ION BEAMS PROVIDED BY SMALL ACCELERATORS FOR MATERIAL SYNTHESIS AND CHARACTERIZATION

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INTRODUCTION

As a result of ion beam irradiation of a material, two types of collision occur: inelastic collisions and elastic collisions.

In inelastic collisions two phases exist. In the first phase particles are emitted (NRA – Nuclear Reaction Analysis). This is followed in the second phase by the emission of γ-rays (PIGE – Particle Induced Gamma-ray Emission spectroscopy) or X-rays (PIXE – Particle Induced X-ray Emission spectroscopy).

In elastic collisions two main phenomena are taking place: (i) the primary ion beam is back-scattered and is used in Rutherford Back-Scattering spectrometry (RBS) and (ii) lighter atomic nuclei can be ejected, recoiling from the heavier projectile ions. This is the principle of Elastic Recoil Detection Analysis (ERDA).

The IBA methods employ ion beams of various elements with kinetic energy ranging from hundreds of keV up to tens of MeV, beam currents are at most units of microA. For production of the probing ions different types of mostly electrostatic accelerators (single-ended Van de Graaf or Cockroft-Walton accelerator, Tandetron) are utilised.

The information about investigated samples is provided via measurement of energy spectra of scattered ions, recoiled atoms or secondary radiation induced by ion bombardment.
INTRODUCTION

• Modification of crystalline materials and glasses by ion implantation, preparation of nano-structures with significant optical, magnetic or electrical properties.
• Ion beam analysis of multi-layered, crystalline, amorphous materials for optics, electronics, spintronics.
• MC modelling of ion and matter interaction, defect creation, radiation damage, ion beam transfer through crystalline samples.
• 3D elemental mapping using ion microprobe it means the focused ion beam irradiation.
• Trace elements study in aerosols for the environmental studies.
• Ion beam micromachining, optical microstructure deposition.
• Study of energetic ion interaction with matter, energy losses and energy straggling, fundamental study of ion interaction with solids.
• Irradiation of the living cells using external beam of energetic ions for dosimetry.
• Study of chemical composition of the materials for nuclear power plants (nuclear fuel rods, study of heavy element diffusion in rocks for nuclear waste storage), materials for nuclear fusion.
• Characterization of materials for biomedicine, environmental research, archaeometry.

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• Irradiation of the living cells using external beam of energetic ions for dosimetry.
ACCELERATOR TANDETRON

RBS (Rutherford Back-Scattering spectrometry)
ERDA (Elastic Recoil Detection Analysis)
PESA (Proton Elastic Scattering Analysis)
PIXE (Particle Induced X-ray Spectroscopy)
PIGE (Particle Induced Gamma-Ray Spectroscopy)
NRA (Nuclear Reaction Analysis)
TOF-ERDA (Time of Flight ERDA)
RBS-channeling
Ion implantation

** Ion energy $E$, terminal voltage $U_T$ 

$E = (n+1) \cdot U_T$

Tandetron 4130 MC, Nuclear Physics Institute, Prague

Figure 2.2: The scheme of the Tandetron 4130 MC. Labelled parts: Duoplasmatron ion source (A), Cs sputter ion source (B), Li charge exchange canal (C), ion optics elements (D), 90° switching/analyzing magnet (E), Q-snout lens (F), Low-energy accelerator tube (G), HV terminal with gas stripper (H), High-energy accelerator tube (I), Electrostatic quadrupole triplet lens (J), High-energy switching/analyzing magnet (K), RF driver electrode (L), Rectifier stack (M), Capacitor coupling ring (N), RF oscillator coil (O), RF driver (P). Ref. [9].
Particle Induced X-ray Emission spectroscopy (PIXE), Particle Induced Gamma-ray Emission spectroscopy (PIGE) and Proton Elastic Scattering Analysis (PESA)
Ion-Microprobe with 1 μm lateral resolution, external beam accessories for on air irradiation
High-energy ion implantation - modification of materials, nano-structure synthesis.
Scanning Ion Microprobe – enables precise lateral elemental mapping.

