APPLICATIONS OF NUCLEAR PHYSICS
(Working Group 6)

General remarks of the convener

P.A. Mandò

Dipartimento di Fisica dell'Università di Firenze
Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Italy

I must start with a number of preliminary thoughts.

First, I must frankly say that at this stage (before this Town Meeting in Darmstadt) our work is largely incomplete: for a number of reasons, the time actually at my disposal to organise the contributions was very short and this can explain many failures. In particular, the lack of time is the reason why a draft report has not been published in the web in advance, as happened for those of the other groups. I apologise for this and intend therefore to consider the Town Meeting as a starting point rather than the final one for the work of the group. Contributions, suggestions, criticisms are welcome and strongly encouraged to come from the meeting attendants in Darmstadt, and also from the wider community of nuclear physicists during the next few months.

The second consideration is that the topics of applied nuclear physics are so many that - even with sufficient time at disposal - a comprehensive overview on all of them is a very hard task to anybody. The sphere of competences involved by the applications of nuclear physics is dramatically varied since they include disciplines thousands of miles away from each other, not only as to their subjects but also in terms of the mental attitude to approach them. Indeed, they span from life sciences and medicine, to humanistic disciplines like art-history, history itself and archaeology, to environmental sciences, to other scientific disciplines and technological or industrial fields; and also include the field of social security and humanitarian problems like contraband detection, anti-terrorism, demining. In addition, if providing a satisfactory survey of the present state of the art in all these fields is a difficult job, even harder is to make predictions on their future developments. Experience has shown that especially for applications the future is unpredictable; however, some trends can be anticipated and an attempt should be done to direct the efforts of the community towards those goals that appear to be more promising. Just this may be the output of our group's work and of the discussion that we will succeed in stimulating during the meeting and in the following months.

A third point arises from the recent work performed within NuPECC itself; the final report of the Dourdan meeting of November 2001 was just now (Jan 2003) published, and it contains a comprehensive review of impact, applications and interactions of nuclear physics with energy-related problems, life sciences and medicine, atomic and condensed matter physics. This report, being the result of a work started only about two years ago, is still by all means up-to-date, and we will therefore adopt it as the reference for the discussion on those topics. In any case, even to such a satisfactory review some items – untreated there - can be added, or adjournments made, and something will be done in this direction by our group. Furthermore - as by the way pointed out also in the preamble by the NuPECC board to the Dourdan report - other important fields of application of nuclear physics remained completely to be addressed, environmental studies and archaeometrical applications in particular. Besides these, what I mentioned above as "social security and humanitarian problems" is a dramatically topical subject where the techniques of nuclear physics can play an important role. Onto all these subjects we will focus with special attention in the new report to be produced after this Town Meeting in Darmstadt.

As to the organisation of our session there, in the past few weeks I had many reactions to my call for help, and received the contributions that are included as abstracts in the following pages. I am very grateful to all those colleagues who spent efforts to help me. However, due to the limited time available in the session at Darmstadt, it was not possible to allocate all the contributions for an oral presentation, and together with the NuPECC liaisons we were forced to cancel some as talks, which was a hard decision to make for me, especially because this happened after I had personally solicited some of the authors to contribute. These contributions will anyway be included in the final report, and we do hope that the authors will be willing to expand them (as is obviously expected for those that will be given as talks).

Let me conclude with some general – may be obvious but necessary – considerations on the importance of applications for nuclear science. The relationship between basic research and its fields of applications is crucial for all sciences, especially nowadays. It is particularly crucial for nuclear physics, since one way or the other the association of "nuclear" with something bad is still deep-rooted in the collective imaginary, and we have instead to show how useful for society the achievements of our science can be. And this is not a demagogical attitude to obtain the public's consensus and eventually more money from the politicians (it may be partially so, in fact, but not only). There are, indeed, further and nobler arguments that should push into the direction of enhancing the community's effort towards applications. I believe that the key role of the applications is the one of preventing us from closing ourselves within an ivory tower where we, and we only, can judge how interesting and good is a field of research. The need of continuously confronting with people having different cultural interests, different mentalities, different practical needs and different points of reference - a need which is the rule for those who work in applications - is a source of cultural enrichment that reflects also on the basic research from which those applications have derived. Not only we can give to other fields, we certainly also get from them. I have worked for almost twenty years now in applied nuclear physics and - although sometimes learning “different languages” to interact with the colleagues of other disciplines may have been hard - I am personally very happy of my choice.

A novel therapy for liver metastases: a concrete hope after the first human treatment

T. Pinelli, A. Zonta*[+]*, S. Altieri*, S. Barni*[++]*, A. Braghieri*, P. Pedroni*, P. Bruschi*, P. Chiari*[++]*, C. Ferrari*[+]*, F. Fossati* R. Nano*[++]*, S. Ngnitejen Tata*[+]*, U. Prati*[+]*, G. Ricevuti*[++]*, L. Roveda*[+]*, C. Zonta*[+]

*****INFN, Pavia and Dept. of Nuclear and Theoretical Physics, University of Pavia, Italy
[+]Dept. of Surgery, Div. of General Surgery, University of Pavia and Polyclinic S. Matteo, Pavia, Italy.
[++]Dept. of Animal Biology, University of Pavia and Centre of study for Histochemistry, C.N.R., Pavia, Italy.

Abstract

This letter reports how a novel method has been developed for the therapy of human organs affected with multi-focal and diffused metastases, a pathology without any effective remedy up to now.

The essentials of the methodology are described as well as the findings of our research. The therapeutic concept is based on the neutron irradiation of the isolated organ which, soon after such a treatment, is re-implanted according to the self-transplant procedure. Until now the research has been addressed to the case of liver metastases responsible of a significant contribution to the deaths caused by cancer(1,2,3). In the following we describe how the feasibility of the method has been proved. Pre-clinical trials performed both in vitro and in vivo are described too. Finally details of first human treatment will be reported and discussed together with the achieved results.

* * * *

The problem to treat the secondary liver metastases incidental to a primary tumour surgically resected does not meet definitive solutions neither in the medical therapy nor in traditional and most recent surgical techniques. Such metastases are generally numerous and not completely detectable by the current diagnostic methodologies (CT, NMR, PET etc).

After having considered the problem in every respect, we realized that the neutron irradiation of the entire liver could be the only way to destroy all detected and undetected metastases. So, following this idea never proposed before, we directed our attention on the isolated liver treatment in a thermal neutron field where neutrons, coming from all directions, go to cross the liver surface without neglecting any detail of the organ(4).

Of course the feasibility of such a treatment requires the solution of this fundamental problem: How to give lethal radiation doses to neoplastic tissue preserving the healthy tissues at the same time.

In 1987 we started to carry out a long term research, TAOrMINA[1], whose main objective was to study the possibility to solve the problem by exploiting the property of tumours to absorb easily boron from particular solutions injected into the blood circle(4,5). The use of boron for enhancing radiation dose in tumours hit by collimated neutron beams was suggested in 1938, six years after the neutron discovery. The absorbed dose, in this particular treatment of cancer, is released by 2 particles emitted in the final state of the thermal neutron induced reaction

$$^{10}B(n,\alpha)^{7}Li.$$

This process presents an extremely large cross-section ($\sigma = 3840$ barns) and a sensible energy release (Q=2.79 MeV). In 94% of cases the particle kinetic energies are 1.47 and 0.84 MeV for ^4He and ^7Li ion respectively. Due to their short range in tissues these particles release intense doses of radiation localized just into the single cell.

Boron Neutron Capture Therapy (BNCT) has been experimented in USA, Japan and Europe to treat malignant brain tumours by collimated thermal and epithermal neutrons. Up to now the clinical trials did not produce satisfactory results(6).

In our case collimated neutron beams are absolutely unfit to realize an effective therapy on the liver in presence of diffused cancerous nodules.

Preliminary calculations and measurements pointed out that a safe and effective treatment is ensured when the ratio (T) of boron concentration in tumour (C_T) over normal tissues (C_H) is 3.5-4 at least:

$$T = \frac{C_T}{C_H} \geq 3.5 \div 4$$

In particular cases, characterized by high values of boron concentration in tumour, lower values of this ratio can be accepted.

In addition to the above fundamental limit, the feasibility of the project depends on further conditions:

1) the neutron treatment must be concluded in few minutes to avoid severe damages to the patient in anhepatic condition;
2) the doses produced by gamma background and processes other than the neutron-boron reaction must be strongly reduced in comparison with the total absorbed dose;
3) neutron flux distribution at the irradiation position must be characterized by a good degree of uniformity;

---

[1] Italian acronym for: Advanced Treatment of Organs by Neutron Irradiation and Auto-graft

4) the minimum dose absorbed by tumour during the treatment must be higher than 40 Gy-Eq.;
5) the maximum dose given to normal tissues must be lower than 15 Gy-Eq, assumed as a conservative tolerance level(12).

When the TAOrMINA project started its activity, the existing boron measures were few, statistically unsatisfactory and limited to the brain tumour.

To give a clear answer to the mentioned feasibility conditions, we studied, for the first time with a significant statistics, the boron uptake by assuming the rat as the experimental model(4,7,8). 100 animals have been processed, 83 procedures resulted useful to get reliable data. We measured C_T and C_H in hepatic and tumour tissues after the sacrifice of the animal at predetermined times ranging from 1 to 12 hours after the boron administration. Boron was infused throughout a Fructose-BPA solution containing 250 mg of BPA per Kg of the treated rat.

The boron measurement was a crucial and difficult phase of our research. We solved the problem by an original method based on the range-energy particle relations(4,5). Boron concentrations were evaluated by analysing the α particles spectra obtained during the neutron irradiation of tumour and normal tissue samples.

Before the boron uptake study, we performed a drastic modification of the reactor thermal column (Fig.1) in order to realize new improved performances:

1) a clean position for the human liver treatment;
2) a high neutron flux (order of 10^{10} cm^{-2} sec^{-1}) in the irradiation position. Such a high flux value makes possible a fast liver treatment time from 10 to 30 minutes (Fig.1);
3) a neutron field of satisfactory uniformity;
4) a strong reduction of gamma background. In particular, the low gamma background allowed to reach a very good resolution in the boron concentration measurements (0.5 ppm).

The experimental analysis of boron uptake by tumour and hepatic tissues evidenced a clear and positive result. Such a conclusion is proved in Fig. 2 where we can verify the safety and potential effectiveness of the therapy. The observation of the figure allows to point out an important and decisive correlation: In the time interval from 2 to 4 hrs after the boron infusion, the tumour assumes the highest values of boron concentration while the normal liver goes fast to reach its minimum; the time distribution of the average value of T, the ratio of tumour boron concentration over normal liver, evidences values larger than 4. Such findings clearly prove that the neutron irradiation starting during the above interval offers a solid guarantee for a safe and effective treatment.

The excellent results of boron uptake analysis together with the satisfactory answers to the above conditions from 1 to 5 proved the feasibility of the procedure.

At this point we entered the last phase of our research including pre-clinical and clinical experiments.

Pre-clinical trials have been performed in “vivo” by utilizing the experimental rat model and in “vitro” by studying the effect of neutron irradiation on adenocarcinoma cells from DHDK line(9). In vivo experiments consisted in submitting a population of rats to the same procedure as planned for the human liver. By considering Figure 2, we evaluated doses of 82.5 and 15.0 Gy-Eq given to tumour and normal parenchyma respectively. Groups of animals were used as control for the various comparisons useful to make clear every information evidenced by the experimental data(8).

In “vivo” results are resumed in table I. Only data limited to the animals free from severe surgical damages are reported. In reading the table it’s important to take into account that in column IV, concerning the animals submitted to the complete procedure, the survival is limited to the time of their sacrifice. This because valid samples were necessary in order to individuate and study the various damages induced by the treatment in tumour and normal liver . Soon before the sacrifice the medical inspection evidenced all animals, reported in column IV, in very good general conditions.

Hepatic tissues obtained by this last population provided tumour and liver samples for the optical and electronic microscopy. Severe and irreversible damages (apoptosis and necrosis) were frequently observed in tumour cell while, after the screening of hundreds microscopy fields, none of such damages were observed in normal liver samples.

The “in vitro” experiments have substantially confirmed the “in vivo” pre-clinical trials.

The clinical trials consist up to now just in the treatment of a male 48 years old on December 19th 2001. The self-graft procedure and the neutron therapy were performed at S. Matteo Polyclinic and inside the thermal column of Triga Mark II reactor of the University of Pavia respectively. The complete operation required a time around 46 hrs. The patient’s liver contained more than 20 metastases following the removal of a colon-carcinoma few months before.

During two hours, before the liver explantation, a solution of BPA-Fructose was infused via blood circle. The BPA dose was 300 mg/Kg of the body weight. After 1 and 2 hrs from the infusion beginning, two biopsies were drawn, washed, and sent to the physicist team for boron concentration measurement in both tumour and normal liver. Then the liver was removed and, after washing, immediately sent to the reactor laboratory. Here, by following the treatment plan, the explanted liver was submitted to the thermal neutron irradiation up to reach the fluence of 4×10^{12} cm^{-2}.

The high value of tumour over normal liver boron concentration ratio ensured an optimal treatment of the liver in such a way that the normal tissues received a radiation dose noticeably under the tolerable level while the dose absorbed by the tumour tissues was such to guarantee severe and irreversible damages. Doses were calculated by using the RBE values given for both tumour and normal tissue(10,11).

Having been completed the neutron irradiation (11 min.), the organ was returned to the surgery room and re-implanted in the same donor. The patient was discharged on January 25th 2002, 37 days after the treatment; before leaving the Polyclinic, he recovered all of his functions and his general condition was good.

As regarding the neutron therapy outcome, the CT scanning evidenced, about 10 days after treatment, the liver in normal condition while the adenocarcinoma metastases appeared in a severe necrotic state.

It's particularly significant that after the neutron therapy the number of metastases detected by CT resulted larger than those visible before the treatment. Such a circumstance makes clear and concrete one of the most important characteristic of our novel therapy: neutron treatment operates everywhere inside the liver volume: small and large, visible and invisible metastases are attacked with the same effectiveness.

It's important to remark that, differently from any previous radio-therapeutic procedure the patient, except his liver, was free from any radiation damage(4,7).

Boron uptake by the human liver resulted in full agreement with the results obtained in the study on the experimental model.

Boron concentration in tumour and liver resulted of 47 ± 2 and 8 ± 1 ppm while the consequent absorbed doses were 66 ± 2 and 9 ± 1 Gy respectively. Such values configure the ideal treatment we hoped to realize. Particularly relevant is the dose absorbed by normal liver, largely lower than the tolerance dose(12).

At the present moment the situation can be focused as follows:

a) The physical therapy set up according to the lines of our scientific project met full success: the first human treatment, based on the described feasibility conditions, gave tangible proof of the possibility to irradiate the explanted organ into a thermal neutron field with no use of collimators, screens and similar. The result clearly evidenced the first and complete victory over the incurable pathology of cancer metastases.

b) Twelve months after treatment all radiological and clinical checks indicated a positive and hopeful trend of the patient's condition. This time is longer with respect the survival expected for our patient.

c) If future procedures will confirm our first result, the way to treat out of body organs will be open to face cancer more effectively.

References

1) A.M. Cohen, S. Y. Winauer, M.A. Friedman et al:
"Epidemiology", in: *Cancer of the colon, rectum and anus,* D. Schottenfeld Ed, McGraw-Hill, New York, 1995 , pp. 11-24.

2) H.C. Hoover jr., C.G. Willet:
"Overall Survival and Patterns of Failure for Surgery of Colonic Cancer" , in: *Cancer of the colon, rectum and anus,* D. Schottenfeld Ed., McGraw-Hill, New York, 1995, pp. 493-497

3) B.S. Scharschmidt:
"Human liver transplantation: analysis of data on 540 patients from four centres"
Hepatology, 4, 1984, pp 95-101.

4) T. Pinelli, S. Altieri, F. Fossati, A. Zonta, D. Cossard, U. Prati, L. Roveda, G. Ricevuti and R. Nano:
"Development of a method to use Boron Neutron Capture Therapy for diffused tumours of liver (Taormina Project)"
Proceedings of the Sixth International Symposium on Neutron Capture Therapy for Cancer, Kobe (Japan), Oct. 31st-Nov. 4th 1994, Y. Mishima Ed. , Plenum Press, New York, 783-794, 1994.

5) S. Altieri, A. Braghieri, F. Fossati, P. Pedroni, T. Pinelli, A. Perotti, M. Specchiarello, G. Perlini, H. Rief, D. Chiaraviglio, F. De Grazia and A. Zonta:
"Evaluation of a selective boron absorption in liver tumours"
Proceedings of the Third International Symposium on Neutron Capture Therapy for cancer, Bremen, May 31st-June 3rd, 1988. Strahlentherapie und Onkologie, 165, pp. 170-172, 1989.

6) A.Z. Diaz, A.D. Chanana, J. Capala, M. Chadha, J.A. Coderre, E.H. Elowitz, J. Iwai, D.D. Joel, H.B. Liu, R. Ma, N. Pendzick, N.S. Peress, M. S. Shady, D.N. Slatkin, G.W. Tyson, and L. Wielopolski
"Boron Neutron Capture Therapy for Glioblastoma Multiforme"
Frontiers in Neutron Capture Therapy, edited by M.F. Hawthorne, K. Shelly, and R.J. Wiersema. *Proceeding of the Eight International Symposium on Neutron Capture Therapy for Cancer,* Sept. 13-18 1998, Los Angeles, Ca., Kluwer Academic/Plenum Publishers, New York (2001)

7) T. Pinelli, S. Altieri, F. Fossati, A. Zonta, U. Prati, L. Roveda and R. Nano:
"Development of a method to extend, by boron neutron capture process, the therapeutic possibilities of the liver auto-graft"
Proc. Int. Conf.: Neutrons in Research and Industry, G. Vourvopoulos Ed, Crete 1996, SPIE Editor 2867, pp. 92-96, 1997.

8) T. Pinelli, S. Altieri, F. Fossati, A. Zonta, C Ferrari, U. Prati, L. Riveda, S. Ngnitejeu Tata, S. Barni, P. Chiari and R. Nano:
"Operative Modalities and Effects of BNCT on Liver Metastases of Colon Adenocarcinoma. A Microscopical and Ultrastructural Study in the Rat"
Frontiers in Neutron Capture Therapy, edited by M.F. Hawthorne, K. Shelly, and R.J. Wiersema. *Proceeding of 8th International Symposium on Neutron Capture Therapy for Cancer*, Sept. 13-18, Los Angeles, Ca., Kluwer Academic/Plenum Publishers, New York (2001)

9) A. Caignard, M.S. Martin, M.F. Michel and F. Martin:
"Interaction between 2 cellular subpopulation of a rat colonic carcinoma when inoculated to the syngeneic host", *Int. J. Cancer*, 36, pp.273-279, 1985

10) J.A. Coderre, M.S. Makar, P.L. Micca, M.M. Nawrocky, H.B. Liu, D.D. Joel, D.N. Slatkin, H.I. Amols:
"Derivations of relative biological effectiveness for the High-Let radiations produced during Boron Neutron Capture Irradiation of the 9L rat Gliosarcoma in vitro and in vivo"
Int. J. Radiation Oncology Biol. Phys., vol. 27, pp. 1121-1129

11) G.M. Morris, J.A. Coderre, J.W. Hopewell, P.L. Micca, and L. Wielopolski
"Boron Neutron Capture Therapy: Re-irradiation response of the rat spinal cord"
Frontiers in Neutron capture Therapy, edited by M.F. Hawthorne, K. Shelly, and R.J. Wiersema, *Proceedings of the 8th International Symposium on neutron Capture Therapy for Cancer*, Sept. 13-18, 1998, Los Angeles, Ca., Kluwer Academic/Plenum Publishers, New York (2001).

12) R.L. Jirtle, G. Michalopoulos, S.C. Strom, P.M. DeLuca,, and M.N. Gould:
"The survival of parenchymal hepatocytes irradiated with low and high LET radiation"
Br. J. Cancer, 49, Suppl. VI, pp.197-201, 1984.

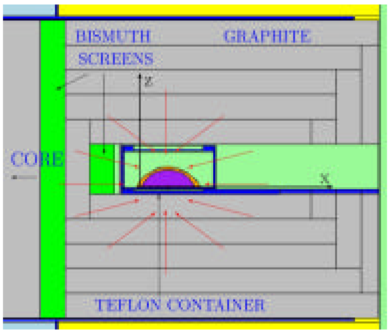

Fig.1

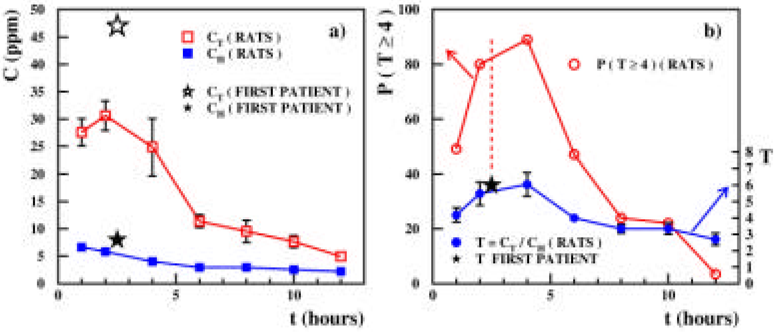

Fig.2

Nuclear techiques of analysis in the development of biokinetic models for radiological protection

M.C.Cantone

Università degli Studi di Milano,
Istituto Nazionale di Fisica Nucleare, Sezione di Milano.
Via Celoria 16, I-20123 Milano, Italy.

Since the advances introduced in ICRP Publ. 30, the efforts in developing biokinetic models for dosimetry of internally deposited radionuclides are directed towards an increased physiological realism and this trend is expected to continue in the future.

The modelling approach generally combines information from all available sources, including accident cases, studies in humans and in animals, and use of chemical analogies. Direct observation in humans volunteers provides great confidence in the biokinetic models based on and it is ethically achievable by using stable isotopes.

The high performances of nuclear activation, performed by using neutrons, photons or charged particles, which provides elemental analysis through identification and quantification of stable isotopes, have not yet been fully exploited in this field of research. In the framework of properly designed experiments conducted on volunteer subjects, this technique can contribute in the definition of kinetics and absorption processes for those elements having relevant radionuclides, but still poor or even missing data in humans.

The application of proton beams in radiobiology

Marco Schippers, PhD

Paul Scherrer Institut, 5232 Villigen, Switzerland, email: marco.schippers@psi.ch

Radiation therapy is often used to cure cancer. However, the dose that can be given to the tumor is frequently limited by the tolerance of the surrounding healthy tissue, especially when the tumor is located near a critical organ. Novel irradiation techniques, such as e.g. proton or ion therapy are developed to minimize the volume of healthy tissue that is irradiated. The goal of all these novel techniques is to increase the target dose (to obtain a higher cure rate), while maintaining the same level (or reaching a lower level) of complications due to the unavoidable radiation dose in the healthy structures.

Despite the application of the most advanced techniques, always a certain volume of healthy tissue will receive a significant fraction of the tumor dose. It is expected, however, that a reduction of irradiated volume will increase the tolerance dose of the healthy tissue. The question is how the tolerance dose of a healthy organ depends on the irradiated volume fraction. Although the tolerance dose of most healthy tissues is very well known, the relatively poor geometric selectivity of photon-dose distributions, has limited the available experience to irradiation of rather large volume fractions of the healthy organs. Therefore important tasks are to obtain data of tolerances to partial and inhomogeneous irradiation of healthy organs and to understand "dose-volume effects" in different organs.

In a collaboration between the KVI, Groningen and radiobiology groups from Groningen and Nijmegen, studies have been made of the influence of the irradiated volume of the spinal cord on its tolerance dose for paralysis. Recently a program has been granted by the Dutch Cancer Society (NKB) to study dose-volume effects in the salivary glands (the "complication" is a reduction of the saliva production) and lungs (reduction of lung functions). The aim of the program is not only to collect data, but also to develop mathematical models that can predict the complication chance from a planned dose distribution. These models are needed to predict the outcome of treatments and to evaluate the quality of planned dose distributions.

The high precision experiments are performed with rats and use 150 MeV protons from the AGOR cyclotron at the KVI. The big advantage of these proton beams is their rather sharp dose-fall off in lateral direction. This results in a clear separation between irradiated and non-irradiated tissue within the irradiated organ. The possible volume effects will thus become more apparent, but also the sharply defined dose distributions offer a unique tool to design specially shaped dose distributions in the organ. This gives very powerful means to understand underlying mechanisms that may play a role in the development and repair of tissue damage.

As an example, we have found that low (regarded as "sub-critical") doses significantly reduce the tissue tolerance to local high-dose spots. Such a situation, in which a small part of the organ receives a high dose, and the rest of the organ only gets a small dose, often occurs when the healthy organ is located adjacent to the tumor site. Also selective partial irradiation of an organ (e.g. one lateral half, or only the central part of the spinal cord) has been performed, which yielded that a uniform organ model (as employed in many mathematical dose-effect models) is too simplistic.

Particle beams, when applied with high precision, thus offer very accurate and efficient methods to investigate dose-volume effects in animal studies. These beams offer excellent possibilities to vary the shape of dose-distributions, dose homogeneity, RBE and other interesting parameters that may influence the tolerance of healthy tissue to therapeutic irradiation doses.

Accelerator Mass Spectrometry for the environment at large

R.Golser, W.Kutschera
VERA (Vienna Environmental Research Accelerator), Austria

Environmental research is perhaps one of the most important tasks of natural sciences in the near future. Sometimes, though, environmental research is considered to be a field dealing only with pollution of the environment. This is certainly a misconception, since environmental research at large includes essentially phenomena of the entire physical world. For simplicity, one may divide the environment into seven major domains: Atmosphere, biosphere, hydrosphere, lithosphere, cryosphere, cosmosphere, technosphere. Although we know the basic laws which govern the physical and chemical processes within and between these spheres, we are far from understanding the environment as a whole. Our current predictions about changes in the environment (e.g. the climate) are working hypotheses at best, far away from solid theories with real predictive power. What is needed most are good data to back up model predictions. Here nuclear physics applications can make important contributions. The following fields may be identified for experiencing promising developments in the years to come:

Accelerator Mass Spectrometry (AMS)

As a true spin-off from nuclear physics laboratories using tandem accelerators, AMS evolved into one of the most powerful tools to study our environment through ultra-low isotope ratio measurements of long-lived radioisotopes (10^{-10} to 10^{-16}). The origin of these isotopes may be cosmogenic, radiogenic or anthropogenic. AMS is a rapidly growing field with seemingly limitless applications (see Table 1). The major isotope measured with AMS is ^{14}C, but the use of other isotopes is growing rapidly [1-3]. AMS provides a unique tool to study our environment at large through the combination of ultra-sensitive isotope detection with small sample sizes and high sample throughput. The steadily growing number of AMS facilities indicate the large demand for this technique. Table 2 indicates that Europe has a large share of world-wide AMS facilities. It is evident that there is a bright future ahead for this field.

References

[1] W. Kutschera, *Accelerator mass spectrometry: Analyzing our world atom by atom*, AIP Conf. Ser. 495 (1999) 407-428.

[2] K. Fifield, *Accelerator mass spectrometry and its applications*, Rep. Prog. Phys. 62 (1999) 1223-1274.

[3] Proc. 8th Int. Conf. on Accelerator Mass Spectrometry, Vienna 1999, W. Kutschera, R. Golser, A. Priller, B. Strohmaier, eds., Nucl. Instr. Meth. Phys. Res. B 172 (2000) 1-977.

Table 1. Overview of AMS applications in the environment at large

Domain	**Area of application; nuclides measured with AMS are given in parenthesis**
Atmosphere	Production and distribution of cosmogenic and anthropogenic radionuclides (^{3}H, ^{7}Be, ^{10}Be,^{14}C, ^{26}Al, ^{32}Si, ^{36}Cl, ^{39}Ar, ^{81}Kr, ^{85}Kr, ^{129}I)
	Study of trace gases: CO_2, CO, OH, O_3, CH_4 (^{7}Be,^{10}Be, ^{14}C)
	Transport and origin of aerosols (^{14}C)
	Exchange of stratospheric and tropospheric air (^{7}Be, ^{10}Be)
Biosphere	Dating in archaeology and other fields (^{14}C, ^{41}Ca)
	^{14}C calibration studies in tree rings, corals and sediments (^{14}C)
	Studies in forensic medicine through bomb-peak dating (^{14}C)
	In-vivo tracer studies in plants, animals, and humans (^{14}C, ^{26}Al, ^{41}Ca, ^{79}Se, ^{99}Tc, ^{129}I)
Hydrosphere	Dating of groundwater (^{14}C, ^{36}Cl, ^{39}Ar, ^{81}Kr, ^{129}I)
	Global ocean circulation pattern (^{14}C, ^{39}Ar, ^{99}Tc, ^{129}I)
	Paleoclimatic studies in lake and ocean sediments
Cryosphere	paleoclimatic studies in ice cores from glaciers and polar ice sheets (^{10}Be, ^{14}C, ^{32}Si, ^{36}Cl, ^{39}Ar, ^{81}Kr)
	Variation of cosmic ray intensity with time (^{10}Be, ^{14}C, ^{36}Cl)
	Bomb-peak identification (^{36}Cl, ^{41}Ca, ^{129}I)
Lithosphere	Exposure dating and erosion studies of surface rocks (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl)
	Paleoclimatic studies in loess(^{10}Be)
	Tectonic plate subduction studies through volcanic rock measurments (^{10}Be)
	Plarimun group elements in monerals (stable trace isotopes)
Cosmosphere	Cosmic ray record in meteorites and lunar materials (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{44}Ti, ^{59}Ni, ^{60}Fe, ^{107}Pd, ^{129}I). Life on Mars ? (^{14}C)
	Evidence for supernovae occurrence through the measurment of extinct and life radionuclides in meteorites and deep-sea manganese crusts (^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{60}Fe, ^{107}Pd, ^{146}Sm, ^{182}Hf, ^{244}Pu)
	Geochemical solar neutrino detection (^{99}Tc, ^{205}Pb)
	Search for exotic particles (superheavy elements, fractionally charged particles, strange matter)
Technosphere	Releases from nuclear industry (^{14}C, ^{36}Cl, ^{85}Kr, ^{90}Sr, ^{99}Tc, ^{126}Sn, ^{129}I)
	Half-life measurements (^{32}Si, ^{41}Ca, ^{44}Ti, ^{60}Fe, ^{79}Se, ^{126}Sn, ^{182}Hf)
	Temperaure measurement of fusion plasma (^{26}Al)
	Neutron flux of the Hisoshima bomb (^{36}Cl, ^{41}Ca, ^{63}Ni)
	Nuclear safeguards (^{233}U, ^{236}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{244}Pu)
	Trace elements in semiconductor materials (stable trace isotopes)

Table 2. AMS Facilities of the World (Status December 2002)

Country	Accelerator	Location	Isotopes
NORTH AMERICA			
Canada	2.5 MV Tandetron	U. of Toronto, Toronto	^{14}C, ^{10}Be, ^{26}Al, ^{129}I, ^{236}U, trace elements
USA	0.5 MV Pelletron	U.. of Georgia, Athens	^{14}C
	0.5 MV Pelletron	U. of California, Irvine	^{14}C
	1 MV Pelletron	LLNL, Livermore	^{14}C, ^{3}H
	1 MV Tandem	NSI/MIT, Cambridge	^{14}C, ^{3}H
	2.5 MV Tandetron	U. of Arizona, Tucson	^{14}C, ^{10}Be
	2.5 MV Tandetron	WHOI, Woodshole	^{14}C
	3 MV Pelletron	U. of Arizona, Tucson	^{14}C, ^{10}Be,^{129}I
	3 MV Pelletron	NRL, Washington D.C.	^{14}C
	3 MV Pelletron	U. of North Texas, Denton	trace elements
	9 MV FN Tandem	Purdue U., West Lafayette	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{129}I
	9.5 MV FN Tandem	LLNL, Livermore	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{129}I, ^{236}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu,
	ATLAS Linac	ANL, Argonne	^{39}Ar, ^{236}U, ^{244}Pu
EUROPE			
Austria	3 MV Pelletron	U. of Vienna, Vienna	^{14}C, ^{10}Be, ^{26}Al, ^{129}I, ^{182}Hf, ^{210}Pb, ^{236}U, ^{239}Pu,’ ^{240}Pu,’ ^{242} Pu,’ ^{244}Pu
Denmark	*6 MV EN Tandem*	*U. of Aarhus, Aarhus*	^{14}C
Finland	5 MV Tandem	U. of Helsinki, Helsinki	^{14}C
France	2.5 MV Tandetron	NSR, Gif-sur-Yvette	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{79}Se, ^{126}Sn, ^{129}I
	3 MV Pelletron	CEA, Saclay	^{14}C
Germany	0.1 MV Tandem	FZ Rossendorf, Dresden	^{3}H
	3 MV Tandetron	U. of Kiel, Kiel	^{14}C
	3 MV Tandetron	MPI f. Biochemie, Jena (**2003**)	^{14}C
	6 MV EN Tandem	U. of Erlangen, Erlangen	^{14}C
	14 MP Tandem	BL Muenchen, Garching	^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{63}Ni, ^{244}Pu,
Hungary	2.5 MV Tandetron	INR, Debrecen (**2003**)	^{14}C
Italy	3 MV Tandetron	U. of Florence (**2003**)	^{14}C, ^{10}Be, ^{26}Al, ^{129}I
	3 MV Tandetron	U. of Lecce, Brindisi	^{14}C
	3 MV Tandem	University of Naples	^{14}C
Netherlands	3 MV Tandetron	U. of Groningen, Groningen	^{14}C
	6 MV EN Tandem	U. of Utrecht, Utrecht	^{14}C, ^{10}Be
Poland	0.5 MV Pelletron	AM University, Poznan	^{14}C
Romania	8 MV FN Tandem	NINPE, Bucharest	^{26}Al, ^{129}I
Sweden	3 MVPelletron	U. of Lund, Lund	^{14}C, ^{59}Ni
	5 MV Pelletron	U. of Uppsala, Uppsala	^{14}C, ^{10}Be, ^{129}I

Table 2. AMS Facilities of the World (Status December 2002), cont‘d

Country	Accelerator	Location	Isotopes
EUROPE			
Switzerland	0.5 MV Pelletron	PSI/NEC/ETH, Zuerich	^{14}C, ^{10}Be, ^{244}Pu
	6 MV EN Tandem	PSI/ETH, Zuerich	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{60}Fe, ^{126}Sn, ^{129}I
UK	3 MV Tandetron	U. of Oxford, Oxford	^{14}C
	5 MV Pelletron	U. of York, Sand Hutton	^{14}C, ^{129}I
	5 MV Pelletron	SUERC, Glasgow	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{129}I
NEAR EAST			
Egypt	3 MV Tandetron	AEA, Anshas, Cairo (**2003**)	^{14}C
Israel	14 MV Pelletron	WIS, Rehovot	^{14}C, ^{7}Be, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{44}Ti, ^{59}Ni, ^{90}Sr, ^{129}I, ^{236}U, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{244}Pu
ASIA & FAR EAST			
China	0.05 MeV Cyclotron	SINR, Shanghai	^{14}C
	6 MV EN Tandem	Peking U., Beijing,	^{14}C, ^{10}Be
	13 MV MP Tandem	CIAE, Beijing	^{36}Cl, ^{41}Ca, ^{79}Se
India	3 MV Pelletron	Inst. of Physics, Bhubaneswar	^{14}C
Japan	2.5 MV Tandetron	Nagoya U., Nagoya	^{14}C, ^{10}Be
	3 MV Tandetron	Nagoya U., Nagoya	^{14}C
	3 MV Pelletron	IAAA, Kanagawa	^{14}C, ^{10}Be
	3 MV Tandetron	JAERI, Mutsu	^{14}C, ^{129}I
	5 MV Pelletron	JNC, Tono, Toki	^{14}C, ^{10}Be
	5 MV Pelletron	U. of Tokyo, Tokyo	^{14}C, ^{10}Be, ^{26}Al
	5 MV Pelletron	NIES, Tsukuba	^{14}C
	8 MV Pelletron	Kyoto U., Kyoto	^{14}C
	10 MV Tandem	**U. of Kyushu, Fukuoka**	**^{14}C, ^{36}Cl**
	12 MV Pelletron	U. of Tsukuba, Tsukuba	^{36}Cl
South *Korea*	3 MV Tandetron	Seoul Nat.U, Seoul	^{14}C, ^{10}Be
AUSTRALIA & NEW ZEALAND			
Australia	2 MV Tandetron	ANSTO, Menai, Sydney (**2003**)	^{14}C
	2.5 MV Tandetron	CSIRO, North Ryde, Sydney	trace elements
	8 MV FN Tandem	ANSTO, Menai, Sydney	^{14}C, ^{10}Be, ^{26}Al, ^{129}I, ^{236}U, trace elemts
	14 MV Pelletron	ANU, Canberra	^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{99}Tc, ^{129}I, ^{236}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{244}Pu
New Zealand	6 MV EN Tandem	NIC-GNS, Lower Hutt	^{14}C, ^{10}Be, ^{26}Al
SOUTH AMERICA			
Argentina	8 MV FN Tandem	NRA, Buenos Aires	^{14}C, ^{129}I, actinides
	20 MV Pelletron	NAEC, Buenos Aires	^{36}Cl
Brazil	9 MV Pelletron	U. of Sao Paolo, Sao Paulo	^{36}Cl

Accelerators in art and archaeology: the AGLAE experience at the Louvre

Thomas Calligaro

Centre de recherche et de restauration des Musées de France CNRS UMR171
6, rue des Pyramides 75041 Paris cedex 01

A large set of modern analytical techniques is currently applied to get a better insight on art and archaeological objects as well as to contribute to their conservation and restoration. Because of the precious and sometimes unique character of the works, non-destructive techniques and even those requiring no sampling, are preferred. From this standpoint, ion beam analysis (IBA) constitutes one of the best choices, since it combines quite good analytical performance and non-destructiveness. For almost 15 years, an IBA facility has been installed in the Centre for Research and Restoration of the Museums of France, in the Louvre museum. Until now it is the only facility of this kind entirely devoted to the study of cultural heritage. A special set-up, namely an external beam line, has been developed which permits the in-air analysis of large or fragile works of art without sampling. This facility is used for both short investigations at the request of museum curators and extensive research works in art history, archaeology and conservation science. A few examples of applications, dealing with the identification of ancient gemstones and determination of their provenance as well as the alteration of metallic artefacts, will be given to highlight the usefulness of this tool.

The experience at LNL; an example of mutual fruitful interaction between material scientists and nuclear physicists

A.Patelli, A.Vomiero

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Italy

The activities of the Materials for Detectors Laboratory at the National Laboratories of Legnaro of the INFN are focused on the deposition and characterization of inorganic, organic and hybrid thin films to be applied both for fundamental studies and technologies applied to nuclear science.

Low ionized plasmas are used in magnetron sputtering equipments. The Laboratory is equipped with five DC and RF magnetron sputtering systems, in which both reactive and inert sputtering are performed, with a series of plasma diagnostic systems: optical emission monitoring, Langmuir probe, mass spectroscopy. DC and RF sample bias can be applied during growth and temperatures up to 800°C can be attained.

The deposition of hybrid and organic compounds is also based on plasma-assisted techniques and on other two methods of chemical synthesis: sol-gel from silicate precursors and solvent–based polymerization.

A high current density ion implanter is also available for several applications.

Ion Beam analytical techniques are extensively applied to materials analysis with a thirty years experience, using the AN2000 and CN Van de Graaff accelerators at the LNL. Compositional characterization is performed by RBS, ERDA, NRA, and non-Rutherford Backscattering techniques. Ion Beam Induced Luminescence (IBIL) has been developed to test scintillating materials. As usually accurate compositional analysis even with depth resolution are necessary, a laboratory tradition is to measure and check several cross sections in particular of light elements (B, C, O, N) both for elastic resonant non-Rutherford scattering and nuclear reactions in the range of energies allowed by LNL accelerators. Stopping powers of ions used in IBA are in progress for several materials to correct data in literature and enhance accuracy of the results obtained with nuclear techniques.

A further series of characterization techniques for thin films are available on the Laboratory: atomic force microscopy, scanning electron microscopy, Fourier transform infrared spectroscopy, surface conductivity measurements for insulating and semi-insulating materials, nano-indentation and micro scratch test for mechanical characterization.

Recent works and collaborations connected to nuclear activities:

- Nitrogen rich films with enhanced radiation resistance have been deposited in the framework of LUNA collaboration, which is funded by INFN. Experimental data collected at Laboratori Nazionali del Gran Sasso of INFN using the solid target demonstrated very good performances of TiN sputtered thin films.
- In the aim of the INFN ARCHIMEDE project in collaboration with the Daϕne INFN accelerator (Lab. Naz. di Frascati), Mo/Si multilayer structures for soft X-rays and EUV mirrors have been produced and optimized. The laboratory is also developing multilayer mirrors for HERSCEL coronagraph already commissioned by the Italian Space Agency.
- In collaboration with the CIEMAT (Madrid, Spain) the Laboratory is carrying on a study funded by the European Community of the radionuclides migration within the barriers of a geological repository for high-level radioactive waste. The mechanisms of transference of the radionuclides through the granite/bentonite interface by clay-mediated diffusion have been analyzed using RBS and μPIXE. The effects of the colloid size, PH and radionuclide species are investigated.
- Synthesis of new polyimidic hosts to be applied in the field of radiation detection in high radiation environments in collaboration with the Engineering Material department of the University of Trento. The radiation hardness of several polyimidic thin films was demonstrated to be up to one order of magnitude greater than polyvinyltoluene, which is one of the most common matrices in plastic scintillators.
- MoS_2-based self-lubricating coatings for lubrication in vacuum environment have been widely studied in the past. These coatings are often used for lubrication in space environment.

Future applications

- Multilayer mirrors for the “water window” radiation range (200 – 600 eV) for the application in X-ray microscopy of living cellules.
- High resistant polyimide-based plastic scintillators for high dose beam monitoring and radiation detection.
- Wave Length Shifters - based compact, large area and cheap UV detectors and mixed optical-electrical gas sensors.

- Ultra-hard (TiN, oxy-nitride and multilayer) coatings, which can improve hardness, wear resistance of the devices and can act as thermal and diffusion barriers suitable for applications in nuclear instrumentation and industrial applications.
- Nanostructured ternary amorphous systems for diffusion barriers in microelectronic.

Dedicated facility for applications of fast ions

H.Homeyer
Hahn-Meitner Institut Berlin, Deutschland

Most non-nuclear applications of fast light and heavy ions have been developed at nuclear physics laboratories, such as radiotherapy, materials analyses, fabrication of microfilters, and, of course, basic research in solid state physics. For radiotherapy dedicated accelerators are being built in hospitals. The other applications are gaining importance. We observe an increasing demand of solid state and medical physics as well as materials science for high energy ions with energies above 1 MeV/u.

It has turned out that apart from the need of fast ion beams non-nuclear users of fast ion beams have quite different demands on the accelerator facilities. Industrial collaborations and tumour therapy have high demands on the reliability and stability of the machine. In particular, for the irradiation of polymer foils to produce microfilters the requirements on the accelerators are extremely high in terms of stability and ion beam intensity to make the production line profitable. Ion track technology is the only tool to produce the various kinds of filters for an expanding market.

Tests of electronic devices for their radiation hardness utilise both light and heavy ion beams. The possibility of fast changes of the ion species are needed (cocktail beams) and specific beam delivery systems are necessary.

Complex layered structures are analysed by ERDA (Elastic Recoil Detection Analysis). Making use of 300 MeV Au ions gives an immediate information on the composition of thin films for all elements including hydrogen The investigation of art and archaeological objects has to be non-destructive. High energy PIXE (Proton Induced X-ray Emission) allows elemental analysis of deep-seated layers. These analytical applications profit from excellent beam qualities.

Basic solid state physics research concentrates on the effects of single ions or high dose irradiations on materials. Target areas should comprise further analytical tools such as electron microscopy or x-ray diffractometry.

Thus, it is of utmost importance to establish in Europe three to four fast ion laboratories dedicated to the improvement and the development of fast ion technologies. They should offer vast choice of ions available, from hydrogen up to uranium, dedicated beam preparations, from microfocus to large area irradiations, intensities from some ions to particle micro-

Ampere per second. These facilities should enhance multidisciplinary studies in serving a heterogeneous user community ranging from art historians over physicists and semiconductor specialists to physicians.

HINDAS
A European nuclear data program for accelerator-driven systems

Arjan Koning

Nuclear Research and consultancy Group, P.O. Box 25, NL-1755 ZG Petten, the Netherlands

Abstract

In the HINDAS program, nuclear data in the 20-2000 MeV range are evaluated by means of a combination of nuclear models and well-selected intermediate- and high-energy experiments. A panoply of European accelerators is utilized to provide complete sets of experimental data for iron, lead and uranium over a large energy range. Nuclear model codes are being improved and validated against these new experimental data. This should result in enhanced ENDF-formatted data libraries up to 200 MeV, and cross sections for high-energy transport codes above 200 MeV. The impact of the new data libraries and high-energy models will be directly tested on some important parameters of an accelerator-driven system (ADS).

HINDAS

The starting point of any serious study on a realistic nuclear device is basic nuclear reaction information. One such device, an accelerator-driven system (ADS) has received much attention during the past decade as a potential solution to the radioactive waste problem. Spent nuclear fuel from power reactors consists of long-lived fission products and minor actinides which need to be taken care of in order not to burden future generations. One solution is to transmute this radioactive waste through an intense neutron source, produced by an accelerator coupled to a subcritical reactor. Feasibility calculations of such ADS systems, which include items such as neutron and energy balance, the radiotoxicity of spallation products, damage and activation, rely critically on well-tested nuclear cross sections. It has been argued several times recently that the present quality of basic nuclear data is not sufficient for ADS simulations. Besides the gaps in the existing evaluated data libraries below 20 MeV, there is an urgent need for high-energy nuclear data for several ADS-related materials. Therefore a European project, HINDAS, has been initiated to take care of this situation. HINDAS (High and Intermediate energy Nuclear Data for Accelerator-driven Systems) is a project supported by the European Commission, from September 2000 - December 2003, and involves 16 European laboratories. Its objective is to obtain a thorough understanding and complete modeling of nuclear reactions in the 20-2000 MeV region, in order to build reliable and validated computational tools for the detailed design of the spallation module of an accelerator driven system. To achieve this, an ambitious experimental and theoretical program has been launched.

Six European facilities, listed in Table 1, are participating in the measurement of the following observables:

- double-differential $(p, xn\ldots xa)$ and $(n, xn\ldots xa)$ cross sections,
- residual nuclide production, by activation and inverse kinematics techniques, and residual kinetic energies,
- neutron elastic scattering angular distributions,
- neutron and charged-particle multiplicity distributions,
- thick target neutron spectra.

The diversity of the used accelerators is such that the complete energy region between 20 and 2000 MeV is covered. A suitable coverage of the periodic table of elements is obtained with the choice of target elements: Fe, Pb and U. Lead and iron are representative of materials used in ADS, while uranium represents the actinide region.

Parallel to the measurement program, theoretical models are under development. For energies from zero up to 200 MeV, the new nuclear model code TALYS has been designed. It includes the optical model, direct, pre-equilibrium, fission and statistical models and thereby gives a prediction for all the open reaction channels. In addition, for energies up to 2000 MeV, a new intranuclear cascade model is under development. During the measurement program, the nuclear model codes are directly benchmarked against the new experimental data. The intermediate energy models will be used to create ENDF-libraries up to 200 MeV, while the high-energy nuclear models will be implemented in highenergy transport codes. Finally, calculations of several quantities important in the design of ADS target or window, such as activity, radiation damage, gas production, etc., will be performed in order to assess the improvements brought by the new data and models.

Table 1: European facilities participating in HINDAS

Institute	Accelerator	Energy range (MeV)
UCL-Louvain-la-Neuve	CYCLONE	20-70 (p and n)
UU-Uppsala	TSL	20-180 (p and n)
KVI-Groningen	AGOR	130-190 (p)
PSI-Villigen	cyclotron	45-70 (p)
FZ-Jülich	COSY	50-2500 (p)
GSI-Darmstadt	SIS	300-1000 (MeV/A)

Status of the applications of nuclear techniques in the field of humanitarian de-mining.

M. Cinausero, G. Viesti

Dipartimento di Fisica dell' