LARGE DEPTH PROFILE MEASUREMENTS OF D, ³He, AND ⁶Li BY DEUTERON INDUCED NUCLEAR REACTIONS

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The method of depth profiling by nuclear reactions is discussed for D, ³He, and ⁶Li atoms in solid absorbers. A detailed discussion is given on the quality data of this technique, especially the depth resolution. The results of some representative experiments are reported in order to show the applicability of the method with respect to the behaviour of foreign light atoms in solid materials.

1. Introduction

The knowledge of the depth distributions of implanted atoms in solid materials is of interest in the field of basic research in the interaction of ions with matter; it is also of importance for the field of applied physics and technology. The measurement of depth profiles provides information on the diffusion of the implanted ions, the radiation damage of the irradiated material, or the reemission of foreign atoms. All those effects may play an important role for the design of controlled fusion reactors.

The experimental methods which have been developed to determine such depth profiles fall into two classes: In “destructive” techniques the surface is removed either by anodic oxidation or by sputtering, the profiles being observed simultaneously by Auger-electron spectroscopy, secondary ion mass spectrometry or detection of electrons emitted from neutron-activated implants. In the case of light ions, experiments are reported using residual gas analysis. On the other hand, “non-destructive” methods offer obvious advantages, especially if variations of the depth profiles after implantation are under consideration. For heavy implanted atoms the Rutherford-backscattering method has been applied successfully by many authors, whereas in the case of light ions satisfactory results are available only for thin films. In thick absorbers, however, indirect measurements may be carried out using the (often doubtful) Bragg's rule to extract the depth profile from the modified backscattering spectrum of the host material. The technique of observing the light recoils after heavy ion induced scattering, which was published recently, has been applied to small depth regions (≤ 100 nm) only.

Especially for the detection of light ions in thick absorbers, some techniques involving nuclear reactions have been developed. The best results are obtained in thermal neutron induced reactions. Those experiments, however, are confined to the detection of isotopes with extremely high cross sections for neutron capture, and require long times of data acquisition due to limited neutron fluxes. Using nuclear reactions with charged particles, there are again two distinct techniques: In the “resonance” method reactions are used the excitation curves of which show a resonance structure. The depth profiles are obtained by total yield measurements step-by-step, with incident energies equal to and slightly higher than the resonance energy, i.e. by “shifting” the resonance through the absorber. Such experiments have been carried out to detect heavier atoms and even protons, with excellent depth resolution. They have been less successful in the case of D or ³He due to the large resonance width. In contrast, the method of “energy analysis” requires nuclear reactions in an energy range far from narrow resonances. The depth profile is evaluated directly from the energy spectrum of an emitted particle, as will be discussed in detail below.

Deuteron-induced nuclear reactions in connection with the energy analysis method have been applied to the depth profiling of D and ³He in the past. Earlier publications, however, present a rather crude evaluation of the proton energy spectra or a qualitative discussion of the spectra, only. The direct computation of the profiles from the energy spectrum has been carried out successfully at low detection depth (< 200 nm). At larger depths, however, no satisfactory results were obtained; the depth profiles showed unphysical divergences towards the mean range of the implanted deuterons or ³He atoms.

In this work it will be shown that the deuteron-induced nuclear reactions D(d,p)T, ³He(d,p)⁴He, and ⁶Li(d,a)⁴He may be used successfully to study the depth...
profiles of D, $^3$He, and $^6$Li, respectively, provided the detection parameters, mainly the deuteron energy, are chosen properly. After a short description of the method, a detailed discussion of errors and the depth resolution will be given. Finally, some specific experimental results will be presented.

2. Method

The experimental method used here has been described in detail by Johnson and Hufschmidt et al. Fig. 1 shows the basic geometry: The probing deuterons hit the surface of the absorber with an energy $E_{10}$ and may initiate a nuclear reaction together with an implanted ion at the (normal) depth $x = -x_1 \cos \alpha$. The energy of the observed reaction products (protons or alpha particles) depends on the retardation of the incoming beam along $x_1$ and of the outgoing particles along $x_2$, and on the kinematics of the nuclear reaction. Thus, the energy scale of the observed energy spectrum can be converted into a depth scale. The depth distribution of the implanted atoms and the differential cross section of the reaction determine the number of observed particles per channel of energy. In this way, the density profile $n(x)$ as function of the channel content $I(E_2)$ is obtained according to