Multianalytical chamber
PIXE, PIGE, PESA and RBS
RBS (Rutherford Back-scattering Spectrometry) is a non-destructive nuclear method for elemental depth analysis of nm-to-μm thick films. It involves measurement of the number and energy distribution of energetic ions (usually MeV light ions such as He⁺) back-scattered from the atoms within the near-surface region of solid targets.

A projectile ion of the mass $M_1$, atomic number $Z_1$ and initial kinetic energy $E_0$ penetrates the sample into the depth $x$, where it elastically scatters from a target atom of the mass $M_2$ and atomic number $Z_2$ under the scattering angle $\theta$, having kinetic energy $E_2$. The back-scattered ion escapes from the sample with kinetic energy $E_3$.

$$E_1 = E_0 - \Delta E_{in}$$
$$E_3 = E_2 - \Delta E_{out}$$

We have to take into account the energetic losses of ions $\Delta E_{in}$ penetrating to the depth $x$ and the energetic losses of ions $\Delta E_{out}$ after elastic collision. Energy losses are described by linear stopping power $S_p$, which is a function of energy.

$$\Delta E_{in} = S_p(E_0) \cdot \frac{x}{\cos \alpha}$$
$$S_p(E_0) = - \frac{dE}{dx}$$

Number of back-scattered ions in the spectra $Q_D$ is given by the cross section of elastic scattering $\sigma(\theta)$, the detector solid angle $\Omega$, the flux of ions $Q$ and areal density of target $N_s$.

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

RUTHERFORD BACK-SCATTERING SPECTROMETRY - RBS
Detection limit $10^{13}$ atoms/cm$^2$. Mass resolution should be improved using heavy ion projectiles $\Delta M < 2$.

Rutherford differential cross section

$$d\sigma = \frac{(Z_1 Z_2 e^2)^2}{16 E^2} \frac{1}{\sin^4 \Theta / 2}$$

Measurement of light elements - sensitivity will be improved using resonance cross sections

2.4 MeV H$^+$ - C, N, O, Si

3.04 MeV He$^+$ - O
Heavy ions enable us to get the better mass resolution.
RBS-CHANNELING

RBS-channeling spectrometry - enables us to investigate crystalline materials. The signal of the impurity and host lattice in RBS spectra is separated by scattering kinematics. The angular yield curve (scan) is obtained by monitoring the yield of the impurity and host lattice along the channeling axis using ion beam impact angle changing. From the angular yield curves of the axial channels in material we obtain the impurity position in the measured crystallographic direction. In order to determine the lattice position of impurities several relevant crystallographic directions have been selected.

\[ \psi_c = \sqrt{\frac{U(r_{\text{min}})}{E}} \]
\[ \psi_c \approx 1^\circ \]

Lindhard theory

\[ \chi_{\text{min}} = Nd\pi \rho^2 \]
\[ \psi_c = (2Z_1Z_2e^2 / Ed)^{1/2} \]
RBS- CHANNELING

STUDY OF CRYSTAL DAMAGE

Dechanneled yield of back-scattered ions
-- given by part of ions randomly redistributed
\[ \chi_D(z) = \chi_R(z) + (1 - \chi_R) f \frac{n_D(z)}{n} \]
-- given by disordered atoms – disordered atoms density \( n_D \)

\[ \chi_R(z) = \chi_V(z) + [1 - \chi_V(z)] \left[ 1 - \exp \left( -\int_0^z \delta_D n_D(z') dz' \right) \right] \]

- yield of ions in virgine crystal \( \chi_V(z) \)

dechanneling – parameter
\[ \delta_D \approx \frac{\pi Z_1 Z_2 e^2 d}{2 E} \]

\( E \) – ion energy
\( Z_1, Z_2 \) – projectile and lattice nuclei charge
\( d \) – lattice constant

The relative amount of the dislocated atoms for \( N_D/N \) is deduced from the equation \( N_D/N = (\chi_D - \chi_V)/1 - \chi_V \), where \( \chi_V \) is the minimum yield in the aligned virgin spectra and \( \chi_D \) is the minimum yield in the aligned spectra of the implanted samples.
MC simulation of the large number of ions incoming into the crystal lattice was performed. The string potential was used with taking into account the screened Thomas-Fermi potential.

