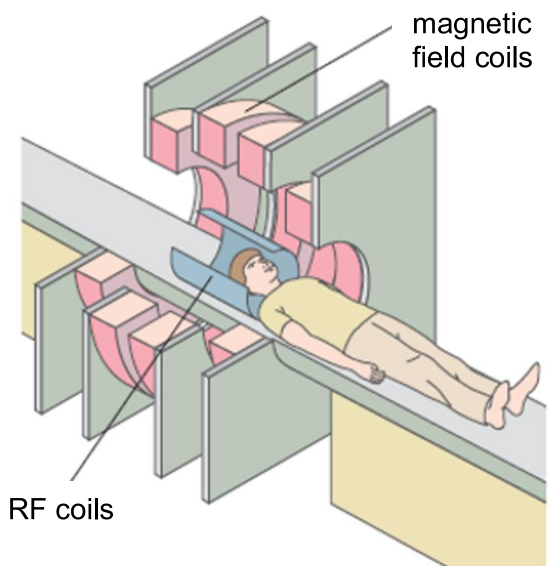

Fig. 9.3

The formation of a two-dimensional or three-dimensional image can be done using techniques similar to those for computed tomography. The simplest thing to measure for creating an image is the intensity of absorbed and or re-emitted radiation from many different points of the body, and this would be a measure of the density of Hydrogen atoms at each point.

One technique to know which part of the body an emitted photon comes from is to give the static magnetic field a gradient; that is, instead of applying a uniform magnetic field, the field is made to vary with position across the width of the sample (or patient) as shown in Fig. 9.4.

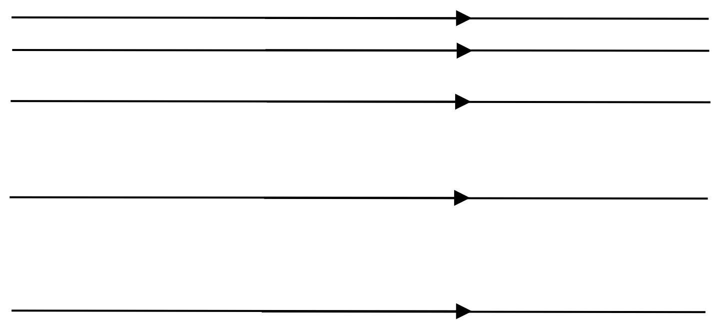

Fig. 9.4

NMR imaging is considered to be non-invasive. Since molecular bonds are in the order of 1 eV, the RF photons can cause little cellular disruption. This should be compared to X-rays, whose energies can cause significant damage. The static magnetic fields, though often as high as 1.0 to 1.5 T, are believed to be harmless except for people who wear heart pacemakers.

(a) Calculate the proportionality constant *k* for a free unbounded hydrogen nucleus in a magnetic flux density of $B = 1.00$ T.

k = ……………………… J T^{-1} [3]

(b) The variation of some values of *B*/T with RF frequency/ Hz for a free unbound hydrogen nucleus is shown in Fig. 9.4.

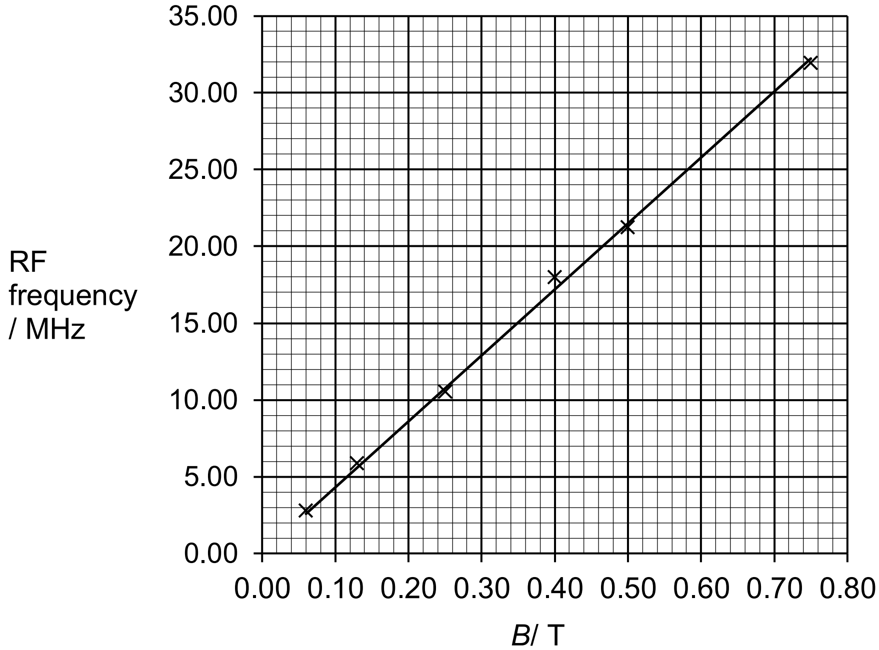

Fig. 9.4

(i) State and explain, using the features of the graph, whether RF frequency is proportional to *B*.

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…………………………………………………………………………………………… [2]

(ii) Suggest how the proportionality constant *k* for a free unbounded hydrogen nucleus can also be found using the gradient of the trend line in Fig 9.4.

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(iii) Describe which feature of the graph shows that the presence of random errors.

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…………………………………………………………………………………………… [1]

(c) Explain how a gradient magnetic field allows us to know the part of the body that is absorbing or emitting photons.

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(d) Starting by estimating the wavelength of X-rays and using information from the passage, explain quantitatively why X-rays can cause significant damage to the human body.