$$ n(x) = \frac{z e}{Q} \frac{d \sigma}{d \Omega} (E_1, \theta, \Delta \Omega)^{-1} \left| \frac{d E_2}{d x_1} (x_1) \right| I(E_2), \quad (1) $$

where $Q/z e$ denotes the total dose of probing deuterons, $d \sigma/d \Omega$ the differential cross section and $\Delta \Omega$ the solid angle of observation. The function $d E_2/d x_1$ combines stopping power and kinematical data; it has to be monotonic, which is guaranteed by observation at forward angles.

The poor results reported from earlier experiments indicated deviations from the ideal geometry of fig. 1 due to straggling effects. If we assume that the main contribution originates from angular straggling (as will be shown in sect. 3), a broadened distribution of the observation angle will lead to an uncertainty of the energy–depth relation $E_2(x)$. Since those angular deflections occur mainly at low energies, when the probing particles are stopped almost completely, a central condition for the application of the nuclear reaction method can be formulated as

$$ -R_d \cos \alpha > x_{\text{max}}. \quad (2) $$

that is, the mean range $R_d$ of the probing deuterons has to be larger than the depth region under investigation, denoted by $x_{\text{max}}$. (Scattering processes of the observed particles are neglected here because of their high energy received in exothermic reactions.) It may be disadvantageous, however, to use very high energies due to decreasing nuclear cross sections and a deterioration of the depth resolution (see sect. 3). Furthermore, unnecessary large thermal loads to the absorber should be avoided during the detection period. According to these considerations, we chose a detection energy of $E_{10} = 2 \text{ MeV}$ corresponding to a mean range of $R_d = 12 \text{ mg/cm}^2$ at a maximum depth of detection $x_{\text{max}} = 3 \text{ mg/cm}^2$. (In nickel, the thickness of $1 \mu m$ corresponds to 0.89 mg/cm$^2$.) As we deal with comparatively large absorber depths, the evaluation of eq. (1) is more complicated compared to near-surface depth profiling, where average stopping powers and constant nuclear cross sections are used. Our calculation is carried out by a FORTRAN-IV program (“AUDIVE”), which computes the expression $d E_2/d x_1$ by a numerical iteration procedure utilizing the stopping power data of Northcliffe and Schilling.

The nuclear cross section data are fed into the program as polynomial fits to the total cross sections and the Legendre coefficients of anisotropy for the reactions $D(d,p)^T$ 52–56), $^3$He(d,p)$^4$He 37), and $^6$Li(d,$\alpha$)$^4$He 38–42).

3. Characteristics and error analysis

3.1. Reliability

It may be stated as a basic requirement for any method of analysis that the influence of the probe on the quantity under consideration should be negligible. In the case of nuclear reaction depth profiling, the probing ions might cause a radiation enhanced diffusion of the implanted atoms. No changes were found, however, when measuring several energy spectra after each other of the same area following deuteron implantation. This may be explained by the fact that radiation damage is produced mainly near the end of the range of the probing ions 43). Therefore, eq. (2) should guarantee reliability even in this respect.
Table 1

Characteristics of depth profiling experiments with 2 MeV probing deuterons in nickel (angle of observation: \( \theta = 40^\circ \), angle of incidence: \( \alpha = 115^\circ \)).

<table>
<thead>
<tr>
<th>Depth profiling of</th>
<th>( \text{D(d, p)}T )</th>
<th>( ^3\text{He(d, p)}^4\text{He} )</th>
<th>( ^6\text{Li(d, z)}^4\text{He} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>4.033</td>
<td>18.354</td>
<td>22.375</td>
</tr>
<tr>
<td>( Q )-value (MeV)</td>
<td>4.1 - 5.3</td>
<td>16.6 - 18.1</td>
<td>11.4 - 14.6</td>
</tr>
<tr>
<td>( E_p, E (\text{MeV}) )</td>
<td>0.06 - 0.5</td>
<td>0.08 - 0.6</td>
<td>0.03 - 0.35</td>
</tr>
<tr>
<td>Accuracy of surface position (mg/cm(^2))</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Max. detection depth (mg/cm(^2))</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Accuracy of depth scale (%)</td>
<td>±5</td>
<td>±5</td>
<td>±10</td>
</tr>
<tr>
<td>Accuracy of density scale (%)</td>
<td>±5</td>
<td>±5</td>
<td>±10</td>
</tr>
<tr>
<td>Lower detection limit (at%)</td>
<td>0.2</td>
<td>0.05</td>
<td>0.5</td>
</tr>
</tbody>
</table>