- the binary collisions with the closest atoms should be taken into account
- the deflection caused by the string potential of the atoms
- the energy electronic losses, the angle straggling of the ions, the energy straggling
- the thermal vibrations of the crystal lattice (Gaussian isotropic distribution)

\[
V(\vec{r}) = \frac{Z_1 Z_2 e^2}{\vec{r}} (0.1 e^{-6r/a} + 0.35 e^{-0.3r/a} + 0.55 e^{-1.2r/a})
\]

RBS-CHANNELING - INTRUMENTATION

- National Electrostatics Corporation, USA

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The elastic-recoil detection analysis (ERDA) is one of the IBA methods suited for the non-destructive depth profiling of light elements in bulk samples. It is based on the detection of atoms which are knocked out from the sample by incoming heavy ions. When only kinetic energy is measured, ions of different elements coming from various depth within the sample can produce the same signal in the energy detector. In addition, also elastically scattered primary ions can be detected which further complicate the acquisition and evaluation of the energy spectra. To overcome this difficulty Time-of-Flight ERDA (TOF-ERDA) was developed.
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HV ... Time detector high-voltage supply
V ... Energy detector voltage supply
T-DETE ... Time detector
Si-DETE ... Energy detector
CFD ... Constant-fraction discriminator
FAMP ... Fast timing amplifier
PAMP ... Preamplifier
TAC ... Time-to-amplitude converter
Q-MON ... Accumulated charge monitor
AMP ... Amplifier
DELAY ... Delay box
ADC ... Analog-to-digital converter
MPA ... Multi-parameter data acquisition system
PC ... Personal computer
Measurement of the time of flight of ions through the TOF telescope serves for distinguishing the outgoing ions and recoiled atoms according to their mass. The time of flight \( t \) is given by the non-relativistic formula.

\[
t = l \sqrt{\frac{m}{2(E_{\text{out}} - E')}}
\]

\( l \) ... Fixed distance of flight
\( m \) ... Recoiled atom mass
\( E' \) ... Energy loss of recoiled atom in the time detector

**Testing of TOF spectrometer**

**Used parameters**
- Ion beam: 15.4 MeV Cu\(^{6+}\) (terminal voltage: 2.2 MV)
- Used sample: 200 nm LiF layer deposited on glassy carbon
PIXE uses X-ray emission for elemental analysis. Samples are irradiated by an ion beam from an accelerator and characteristic X-rays are then detected.

Ions, or protons, with energies of a few MeV ionize atoms in the sample and induce the emission of characteristic X-rays.

The X-ray yield depends on the number of atoms in the sample, the ionization cross section, the intensity of the ion beam.

Depending on the sample type and measuring apparatus, the concentration of elements with Z>5 can be determined with sensitivities of 0.1–1 μg g⁻¹.
PIXE AND NRA

Nuclear reaction methods are suitable for identifying a range of isotopes from $^1$H to $^{32}$S. The most frequently used reactions are $(p,\alpha)$, $(d,p)$, and $(d,\alpha)$ which provide useful alternative methods for determining isotopes such as $^2$D, $^{12}$C, and $^{16}$O, compared with Rutherford Back-Scattering spectrometry (RBS) or Elastic Recoil Detection Analysis (ERDA).

Isotopes up to $^{32}$S can be determined in heavier matrices at mgg$^{-1}$ levels depending on the maximum beam current that the sample can withstand. The use of glancing measurement geometries or heavy incident ions make possible depth profiling with typical resolutions at the surface of 10–100 nm.

