THE JULY LECTURES IN PHYSICS – 1993

MICROSCOPY WITH PROTONS – NEW WAYS OF SEEING

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This lecture aims to explore new ways of examing very small objects using the scattering of subatomic particles such as protons, or alpha particles. The techniques for doing this new way of seeing have become known as 'nuclear microscopy' and the School of Physics at the University of Melbourne is one of the leaders in the field in applying this powerful new form of microscopy to a wide range of interesting problems.

Before a discussion of nuclear microscopy, and the scattering of protons in matter, it is first necessary to look at the scattering processes involved in ordinary seeing.

Scattering

Scattering is the way we see things. Light scatters from surfaces and enters our eyes. The focusing surfaces of the eye reconstruct an image of the object on our retina. During the scattering process, the surface of the object may alter the scattered light by absorbing a particular colour and reflecting others which we interpret as the colour of the object. In some situations it is helpful to think of the scattering process as that of particles of light, called photons, bouncing off the object into our eyes.

A close look at the scattering process, in particular phenomena associated with the scattering of light from very small objects, shows that each photon can act like a tiny wave. In fact the colour of the light that we perceive is related to its wavelength. For example green light has a wavelength of about 560 nm (1 nm = 10^{-9} m or one billionth of a metre).

The scattering process can be written as:

$$object(\gamma, \gamma)object$$

which means 'photon (γ) in', 'photon out'. We should also pay attention to the directions of the incident photon and the scattered photon since these will be strongly influenced by the properties of the object. A mirror reflects all incident light so that the reflected angle is the same as the incident angle. Clearly the scattering process is a strong function of the *scattering angle*. Most objects scatter light in all directions.

We can generalise the scattering process to include any sort of incident radiation, not just light, and any sort of scattered radiation which may not necessarily be the same as the incident radiation. In the general case we can write the scattering process as:

$$object(p, p')object$$

where p stands for any particle and p' is the scattered particle, which may be the same as p. The number of scattered particles can then be written:

$$Y(\theta) = \sigma(\theta) \cdot \Omega \cdot Q \cdot N_s$$

Scattering of light from a mirror and an ordinary object.

where $Y(\theta)$ is the yield of particles at a particular scattering angle θ, Ω is the size of the detector used to detect the scattered particles (for example the diameter of the pupil of your eye at your viewing distance), Q is the number of incident particles on the object, N_s is the number of things on the surface of the object that do the scattering per unit area and $\sigma(\theta)$, with units of area, is the *scattering cross section.* $\sigma(\theta)$ contains all the physics of the scattering process. For some simple scattering situations it is possible to calculate $\sigma(\theta)$ from first principles. We shall see the important role $\sigma(\theta)$ plays in imaging in the discussion to follow.

Small Objects

When looking at an object, the amount of light scattered into your eye depends on the the amount of light arriving at the surface of the object before scattering, the surface properties of the object that determines how reflective it is and any properties of the surface that may cause it to reflect light in a preferential direction (such as the case with a mirror). This is all described by the form of the scattering cross section, $\sigma(\theta)$. A problem with looking at small objects is that they reflect little light from their small surface, and it is usually not possible to get them close enough to your eye to make the image on your retina big enough to clearly see what is going on. Most people cannot bring objects closer than about 15 cm, called the *near point*, into focus. A microscope can help here.

Optical Microscopy

An ordinary microscope works by providing the eye with a image of the object that is enlarged and appears to be further away than the actual object. As far as the eye is concerned, it is just looking at a big object. The microscope is also fitted with an extra lens, called a condenser lens, to focus a bright light onto the sample to compensate for the fact that the surface of the object is very small.

Most of the magnification of the image is done by the *objective lens* which has a short focal length and forms a large image of the object. The linear magnification, M_l, of a lens is given by:

$$M_l = s_i/s_o$$

where s_o and s_i are the object and image distances from the lens. These are related by the thin lens formula:

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

where f is the focal length of the lens. In a microscope the object is placed very close to the focal point of the objective lens which means that the image distance, and hence M_l, is large. The real image formed by the objective lens is then imaged in turn by another lens, called the *eyepiece*, to make a virtual image which we can see.