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(e) A rigid copper wire carrying a current is balanced on a pivot. The wire is placed within the non-uniform horizontal magnetic field as illustrated in Fig. 9.5a and Fig. 9.5b. The wire is balanced horizontally by means of a small weight W. Section RS of the wire has length 0.85 cm. The perpendicular distance of RS from the pivot is 5.6 cm.

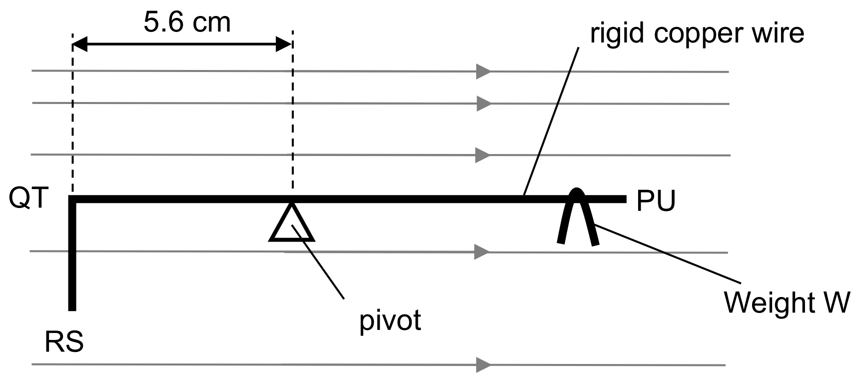

Fig. 9.5a (Side View)

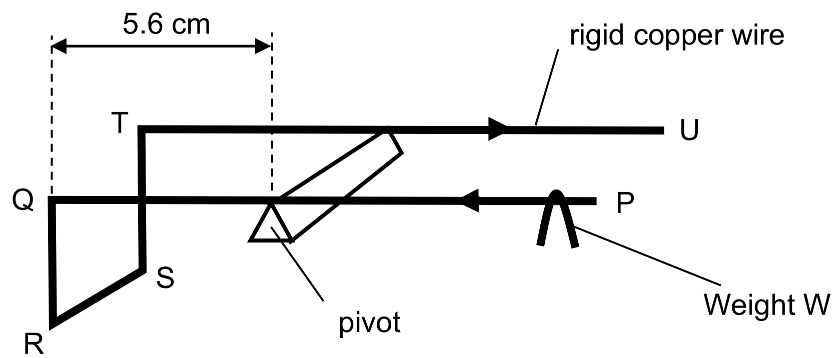

Fig. 9.5b (3D View)

(i) Explain why the following sections of the wire do not affect the equilibrium of the wire.

1. QR and TS

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.... [2]

2. QP and TU

....

.... [1]

(ii) When the current in the wire is changed by 1.2 A, W is moved a distance of 2.6 cm along the wire in order to restore equilibrium.

The mass of W is 2.5×10^{-3} kg.

Determine the magnetic flux density B of the field where RS is.

B = ... T [3]

(f) Fig. 9.6 shows the front view of the non-uniform horizontal magnetic field, with the field directed out of the plane of the paper and magnetic flux density increasing in the vertical direction.

region of magnetic field directed out the plane of the paper

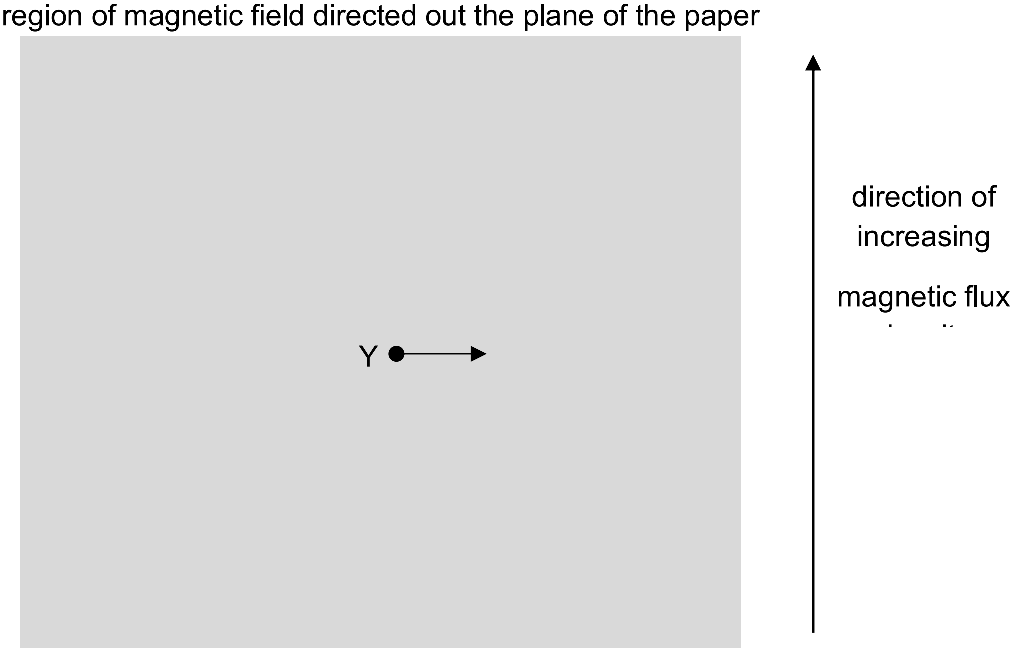

Fig. 9.6 (Front View)

An electron is travelling to the right at point Y. Assuming that the electron undergoes at least one cycle in the field, sketch a possible path of the electron in Fig 9.6. Show the direction of motion clearly.

[2]

[Total: 20]

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