APPLICATIONS OF ION LINACS

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Abstract
Presently a domain of the application of linear accelerators concerns materials research. Many methods and processes have been developed in ion-beam treatment of materials based on atomic as well as nuclear physics.

1. INTRODUCTION

Materials modification as well as materials analysis is a fairly new field of applications as indicated in the chapter 'Non-medical Applications of Linacs'. The requirements on the accelerators are, however, very specific according to the task which has to be met. As indicated in the introduction to the non-medical applications chapter, the name 'linear accelerator' includes by definition also electrostatic machines, not only the RF linacs. Thus the applications for materials analysis are presently mainly using the electrostatic accelerators because of the much better energy resolution which is directly proportional to the depth resolution inside a solid material.

2. ACCELERATOR-BASED METHODS IN MATERIALS RESEARCH

Accelerators are basic instruments in materials modification as well as materials analysis. Materials modification covers the ion implantation which has developed to such an extent that materials can almost be tailored by the proper selection of parameters. Some examples of relevant material properties are:

Mechanical properties: wear, friction
ductility, elasticity
brittleness, machinability
shape persistence
stability against traction,
compression, torsion

Electrical properties: conductivity (T dependent)
persistence against light
superconductivity
magnetic susceptibility

Thermal properties: thermal conductivity
heat persistence
shape persistence
surface resistivity

The energy deposition during ion bombardment of systems containing several components leads to mixing processes which also include ion-beam enhanced, radiation-induced diffusion. These processes are important, for example in the metallizing of ceramics.

Additional fields of application in materials science cover topics in catalysis, corrosion studies, and porosity of materials for which the density of holes are important. Some fields outside natural science and technology are criminology, archeology, art and history.
Many new materials are tailored on an atomic basis as the following list of new materials indicates:

Ceramics with special thermal-insulation properties or high-temperature resistivity (nitrides, zirconia, carbides);

Biomaterials;

Composites (polymer fibres or new polymers);

Memory alloys;

Metallized glasses

Powder metallurgy.

3. METHODS FOR MATERIAL ANALYSIS

Table 1 summarizes the methods and indicates their detection limits. Some of them will be described subsequently.

<table>
<thead>
<tr>
<th>ACRONYM</th>
<th>TITLE</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBS</td>
<td>Rutherford Back Scattering</td>
<td>Element profiling, determination of quantities, level (10^{-3}) at. %</td>
</tr>
<tr>
<td>ERDA</td>
<td>Elastic-Recoil Detection Analysis</td>
<td>Determination of quantities, H - profiling, level (10^{-3}) at. %</td>
</tr>
<tr>
<td>NRA</td>
<td>Nuclear-Reaction Analysis (prompt)</td>
<td>Profiling, quantities, level (10^{-4} - 10^{-5}) at. %</td>
</tr>
<tr>
<td>NRRA</td>
<td>Nuclear-Resonance Reaction Analysis</td>
<td>Profiling, quantities, level (10^{-3}) at. %</td>
</tr>
<tr>
<td>CPAA</td>
<td>Charged-Particle Activation Analysis</td>
<td>Quantities (bulk), level (10^{-6} - 10^{-7}) at. %</td>
</tr>
<tr>
<td>NAA</td>
<td>Neutron-Activation Analysis</td>
<td>Quantities, level (10^{-9}) at. %</td>
</tr>
<tr>
<td>PIXE</td>
<td>Particle-Induced X-Ray Emission</td>
<td>Quantities</td>
</tr>
</tbody>
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Materials analysis is presently one domain of accelerator applications. The fundamental fact that charged particles are specifically scattered from other charges (Rutherford- or Coulomb-scattering) which makes it possible to determine the atomic number of the scatterer, was first applied in the 60's by Turkevich in an unmanned space mission to the moon to determine the consistency and composition of the moon's surface [1], which started the RBS method.

The Rutherford scattering is mainly used as a diagnostic method for composite solid-state material in the near-surface region (several mm) using helium beams. The energy mostly used up to now barely exceeds 2 MeV. Analysis of heavy elemental impurities in light matrices can
reach a very high degree of sensitivity. For example, heavy impurities in silicon can easily be detected up to a few ppm(a). For the data analysis a simulation is mainly used which not only allows the composition to be determined but also the distributions of the elements under consideration [2].

![Graph showing analysis of magneto-optical layers by RBS](image)

**Fig. 1** Analysis of magneto-optical layers by RBS

The measurement of a scattering process deals in the majority of cases with the scattered particle. The spectroscopy of the recoiling particle, however, has the advantage – particularly if a heavy particle hits a light nucleus e.g. hydrogen – of measuring these recoils almost background-free. The method, called elastic-recoil detection analysis (ERDA), has gained much attention in recent years.

In the case of light impurities being detected in a heavy matrix the RBS is less favourable; because of the statistical nature of counting, the sensitivity is reduced to the percent region. There are, however, nuclear-scattering effects in addition which can be used for determination of light elements in a heavy matrix. The cross sections of some scattering processes as well as nuclear reactions show resonances at specific excitation energies. If the projectiles approach that energy the reaction or scattering yield is considerably enhanced (see Fig. 2). In these resonances the cross section can exceed the average cross section by several orders of magnitude such that at these projectile energies the sensitivity of the measurement is considerably enhanced. One widely used method to determine oxygen is the $^{16}\text{O}(\alpha,\alpha')^{16}\text{O}$ reaction which shows a resonance at 3.036 MeV. Since the information about oxygen is important in almost all materials analytical laboratories will in future tend to use accelerators which can reach at least that energy. Similar effects are known for other light elements such as nitrogen and carbon at different energies, for which some data is given in Table 2:
Fig. 2  The enhancement of the counting yield for oxygen detection at 3.036 MeV