So it would seem to look at ever smaller objects, it is only necessary to increase the magnification. Unfortunately, when you seek to zoom in on features of the object that are small by using objective lenses of shorter focal lengths and larger magnification, new effects start to degrade the image.

So far, this discussion has treated light as if it were small particles that bounce off surfaces. In our everyday life the fact that light can also behave like a wave is not important, since most of the things we have to look at are much, much bigger than the wavelength of the light that bounces off them. This is not the case when we start looking at things that are very small. Small in this context means as small as the wavelength of the light, or smaller.

When light scatters from things which are very small, the scattering process is very complicated owing to the effects of diffraction. If the object doing the scattering has an irregular shape and is very small, it is usually not possible to see it with light, because all the diffraction effects turn any image into a mush of overlapping diffraction patterns.

It is possible to do a little better by using only light of the shortest visible wavelength (blue). But to really make progress it is necessary to use radiation with even shorter wavelengths. In principle it is possible to make use of invisible ultra–violet light, or even x–rays. But these types of radiation are difficult to focus. Instead, an entirely different type of radiation has been used: electrons.

Electron Microscope

In an electron microscope, electrons replace light and magnets replace glass lenses. A beam of electrons boiled from a hot filament is first accelerated up to high speed, then passed through a magnetic lens that acts in the same way as the condenser lens in a light microscope. The condenser lens focuses as many electrons as possible onto the specimen. The specimen then scatters the electrons:

$$object(e, e)object$$

In a common sort of electron microscope the electrons pass entirely through the specimen as they are scattered by it. This is a Transmission Electron Microscope (TEM). The scattered electrons are captured by a special magnetic lens called the objective lens. This lens is special because it is made to very high precision and its purpose is to refocus a greatly enlarged image of the scattered electrons, just like the objective lens in a light microscope. After one or two further magnetic lenses, called projector lenses, the electron beam is focused onto a scintillating screen so that the invisible electron image can be converted into a light image to be seen.

The electron microscope can focus images of very tiny objects, indeed even single rows of atoms. This is possible because the electron wavelength can be made very small. Indeed the electron wavelength, λ is related to its energy, E, by the deBroglie formula. For non–

An optical microscope An electron microscope.

From: 'Electron optics and the electron microscope', V.K. Zworykin, et al., Wiley, New York, 1945.

relativistic electrons this is:

$$\lambda = h/\sqrt{2mE}$$

A short electron wavelength for imaging small objects requires a high energy electron. This means that the electron microscopes able to image the smallest objects are the biggest, mainly because of the very large accelerating column necessary to accelerate the electrons up to very high energies.

Both electron and light microscopes take advantage of the very large scattering cross sections, $\sigma(\theta)$, for electron and light scattering. This means a good quality image can be obtained in real time, it is possible to view the specimen directly. Later we will encounter scattering processes where $\sigma(\theta)$ is small so it is necessary to wait while the image accumulates.

Another thing that both electron and light microscopes have in common is that they both focus the scattered particles *after* the scattering process has occurred.

Beyond Imaging – Nuclear Microscopy

You might wonder what more could possibly be required of a microscope beyond the ability to image single atoms. The answer is the ability to perform *analysis* of the composition of the specimen from tiny areas, or the ability to look *beneath the surface* at hidden features. These abilities go beyond what is possible with a simple imaging microscope. It is these difficult tasks that are performed by *nuclear microscopy*.

Nuclear microscopy makes use of beams of high energy subatomic particles, typically protons, to form images and perform analysis. The particles typically have millions of electron–volts (MeV) of kinetic energy. This means that they are travelling at around 10 % of the speed of light. These particles can be produced by a Van de Graaf accelerator which is nothing more than a large potential difference across which positively charged particles, called ions, are accelerated. The ions are generated from a gas plasma. A hydrogen plasma produces protons, a helium plasma produces alpha particles. The machine in Melbourne is called a Pelletron and can reach up to 5 million volts. We shall discuss protons in what follows, but exactly the same principles also apply to alpha particles.