3.2. LOWER DETECTION LIMIT

Nuclear reaction depth profiling methods may be applied preferentially to high concentrations of foreign atoms because of their small cross sections. The sensitivity cannot be improved by simply enlarging the detection dose, since surface contaminations or the absorber itself produce an unavoidable background in the energy spectra. Deuteron depth profiles obtained from the D(d,p)T reaction are falsified additionally by the depth distribution of the probing deuterons. The values of the lower detection limits given in table 1 are estimated from the experiments; to obtain a satisfactory resolution, however, higher concentrations are required.

3.3. DEPTH RESOLUTION

In order to allow a correct interpretation of the depth profiles obtained from nuclear reactions, a detailed analysis of the depth resolution is indispensable for each problem. Furthermore, the results of those considerations determine the optimum choice of the detection parameters, that is, the energy of the probing particles, their angle of incidence, and the angle of observation. In the case of the \( ^3\text{He(d, p)}^4\text{He} \) resonance method, Pronko\(^{44}\) found that the depth resolution is improved by an oblique incidence. Similarly, an enhancement of the depth resolution is reported by Eckstein et al.\(^{45}\) by varying the angle of observation for \( ^3\text{He(d, z)}^3\text{H} \) at low depths (< 50 nm). In the latter case, the depth resolution results from the slowing down of the emitted \( \alpha \)-particles, the solid angle of observation and the detector resolution only. A discussion based on the same assumptions is given by Turos et al.\(^{46}\) for oxygen profiling in large depths (< 10 μm) by means of the reaction \( ^1\text{O(d, z)}^1\text{H} \); straggling effects of the particles within the absorber are neglected. This deterioration of the depth resolution due to straggling, however, presents the main contribution at large depth, as shown below.

The total depth resolution \( \delta x \) is expressed by the total energy resolution \( \delta E_2 \) of the method according to

\[
\delta x = \left| \frac{dx}{dE_2} \right| \delta E_2.
\]

In the following, we will always set the full width at half maximum (fwhm) for the \( \delta x, \delta E_2 \) etc. A good depth resolution requires a small derivative \( dx/dE_2 \), with is achieved for small (forward) angles of observation. Fig. 2 shows this function, which has been discussed in sect. 2, in the case of D(d,p)T for different observation angles and for all three reactions utilized here. Already at this point, a comparatively small depth resolution may be expected for the \( ^6\text{Li(d, z)}^4\text{He} \) depth profiling, which is related to the large stopping power of the \( \alpha \)-particle. All our calculations are carried out using nickel as absorber substance; the results, however, vary only slowly as function of the atomic number \( z_2 \) of the absorber.

The total energy resolution \( \delta E_2 \) is composed of several contributions, which will be treated individually. Firstly, the energy resolution of the particle detector together with the energy analysing equipment gives rise to an amount (\( \delta E_{2D} \)). The area of the beam and of the particle detector lead to an uncertainty \( \delta \theta_p \) of the
observation angle. The correspondent energy width is expressed in terms of the reaction kinematics $E_{20}(E_1, \theta)$ and the residual energy $E_2(x_2, E_{20})$ according to

$$
(\delta E_2)_A = \frac{dE_2}{d\theta}(E_1, \theta) \frac{dE_2}{dE_{20}}(x_2, E_{20}) \delta\theta_A.
$$

(4)

The contributions $(\delta E_2)_A$ and $(\delta E_2)_B$ may be regarded as "apparatus" fractions, whereas in the following we will deal with "immanent" straggling effects, which affect the probing deuterons as well as the outgoing particles. Even if the particles travel along straight lines, electronic energy loss fluctuations give rise to an energy straggling $\delta E_{ES,1}$ and $\delta E_{ES,2}$, respectively, and the corresponding contributions

$$
(\delta E_2)_{ES,1} = \frac{dE_2}{dE_1}(E_1, \theta) \frac{dE_2}{dE_{20}}(x_2, E_{20}) \delta\theta_{ES,1},
$$

