Material analysis with ion beams

Ion-beam analysis, with its prime asset that the energetic projectile ions interact only with target nuclei, has provided quantitative information in many diverse investigations.

James F. Ziegler

All methods of material analysis by target stimulation, whether by photons, electrons or ions, yield a mixture of quantitative and qualitative information. Those techniques that give quantitative information are usually weak on qualitative chemical-binding information, because they are insensitive to the complex perturbations of the outer-shell binding electrons. Energetic ion beams, which interact only with target nuclei, are usually very quantitative and provide no binding information at all. This aspect of ion-beam analysis is its prime asset.

The use of these energetic ion beams for analysis[1] has expanded rapidly during the last decade, largely because of the development of high-resolution semiconductor detectors and improved data-processing equipment. Ion-beam analysis can be used for such problems as the protein content of grain, the poisoning of chemical catalysts and the measurement of material porosity. Since 1965, eight major conferences have been devoted to evaluating material-analysis techniques that involve energetic-ion bombardment.[2-5] By now, the use of ion accelerators for purposes other than nuclear-physics research has expanded to the point where "other uses" are the most typical. There are about as many accelerators in industry as in universities, and the bulk of new accelerator purchases appears to be for applied purposes.

We can consider material analysis with ion beams as consisting of three major types of experiments: nuclear-reaction studies can detect and provide concentration-versus-depth profiles of special elemental isotopes—particularly those of low atomic number—in complex matrices. This technique is the only known nondestructive way to obtain concentration profiles of hydrogen and helium in metals, for example. In nuclear-backscattering studies, one detects the backscattered incident ions in order to determine, in a nondestructive way, the depth profiles of elements near the target surface. This technique is widely used for analysis of semiconductor device problems. Ion-induced x rays are quantitative and sensitive, as is required in such problems as the analysis of particulate matter in air pollution, or for analysis of targets at atmospheric pressure (nonvacuum analysis, see figure 1).

We shall describe these three general categories in detail, and will show several applications of each. Other types of ion-beam analysis—such as detection of electron emission, of optical-photon emission, or any techniques that use ion beams primarily for sputtering—will not be considered.

Nuclear reactions as probes

Nuclear reactions are used when the analysis is concentrated on a single element. The specific nuclear reaction selected is primarily chosen because the incident ion energy is within the energy range of accessible accelerators; the ion reacts with few other elements, minimizing interferences; the cross-section is accurately known; and the reaction can be used to determine a depth profile.

In many analytic problems, the desired information is a quantitative depth profile of a given element in the target. With nuclear reactions, depth information can be obtained in two ways. If we use a very sharp resonance, by raising the incident ion energy in steps we can make this resonance occur progressively deeper in the target: The ions slow down, reach resonance energy and sample the target elements in narrow depth layers. This technique is limited in detection sensitivity by the size of the nuclear resonance cross section; the accuracy of the depth distribution is limited by one's knowledge of the projectile's energy loss in the target. A second profiling technique is to produce an experimental geometry (arrangement of beam axis, target surface and detector position) that causes the instantaneous energy of all the particles of one type produced by the nuclear reaction to be equal, independent of the depth at which they are produced (see figure 2). The product particle is then slowed as it travels to the target surface, so that the final energy of the particle as it emerges from the target surface will indicate (by its energy loss) how deep in the target the nuclear reaction occurred. This type of experiment then measures a complete depth profile with the incident beam at a single fixed energy. It has been used in the profiling of H^2 or He^3 in metals as indicated in figure 2.

Measuring hydrogen in materials is very important because hydrogen can diffuse into most metals at room temperature, and such phenomena as "hydrogen embrittlement" of steel are well known. Until recently no analytic techniques existed for profiling the hydrogen concentration in materials. Several nu-

