Foreword

In 2001 we presented a first report on the status of the Centro de micro-Análisis de Materiales (CMAM). Now in the second edition of such a document we report for the first time on the activity of CMAM since the 5 MV tandem accelerator, the heart of the research centre, was installed by the engineers of High Voltage Engineering Europa and passed successfully the acceptance tests in August 2002.

In the two years elapsed since this date, the CMAM has experienced a formidable development activity conceiving and constructing new beam extensions lines to undertake exciting research projects and experiments. Originally the accelerator was delivered with one multipurpose extension line, the standard line. Now, as described in detail in the report, two extra lines are practically ready to be used, and five more are in the way of construction or design. So far, with the existing facilities, different techniques have been used to understand the properties of a wide range of systems, from those at the technological edge like materials for photonics, to issues of environmental importance like the level of contamination in our soil and air; from the implantation of ions to modify properties, to elements of fine arts like paintings from the Museo Nacional del Prado.

The goals of the CMAM are to facilitate the use of its sophisticated equipment to the scientific and industrial community, both at a national and international level. The Centre is continuously increasing its collaborations with other universities, research centres and private institutions. Besides, as this laboratory is installed in the Campus of the Universidad Autónoma de Madrid (UAM) and in the staff of CMAM there are professors of UAM, the use of the laboratory for teaching students, senior undergraduate or graduate, is also foreseen.

To stand and maintain such ambitious projects the CMAM has experienced an increase on its staff in the last two years. The enthusiasm and motivation shown by the staff involved in CMAM, allows us to look ahead with optimism. The Centre has also received the support of the Universidad Autónoma de Madrid and the Parque Científico de Madrid. Here, we publicly acknowledge and appreciate their involvement.
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1. INTRODUCTION

The Centro de Microanálisis de Materiales (Center for Microanalysis of Materials) hereon designated as CMAM was officially inaugurated by the Rector of Universidad Autónoma de Madrid (UAM) on March 24, 2003. It is the first scientific Center installed at the Cantoblanco premises of the Scientific Park of the Community of Madrid (PCM). The executive board of the PCM is constituted by the Regional government of Madrid, the University Autónoma of Madrid (UAM), the University Complutense of Madrid (UCM), the National Research Council (CSIC), the Center for Energy and Environmental Research (CIEMAT) and the Santander-Central-Hispano (BCSH) Bank. The CMAM is located in a new building at the Michael Faraday Street in the Cantoblanco Campus of UAM (Madrid). This report describes the present status of CMAM as of June 2004 and summarizes the main scientific and technical activities carried out at CMAM during the period January 2002- June 2004.

2. OBJECTIVES

The main objectives of CMAM are:

- Provide scientists in Universities, Research Centers and Industries with the powerful ion-beam analysis (IBA) techniques using the 5 MV tandem accelerator installed at the Center.
- Develop an ambitious program of research that will be focused on Materials Science, Art and Archaeometry, Environmental Sciences, Biology and Biomedicine and Nuclear Physics.
- Establish scientific links and develop joint research projects with other national and international Institutions.
- Contribute to the scientific and technical education of students in Accelerator and Ion-beam Physics and Applications.

The Centre aims at becoming a reference Laboratory in Europe.
3. PERSONNEL

Presently, the personnel of the Centre is constituted by:

Aurelio Climent Font (Professor of Applied Physics, Director, since beginning of project, April 1998)
Gaston García López (Chief Engineer, Vice-director, July 2000)
Fernando Agulló-López (Professor of Applied Physics, since beginning of project, April 1998)
Dirk O. Boerma (Professor of Surface and Thin Layers Physics, Sept. 2001)
Tomás Calderón (Professor of Mineralogy, Research Ass. to CMAM, Sep. 2002)
Maria Teresa Fernández (Post-doctoral Researcher, May 2001)
José Emilio Prieto (Ramon y Cajal Researcher, June 2004)
David Martín y Marero (Ramón y Cajal Researcher, July 2004)
Raúl Gago (Ramón y Cajal Researcher, September 2004)
Juan de la Figuera (Ramón y Cajal Researcher, assoc. to CMAM, Nov. 2002)
José Olivares Villegas (CSIC Senior Scientist, associated to CMAM, Jan. 2003)
Raquel González Arrabal (Post-doctoral Researcher, February 2003)
Ángel Muñoz Martín (Post-doctoral Researcher, February 2003)
Javier García Zubiri (Electronic Engineer, September 2001)
Olga Enguita Pedrosa (Mechanical Engineer, January 2000)
Angel Guirao Elias (Electronic Engineer, June 2004)
Oscar Espeso Gil (Computing Engineer, September 1999)
Diego Obradors Campos (Engineer from CSIC, April 2004)
Beatriz Renes Olalla, (Management and Administration, since beginning of project, April 1998)
Antonio Javier Rodríguez Nieva (Technician, December 2000)
Jaime Narros Fernández (Technician, November 2002)
Carlos Pascual Izarra (Ph.D. Student, Sept. 1999)
Farid El Gabaly (Ph.D. Student, November 2002)
Roch Andrzejewski (Ph.D. Student, July 2003)
Ewelina Andrzejewska (Ph.D. Student, July 2003)
Nuria Gordillo García (Ph.D. Student, April 2003)
Helena Calvo del Castillo (Ph.D. Student, June 2004)
Jeroen Hofstee (Undergraduate ERASMUS Student, May 2004)
4. COMMITTEES

The operation of CMAM is managed by an Executive Committee, assisted and advised by a Scientific Committee:

a) Executive Committee

This committee is in charge of all administrative, technical and scientific aspects of the Centre. It is presently formed by:

Aurelio Climent Font (Chairman)
Gastón García López
Fernando Agulló López
Dirk O. Boerma
Maria Teresa Fernández Jiménez
Javier García Zubiri
Beatriz Renes Olalla (Secretary)

b) Scientific Committee

The objective of this committee is to make suggestions and advise on the main lines of the scientific policy. It has been established by the Rector of the University Autónoma of Madrid and is chaired by the Vicerrector of Scientific Infrastructure. The committee was appointed the 26th March 2004 and will serve for a two years term. Its members are:

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<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<tbody>
<tr>
<td>Excmo. Sr. D. José Mª Sanz</td>
<td>Vicerrector de Infraestructura y Promoción Tecnológica</td>
</tr>
<tr>
<td>Excma. Sra. Dª Mª Jesús Matilla</td>
<td>Vicerrectora de Investigación</td>
</tr>
<tr>
<td>Sr. D. Aurelio Climent</td>
<td>Director del Centro de Micro-Análisis de Materiales</td>
</tr>
<tr>
<td>Sr. D. Cayetano López</td>
<td>Director del Parque Científico de Madrid</td>
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<tr>
<td>Sr. D. Fernando Agulló</td>
<td>Centro de Micro-Análisis de Materiales</td>
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<td>Sr. D. Fernando Sols</td>
<td>Director del Instituto de Ciencia de Materiales Nicolás Cabrera</td>
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<td>Sr. D. Dirk Boerma</td>
<td>Centro de Micro-Análisis de Materiales</td>
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<td>Sr. D. Carlos Sánchez</td>
<td>Departamento de Física de Materiales</td>
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<td>Sr. D. Juan Piqueras</td>
<td>Departamento de Física Aplicada</td>
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5. FACILITIES OF CMAM

5.1 Building

The CMAM occupies a new building that is located at the premises of the Scientific Park of the Community of Madrid (see Fig. 1). It consists of two different structures: the accelerator hall and the complementary building.

The accelerator hall has an approximately rectangular shape with dimensions of 34 m by 17 m. The useful height is 5 m. The hall is shielded with concrete walls of 1 m thickness to assure the outside radiation levels comply with the regulations established by the Spanish Nuclear Safety Council (CSN). The hall is connected to the complementary building through the control room. Two labyrinths (a narrow one for personnel and a wider one for small equipment) allow for the access to and from the hall to the control room. Cables and piping lie mostly inside covered trenches. The complementary building contains offices, mechanical and electronic shops, a meeting and seminar rooms, and laboratories for sample preparation, optical measurements and Mossbauer spectroscopy.

The accelerator hall and control room are equipped with neutron and gamma ray area detectors that continuously monitor the radiation levels. The entrance to the hall is provided with safety interlocks and signals in accordance with legal requirements.
The accelerator is a 5 MV tandetron electrostatic machine supplied by High Voltage Engineering Europe (HVEE). A photograph of the accelerator at the CMAM hall is shown in Fig. 2. Two negative ion sources are available: a duoplasmatron gas source and a sputtering source. Ions acquire a positive charge $Z$ after crossing the charge stripper canal. After the second accelerating stage the energy reached for a terminal voltage setting $V$ [MV] is $(Z + 1) V$ [MeV]. The high voltage is generated by the Cockcroft-Walton multiplier system, without moving parts. A remarkable high voltage stability and low noise have been assessed, as well as the possibility of low energy operation. Aside from the conventional IBA techniques the maximum terminal voltage of 5 MV allows for:
a) Production of light ion beams up to 10 MeV (hydrogen) and 15 MeV (He). Production of intermediate mass ion beams with energies above 1 MeV / amu (e.g. Si up to 40 MeV).

b) Production of heavy mass ion beams with enough energy to use the ERDA-TOF technique (e.g. I or Au at 60 MeV).

c) To use the PIXE technique with heavy ions.

d) To deeply implant ions in materials for Microelectronics and Optoelectronics purposes.

The whole system is computer controlled from the control room, allowing for the operation of the machine under significant levels of radiation.

Fig.2: General view of the 5 MV tandetron accelerator at the CMAM hall.

The installation and testing of the accelerator were successfully completed on August 2002. After commissioning, the performance figures obtained were above expectations, and some of the values can be observed in Fig. 3.
Fig. 3: Performance figures obtained after commissioning of the accelerator.

5.3 Beam Extension Lines

The present status of the planned experimental lines is as follows:

1. Standard Line (in operation)
2. External microbeam Line (in operation)
3. PIXE Line for Environmental Studies (in operation by summer 2004)
4. ERDA-TOF Line (under construction)
5. UHV Line for Surface Physics (under testing)
6. Nuclear Physics Line (under construction)
7. High resolution Line with Magnetic Spectrograph (under construction)
8. Implantation and Radiation Damage Line (under design)

The general layout of the lines is shown in figure 4 and some details of the lines are summarized below.
5.3.1 Standard Line (Responsible: Aurelio Climent)

This is a multipurpose line (RBS, ERDA, PIXE, PIGE, NRA and Channeling) provided by HVEE together with the accelerator. It includes an experimental chamber equipped with a 3 axes goniometer. The control and data acquisition software allows for the remote control of all movements in the chamber and the automated realization of experiments. This line was operative at the same time as the accelerator (August 2002) and benefited from useful up-dating contributions by Dr. Ferenc Pastzi. A general view of the standard beamline is shown in figure 5.
This line permits to send a focused beam (with a size around or smaller than 100 microns) outside the vacuum system through a thin window. It can be scanned over the object and will be particularly useful for studies of Art and Archaeometry. The key elements of the line (slits and a doublet of quadrupole lenses) have been purchased from Oxford Microbeams. The supporting table for automatic positioning and scanning of the samples has been manufactured by RLS Merilna Technika, Ljubljana (Slovenia). The rest of the line has been built at the central shop of UAM. The assembling of this line has been part of Olga Enguita Pedrosa Ph.D. Thesis, and has benefited from the experimental contributions of Dr. Alessandro Zuchiatti. Regular operation started in November 2002. A general view of the beamline is shown in figure 6 and an example of its use to study the ink of an Italian drawing from the XVI century is shown in figure 7.

Fig. 6: General view of the external microbeam line.

Along the year 2003 the following main technical and development activities have been performed:

1) Optimization of the beam focusing system based on a high precision electromagnetic quadrupole doublet.
2) Determination of the beam size by optical methods recording the ion-luminescence from a fluorescent screen. A beam size of 60 to 100 micrometers is obtained routinely.

3) Performance of the first PIXE measurements on two Chinese Tang ceramic figures.

4) The external microbeam facility has been presented at the 2003 International Conference on Ion Beam Analysis held in Albuquerque, New Mexico.

![Fig. 7: Studying an Italian drawing from the XVI century with the external microbeam line.](image)

5.3.3 PIXE Line for Environmental Sciences (Responsible: María Teresa Fernández)

The PIXE line will be devoted to environmental studies and eventually to biological and biomedical ones.

Most elements of the line come from a similar line installed in the accelerator of the University of Groningen and transferred to Madrid by Prof. D. Boerma. In particular, it
uses a chamber allowing for the automatic computer controlled measurement of a high number of samples (51) mounted on a three-faced sample holder. A part of the line and its electronic control has been built at the UAM and is shown in figure 8.

The chamber can be filled with helium gas for cooling of the sample during irradiation, to prevent electrical charging and to reduce evaporation of volatile components. The unfocused proton beam passes through a pair of slits, defining the opening, and a pair of magnetic sweeping coils, so homogeneous irradiation of the sample is obtained. This line is at final installation stage and regular operation is expected during summer 2004.

Fig. 8: General view of the PIXE line for environmental sciences.

5.3.4 ERDA-TOF Line (Responsible: Aurelio Climent)

In this line the energy and velocity of the recoil atoms of the sample will be simultaneously measured. The velocity will be determined from the flight time of the ions between two detecting stations. The line will be used to measure the concentration
profiles of the atoms ejected from the sample by impact with incoming heavy ions. The line has been designed by CMAM (Prof. Aurelio Climent, Dr. Angel Muñoz and Mr. Oscar Espeso) and is being built at the central shop of the UAM. As a second stage in the building of this setup, a gas ionization chamber detector will be also installed using another port of the main experimental chamber. This detector will provide a robust and easily-handled alternative to obtain information similar to that of the TOF system. The line is presently under construction and its telescope can be seen during tests in figure 9.

![Telescope of the TOF line during tests in the workshop](image)

**Fig. 9: Telescope of the TOF line during tests in the workshop**

### 5.3.5 UHV Line for Surface Physics (Responsible: Dirk Boerma)

The main set-up consists of a number of coupled UHV chambers obtained from the University of Groningen. It has been transferred to the CMAM and is now ready for operation. The set up and commissioning of the equipment was part of Raquel González Arrabal post-doctoral research and the Ph.D. Thesis of Nuria Gordillo Garcia and
Ewelina Andrzejewska. The system is provided with evaporation cells for metals and a radio-frequency source for atomized gases (N, O) for the growth of epitaxial layers of metal nitrides and oxides. These layers can be studied on-line with low-energy electron diffraction (LEED), low-energy ion scattering (LEIS) and (as soon as the beam line is mounted) with RBS/Channeling. The beamline connecting it to the accelerator will be mounted in the autumn of 2004. The system is used for the growth of Fe-nitride and -oxide layers with special magnetic and optical properties. It will also be used to create nano-structured layers with special electrical or magnetic properties for device applications.

5.3.6 Nuclear Physics Line (Responsible: Olof Tengblad)

This line is going to be set up by the group of Prof. O. Tengblad at Instituto Miguel Catalán (CSIC) and financed by this organism. The beamline is already under construction.

5.3.7 Line of the Magnetic Spectrograph (Responsible: Dirk Boerma)

We are building a magnetic spectrograph with a design value for the energy resolution enabling the probing of the composition and atomic structure of samples with a sub-nanometer resolution. This resolution can be achieved near to the surface. For deeper layers the resolution is gradually degraded due to energy straggling of the ions in the sample. The instrument combines the high resolution with a solid angle for ion detection of ~ 20 milli-steradian, which is larger by almost two orders of magnitude as compared with most existing spectrographs. As far as we know the entire concept is new for materials science applications.