Experimental chamber for simultaneous analyses by PIXE, RBS, PESA and PIGE

- RBS detector determination of major elements (N,C,O ...)
- PESA detector determination of H
- Si(Li)PIXE determination of Al - U
- Si(Li)PIXE determination of Li,B,F,Na,Mg,Al ...
PIGE INSTRUMENTATION

- PIGE (particle-induced gamma-ray emission) is a versatile non-destructive analytical and depth profiling technique based on the $(p, \gamma)$ reaction. The energy and intensity of the $\gamma$-ray lines indicate the elements that are present and their amounts, respectively.
- For protons with energies from 1 to 3MeV, the best sensitivities are found for Li, B, F, Na, and Al.
- The highest cross sections are for light isotopes ($A<30$), which can be determined with a sensitivity of 1 $\mu$gg$^{-1}$ or less.
ION MICROPROBE AND EXTERNAL BEAM

Microbeam elemental Th mapping in rocks for nuclear waste disposal

Heavy ion beam micromachining – microstructures for Laser generated multi energetic ion beams

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The oxidation dynamics study, different oxygen concentration in the different depths, RBS gives information about the oxygen depth distribution, while the nuclear reaction separates information about $^{18}$O concentration, the oxidation is observed at grain boundaries.

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>ZrO$_2$ Concentration</th>
<th>O$_{18}$ Concentration</th>
</tr>
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<tbody>
<tr>
<td>1 (11 x 50 µm) ZrO$_2$</td>
<td>50 %</td>
<td>50 %</td>
</tr>
<tr>
<td>2 (11 x 50 µm) ZrO$_2$</td>
<td>18 %</td>
<td>82 %</td>
</tr>
<tr>
<td>3 (30 x 30 µm) Zr</td>
<td>1.7 %</td>
<td>?</td>
</tr>
</tbody>
</table>

3D elemental mapping
- Oxidation study of Zr alloys
- Oxidation in $^{16}$O and afterwards in $^{18}$O

Used ion beam
H$^+$ ions, $E = 2050$ keV
1 h 40 min, scan 75 x 75 µm
ION IMPLANTATION

High energy ion implantation line

Beam Scanning

Electrostatic scanning (low/medium beam current implanters (I < 1mA))

Scan Patterns

This type of implanter is suitable for low dose implants. The beam current is adjusted to result in \( t > 10 \) sec/wafer. With scan frequencies in the 100 Hz range, good implant uniformity is achieved with reasonable throughput.

Production of Au ions

Different charge states

<table>
<thead>
<tr>
<th>Q</th>
<th>fraction</th>
<th>MeV</th>
<th>ME/Q^2</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>26%</td>
<td>6</td>
<td>1162</td>
</tr>
<tr>
<td>2</td>
<td>34%</td>
<td>9</td>
<td>443</td>
</tr>
<tr>
<td>3</td>
<td>22%</td>
<td>12</td>
<td>263</td>
</tr>
<tr>
<td>4</td>
<td>7%</td>
<td>15</td>
<td>185</td>
</tr>
<tr>
<td>5</td>
<td>1%</td>
<td>18</td>
<td>142</td>
</tr>
<tr>
<td>6</td>
<td>0%</td>
<td>21</td>
<td>116</td>
</tr>
<tr>
<td>7</td>
<td>0%</td>
<td>24</td>
<td>96</td>
</tr>
<tr>
<td>8</td>
<td>0%</td>
<td>27</td>
<td>83</td>
</tr>
<tr>
<td>9</td>
<td>0%</td>
<td>30</td>
<td>73</td>
</tr>
<tr>
<td>10</td>
<td>0%</td>
<td>33</td>
<td>65</td>
</tr>
</tbody>
</table>

Gas Stripper Charge Distribution

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NANOSTRUCTURES IN CRYSTALS AND GLASSES

- Nanocomposite glasses containing metal or semiconductor nanoparticles in glass matrix have promising utilisation in optoelectronics and photonics as all-optical devices.
- The presence of metal nanoparticles leads to an increase in nonlinear optical response, which is caused by surface plasmon resonance. Due to the Kerr optical effect, the typical values of the nonlinear refraction index can be increased from $10^{-18}$ cm$^2$ W$^{-1}$ (undoped silica glass).
- The resulting nonlinear optical properties of nanocomposite materials depend on the size, shape as well as distribution of the embedded metal nanoparticles.
- Concerning the nucleation of Ag nanoparticles in the glass, it is well known that precipitation occurs mainly during high-ion-fluence implantation.
- At lower ion fluence, the precipitation of Ag nanoparticles can be supported by increasing the energy of the implanted ions or by changing the composition of the glass matrix.