Because of the unique attributes of the scattering of MeV protons from matter, a rich variety of images can be made. Before an explanation of how this imaging is accomplished, it is necessary to review what happens when a fast proton scatters from matter.

When a fast proton enters a lump of matter it produces a large number of effects. The most important of these are:

1) The protons can bounce off the nuclei in the atoms of the matter and recoil back out:

$$object(p,p)object$$

2) Various types of radiation can be produced, including x–rays or even visible light:

$$object(p,\gamma)object$$

We now have the possibility of making an image by a very different method to either optical or electron microscopy. The unique and useful features of these images arise from the fact that the scattering process is very well understood, allowing precise analytical information to be obtained about the composition and structure of a wide variety of specimens. The information often cannot be obtained any other way. Some useful examples are discussed below.

One important difference between the scattering of protons to light or electrons is that the scattering cross sections are much smaller. This usually means that images have to be accumulated over a short period of time until features in the specimen can be identified. The cross sections are small because the protons interact with with small parts of the atom, rather the whole lump of matter at once as is often the case with light and electrons. Thanks to the fact that the scattering process is a results of the electrostatic force from the point–like nucleus, the scattering cross section, $\sigma(\theta)$, is easy to calculate. This is unlike the much more complicated situation for light or electrons where the scattering process is in interaction with the entire atom.

The problem now is to use the scattered protons or induced radiation to generate images.

Scanning

In an optical or electron microscope, the scattered particles were the same as the incident particles. In nuclear microscopy the scattered particle is generally not the same! It is a particle produced by atoms in the specimen as a result of the particle bombardment. To generate images with these new particles a new approach is required. Instead of focusing the scattered particles *after* the specimen, the incident particles are focused *before* the specimen.

A small, intense spot, called a probe, is focused onto the region of interest of the specimen. The radiation produced in the specimen is then picked up by a suitable detector. The image is produced by scanning the probe over the region of interest on the specimen and arranging for the intensity of the radiation produced at each place to be used to generate an image. The image is now a *map* of the strength of the relevant radiation as a function of position.

A scanning MeV ion microprobe. Pelletron accelerator: (A–G) components of the ion source, (H–I) acceleration sections (5 MeV potential difference). Energy analysing 90° bending magnet: (J,L) slits, (K) magnet. MeV ion microprobe beamline: (N–Q) object diaphragm, (R,Z) vacuum pumps, (S–U) aperture diaphragm, (V) probe forming lens system, (W) cryogenic x-ray detector, (X) magnetic scanning coils, (Y) specimen chamber. (S1, G1) beamline supports. Inset above: the connections between the computer and the scanning coils and detectors.

In practice the scanning is accomplished by a special set of magnetic scan coils which move the beam in a raster pattern over the region of interest on the specimen. This raster pattern can be just like the raster pattern of an electron beam scanning over the front of a TV tube. A computer can be used to generate the scan pattern whilst simultaneously recording the intensity of radiation being picked up by the detector at each point. The computer then uses this information to produce images. A different type of electron microscope to the TEM, called the Scanning Electron Microscope (SEM) works in the same way.

The instruments used to generate images using the MeV protons is collectively known as a *MeV ion microprobe.*

Probe Forming Lens System and Ion Optics

Although the concept of the MeV ion microprobe is relatively simple, it is very difficult to put into practice. The major difficulty lies with the magnetic lenses required to focus the energetic protons into a small probe. In an electron microscope, magnetic solenoid lenses are used with the electron beam passing along the axis of the solenoid. Solenoids are circularly symmetric and relatively easy to make to high precision. However in a solenoid, the magnetic field is parallel to the axis and hence has no effect on the beam. This is because the magnetic field lines, $\vec{B}$, are parallel to the velocity vector, $\vec{v}$, of the beam and the magnetic force is therefore zero:

$$\vec{F} = z\vec{v} \times \vec{B}$$

In this equation, z is the charge on a beam particle and $\times$ designates a vector cross product.