Briefly the instrument works as follows: Elastically scattered or recoiled ions emerging from a sample are detected within a solid angle of ~20 msr, and the emission direction within this solid angle is determined in two dimensions with a resolution of 0.2 degrees. This is done by inserting a foil of diamond-like carbon (DLC) with a thickness of only ~5 nm in the cone of ions to be detected. The foils are produced in collaboration with a Kurchatov Institute in Moscow. The thickness of the foil is sufficient to obtain charge equilibration of the ions. On the other hand it is thin enough not to impede the energy or
angular resolution significantly. Secondary electrons emerging from the foil upon the 
passage of an ion are guided by a combination of electric and magnetic fields to a 2-D 
position-sensitive channelplate detector. In this way the position of the ion passing the foil 
can be determined. The rest of the spectrograph is more or less “standard”, with the 
exception of the extra large gap of the 110 degrees sector magnet needed for the large solid 
angle and the short object and image distances. In the focal plane the ions are detected with 
a 1-D position-sensitive detector. The energy of the ions is derived from the position of the 
impact in the second detector. The time-relation between counts in the first and second 
detector is measured, enabling the unique identification of the velocity of the ion. Combined with the measured energy the mass and charge state of the detected ion are 
uniquely determined, after applying on-line computer processing of the collected data.

With the spectrograph depth profiles of elements in the sample can be measured with 
ultra-high depth resolution and on an absolute concentration scale. This scale is determined 
by the known (near-to-Rutherford) cross sections for scattering or recoiling of ions. The 
charge state of the ions emerging from the sample drops out of the calibration, because 
each charge state will be translated into the same charge-state distribution after passage 
through the foil. The necessary corrections for kinematical effects can be made, knowing 
the angle of emergence from the sample. For mono-crystalline samples the angular 
distribution of the ions measured within the detection cone, with the sample oriented in a 
special direction, contains information about the location of the atom involved in the 
scattering or recoiling process (channeling/blocking technique). To extract this information 
from the data, computer simulations of the trajectories of the ion through the sample into 
the detector are necessary. In these simulations all the physical processes of importance for 
ion solid interactions, like charge exchange and energy loss, should be included. Simulations of this type (that is for incoming or recoiled ions heavier than He) have not 
been tried until now. The necessary programs have been created in collaboration with a 
group at the Moscow State University (Dr. V. A. Khodyrev) that has a large reputation in 
the field.

The information to be obtained by these measurements, namely composition, atomic 
positions of the different (possibly implanted) species, crystalline order (damage), all as a 
function of depth, is unique and very useful, for instance for device physics. The depth 
range for which this information can be obtained can be extended to the micrometer range 
by beveling the sample under a small angle.
At present the design of the spectrograph and the electronic system is finished and the instrumentation is being commissioned. It was part of Roch Andrzejelewski Ph.D. thesis. An artist impression is shown in figure 10. The very thin diamond-like carbon (DLC) foils supported by a very thin-wired grid and the accelerating grid are almost finished at a Kurchatov Institute in Moscow. We are now designing the (ultra-high) vacuum systems and transfer systems. These systems are equipped with limited facilities for sample preparation, and without any growth facilities. Samples will be transferred into the magnetic spectrograph from a “vacuum suitcase”. This is an UHV system into which samples from external systems in different institutes can be inserted under UHV conditions and, after transport, can be inserted without breaking the UHV condition; into the spectrograph. The transport system is such that it can be easily adapted to any external system provided with a sample introduction system. The design is suited for the transport of samples from UHV facilities of the department of solid state physics of the UAM, of the Institute for Micro Electronics in Tres Cantos, and of the Institute of Materials Science, Cantoblanco.

Fig. 10: The magnetic spectrograph including the scattering and detector chambers
5.3.8 Radiation Damage and Implantation Line (Responsible: F. Agulló-López)

A project has been started in cooperation with CIEMAT for the installation of a line devoted to radiation damage and ion implantation. The design and construction of the line would be under the supervision of E. Hodgson (CIEMAT) and the CMAM team.

5.4 Complementary Facilities

- A laboratory with a Scanning Tunneling Microscope (STM) has been installed at CMAM by the Surface Physics group from the Condensed Matter Physics Department (UAM). Responsible: Juan de la Figuera
- A general usage laboratory for sample preparation and manipulation is being equipped in the upper floor of the CMAM building. Responsible: María Teresa Fernandez
- A room for manipulation of environmental and biological samples is being installed. Responsible: María Teresa Fernández
- A Mössbauer spectroscopy laboratory for the study of samples containing the enriched isotope $^{57}$Fe is now in operation. Responsible: Dirk Boerma
- An Optics laboratory. Responsible: José Olivares.

6. EXTERNAL USERS OF THE ACCELERATOR

The regular operation of the accelerator and the experimental program were started in October 2002 after alignment and calibration of the standard line and testing of the goniometer. So far the following types of measurements have been performed:

- RBS with He at 2-4 MeV
- RBS channeling with He at 2-3 MeV
Simultaneous RBS and ERDA with He at 1.6 MeV
ERDA/RBS with Si at 30-35 MeV
ERDA/RBS/Channeling with C, in the range 1.8-14 MeV.
Implantations of Si, Cu, F, O, Nb, Mg ...at energies of up to tens of MeV.
Implantations of H in the energy range of 1 to 3 MeV.
PIXE measurements in the microbeam and Standard lines have been carried out with protons at around 3 MeV.
PIGE measurements in the Standard line with protons at around 3 MeV.