(5)

and

$$
(\delta E_2)_{ES,2} = \delta E_{ES,2}.
$$

(6)

Numerical values of the energy straggling were obtained using the formula of Symon\(^{47}\)), which allows a direct computation from the stopping power data, provided the mean ionization potential has been adjusted as proposed by Tschalär and Maccabee\(^{48}\). As the result, the energy fluctuation is written conveniently in Lindhard's\(^{49}\) reduced units:

$$
(\delta e)^2 = \frac{8 \ln 2 m_2^2}{m_1 x_2^2} \left[\zeta(e_1)\right]^2 \times

\times \int_{e_1}^{e_0} \left[1 - \exp\left\{-4 m_0 x_2 \varepsilon(e) \left[\zeta(e)\right]^3\right\}\right] d\varepsilon,
$$

(7)

where $\varepsilon_0$ and $\varepsilon_1$ denote the reduced mean energies of ions initially and after having transversed the specified distance, $m_0$, $m_1$, and $m_2$ the masses of electron, ion and absorber atom, and $\zeta(e)$ the reduced stopping power. As to be seen from fig. 3, the results approach the simple Bohr\(^{50}\) expression in the limit of high energies.

Finally, multiple scattering causes the most important deterioration of depth resolution at large depth. The resultant effects are sketched in fig. 4 for the incoming ion only, but have to be taken into account for the outgoing one as well. The angular distributions of width $\theta_{1/2}$ define a spectrum of observation angles of width $\delta\theta_{MS}$. More precisely, the planar distribution of observation angles is derived from the spatial angular distribution by projection onto the reaction plane; there is, however, merely a small difference between $\theta_{1/2}$ and $\delta\theta_{MS}$. Values of $\theta_{1/2}$ from the tabulation of Sigmund and Winterbon\(^{51}\) are displayed in fig. 5 as function of the penetration depth and the mean energy along the path. Taking into account stopping power and reaction kinematics again, the correspondent contributions to the energy resolution result in $(i=1,2)$:

$$
(\delta E_2)_{MS,i} = \frac{dE_2}{d\theta}(E_1, \theta) \frac{dE_2}{dE_{20}}(x_2, E_{20}) \delta\theta_{MS,i}.
$$

(8)

![Fig. 2. Resolution function vs detection depth in nickel for D(d, p)T depth profiling at different observation angles (a) and for different profiling reactions (b).](image)

![Fig. 3. Energy loss fluctuation of protons and deuterons in nickel (\sigma: standard deviation).](image)
Looking at fig. 4 again, an additional straggling effect at large depth and oblique angles is due to the path length distribution of the ions arriving at the depth $x$, which is characterized by a width $\delta l$. This quantity is related approximately to the lateral spread $\delta x_1$ by

\[ \delta l = -\delta x_{1,1} \tan \alpha, \]  

(9)

for the probing deuteron and

\[ \delta l_2 = \delta x_{1,2} \tan(\alpha - \vartheta), \]  

(10)

for the outgoing particle. The lateral spread is obtained from the angular distribution using the scaling law of Marwick and Sigmund.\(^{32}\)

\[ \delta x_{1,i} = \frac{x_i}{\Gamma} \delta \Theta_{MS,i}, \]  

(11)

where $\Gamma \approx 1.8$ in our range of thicknesses. The diffuseness of energy is then given by

\[ (\delta E_2)_{LS,1} = \frac{dE_{20}}{dE_1} (E_1, \vartheta) \frac{dE_1}{dE_{20}} (x_2, E_{20}) \frac{dE_1}{dx_1} (x_1) \delta l_1, \]  

(12)

and

\[ (\delta E_2)_{LS,2} = \frac{dE_2}{dx_2} (x_2, E_{20}) \delta l_2. \]  

(13)

Although the individual processes which influence the resolution do not occur independently of each other, we assume that their effects on the total energy resolution may be summed up quadratically:

\[ (\delta E_2)^2 = (\delta E_2)^2_0 + (\delta E_2)^2 + \]  

\[ + \sum_{i=1}^{2} [(\delta E_2)^2_{ES,i} + (\delta E_2)^2_{MS,i} + (\delta E_2)^2_{LS,i}]. \]  

(14)