<table>
<thead>
<tr>
<th>REACTION</th>
<th>RESONANCE ENERGY (MeV)</th>
<th>RESONANCE WIDTH (keV)</th>
<th>$\sigma_{res}/\sigma_{Ruth}$</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}(\alpha, \alpha)^{12}\text{C}$</td>
<td>4.265</td>
<td>27±3</td>
<td>120 (170.5)</td>
<td>[3]</td>
</tr>
<tr>
<td>$^{14}\text{N}(\alpha, \alpha)^{14}\text{N}$</td>
<td>3.576</td>
<td>&lt; 4</td>
<td>~3 (168.2)</td>
<td>[4]</td>
</tr>
<tr>
<td>$^{16}\text{O}(\alpha, \alpha)^{16}\text{O}$</td>
<td>3.036</td>
<td>8.1±0.3</td>
<td>~10 (165)</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>300</td>
<td></td>
<td>[7]</td>
</tr>
</tbody>
</table>

This table should just be regarded as an example to show how the requirements of the energy resolution is urgent for analysis applications, particularly of the small width of some resonances in nuclear excitation functions.

If we follow the list of acronyms the nuclear reaction analysis (NRA) is one of the most widely used methods for analysis, because for all isotopes of the chart of nuclei data the structure of the nuclei exist. In almost all cases very specific features can be selected which allow almost uniquely to determine the species and its quantity and in many cases their distribution. In particular, the combination of the nuclear analysis with other methods allows a better insight into the condensed-matter material. This is particularly true if the reaction analysis
is performed under channeling conditions. Here it is possible, if single-crystalline material is used, to determine the location of an impurity inside a channel [8].

Nuclear-resonance reactions can be applied very successfully. The specific energy at which their resonance occurs is well suited to determining the nucleus under consideration at a well-defined depth inside the material. Therefore the method can also be applied to detect elements which otherwise cannot be measured. As an example the detection of hydrogen should be mentioned. From nuclear physics studies the reaction $^{15}\text{N}(p, \alpha\gamma)^{12}\text{C}$ [9] was well known, particularly the excitation function was measured very accurately, as shown in Fig. 3. The reaction was measured in the mode indicated by the bottom abscissa, the inverse mode with nitrogen as projectile needs energies as indicated on the top abscissa of the figure.

![Graph showing the excitation function for the reaction $^{15}\text{N}(p, \alpha\gamma)^{12}\text{C}$](image)

Fig. 3 The excitation function for the reaction $^{15}\text{N}(p, \alpha\gamma)^{12}\text{C}$ [9]

The inverted reaction allows the hydrogen content to be determined. The principle is shown in Fig. 4. Starting with a bombarding energy $E_0$ the nitrogen ions loose energy in penetrating the hydrogen containing material. All along the path nuclear reactions occur, but if the resonance energy is reached the $\gamma$-ray yield is drastically increased. From the energy loss the depth can be calculated and the $\gamma$ counting rate is proportional to the hydrogen content. Figure 5 shows an analysis of a layered structure of TiO$_2$ and SiO$_2$ which show different hydrogen content depending on the production process [10]. At present the nuclear analysis is the only method by which hydrogen in a solid-state matrix can be measured.

The formation of radioisotopes in particle bombardment is a well-known process since the artificial radioactivity was discovered by F. Joliot and I. Curie in 1934. Many isotopes are used as tracers in industrial applications but most of the long-living isotopes are produced in nuclear reactors. Isotope production using accelerators allows the analysis of impurities in solid material down to extremely low levels. The Charged-Particle Activation Analysis (CPAA) is a favourite method to detect impurities in semiconductor material where the role of the light elements carbon, nitrogen and oxygen is still a matter of research. The method is explained in Fig. 6. The samples to be investigated are activated in period (1) until time $t_q$. The second period (2) is necessary to dismount the samples from the irradiation chamber and to clean the
surface and in the third period (3) the usual measurement of a decay curve follows. From the different half-lives the isotopes can be identified and the extrapolation to $t_0$ allows the quantity to be determined. The detection limits for CPAA were already mentioned in the introductory table of this paragraph.

Fig. 4 The measurement principle for hydrogen detection

Fig. 5 Hydrogen content in a multi-reflection layered structure. The open and closed symbols indicate different production methods [10].

The detection limits of Neutron-Activation Analysis (NAA) exceed those of CPAA by several orders of magnitude. However, the light elements cannot be analysed by NAA. NAA is still a domain of nuclear reactors.

The last of the listed methods, the Particle-Induced X-ray Emission (PIXE), is also an accelerator based method. It allows the elements to be determined by their characteristic X-ray emission. This method also allows quantities to be determined but not elemental distributions.
4. **FINAL REMARKS**

The above mentioned methods are still at the beginning of their development, particularly in industry. There is a great potential for their use and for their improvement. The application of linacs has not at all been explored but there is still a need for higher ion energy which would allow the analysis depth to be extended considerably. The limiting factor will be the energy straggling of the penetrating ions which in a certain depth, depending on energy, sample material and ion species, will overcome the initial energy resolution. But that should not be done at the expense of spatial or depth resolution.

Furthermore, it should be emphasized that all the ion-beam-based methods give only part of the results necessary for the understanding of solid materials and their properties. The ion-beam analysis results have to be combined with results from other methods concerning the gross properties of the material e.g. conductivity, mechanical stability, etc. Many more methods and particularly the improvements of the necessary apparatus will be the tasks for the near future.

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**REFERENCES**