The chemical composition of the silica glasses used as a host matrix for metal nanoparticles [in at. %].

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Density [g·cm⁻³]</th>
<th>Si [at %]</th>
<th>Na [at %]</th>
<th>Al [at %]</th>
<th>Ca [at %]</th>
<th>Mg [at %]</th>
<th>K [at %]</th>
<th>O [at %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass A</td>
<td>2.49</td>
<td>25</td>
<td>10</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>0.2</td>
<td>60</td>
</tr>
<tr>
<td>Glass B</td>
<td>2.32</td>
<td>31</td>
<td>3</td>
<td>1.2</td>
<td>0.004</td>
<td>-</td>
<td>-</td>
<td>65</td>
</tr>
<tr>
<td>Silica glass</td>
<td>2.2</td>
<td>33.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>66.67</td>
</tr>
</tbody>
</table>

Various silica-based glasses were implanted with 1.7 MeV Ag⁺ ions with fluences of 1x10¹⁶ cm⁻² and annealed at 600 °C for 5 hours.
Ag\textsuperscript{+} ions, 330 keV, fluence $1 \times 10^{16}$ cm$^{-2}$, annealing 600 °C, 5 h.
UV-VIS spectra were collected at ICHT using a CARY 50 dual beam spectrometr in transmission modes in the range from 300 to 800 nm.

Glasses A and B became yellow after the ion implantation, the absorption maxima were observed at 390 and 380 nm. In silica glass maximum appears at 400 nm.


LiNbO₃ IMPLANTATION – RBS CHANNELING ANALYSIS

1. RBS dopant depth profiling in as-implanted and as-annealed samples. RBS channeling structural study of the crystal recovery in different crystallographic orientation after the annealing procedure.

2. The mechanism of recovery of the damaged structure of LN during the post-implantation annealing. In the Y⊥ cuts the recovery of LN lattice as well as defects migration is slow.

3. In such a case erbium ions seem to be more mobile and do not create clusters, which was proved by broadening the erbium concentration profiles (RBS) and by increasing luminescence intensity.

<0001> LN, 330keV, Er⁺ 2.5 x10¹⁵ cm⁻²

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Axial angle scan along the main crystallographic axes <0001>, <01-10> and <11-20>.

Er dopant positioning in crystalline matrix of LiNbO$_3$. 
Wide bandgap semiconductors such as GaN can be used for blue to ultraviolet (UV) light-emitting diodes, lasers, and detecting devices as well as high-frequency, high-temperature, and high-power electronic devices.

Ion implantation is successfully used for this purposes, but in order to make the implanted ions optically and electrically active, the implantation damage-related defects must be annealed out without dissociation of host atoms.

The structure after the annealing especially in the case of the $1 \times 10^{15}$cm$^{-2}$ implantation fluence is recovered significantly; some remaining disorder is presented in the implanted layer as shown by Raman spectroscopy. The surface morphology changes are influenced by the chemical properties of the implanted elements.
A channeling RBS spectrum’s yields (aligned spectrum), at a selected depth \( z \), are increased by direct scattering of the channeled component from displacements and the scattering of the dechanneled component from lattice atoms. The usage of the known minimum yields depth profiles \( c_D(z) \), which is deduced from the RBS aligned spectra enables us to extract by the iterative procedure the depth profiles of the displaced atoms by iterating channel by channel the aligned spectrum and converse it into the dislocated atoms density.

A damage-buildup behavior is illustrated by the disorder depth profiles containing the surface peak caused by the surface disintegration under the high fluence implantation and the peak ascribed to the disorder distributed in the implanted layer.
Graphene, a two-dimensional (2D) sheet of carbon atoms arranged in a honeycomb lattice, attracted recently a huge scientific interest, due to its outstanding transport properties, chemical and mechanical stability and to the scalability of graphene devices to nanodimensions.