The part of the field responsible for focusing the beam is the fringe field at each end of the solenoid. For this reason solenoid lenses are generally too weak for focusing energetic protons. Remember that protons are 2000 times heavier than electrons, but with the same magnitude of charge!

Instead it is necessary to use *quadrupole* lenses. In quadrupole lenses, all of the magnetic field lines point at right angles to the proton trajectories, hence the full field, not just the fringe field, is employed to focus the beam.

Proton beam particle's view of a magnetic quadrupole lens showing magnetic field lines and force vectors shown as small arrows labeled 1–5. *From 'Beam optics of Quadrupole Probe-forming Systems', G.W. Grime and F. Watt, Adam–Hilger, Bristol, (1984).*

It is desirable to focus the energetic protons into a 1 micrometer diameter probe (1 micrometer

= 10^{-6} m) so that many interesting specimens can be examined. However is is very difficult to manufacture the complicated quadrupole shape to a sufficient degree of precision. If the magnetic field departs from ideal four–fold symmetry, perhaps due to mechanical defects, aberrations prevent the proton beam from being focused into a 1 micrometre probe. For the Melbourne system, the lenses have been specially made and several exotic machining techniques have been employed, including computer controlled wire plasma cutting that can produce the required hyperbolic pole profiles to an accuracy of 2 micrometres.

Furthermore, a single magnetic quadrupole lens acts on the proton beam in quite a peculiar way: as can be seen from the diagram of the magnetic field, the lens squeezes the beam in the vertical plane and expands it in the horizontal plane. Consequently more than one quadrupole lens is necessary to focus the beam to a fine probe. If this was not enough, quadrupole lenses suffer from relatively large spherical aberration. This is the aberration that causes rays (or proton trajectories) which enter the lens a long way off axis to be bent too much compared to rays which pass near the lens axis. The aberration pattern of a system of quadrupole lenses is complicated, but it is possible to minimise its effect by several strategies, such as limiting how far off axis the protons can go inside the lenses.

With a carefully crafted magnetic lens system it is possible to focus the proton beam from the Pelletron accelerator into a probe 1 micrometre in diameter. This is done by using the probe forming lens system with a long object distance, s_o, and a short image distance, s_i, to produce a greatly demagnified image (the probe) of the source of protons. The probe forming lens system is therefore just like an objective lens in reverse.

We can now turn to discuss each type of radiation produced by the proton probe when it interacts with the atoms in a specimen.

1. Particle Induced X–ray Emission.

One of the most important of effects of the proton bombardment is the production of x–rays. This occurs when a proton collides with an inner shell electron of an atom, knocking it clear our of the atom. The resulting vacancy in the electron cloud of an atom is then filled by a cascade of electrons from the higher levels. During the cascade, the energy difference between the higher level and the vacant level is radiated as x–rays. As the inner electron shell is very close to the nucleus of the atom, the charge of the nucleus has a very big influence on the energy of the radiated x–rays. Indeed, each element, differing in the number of protons in the nucleus and hence the nuclear charge, produces its own characteristic x–ray wavelength. This fact was discovered by H.G.J. Moseley who formulated the law relating the x–ray frequency, ν, and hence energy, $E = h\nu$, to the nuclear charge, Z:

$$\nu \propto Z^2$$

Moseley made this discovery in 1913 at the age of 26. Shortly after this, in 1915, he was killed in action at Suvla Bay during World War 1.

One of the best things about the production of x–rays with a proton beam is that a great many x–rays are produced as the specimen is scanned. Loosely speaking, this is because the speed of the MeV proton closely matches that of an inner shell electron as it speeds in its orbit around the nucleus. This maximises the probability of an interaction.

Thanks also to the fact that each element has its own characteristic x–ray energy, it is possible to make image of the specimens as if just one element of interest was present, even if that element is present in only trace amounts. This has important applications in microelectronics, where intricate structures composed of different metals have to be accurately examined for processing errors to ensure devices to work properly. It is also useful in the study of cells from living organisms where trace elements play an important role in many vital biological functions.

A proton induced x–ray spectrum of a superconductor crystal with the major element x–ray lines identified.