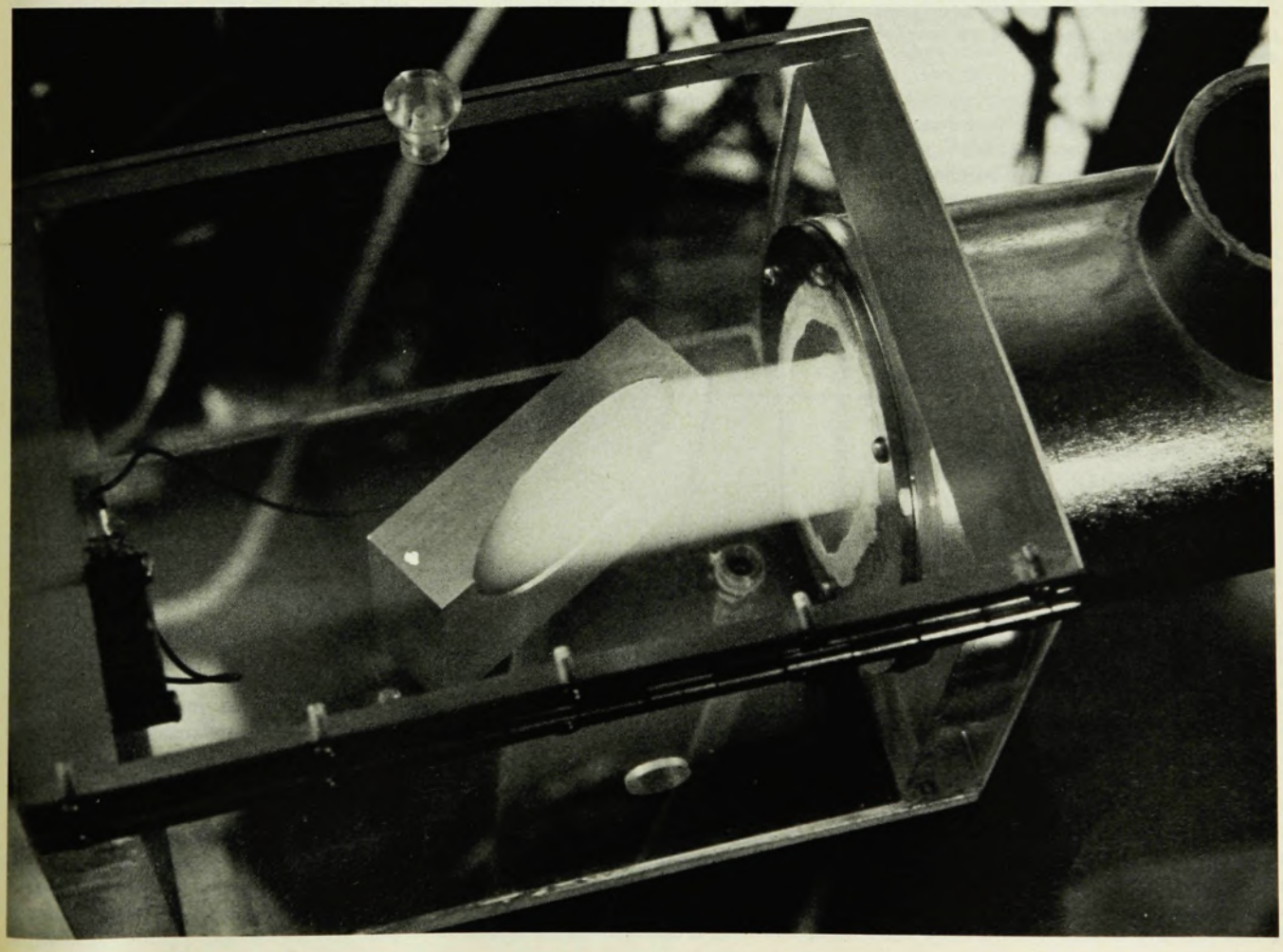
In this nonvacuum analysis technique a beam of 2-MeV protons flood a silicon crystal wafer 2.25 inches in diameter, a typical size in transistor manufacture. From the proton-induced x-rays the technique can detect surface contaminants such as iron and nickel with a sensitivity equivalent to a monolayer (about 10^{15} atoms per cm^2) in about two minutes. Figure 1

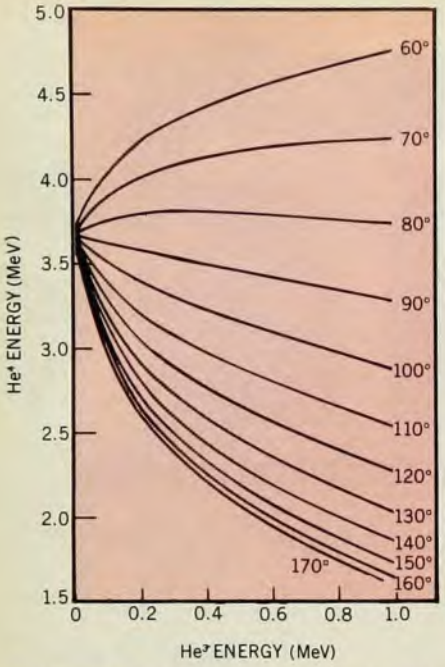
James Ziegler is manager of ion-beam techniques at the IBM Thomas J. Watson Research Center, Yorktown Heights, New York.

clear techniques have been tried. For example, one technique[6] offers very good depth resolution (7–10 nm), moderate senstivity (1000 ppm), reacts with no other elements and can be used to depths of several microns. Here N^{15} ions are a probe to induce the nuclear reaction

$$H^1 + N^{15} \rightarrow C^{12} + He^4 + \gamma$$

The incident N^{15} beam has an energy above the 6.385-MeV resonance energy. As it penetrates the material, the beam loses energy until it is at 6.385 MeV. The nuclear resonance is very sharp, about 14 keV wide, and since nitrogen ions lose energy at a rate of about 3.8 keV per nm at the resonance energy, the active depth "window" is very narrow, less than 20





Determining deuterium depth profile in a metal. The deuterium impurity participates in a nuclear reaction whose cross section changes slowly with incident ion energy. An incident beam of He^3 ions interacts with the deuterium, producing high-energy He^4 ions. We see that for emergent He^4 at a 77-degree lab scattering angle, the instantaneous He^4 energy is 3.8 MeV, independent of the energy loss of the He^3 projectile as it penetrates the target. The *final* (detected) He^4 energy, after the He^4 loses energy as it travels to the surface, is a measure of the reaction depth. (From reference 7.) Figure 2

lattice spacings. The nuclear reaction produces gamma rays at 4.43 MeV, which can be detected outside the chamber. The hydrogen concentration profile can be calculated from the known energy dependence of the nuclear cross section and the energy loss of the projectile in the target. Alternatively, hydrogen concentration standards can be prepared by implanting hydrogen into Al_2O_3, which retains at least 94% of moderate implant doses.

This hydrogen-profiling technique has the drawback that an initial beam energy of about 7 MeV is required. Such energies are generally available only in large nuclear-structure laboratories with tandem accelerators. An example of its use is shown in figure 3.

Another nuclear reaction is used to profile the hydrogen isotope deuterium in materials and needs only a 1-MeV accelerator. The nuclear reaction used is

$$H^2 + He^3 \rightarrow He^4 + H^1$$

with the He^4 being detected. (See figure 2.) This technique[7] can give good depth resolution (40 nm) and good sensitivity (10 ppm), and it is insensitive to target elements with atomic numbers greater than seven. In this analytic method the particle detector, set at an angle of 77 deg to the primary beam, is flooded by forward-scattered primary He^3 ions. These low-energy He^3 ions can be eliminated by placing Mylar over the detector, but this Mylar adds energy straggle to the He^4 and reduces the depth resolution that can be attained. Without the Mylar, typical limitations of counting electronics necessitate a three- to five-hour run to profile a single sample with statistical reliability.