The total depth resolution which has been calculated from eqs. (3)-(14) is plotted in fig. 6 as function of the detection depth $x$ with the observation angle $\vartheta$ as parameter. A symmetric position of the absorber is chosen with respect to beam and detector directions. Apparently, an observation angle $\vartheta = 40^\circ$ is best suited for the depth range 0–3 mg/cm². A slight improvement of the depth resolution may be achieved by tilting the surface of the absorber a little bit more into the beam, which reduces the dominating effect of multiple scattering of the probing beam. This situation is outlined in fig. 7, together with all individual contributions, for the D(d, p)T deuteron depth profiling. All three profiling reactions which are discussed in this paper are displayed in fig. 8. A somewhat better depth resolution is found in the case of $^6$Li(d, p)$^4$He compared to D and $^3$He depth profiling. From the point of view of fig. 7 one might suppose that the depth resolution could be

![Fig. 4. Multiple scattering effects on probing deuterons.](image1)

![Fig. 5. Width of angular distributions of protons and deuterons in nickel.](image2)

![Fig. 6. Relative depth resolution of D(d, p)T in nickel at different observation angles.](image3)
improved by increasing the detection energy $E_{10}$: indeed, the multiple scattering of the incoming particle would be diminished, but the resolution function $dx/dE_2$ would increase considerably, so that an effective deterioration would result.

Summarizing we state that the depth resolution in the nuclear reaction depth profiling experiments considered here is deduced mainly from the multiple scattering of the involved ions, if depths larger than about 100 nm are under consideration. As relative amounts of about 25% are obtained, the depth resolution of the method may not be neglected when interpreting the results from such profiling experiments on D, $^3$He, or $^6$Li.

3.4. ERROR OF DEPTH AND DENSITY SCALES

To complete the error analysis, we consider the influence of experimental and systematic errors on the scales of the resulting depth distribution profiles. The error $\delta x$ in the position of the absorber surface deduced from the energy spectrum is given by the error of the observation angle $\delta \theta$:

$$\delta x = \left| \frac{dx}{dE_2} \right| \frac{dE_2}{dE_{20}} (x_2, E_{20}) \frac{dE_{20}}{d\theta} (E_1, \theta) \delta \theta. \quad (15)$$

Compared to this quantity, the error of the energy calibration of the detector is negligible. From the conversion of energy to depth, the depth scale is affected by an error factor according to the accuracy of the stopping data. The accuracy of the density scale is related to the accuracy of the cross section data. Besides, statistical errors may be important at very small concentrations.

Table 1 gives a compilation of the reactions utilized together with all corresponding data of quality discussed above.

4. Experiments

4.1. EXPERIMENTAL SET-UP

The experiments were carried out in a scattering chamber, which is connected to the Bochum 4 MV Dynamitron Tandem accelerator as well as to a 400 KV SAMES accelerator. Thus, implanted low energy ions can be detected in situ by 2 MeV deuterons. In order to avoid uncontrolled diffusion effects, the temperature of the absorber was stabilized by means of liquid nitrogen cooling and/or electron gun heating. The beam is collimated by four circular apertures to a diameter of 1.5 mm at the absorber position, the beam current being monitored by a rotating vane wheel. Instead of the absorber, thin foil targets can be exposed to the beam in order to calibrate the energy analysing system by means of the nuclear reactions $^{12}$C(d,p)$^{13}$C,
16O(d, p)17O, 6Li(d, p)7Li, 6Li(d, α)4He, and 10B(3He, p)12C. The energy resolution of the particle detector together with amplifiers and multichannel analyser was 15 keV for protons and 20 keV for α-particles, using a surface barrier detector of 500 µm depletion depth. For the high-energy protons from 10B(3He, p)12C and 3He(d, p)4He, a lithium drifted silicon detector was taken, which showed an energy resolution of 30 keV.