It is possible to utilise this type of imaging in scanning electron microscopes, but not to anything like the same sensitivity. This is because electrons suffer from the unfortunate property that they strongly radiate large numbers of x–rays whenever thet are perturbed from a straight path, such as when they scatter from a specimen. These x–rays, called *bremstrahlung radiation*, has exactly the same range of energy as the characteristic x–rays from the trace elements in the specimen. The weak signal from the trace elements is swamped by the much stronger signal from the bremstrahlung. MeV ions produce negligible amounts of bremstrahlung as they scatter in the specimen, so the weak signal from the trace elements is not obscured. With proton induced x–rays, trace elements present with concentrations as little as a few parts per million can be imaged.

2. Particle Backscattering.

It is a unique property of energetic protons that they can penetrate deeply into a specimen before encountering a nucleus from which they can scatter and perhaps recoil back out of the specimen. This is not surprising given that atoms consist of a tiny, dense nucleus surrounded by a diffuse cloud of electrons. Indeed an atom has been likened to a dust mote (the nucleus) floating in a cathedral (the electron cloud). The electron cloud is too diffuse to have much effect on the incoming ions, but it does cause them to slow down a little.

Dramatic things happen if an incoming proton scores a direct hit on a nucleus. The Coulomb repulsion force, F, between the positive ion, charge z, and the positive nucleus, charge Z, acts like a powerful spring that can cause the ion to bounce off the nucleus:

$$F = \frac{zZ}{4\pi\epsilon_0 r^2}$$

Here ϵ_0 is the permittivity of the vacuum (a constant) and r is the distance between the ion and the nucleus.

Indeed, the ion can can bounce back out of the specimen, but not with the same energy as it had originally. This is because the nucleus recoils a little, carrying off some of the original ion energy. The amount of energy carried off by the backscattered proton depends on the relative mass of the proton and nucleus. If the nucleus is only slightly heavier than the proton, it recoils a lot and carries of a lot of energy. If the nucleus is very heavy compared to the proton, it does not recoil very much and so does not carry off much energy. The amount of energy, E_1, the scattered proton has left when it backscatters out of the specimen depends on its mass, m, the mass of the nucleus, M, and the scattering angle, θ:

$$\frac{E_1}{E_0} = \left[\frac{(M^2 - m^2 \sin^2 \theta)^{1/2} + m \cos \theta}{M + m}\right]^2$$

where E_0 is the original energy of the proton before scattering. When nuclei in the specimen are towards the low end of the periodic table it is easy to distinguish them on the basis of the differences between the energies of the scattered protons. However, when the nuclei in the specimen are from the high end of the periodic table, it makes little difference to the energy of the scattered protons. The net result of these processes is that it is often possible to determine the mass of the atoms in the specimen from the energy of the backscattered particles.

In the same way a cricket ball bouncing off a small Volkswagon or a big Mercedes will return with its original energy, but bouncing off a batsman's head will return with just a trickle of energy owing to the significant recoil of the head!

It was Ernest Rutherford, studying scattering of alpha particles from gold nuclei, who worked out the scattering cross section for this process:

$$\sigma(\theta) = \left(\frac{zZ}{4E}\right)^2 \frac{1}{\sin^4 \theta/2}$$

This simplified formula, which ignores the fact that the nucleaus recoils, shows that most particles scatter in the forward direction ($\theta \approx 0°$, the nucleus gets in the way for $\theta = 0°$), but quite a few recoil at $\theta = 180°$ where they come out of the target and can be detected.

Later experiments of higher energy ions (both alpha particles and protons) scattering from light nuclei showed Rutherford's equation broke down. In this case the Coulomb repulsive force is unable to prevent the fast ion from penetrating into the nucleus. When this happens, a new force begins to dominate the interaction. This is known as the *strong nuclear force*. The scattering process then becomes very complicated and it is not possible to write down a simple formula for the scattering cross section like the Rutherford law.

However, scattering processes where the strong nuclear force is influential are advantageous for imaging purposes. This is because the yield of particles which recoil out of the specimen is greatly enhanced. Since these are the only particles we can detect, this allows us to make images in less time.