The hydrogen and deuterium techniques described have both been developed in the last two years; the analytic art of hydrogen profiling is improving so rapidly that new nuclear techniques may be developed within the next year or two.

Porosity of carbon and metals

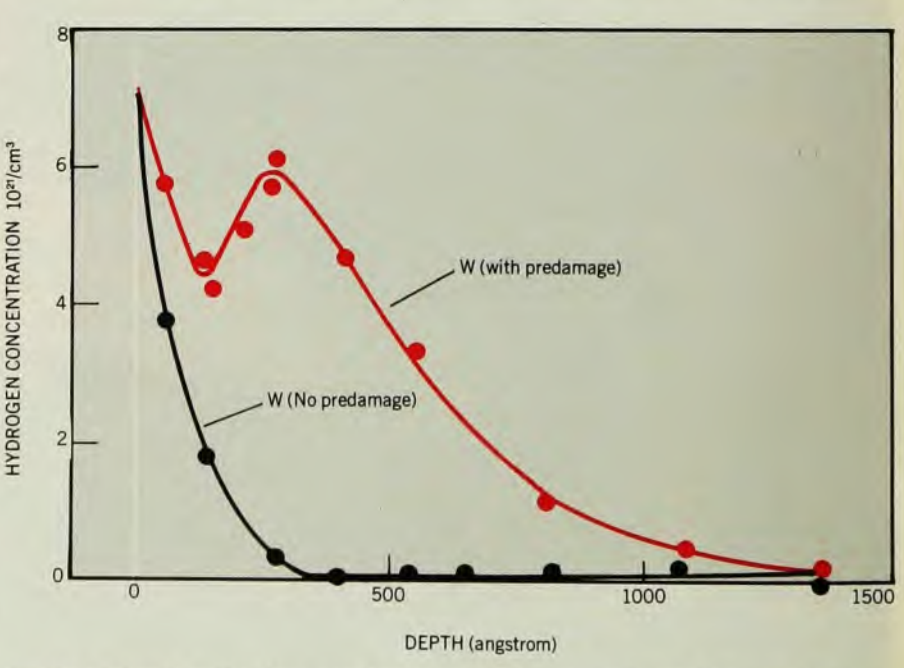
The determination of the porosity of materials is important to many industries, and ion-beam analysis may be useful in these measurements. Fission reactor metals become porous from radiation-induced void formation, strongly limiting the efficiency of reactor core packing. Some industries use high-pressure powder compaction to form castings of exotic alloys. The surface porosity of products ranging from ball bearings to dielectric oxides on transistors can be directly related to the product effectiveness. One traditional instrument for measuring porosity volume is the mercury porosimeter, in which pressure is applied to a nonwetting liquid such as mercury so that open pores are penetrated in progressively decreasing entrance diameter.

Ion beams can measure porosity in two ways.[8] If the material contains an element for which there is a low-energy elastic scattering resonance, a backscattering geometry can be used. This type of resonance exists for most elements with atomic number $Z \leq 13$. In figure 4 we see backscattering spectra from He^4 ions at 3.11 MeV incident on two different Al_2O_3 targets. Note the sharp peak in the lower spectrum, which is due to strong narrow resonance in the scattering of He^4 from O^{16} at 3.05 MeV. The upper spectrum is from porous Al_2O_3; this spectrum shows a much broader O^{16} resonance peak. One may understand this broadening by considering that any monoenergetic beam will begin to spread out as it penetrates a target, a phenomenon called "straggling". Energy straggling occurs because of the statistical nature of the energy loss of the beam ions to the individual target atoms. If the target contains pores, the backscattered beam energy distribution will be additionally broadened because the pores contribute little stopping as the ions traverse the open volumes. The peak broadening in the upper spectrum of figure 4 can be related to the statistical distribution of the pores, which in turn is related to material porosity.

If one can assume a pore shape—for example spherical—one can then measure the physical mass and volume of the target. From these and the straggling one can deduce a mean pore radius.

Protein in grain

The protein content in many grains (especially corn, wheat, peas and beans) can be estimated by measurement of nitrogen content. Usually this content has been measured by the Kjeldahl method, a time-consuming wet-chemistry tech-



Nuclear resonance profile of hydrogen trapping in metals. Here H^1 and N^{15} interact with a very sharp nuclear reaction, which is stepped progressively into the target. The resulting gamma rays are detected. Hydrogen implanted to a depth of about 250 Å in crystalline tungsten is found to disappear within 30 minutes (black curve); in a tungsten crystal predamaged with helium (to a depth of about 70 Å) the hydrogen is trapped (colored curve). From ref. 6. Figure 3

nique. Carbon content (and also sulfur) in the same region as the nitrogen further establishes the presence of protein.

Ion-beam analysis of grains has been shown to be accurate, fast, capable of spatial discrimination as to the location of the protein, and somewhat nondestructive (85% germination of irradiated grains compared to 94% for a nonirradiated control group of wheat grains). Thus, analyzed grain can be planted. The importance of spatial distribution is most notable in rice where, in certain widespread types, most of the protein is discarded during polishing. Spatial resolution can also be used to study the process by which grain fills with protein up to maturity, or how the seed protein distribution affects the initial growth and vitality of germinated seedlings.

The ion-beam technique that appears most promising is the use of an analysis chamber at atmospheric pressure (described in detail later) where the beam is brought out through a thin aluminum foil into a helium-filled box. This atmosphere increases the tolerance of biological specimens to radiation analysis. One useful nuclear reaction is

$$N^{14} + H^2 \rightarrow H^1 + N^{15}$$

and the 8-MeV proton is detected. Data on nitrogen content obtained by the Kjeldahl method are reasonably well correlated to those obtained by this nuclear reaction[9] (86% for a sample of peas and beans).

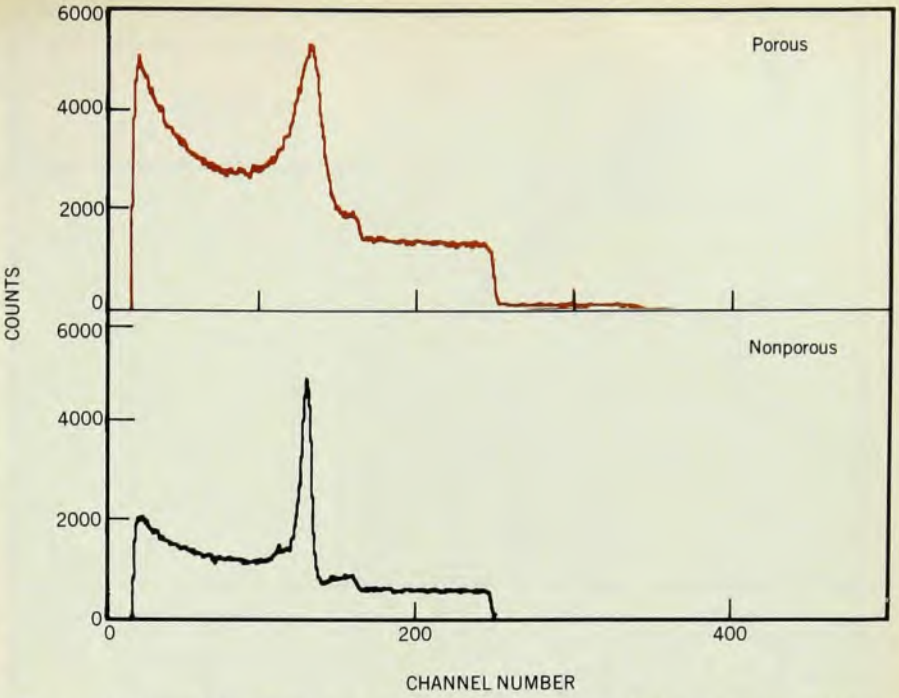
The depth to which the protein can be profiled in grains depends on the incident H^2 energy; typically a 2-MeV beam will be useful to 30 microns, and a 6-MeV beam to 200 microns. The seed-exposure time required to obtain an analytic accuracy equivalent to the lengthy Kjeldahl process is about 40 seconds.

Backscattering methods

The second major ion-beam technique we shall discuss is simply the firing of ions into a target and the determination of their energy distribution after backscattering. It is usually conducted with He^4 ions at 2 MeV to eliminate nuclear resonances and to allow simple Rutherford scattering analysis of the backscattered ion spectrum (which can yield quantitative results without calibration samples). This technique is the most widely used type of ion-beam analysis.[10]

Nuclear backscattering is useful in obtaining the depth profiles of elements in the upper micron of smooth solids. It is a powerful analytic tool because it is simple, quantitative and nondestructive. Its primary limitation is that it provides ambiguous information on samples containing elements of similar mass.

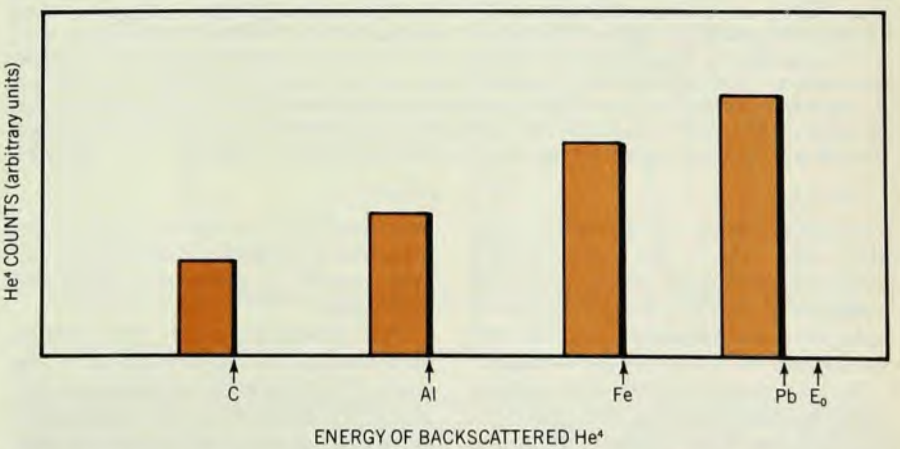
The experimental principle is that the elastic scattering of the low-mass incident ion by the target atoms can be used to identify the mass of the nucleus hit because of its energy loss in the collision.



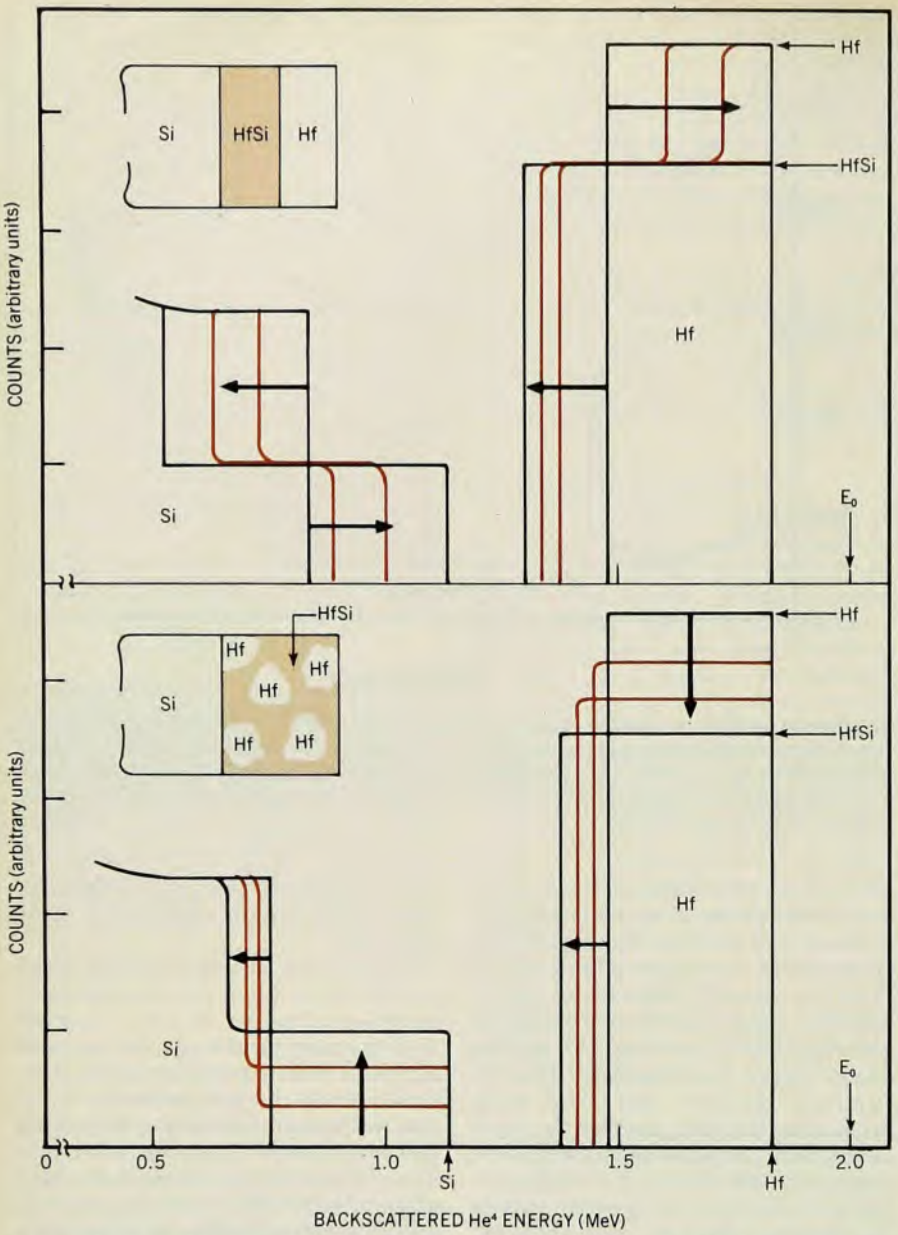
Determining material porosities. Backscattering spectra of He^4 ions at initial energy 3.11 MeV show a pronounced broadening of the sharp $He^4 + O^{16}$ resonance in porous Al_2O_3 (color) compared with nonporous Al_2O_3 (black). This broadening is attributed to the porosity of the material. Along with measurements of sample mass and volume, this technique can give results for pore diameters ranging from 1 nm to 1000 nm. Figure 4

Heavy nuclei absorb little energy in recoil, and the backscattered ion retains most of its energy. If one uses He^4 ions for the beam probe, the recoil effects are as shown in figure 5. This major loss of projectile energy is the way in which one identifies target elements; the smaller energy loss of the projectile, related to electronic processes that occur while penetrating the solid, provides the depth information. If the elemental profiles are reasonably well separated, the backscattering technique can provide reliable concentration profiles. Since the backscattering typically occurs at 0.001 of an atomic radius, the target atom's electronic shell structure has negligible effect on the scattering.

The majority of backscattering applications have been in semiconductor technology, thin-film material science and nuclear-energy technology. In electronic materials, there have been studies of ion implantation, thermal and anodic oxidation, contact formation, dopant profiles and metallization processes. For thin films on substrates, studies have been made of solid-state reactions, impurity diffusion and solubility, epitaxial layer growth, oxidation and corrosion, and the



Nuclear backscattering. The projectile ion (here assumed to be He^4 with original energy E_0) loses significant energy to the recoiling target nucleus, and the backscattered projectile energy is detected. A small amount of energy is also continuously lost by the projectile to the electron sea of the target. Ions scattering from deeper within the film, then, appear as counts at slightly lower energy, and each peak is a depth profile of target-element concentration. Figure 5



Two mechanisms of compound formation. Nuclear backscattering spectra of hafnium and silicon are used here to distinguish between two possible ways of forming HfSi after heating a layer of Hf on Si: diffusion limited (top) or reaction limited (bottom). Note that the original and final spectra (black) are the same in both cases, and that the Si spectrum is initially displaced to lower energies than that corresponding to silicon on the surface, because the He^4 projectiles must traverse a layer of Hf to reach the Si. The intermediate spectra (color) are the ones that differ for the two possible mechanisms. If the diffusion-limited reaction occurs, and the metals slowly diffuse through a layer of completed compound, the pure Hf layer gradually narrows and the Si layer gradually moves toward the surface. If the Si diffuses rapidly into the Hf along grain boundaries, and the HfSi forms slowly from the grain surfaces inward, the two elements have quite different spectra. Figure 6

formation of superconducting and magnetic thin films. In nuclear-energy technology there have been studies of the corrosion of cladding materials, helium and hydrogen incorporation into first-wall metals, and radiation damage to metals.

Because transistor technology requires highly polished surfaces, and silicon is a relatively low-mass substrate atom that does not interfere in the analysis, nuclear backscattering is applicable to many transistor-technology problems. No other microanalytic tool is capable of depth resolution of about 10 nanometers over depths of many hundreds of nanometers, without recourse to destructive layer removal by chemical or sputtering techniques.

One illustration of the simplicity of data analysis in backscattering is the study of the interaction of a hafnium thin film with a silicon substrate, forming HfSi (which has a very high reverse-bias potential to P-type silicon). The schematic spectrum in figure 6 (black curves) indicates how the Hf and the Si parts of the spectrum change when the silicide compound is formed after heat treatment. For both elements the high-energy side (right side) is produced by backscattering from surface atoms. The spectrum of the HfSi compound is clearly distinct from the Hf layer on Si. There is no chemical binding information in the spectrum, but a simple calculation can show that the atomic ratio of Hf to Si is about one to one. The identification of the HfSi as a chemical compound must be done with other techniques.