A special installation is necessary to prevent the probing deuterons of striking the particle detector after being scattered elastically at the absorber, because their high rate (about 10^5 s⁻¹ at typical experimental conditions) would lead to a pile-up background in the energy spectra and a quick destruction of the detector. In earlier experiments⁵⁹, a retarding foil was mounted in front of the detector, which, however, deteriorated the energy resolution considerably due to energy straggling. Therefore, a simple electrostatic analyser was constructed (fig. 9): The incident particles are deflected by an electric field within a wedge, which is formed from two condensor plates (length of plates: 174 mm, angle of wedge: 3.46°, opening at entrance: 1.5 mm). An additional collimation is achieved by a pair of 1 mm slits in front of the analyser. The deflection b at the position of the slit in front of the detector is given by

\[ b = 2.11 \frac{zU(kV)}{E(MeV)} \text{ mm}, \]  

where \( z \) and \( E \) denote the charge number and the energy, respectively, of the particle and \( U \) the voltage applied to the condensor plates. In this way, the particles of requested energy are separated from elastically scattered deuterons. Due to multiple scattering at walls and slits, a complete suppression is not possible, but a reasonably low rate (10^5–10^6 s⁻¹) is achieved.

The slits in front of the electrostatic analyser together with the beam spot define a width of the observation angle \( δθ_p = 0.6° \); the total arrangement is adjusted mechanically to an accuracy of \( δθ = 0.2° \) (see sect. 3).

4.2. RESULTS

In order to show the quality of the nuclear reaction depth profiling method to be used in applications, we will discuss the results of three special depth profiling experiments for deuterons and 3He atoms in nickel and 6Li atoms in germanium. The energy spectra are displayed in fig. 10. They show besides the parts of interest, which originate from reactions with the implanted ions, several other peaks due to surface contaminations of carbon and oxygen. The doses of the implanted ions were 0.18 C/cm² (D), 0.17 C/cm².

Fig. 10. Energy spectra obtained from 2 MeV deuteron bombardment after implantation of D in Ni (a), 3He in Ni (b), and 6Li in Ge (c).
(³He), and 0.2 C/cm² (⁶Li), the correspondent doses of probing deuterons 0.05, 0.042, and 0.025 C/cm². The beam current of the probing deuterons was about 1 μA; therefore, the depth profiling energy spectra are obtained within the time of a few minutes up to half an hour. Fig. 10c shows that the ⁶Li depth profile could be obtained from the ⁶Li(d,p₂)⁷Li or ⁶Li(d,p₃)⁷Li reactions as well, but the depth resolution would be poor compared to that achieved by observation of the α-particles.

The depth distributions were computed from the energy spectra of fig. 10 according to eq. (1) and are displayed in fig. 11. In the case of deuterons, the ¹²C(d,p)¹³C surface peak is superimposed, but may easily be subtracted because of the good resolution which is achieved by the electrostatic analyser. The implantation has been carried out at the temperature of 160 K; compared with even lower temperatures, a long tail of the distribution to the surface is observed. The magnification in fig. 10a indicates that a fraction of the distribution exceeds the real surface position, which is related to the depth resolution of δx ≈ 0.06 mg/cm² near the surface.

The ³He depth profile of fig. 11b was measured after an implantation with a dose exceeding the critical blistering dose⁵). Compared to lower doses, a very broad distribution is found. The formation of small hemisphere-shaped blisters leads to a broad distribution of the angle of incidence α of the probing deuterons, and, therefore, to a broadening of the observed depth profile. Further application of the nuclear reaction depth profiling in blistering experiments is described in an earlier paper⁶).

As the method provides absolute density profiles, we are able to conclude from an integration of the profiles of figs. 11a and 11b that all implanted ions are retained within the absorber.

The depth profile of ⁶Li in germanium displayed in fig. 11c has been obtained by a thermal treatment of the absorber: After implantation at low temperature (T = 170 K) the temperature was raised to 370 K for 20 min. The initial depth distribution has been changed due to diffusion; in this way, we are able to study the diffusion of implanted atoms. Furthermore, a narrow surface peak has formed, the half width of which corresponds to the depth resolution at the surface discussed in sect. 3. Therefore, we conclude that a thin surface layer of ⁶Li is built up on the absorber surface.

5. Conclusions

In this work, we have shown that the depth profiles of deuterons and ³He and ⁶Li atoms in solid absorbers may be investigated by deuteron induced nuclear reactions with satisfactory results in the range of concentrations above about 1 at%. To allow a correct interpretation of the results, however, the question of depth resolution had to be studied in detail.
The method described here may be applied as a powerful clue to problems of the deposition of implanted atoms, of radiation damage, and of the behaviour of foreign atoms in solid absorbers. Such experiments are in progress.

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