Except for a few interruptions due to minor failures the accelerator has operated 4-5 days a week 8 hours a day. Experiments have been performed in collaboration with the following external groups:

1. University Autónoma Madrid
   1.1. Dpto. Física Aplicada
       J.M Martínez Duart, Fernando Rueda, Juan Piqueras, José María Sanz, Alejandro Gutiérrez, Pablo Pernas, Manuel Hernandez, Rafael Pérez Casero and Pilar Prieto.
   1.2. Dpto. Materiales
       José Manuel Cabrera, Ginés Lifante, Gonzalo de la Paliza and Carlos Sánchez.
   1.3. Dpto. Materia Condensada
       Miguel Ángel Ramos.
   1.4. Dpto. Química Agrícola
       Tomás Calderón and Asunción Millán.
   1.5. Departamento de Prehistoria y Arqueología
       Concepción Blasco

2. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)
Angel Ibarra

3. Consejo Superior de Investigaciones Científicas (CSIC)

3.1. Instituto de Ciencia de Materiales de Madrid (ICMM):
José María Albella, Cristina Gómez-Aleixandre, Luis Vázquez, Carlos Prieto and Elisa San Román.

3.2. Instituto de Óptica (IO, CFMAC):
José Olivares, Carmen Alfonso, José Gonzalo and Rosalía Serna

3.3. Instituto de Microelectrónica de Madrid (IMM)
Fernando Briones and Marisol Martín González

3.4. Departmento de Prehistoria, Instituto de Historia
Ignacio Montero

4. British Petroleum Solar:
René Müller and Juan Manuel Fernández

5. Instituto Nacional de Técnica Aeroespacial (INTA):
Dolores Sabau, Armonía Nuñez Peral and Gonzalo Ramos Zapata

6. Museo Nacional del Prado (Madrid)
José Manuel Matilla

7. Instituto del Patrimonio Histórico Español (IPHE)
Marian del Ejido

8. Museo de América (Madrid)
Andrés Escalera Ureña, M. Paz Cabello Carro, Ana Verde Casanova, M. Concepción García Sainz
9. Università di Firenze
   Franco Lucarelli and Maximo Chiari

10. Instituto Nazionale di Fisica Nucleare
    Alessandro Zucchiatti

11. University of Surrey
    Geoff Grime

12. University of Oxford
    Inmaculada Gómez Morilla

13. University of Lisbon
    José C. Soares

14. KFKI-Research Institute for Particle and Nuclear Physics, Budapest
    Ferenc Paszti

15. Soitec (Grenoble, France)
    Konstantin Bourdelle

16. Institute of Physics, National Autonomous University of Mexico (UNAM)
    José Luis Ruvalcaba

7. RESEARCH LINES OF CMAM
The research programme of CMAM is now in its initial stage. In this section the different research lines that have been started are briefly summarized. The section is organized in paragraphs devoted to the various areas of interest.

### 7.1 Physics of Ion-Solid Interactions

Apart from the fundamental point of view, there is also a practical interest in getting first-hand data of the stopping powers for a variety of materials relevant for microelectronics and material science which are being investigated at CMAM. So far the program has focused on:

**a)** RBS-based measurements of stopping power of alphas on Si, Ti, Pd, and their nitrides in collaboration with the CNA (Accelerator Laboratory, Sevilla, Spain). Some NRA measurements were also used to characterize some of the samples.

**b)** High precision RBS measurements and Monte-Carlo simulations to determine the stopping power of He on Silicon Oxide in collaboration with the CNR-IMM (Bologna, Italy). As an extension of this work, a research collaboration has been started between the CMAM, the Optics Institute Miguel Catalán (Madrid, Spain), the CNR-IMM (Bologna, Italy) and the ITN (Lisbon, Portugal), to measure the stopping power of alpha particles on Aluminum Oxide. Special emphasis is devoted to the data analysis techniques, developing methods to obtain continuous stopping power curves from RBS experiments.

**c)** A collaboration has been recently started with the JYFL (Jyväskylä, Finland) to install at CMAM an advanced Time-of-flight technique to measure continuous stopping power curves in transmission geometry. This technique is especially suitable to obtain data of the energy loss of heavy ions in a very efficient way. Some experiments have been already performed for He, O, Si and Ar ions on Silicon Nitride.

Those items correspond to a PhD thesis under way (Carlos Pascual-Izarra, supervised by Aurelio Climent-Font).
7.2 Materials Science

a) A project led by Fernando Agulló-López and Aurelio Climent-Font is underway, on the application of the IBA technique ERDA-TOF to optical waveguides produced on LiNbO₃. Two production techniques are being considered: proton exchange with host lithium and Zn diffusion. The objective is to clarify the exchange and diffusion mechanisms and determine the stoichiometry of the phases generated in the substrate and responsible for the waveguiding behavior. The project is being partly realised in collaboration with the accelerator laboratory of the University of Helsinki (Finland).

b) Research collaboration has been started with the Group of materials for solar cells and hydrogen storage (Carlos Sánchez, UAM). The objective is to characterize the pirite films prepared by electrochemical deposition and explore their potential for microelectronics and photovoltaic applications. Measurements have been performed at the accelerator laboratories of the University of Helsinki and University of Oxford.

c) Research collaboration has been started with the Microelectronics Laboratory at UAM to characterize SiON waveguides on SiO₂ substrates prepared by PVD deposition and determine the optimal growth conditions. In addition to measure the O/N ratio that determines the refractive index of the waveguiding layer the H contents appears very relevant to minimize losses of the propagating modes.

d) A long term research programme on the use of Ion irradiation and implantation for Optoelectronics and Photonics has started in 2003 in collaboration with Instituto de Optica del CSIC (José Olivares). Particularly novel waveguides with nano-structure have been produced in LiNbO₃ with the use of “Ion Track Technology” (Patent pending) and fundamental issues on the amorphization threshold have been addressed (see publications submitted).

e) Study of membranes using porous aluminum. Information on the shape and density of the pores has been inferred from the RBS spectra with He at 4 MeV using a tilted geometry.
f) In cooperation with CIEMAT a project has been started to determine the diffusion profiles of light atoms in insulating materials for nuclear fusion applications. As a first objective, the D diffusion profiles after low energy (60 keV) implantation are being determined by RBS.