A further extremely useful attribute of the scattering of protons is that they can penetrate deeply into the specimen before scattering back out and into the detector. On both the inward and outward path they loose energy. Accordingly, a plot of the yield of backscattered protons as a function of their detected energy provides both an analysis of the mass of the atoms in the target *and* a depth profile of the elemental composition! Interpretation of the resulting plot, The spectrum of backscattered particles from a superconductor crystal with the recoil energies from each element identified.

called an *energy spectrum* can be confusing because the depth profiles of the light elements in the specimen overlap with those from the heavier elements. However powerful computer programs are available to help with the interpretation.

It is typically possible to depth profile elements down to about 10 micrometres below the surface, or to image buried features at this depth. This may not seem like very much, but it is typical of the scale of biological specimens or of multilayer structures in integrated circuits.

One of the earliest applications of this technique was to the analysis of the surface composition of the moon. The robotic Surveyor spacecraft were equipped with radioactive sources that bombarded the moon with alpha particles. A detector then produced an energy spectrum of the backscattered particles from which the composition of the surface of the moon could be determined.

3. Light Output.

As the protons penetrate into the specimen, they can knock out outer shell electrons and electrons in chemical bonds. The vacancies created then refill with electrons that radiate surplus energy as visible light. This light can also be detected and used to produce images. However, quantitative interpretation of the signals is not as straight forward as for the more energetic processes already discussed. This is because the outer shell electrons and bond electrons are remote from the influence of the nucleus. Their behaviour depends more on their local environment, and, being typically easily disturbed, the sample temperature has a strong influence.

Some characteristic colours of the light produced are always associated with certain crystals. For example, diamonds glow a bright blue, glass is white, sapphire is pink, the mineral willemite is brilliant green and magnesium oxide crystals are red.

4. Channeling.

One of the most interesting and useful scattering processes is what happens when a proton interacts with a specimen that is a crystal. In a crystal, all atoms sit on regular lattice sites. Therefore it is possible to line up the crystal so that all atoms in the bulk of the specimen

The shadow of a square lattice of ball bearings in a spherical volume simulated with the computer program *Rayshade*. This is a good model for what happens when protons channel through crystal lattices of atoms.

are hidden behind the atoms on the surface. Recall that the atoms are mostly empty space as far as the protons are concerned, so apart from a few protons that may recoil from the surface of the crystal, nearly all of the protons see the crystal as a vacuum! Consequently, they pass deep into the crystal without scattering from any atoms with the result that the backscattered yield of particles is dramatically reduced.

Indeed this reduction in the yield of backscattered protons for a crystal aligned with the beam compared to a crystal randomly oriented to the beam is a very useful measure of the quality of the crystal. Any defects, which are atoms not located on lattice sites, will show up as a strong signal in the backscattered proton intensity. Also, any foreign atoms introduced into the crystals, such as the dopants used to make silicon either p–type or n–type, can have their location determined. In a microelectronic application, the dopant atoms must reside on lattice sites for the dopant to be effective. Any foreign atoms that do not reside on lattice sites produce a strong backscattered proton signal even when the crystal is aligned with the beam.

All these processes taken together go to make up the technique of nuclear microscopy. We can now turn to a discussion of some applications of this powerful analytical technique.

Elemental maps of a human red blood cell from the proton induced x–ray emission (P, S, Cl, K and Fe) and the yield of backscattered protons (H and C). Each image is 10 μm wide. *From a publication of the Melbourne proton microprobe group.*

Applications.

Medicine.

In human red blood cells, the oxygen is carried throughout the body attached to complicated molecules containing iron. Many other types of blood cell exist and some of these can be hard to tell apart. Also, the cells can change in composition as they age. Nuclear microscopy can be used to image the elemental composition of red blood cells, even though elements like iron are present in trace amounts. This is particularly challenging considering that the average red blood cell looks like a tiny doughnut only 10 micrometres across! The elemental composition is useful in tracing the growth of different types of blood cell.

The study of the processes involved in the formation of defective regions of the brain in people suffering from Alzheimer's disease has been an important application of nuclear microscopy. Some recent results have conclusively shown that elevated levels of the element aluminium is **not** associated with the defective regions of the brain known as plaque cores. Instead silicon appears to play an important role. Once again, both proton induced x–rays and proton backscattering imaging were essential for this work.

Photomicrograph of an area of Alzheimer's disease brain tissue showing a Core Containing Plaque (CCP) and a Diffuse Plaque (DP). A proton backscattering image, 100 μm wide, of the CCP is also shown. *From the D.Phil. thesis of J. Landsberg of the Oxford Scanning Proton Microprobe Unit.*

Photodetectors

One of the most important applications of nuclear microscopy is to the study of materials for microelectronic applications. Over the past two years in Melbourne, extensive studies have been performed on materials used to fabricate infrared (IR) detectors for optical fibre communication systems. The detector devices consist of small rectangular crystals of the IR sensitive material, HgCdTe, connected by strips of gold to other electronic circuitry. Nuclear microscopy can be used to image each of the components of these tiny devices, often only a few tens of micrometres in size. An important result showed that one of the metal layers in the devices was not buried at the correct depth, which would lead to premature device failure. This result was possible even though the defective layer was buried several micrometres below the surface. Other results have shown lines of defective crystal within the photosensitive material that could cause noise on the signals being detected. This information could lead to more reliable devices.

Diamonds

A potentially excellent material for semiconductor devices is diamond. However, diamond–based semiconductor devices have proved to be an elusive goal, mainly because of the difficul-

Images 150 micrometres wide of IR detectors and Au wiring in a device fabricated at the Telecom Research Laboratories, Melbourne. *From a joint publication of the Telecom and Melbourne groups.*

ties of producing n–type diamond. The Melbourne group has devised a method of implanting potential dopants into diamond by shooting them into the diamond at high speed. This has the unfortunate problem of causing a lot of damage to the diamond crystal lattice, so a focused laser beam is used to repair the damage. Images of the laser repaired regions show that the diamond has returned to good crystal in these regions, since the protons are able to channel well into the crystal. Information is now being sought on the lattice location of the dopant atoms, since it is hoped that these have been pushed onto lattice sites of the diamond during the regrowth of the crystal.

Pyrite

Images of inclusions in pyrite crystals from backscattered protons and Si x–rays. *From a joint publication of the Melbourne group and the CSIRO Division of Exploration Geoscience.*

In naturally occurring pyrite crystals, the lattice location, or otherwise, of impurities can provide valuable information on mineral formation mechanisms. In pyrite, as all natural crystals, a microprobe is almost essential for performing analysis owing either to the small crystal size, or to the inevitable profusion of inclusions and imperfections. Some pyrite crystals contain valuable amounts of gold. Nuclear microscopy with alpha particle backscattering revealed

Laser repaired, radiation damaged diamond imaged by nuclear microscopy with proton backscattering from a crystal aligned with the proton beam. (a) Three laser repaired spots (the diamond goes white in the optical image, dark in the Channeling Contrast (Nuclear) Microscopy (CCM) image when it has been repaired), (b) Buried graphite spot formation (bad crystal) and (c) Complete ablation of the damaged layer. *From a publication of the Melbourne microprobe group.*

that about half of this gold was located on lattice sites of the pyrite crystals, suggesting it is chemically bound to the lattice and as therefore present when the pyrite ore originally crystallised. Here a large number of elongated $FeSiO_4$ inclusions were also observed, which have the peculiar property that they appear to be preferentially aligned with the edges of the crystals. The reason for this is unknown.

In all of these examples the full range of proton scattering processes have been employed to obtain useful results for medicine, industry and basic science research. All of the physics involved in these processes was the subject of intensive activity at the frontiers of nuclear physics research only a few years ago. I am sure some of the early nuclear physicists would be very surprised at the uses that have been found for what originally must have seemed like very esoteric research. I hope that in this brief lecture I have been able to convey to you some of the richness available from nuclear microscopy with protons, a new way of seeing.