- Chemical synthesis of graphene relies on the usage of various chemical reagents.
- We demonstrated that these chemical treatments significantly contaminate graphene with heteroatoms/metals, depending on the procedures followed. Graphene was intentionally doped by deuterium to follow the chemical synthesis.


Production of diffractive optical elements by modulating the refractive index of the material well below its surface by use of high energy ion implantation.

- to imitate interferometrically produced optical gratings by producing quasi-sinusoidal refractive index profiles making by modulating irradiation fluence across the grating lines, utilizing that the intensity distribution of the ion microbeam is close to Gaussian
- transmission phase optical gratings with grating constants ranging from 2 µm to 15 µm were designed and fabricated in Pyrex glass by 2 MeV H\(^+\) and 6 MeV C\(^{3+}\) microbeam irradiation.

Metal/polymer nano-structured materials with shallow metal depth profiles are of the high importance for plastic electronics. Polyimide (PI), polyetheretherketone (PEEK), and polyethyleneterephthalate (PET) foils were implanted with 80 keV Co\(^+\) ions at room temperature to the fluencies from 0.2x10\(^{16}\) cm\(^{-2}\) - 1.0x10\(^{17}\) cm\(^{-2}\). Oxygen and hydrogen depletion was examined using RBS and ERDA techniques. The most dramatic changes in electrical resistivity with the increasing ion implantation fluence were observed in PEEK. The Co particles with the largest diameter were observed in PET samples.

Surface electrical resistivity of the metal ion implanted polymers as a decreasing function of the ion implantation fluence in connection to electronic and structural changes of irradiated polymers. A UV VIS spectroscopy indicates the absorption edge shift and saturation effect with ion implantation fluence.

### ELECTRICAL AND OPTICAL PROPERTIES OF IMPLANTED POLYMERS


**Tauc expression**
\[ \alpha(\nu) h\nu = B(h\nu - E_g)^n \]

\( \alpha(\nu) \) – absorption coefficient dependence on the electromagnetic radiation frequency \( \nu \), \( n \) chosen for direct or indirect transitions
ENERGY STOPPING OF ENERGETIC IONS

$\Delta E$ is the energy loss in the foil and $\Delta t$ is the thickness of the foil.

$S = \frac{\Delta E}{\Delta t}$

$E_1$ is the energy of the ions backscattered from the Nb surface layer. The energy of backscattered ions is deduced from the formula $E_1 = KE$.

$E$ is the incident ion energy and $K$ is the kinematic factor.

- The stopping power and energy straggling of energetic ions in matter is important to many applications dependent on the transport of ions in matter such as:
  - ion beam analysis techniques, and in consequences in the application of metal composites in microelectronics optoelectronics prepared by ion implantation
  - the dosimetry of ions and radiology or radiation safety due to similarity of polymers to human tissue.

ION BEAMS PROVIDED BY SMALL ACCELERATOR
The stopping powers of Li, Co and O ions in the mean energy range of 3 - 10 MeV for PC, PP, PI etc. compared to the theoretical predictions made by the SRIM and MSTAR codes.

The measured stopping powers agree within the quoted error with those calculated with SRIM code with implemented CAB model for both ions species.

The significant deviation between the measured stopping powers of the ions in the compounds and the MSTAR-code calculation based on Bragg’s rule is caused by the differences in chemical and electronic structure of the investigated polymers.


- $\Omega_i$ and $\Omega_f$ are the variances of RBS signals for direct and slowed down beams, respectively. $S_i$ and $S_f$ are the ion stopping powers at the entrance and exit of the polymer foil, respectively.
- The theoretical predictions of the Bohr theory $\Omega_B$ were done by SIMNRA 6.06.

$$\Omega^2 = \Omega_{\exp}^2 - \delta^2 \Delta E^2$$

The reduced energy straggling $\Omega/\Omega_B$
The irradiation of non-polar polyolefins (PE, PP, PS and fluoropolymers) leads to creation of polar groups on the polymer surface and in this way it enhances printability, wettability, adhesion with inorganic materials (e.g. metals) or with biologically active components. One of the possible modification techniques is the plasma exposure or ion beam treatment.

The SEM images of PE foils before (HDPE and LDPE) and after 400 s (HDPE/400, LDPE/400) modification in Ar plasma with power 1.7 W.

Concentration depth profile of oxygen incorporated in HDPE and LDPE. The profiles were determined by RBS technique.

The dependence of the contact angle on the plasma exposure time for LDPE and HDPE measured 0.1 h (0.1) and 386 h (386) after the exposure to plasma discharge of 1.7 W power.

The investigation of ion beam modified polymers as materials with better bio-functionality and bio-compatibility and potential application in medicine.

Oxidation of the polymer surface upon ion irradiation increases its wettability and surface polarity.

Bio-compatibility tests
- surface wettability and polarity
- cell adhesion on the surface
- cell proliferation and cultivation

For all ion species the maximum adhesion was observed for the ion fluence of $3 \times 10^{13}$ cm$^{-2}$. It can be concluded that the optimum surface polarity exists for which the adhesion achieves a maximum.

CONCLUSIONS

Ion beam analysis gives us opportunity to get a complex information about the investigated structures and materials. These analytical methods are irreplaceable in material research.

Ion beams are powerful tool for material modification, new structure preparation and study of basic processes taking place in solid state after the irradiation by energetic ions.

Acknowledgements

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A topical review by the Nuclear Physics Division of the European Physical Society
Edited by Anna Macková, Faïcal Azaïez, Johan Nyberg, Douglas MacGregor and Eli Piasezky

Introduction by Walter Kutschera

Published by the
Cultural heritage studies

- The ion microbeam set-up has proven to be versatile and allows many analytical techniques to be in combination. The ion beam is focused onto a spot as small as a few hundred nanometers in diameter. By scanning the beam over the sample surface a 2D distribution of elements can be determined. Varying the ion beam energy may even allow a 3D distribution to be obtained. The results are elemental maps of the investigated artefact. The determination of trace elements often allows information to be deduced regarding the origin of the artefact or its manufacturing process.

- Neutron beams offer a wide range of possibilities to explore the compositional or structural features of the samples. The low energy and relatively low intensity of guided neutron beams ensure no long-term damage is done to the objects studied and any induced radioactivity generally decays within a few days. Neutron beam tomography is used to map the internal structure and morphology of historical artefacts and teaches us about ancient production technologies.

- Radiocarbon dating provided by AMS has proved to be one of the most useful dating tools for archaeological, environmental and geological studies which all benefit from the ability to date organic materials.

- X-ray fluorescence is a valuable technique used in the elemental identification of cultural heritage objects because it is non-invasive, non-destructive, and highly sensitive. It is a quantitative technique which can, in many cases, be used directly on the surface of the objects to provide information about the chemical composition of inks and paint pigments.

- The European initiative for Extreme Light Infrastructure laboratories in Romania (ELI-NP), will shortly provide tunable energy γ-rays from inverse Compton scattering of laser light on a high-energy electron beam. This will allow Nuclear Resonance Fluorescence studies of isotope-specific trace element distributions to be performed with unprecedented sensitivity. It is planned to use this powerful tool for cultural heritage object studies.

- Preservation often requires high intensities of irradiation. One of the main applications is the sterilisation of an object by γ-rays, a method widely used for medical equipment. The purpose is to kill any bacteria, fungi, or woodworms which would otherwise destroy the object over a period of time.

- The topical review paper is extensively illustrated with important discoveries and examples from archaeology, pre-history, history, geography, culture, religion and curation, which underline the breadth and importance of this field.

European facilities using nuclear techniques to study cultural heritage

The map below shows the spread of permanent laboratories and centres with facilities used for nuclear physics studies of Cultural Heritage objects across Europe.

- Ion Beam Analysis Facilities in Europe
- European Neutron Sources
- European Accelerator Mass Spectrometry Facilities
- Other European Centres, Facilities and Laboratories

- The large number of groups and laboratories contributing to the study and preservation of cultural heritage across Europe indicate the enormous effort and importance of this activity.

- For more detail the full paper can be downloaded from the EPS website: http://xxx.xxx.xxx