7.3 Surface Physics

This new line of research is starting with the incorporation to CMAM of Prof. Boerma (from the Groningen University), in collaboration with the Surface Physics group of the Condensed Matter Physics Department UAM (Rodolfo Miranda). In the framework of this collaboration two new experimental set-ups (magnetic spectrograph and UHV Surface Physics set-up) are being established at CMAM.

The initial stage of the research program will focus on the growth and characterization of iron and copper nitrides and the preparation of tunnel junctions. The electrical properties of the (multi-) layers are determined in the Institute for Microelectronics (IMM-CSIC) in Tres Cantos, Madrid. In a second stage of this project the UHV facilities of the CMAM (growth chamber and magnetic spectrograph) will be connected to the growth and characterisation facilities of the group CIII and of the IMM-CSIC. This will enhance the research opportunities and widens the accessibility of the ion-beam analysis applied to surfaces and thin layers.

Additional research lines: Coulomb explosion, FeN phases, Simulation of ion trajectories, Growth of Fe4N, ultrasoft magnetic nano-crystalline Fe-N layers, Comparison of measured and calculated surface phe se transition in Fe4N, Magnetic nano-patches of Fe4N, Depth profiling of He in Si with resonant C scattering.

7.4. Environmental, Biological and Biomedical Sciences
A collaborative project has been started with the group of Analytical Chemistry (M.T. Sevilla Escrivano, UAM), devoted to the combined study of new methodologies for metal speciation in atmospheric particles and in bioindicator plants based on sequential extraction methods PIXE and XRD techniques. The aim of this research study is to develop and validate new analytical methodologies to make studies of atmospheric contamination by metals. These methodologies will allow establishing correlation between metal species concentrations in atmospheric particulate and in bioindicator plants. In a first stage, direct methods for metal analysis in atmospheric particles and in plant tissues will be developed and validated, based on Atomic Absorption Spectrophotometry with electrothermal atomisation (ET-AAS) and Proton Induced X Ray Emission (PIXE). Later on, new strategies will be developed for characterization of heavy metal species in both kinds of samples. Special attention will be paid to obtain information about the bioavailable fraction.

The correlation of the effects of the toxic metals on the plant species and the atmospheric metal concentrations in the sampling sites will allow us to evaluate the pollution level and to characterize certain plant species as bioindicators of the toxic metal contamination process in the zone of the study.

In cooperation with the Department of Atmospheric pollution of the Town Hall of Madrid and within the framework of an official agreement between the City Council and UAM, the analysis and characterization of the urban aerosol of Madrid City will be performed. The project includes comparative studies performed at The Centro de Nacional de Aceleradores of Seville and with the Istituto Nazionale di Fisica Nucleare of Florence. Elemental composition of the suspended matter in air will be determined, evaluating temporal and spatial variability of contaminants, controlling if limit levels directives are achieved, and applying statistical methods to identify the main sources of pollution as well as their effects and apportionment. Finally a comparative study to the aerosol of Seville and Florence will be accomplished.

### 7.5. Art and Archaeometry

Concerning the research projects, during 2003, where the microbeam is playing a relevant role, it is worth mentioning:
1) A study of archaeological bronze axes from the Iberian Peninsula (collaboration with I. Montero from CSIC).

2) A project has been started with the group of Thermoluminiscence dating (Tomás Calderón, UAM), the Institute of Spanish Historical Patrimony (IPHE), the Museum of America (Madrid) and the accelerator laboratory of the Mexico Autónoma University, devoted to the combined study of ancient Mexican ceramics with thermoluminiscence and IBA (mostly PIXE) techniques. The main objectives of that project can be resumed as follow:

   a) Creation of analytical data base of ceramics (matrix and pigment) in order to characterize some American period cultures by PIXE analysis.
   b) Relative dating by PIXE analysis; that is, construction of curves TL Dating-PIXE analysis.
   c) Development of new criteria in order to detect forgeries based in PIXE analysis.
   d) Study and characterization of mineral pigments used in American ceramics and other historical supports (papers, woods...).

3) In order to understand some of the complex phenomena that occurs when minerals are irradiated with protons, we have started to study luminescence of some natural pigments during irradiation, that is, Ionoluminescence (IOL). First results have been obtained with natural carbonate pigments.

Looking ahead to the future, several projects and collaborations are now in progress. Just to mention a few we highlight a collaborations with the Department of Prehistory and Archaeology to study gold coatings on bronze (J. Barrio) and provenance of flint fragments (C. Blasco), with the Prado Museum to study the composition of the ink in the drawings of XVI century Italian artists like Luca Cambiaso and others, or the analysis of pigments in paintings from Velazquez (C. Garrido) and with the Institute of Ancient and Prehistoric Studies from CSIC to analyze the Visigoth gold treasure of Torredonjimeno (A. Perea).
8. FUNDED SCIENTIFIC PROJECTS

Preparation, characterization and optimization of optical waveguides for optoelectronics using ion-beam techniques.