A further analysis of the chemical reaction kinetics is possible if samples are quenched before the transition from Hf to HfSi is completed (figure 6, top). The spectra indicate how the layers could appear if the chemical reaction grows from the interface and is diffusion-limited by one species diffusing through the reacted HfSi until it reaches some unreacted metal. This "diffusion-limited" solid-state reaction can be contrasted with a "reaction-limited" compound formation (figure 6, bottom). Spectra like these take only ten minutes to generate, so that simple thin-film chemical reactions such as those illustrated can be categorized by simple spectra inspection from a series of quenched samples.

Channeling for impurities

Many important physical properties of materials are controlled by the crystallographic location of impurities in solids. In addition, the interpretation of solid-state experiments or the theoretical analysis of solids often requires a knowledge of the impurity location within the lattice. Examples of such experimental studies include spin resonance techniques such as nmr or epr, hyperfine methods such as the Mössbauer effect and perturbed angular correlation, and internal friction measurements. Theoretical studies include electronic, optical and magnetic properties caused by impurities.

Few techniques can directly determine impurity lattice-location. Ion channeling, however, can be used for direct determination of the impurity location within a single-crystal lattice.[11] Under favorable conditions it allows the determination of the lattice position with an accuracy of 0.1 Å. Despite difficulties in the detailed interpretation of the channeling effect, the problem it attempts to evaluate is so fundamental that it receives much attention. The sensitivity of channeling is quite high, and it can be used to study impurities at the level of 0.01 atomic percent, in contrast to the 1% concentrations typically needed for neutron or x-ray scattering techniques.

The general technique is to guide a well collimated beam successively into the various major crystallographic directions of a crystal. The crystal itself will steer the beam by a long series of gentle elastic collisions (see figure 7). The probing beam is inhibited by these elastic collisions from interacting with nuclei along

the lattice column, and also from interacting with impurities shielded by the lattice atoms. By sending the beam first down one direction and then another, the beam interacts with, or is inhibited in its interaction with, impurities at certain lattice locations. Precise lattice location is then obtained by triangulation.

The actual interaction of the ion probe with an impurity can be of several kinds: the ion can backscatter; the ion can excite the impurity atom to give off a characteristic x ray; or it can undergo a nuclear reaction with an impurity such as hydrogen or helium, giving off a reaction product particle that is detected.

An important example of this technique is seen in figure 8 for deuterium in metals. The yield from channeled ions varies with the tilting angle of the target from a particular crystallographic direction. As the crystal tilts, the beam interacts with different portions of the channel. The figure shows scans for deuterium implanted into body-centered cubic crystals of tungsten and chromium. The hydrogen is detected by measuring the emitted protons from the nuclear reaction discussed earlier:

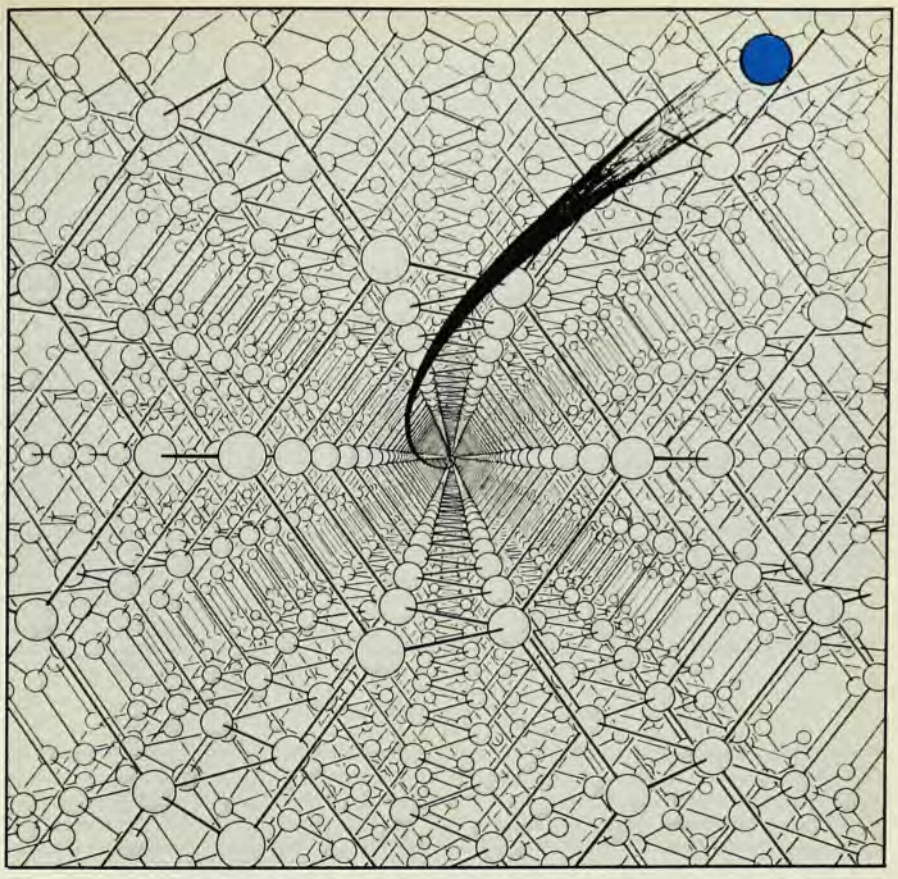
$$H^2 + He^3 \rightarrow H^1 + He^4$$

and the tungsten and chromium are detected by backscattering. For both tungsten and chromium targets the hydrogen exhibits a large central peak; for chromium this peak lies within the envelope of a dip with an angular width similar to that from the chromium lattice. From these scans together with channeling scans along other crystallographic directions, the hydrogen has been interpreted to be predominantly located in the tetrahedral interstitial site in tungsten, and in the octahedral interstitial site in chromium.

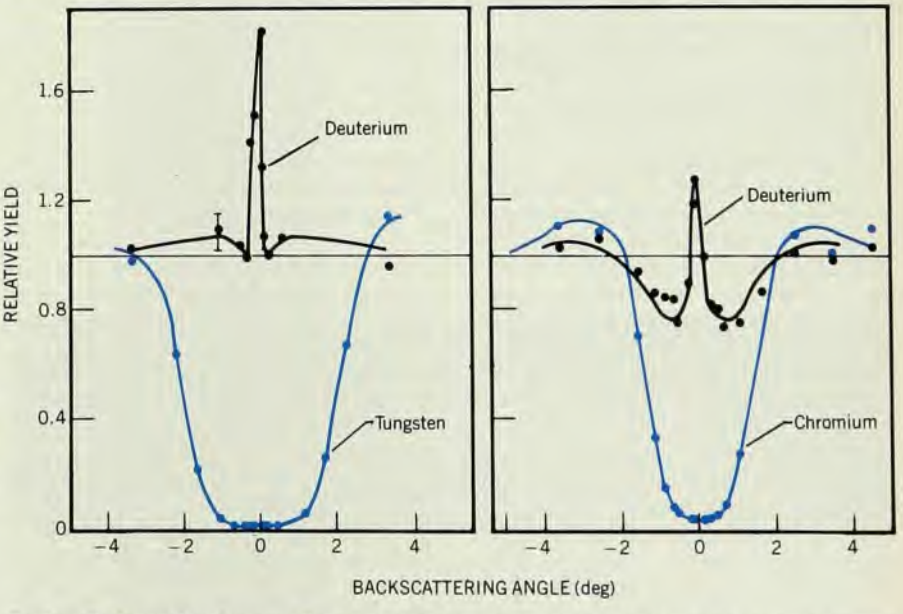
Ion-induced x rays

The use of ion-induced x rays for material analysis is fundamentally different from the use of nuclear reactions or nuclear backscattering in the sense that purely atomic transitions are involved. Analysis with ion-induced x rays directly competes with two well established analytic techniques: photon-induced x rays (x-ray fluorescence) and electron-induced x rays (especially as used in the electron microprobe, which is both an electron microscope and an x-ray analyzer). The advantage of x-ray techniques is that the detector used has such fine resolution that virtually all elements whose x rays are detected can be identified uniquely.

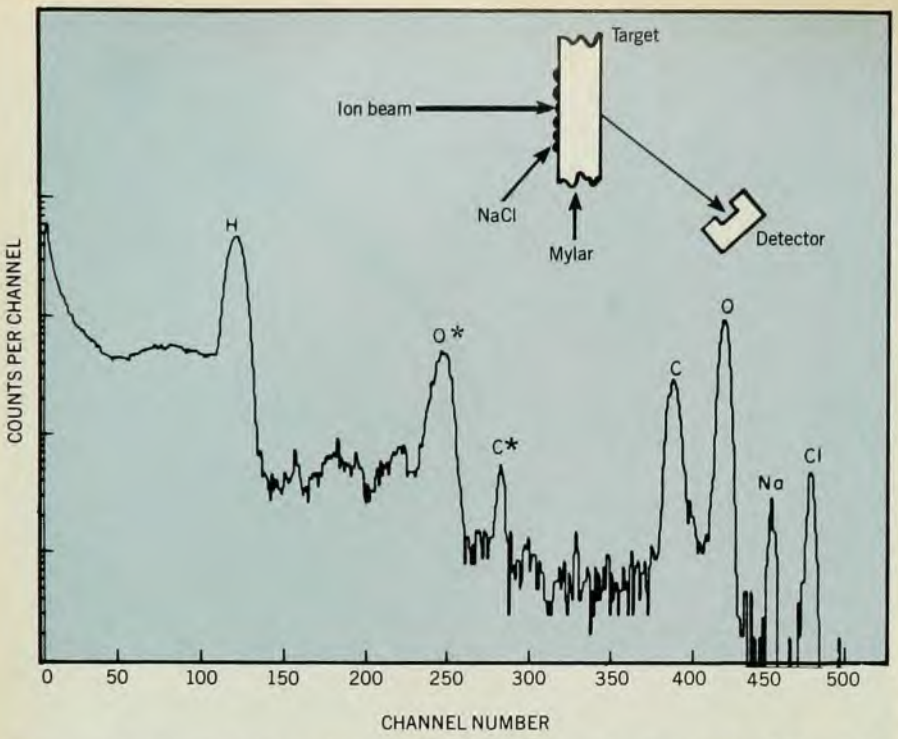
In several ways ion-induced x rays have advantages over other x-ray techniques. Since the ion is orders of magnitude more massive than the electron, it creates much less background when traveling at the same velocity in solids.[12] Ion beams are subject to less straggle and lateral deflection than are electron beams, making the analysis of the excitation processes of



Ion channeling in a diamond-like crystal. Gentle elastic collisions with lattice-row nuclei steer the ion into a helical trajectory with a period of several hundred lattice spacings. Along certain axes there are interstitial locations near the channel center, which have enhanced interaction with a channeled ion, as well as interstitial locations hidden near the atom rows lining the channel. Each channeling direction changes the degree of interaction between an ion and an impurity in a given interstitial position, and impurity locations are determined by triangulation after guiding the ion down different channels. (From "Channeling in Crystals" by Werner Brandt, copyright March 1968 by Scientific American, Inc. All rights reserved.) Figure 7



Backscattering and nuclear reaction analyses were done in this channeling experiment to determine the location of hydrogen impurities in tungsten (left) and chromium (right) crystals. In each case the metal targets were rotated through zero degrees relative to the ⟨100⟩ axis. The hydrogen is detected by a nuclear reaction with the helium projectile, and the crystal lattice positions are determined by backscattering of the projectile. The lower (colored) curves show the metal crystal yield and the upper (black) curves are the results for hydrogen. These data and other angular scans determined that the hydrogen is located predominantly in tetrahedral interstitial sites in tungsten and in octahedral interstitial sites in chromium. Figure 8



Forward scattering analysis is useful in determining impurities with atomic number 2 through 13. Each element appears as a peak rather than as a spread of energies (as in backscattering) because here all projectiles traverse the entire target. Spectrum shown is for He^4 ions elastically scattered 55 deg in a transmission geometry through a NaCl target fixed onto Mylar. In combination with x rays (sensitive to atomic numbers 10–92), forward-scattering provides a total elemental analysis. Note that the starred peaks are from inelastic collisions and that the peak near channel 120 represents H atoms knocked into the detector by the He^4 beam. Figure 9

the incident beam easier and more accurate. The primary advantage of an ion beam over photon excitation is that one can focus the ion beam and generate orders-of-magnitude greater excitation density for near-surface elements.[13]

We shall describe two applications of ion-induced x rays that use to advantage the features we have mentioned. They involve analysis of particulate material and nonvacuum studies.

In various sectors of industry, compositional and trace-element information is needed for materials in powdered form (particle sizes up to 20 microns in diameter). Examples of such sectors include the mining industry, the analysis of air pollution and the development of porous catalysts. Studies of catalysts are estimated to be the most intensive area of all industrial research. Porous catalysts have substrates with very large surfaces (typically 200 square meters per gram) so that the catalysts distributed on the interior surfaces can interact with liquids or gases forced through under pressure. The cessation of catalytic activity may be caused by "poisons" deposited from the carrier stream, and quantitative analysis of the catalysts after their demise is done to determine what reduced their effectiveness. The difficulty here is that the target is porous, brittle, rough and contains degrading contaminants present at levels as low as a few parts per million.

For analysis, a portion of the catalyst is pulverized into powder (perhaps losing the volatile contaminants) and then a few milligrams is fixed on a thin Mylar film.[14] One advantage of ion-beam analysis is that protons (at a few MeV) can penetrate 20 microns of material while losing less than 10% of their energy. This small energy loss minimizes the change of excitation cross section during penetration of the larger particulates, so that the analysis of the excitation process is not dependent on powder-grain size.

A second advantage is the use of simultaneous forward scattering of the proton beam, detected at an angle of 40 deg to 50 deg from the beam axis, as seen in figure 9. The forward-scattering geometry provides increased sensitivity to low atomic-number elements in the target. Elements appear as peaks rather than as spread-out depth distributions (as occurs in nuclear backscattering) because all the projectiles traverse the entire target in the transmission geometry shown in the inset to figure 9. Elements such as lithium, boron, carbon and oxygen are usually clearly seen as isolated peaks, and this technique, which is sensitive up to aluminum (Z = 2 to 13) nicely overlaps and complements the usual x-ray detector sensitivity to the elements of fluorine through uranium (Z = 9 to 92).

This combination of x rays and forward scattering is the only trace-element system sensitive simultaneously to all elements—a significant advantage when one is confronted with a totally unknown catalytic poison, or is concerned with all elements as for a "pollution signature" as found in environmental samples. The analysis of air-pollution samples, especially collectors imbedded with particulate matter, is similar to the analysis of catalysts.[13]

Nonvacuum analysis

In some cases, ion-beam analysis can be done at atmospheric pressure, rather than under vacuum. The advantages are largely related to experimental simplicity, not insignificant when studies are carried out by technicians with little scientific training. Targets can be inserted quickly and beam uniformity checked visually. Also, analysis can be done on volatile targets such as liquids and biological specimens that may be unstable under vacuum irradiation.

Proton beams of 2 MeV, as an example, can penetrate a container of helium at atmospheric pressure for distances of 25 cm. The proton beam can be brought out of a vacuum line through a grid-supported aluminum foil (about 4 microns thick) in beams up to 7 cm in diameter (see figure 1). If a helium jet circulates the gas against the foil, to reduce heating, currents of 20 microamps can be sustained indefinitely. The aluminum foil and the helium gas introduce slight lateral straggle into the beam and this eliminates shadow effects from the grid supporting the aluminum foil.

In figure 1 is an arrangement to analyze the x rays from trace contamination on 2.25-inch diameter silicon crystal wafers, which are typical sizes used in transistor manufacture. The system can analyze for elements such as iron or nickel with a sensitivity equivalent to a monolayer (10^{15} atoms/cm^2) in about two minutes.

There are some major unsolved problems in ion-beam analysis. such as:

- Evaluations of the stopping powers of the H and He ions in rare earths are almost nonexistent. For elements with atomic numbers between 54 and 73, for example, there is only one absolute measurement published for H ions with energies below 1 MeV.
- Few of the scientists involved in ion-beam analysis have any formal nuclear-physics background. To carry out their work efficiently, they need complete tables of low-energy nuclear reactions indexed under targets, bombarding ions and reaction products. Such tables would greatly simplify literature searches for special analytic problems.
- There is no simple, nondestructive and quantitative way to profile oxygen concentrations in the surfaces of materials. Oxygen contamination appears to dominate the problems of scientists creating new materials or working with thin films; a nuclear-reaction method, similar to the

one discussed above for hydrogen profiling, would be quite useful.

The interdisciplinary nature of analysis tends to foster diversity, and among the ion-beam analyses reported have been bicycle tours to study the influx of metals into a river and their gradual settlement; the incorporation of tagged fertilizers into roses; the evaluation of mercury in university tuna salads; the study of hydrogen imbedded in Moon rocks from the solar wind, and the migration across a continent of a new pottery glaze in Stone Age eras.

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