Beamline with a magnetic spectrograph detector of high resolution and sensitivity: optoelectronics applications.

New analytical methods for metal apportionment in atmospheric particles and vegetal bioindicators, based on sequential extraction methods and the PIXE technique.

Characterization of ceramic materials of historic-artistic interest through nuclear techniques (PIXE, RBS): establishment of new criteria for relative dating.

Carbon-based nanostructured systems: synthesis and characterization.

Epitaxial Cu3N layers: a new material for Photonics applications. Syntesis and characterization of epitaxial Cu3N layers.

Experimental study of stopping power in Si, metals and silicides, for ions in the MeV range.
DGICYT project, Ref. PB1998-0065 (1-12-1999 to 1-12-2002). Main researcher: A. Climent-Font.

Beam extension line for environmental and biomedical measurements.
ERDA-TOF beam extension line.

9. PUBLICATIONS

The relation includes all papers published by the members of the CMAM team during the period of the report and corresponding or related to their work at CMAM.


W. Maenhaut, D.J.A. de Ridder, M.T. Fernández-Jiménez, M. A. Hooper, B.
Hooper and M. Nurhayati, Long-term observations of regional aerosol composition

M.T. Fernández Jiménez y A. Climent Font, PIXE: una técnica para la
caracterización de aerosoles medioambientales, Revista Española de Fisica 16 (2002) 2

C. Pascual-Izarra, M. Bianconi, G. Lulli, C. Summonte
Stopping power of SiO2 for 0.2--3.0 MeV He ions, Nucl. Instr. and Meth. B 196 (2002)
209-214.

D.J.W. Mous, A. Gottdang, R.G. Haitsma. G. García López, A. Climent-Font, F.
Agulló-López, D.O. Boerma, Performance and Applications of the first 5MV
Tandetron at the University of Madrid, accepted in Proceedings CAARI 2002.

A. Muñoz-Martín, M. Vila, C. Prieto, C. Ocal and J.L. Martinez
Microstructural characterization of iron thin films prepared by sputtering at very low

M. Vila, J.A. Martín-Gago, A. Muñoz-Martín, C. Prieto, P. Miranzo, M.I. Osendi,
and J.García-López and M.A. Respaldiza, Compositional Characterization of Silicon

R. González-Arrabal, M. Eisterer, H.W. weber, D. Litzkendorf, T. Habisreuther,
W.Gawalek, S. Nariki, M. Muralidhar and M. Murakan, Trapped field

Krabbes, Very high trapped fields in neutron irradiated and reinforced YBa2Cu3O7-δ

Cabrera, A. Climent-Font, Compositional characterization of proton-exchanged
Waveguides in lithium niobate by heavy ion elastic recoil detection, Ferroelectrics 269, (2002) 63.


A.R. Chezan, C.B. Craus, N.G. Chechenin, L. Niesen and D.O. Boerma

E.H. du Marchie van Voorthuysen, N.G. Chechenin, and D.O. Boerma


10. CONFERENCES, WORKSHOPS AND SCHOOLS

10.1. Organization, Advisory and Scientific Committees

**D. Boerma**, co-organizer of Erasmus School on Hyperfine Interactions (Zakopane, POLAND).

**A. Climent-Font**, co-organizer of the International ASEVA Summer School (Ávila, SPAIN), 2002

**A. Climent-Font, D. Boerma**, Co-organizers of 5th DONOSTIA ENCOUNTERS ON PARTICLE-SOLID INTERACTIONS, Donostia International Physics Center, 9-15 September 2003 (San Sebastián, SPAIN).


**J. Olivares Villegas, G. García López**, members of the advisory committee for RADECS 2004 (Madrid, SPAIN).


10. 2. Contributions to Conferences and Workshops


**10.3. Presentations at Courses and Seminars**


R. Gonzalez-Arrabal, *Trapped field characterization in neutron irradiated (RE)Ba$_2$Cu$_3$O$_7$-$\delta$ Melt-textured superconductors*, Invited seminar, Instituto de Ciencia de Materiales, (Barcelona, SPAIN) 2002.

A. Climent-Font, *ERD with heavy ion beams*, ASEVA Summer School (Ávila, SPAIN), 2002


A. Climent-Font, *First measurements with the Madrid accelerator at CMAM*, KFKI, RMKI, (Budapest, HUNGARY), September 2003.
A. Climent-Font, *Depth profiling with RBS and ERDA techniques: an introduction to ion-beam analysis*, X International Summer School, Nicolás Cabrera, (Miraflores de la Sierra, SPAIN), September 2003.


O. Enguita, *Aplicación complementaria de PIXE diferencial y EDX a baja energía al estudio de recubrimientos metálicos*, Seminar at Institute of Physics, Department of Applied Physics, National Autonomous University (UNAM), (México, MEXICO), March 2002.


11. SCIENTIFIC RELATIONS

11.1 Collaborations

A number of scientific collaborations are underway:

- Department of Condensed Matter Physics, UAM
- Department of Physics of Materials
- Department of Applied Physics
- Institute of Microelectronics of Madrid
- Institute of Materials Science of Madrid
- CIEMAT: Radiation-enhanced diffusion, Design and Construction of Implantation line
- Prado Museum (Madrid)
- Museum of America (Madrid)
- Polytechnical University of Madrid
- National Archaeological Museum of Spain (MAN)
- University of Florence
11.2. Visitors to CMAM from other Centers and Institutions

Joseph Gyulai (IKFK, IMF, Budapest)
Ragnar Hellborg (University of Lund)
Peter Townsend (University of Sussex)
José Soares and M.F. da Silva (University of Lisbon and INETI)
José Luis Rubalcava (Instituto de Física, UNAM, Mexico)
Ferenc Pastzi (IKFK, IMF, Budapest)
Franco Lucarelli (University of Florence)
Maximo Chiari (University of Florence)
Marco Bianconi (LAMEL Institute, Bologna)
Alessandro Zuchiatti (INFN, Genova)
Miguel Angel Respaldiza (CNA, Sevilla)
Wladek Traszka (Jubaskula)
Vassily Khodyreff (Moscow)
Geoff Grime (University of Oxford)
Karim (Institute of Physics, National Autonomous University, Mexico)
Behrooz R. Naraghi, Nuclear Research Center, Teheran (Iran)
Konstantin Bourdelle (SOITECH, France)
Peter Bauer (University of Vienna, Austria)
Barney Doyle (Sandia National Laboratories, Albuquerque, USA)

12. PATENTS
Spain submission: P200400452; Date: 25-02-2004, for the use of Ion Track Technology in the production of novel nano-structured LiNbO3 waveguides.

13. BUDGET

The yearly budget for maintenance of the Center is 250.000 E.

Projects have been obtained in the period 2002-03 for the funding of new infrastructures and scientific projects for a total of 952.130 E.

Annex to section 5.3.6

Beam line for Experimental Nuclear Physics

Far from stability beta decay studies is a powerful tool to study nuclear structure. Typically the beta decay of nuclei at or close to the drip line is followed by different particle emissions apart from the usual $\beta\gamma$. These new decay modes appear due to the quadratical increase of the isobaric mass differences and a decrease of the binding energy for the last nucleon as going away from the valley of stability.

The multi-particle emission process is very interesting as it is not fully determined by the kinematics of the system as the break-up in two body does, but depends on the two-body interactions between the subsystems through which the break-up occurs. In a simplify way one speaks of sequential decay equivalent to a gamma cascade or simultaneous emission or direct three body break-up. In the latter case the measured angular and energetic correlations will give us information of the nucleon-nucleon interaction inside the nucleus.

The beta decay studies are characterized by:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection rules</td>
<td>Only certain levels are fed.</td>
</tr>
<tr>
<td>Energetic window</td>
<td>Limited by the $Q_\beta$-value</td>
</tr>
<tr>
<td>Feeding Mechanism</td>
<td>Very clean through a well known operator</td>
</tr>
<tr>
<td>Isospin</td>
<td>Allowed transitions feed levels of a limited isospin value.</td>
</tr>
</tbody>
</table>

Nuclear reactions at low energy give complementary information to beta-decay as it is shown schematically in the following:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Selection rules</td>
<td>Not very strict, Many levels with different spins and parities.</td>
</tr>
<tr>
<td>Energetic window</td>
<td>Large range limited by the energy of the accelerator beam.</td>
</tr>
<tr>
<td>Feeding Mechanism</td>
<td>Non trivial</td>
</tr>
<tr>
<td>Isospin</td>
<td>Depends on the choice of beam and target</td>
</tr>
</tbody>
</table>

We are interested in feeding through reactions the excited states of $^6\text{B}^*$, $^9\text{Be}^*$ y $^{12}\text{C}$ and follow their break-up. These studies are complementary to the ones done by us at ISOLDE (CERN). The breakup mechanism depend on the width of the levels versus the total energy available. The determination of the width of the intermediate states can only be extracted from reactions and the available data is from the sixties [See Rev Mod Phys. 37 (1965)]

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327-460. Only the reaction \(^{11}\text{B}(p,3\alpha)\) of astrophysical interest has been re-done, C. Rolfs et al., Z. Phys. A327 (1987) 341.

The development of detectors and electronics in the last years as well as the increase in computer power for calculations makes worth to repeat some of these experiments installing our experimental setup of high granularity and angular coverage in a tandem accelerator with a well define energy. We plan to use the following reactions:

\[
\begin{align*}
\text{p } + ^{11}\text{B} & \rightarrow ^{12}\text{C}* \rightarrow \square + \square + \square \\
^3\text{He} + ^9\text{Be} & \rightarrow ^{12}\text{C}* \rightarrow \square + \square + \square \\
^6\text{Li} + ^6\text{Li} & \rightarrow ^{12}\text{C}* \rightarrow \square + \square + \square \\
d + ^7\text{Li} & \rightarrow ^{9}\text{Be}* \rightarrow \square + \square + \text{p} \\
\end{align*}
\]

The new tandem of 5MV of CMAM is the ideal machine for this type of studies as it keeps the energy stable in the full range. Besides this accelerator will be very useful to test our development in detector, electronics and DAQ’s. Therefore during 2002 a MoU was signed between the CSIC and the UAM to allow us to built our beam line. In parallel the design of the line was done and it is shown in the next figure. In the figure caption the different pieces are explained.

During the year 2003 the different pieces has been ordered and most of them has been installed. The design of the collimator in the observation box has been done by one of the students, (A. Saban) and is going to be built in our workshop of the IEM (CSIC).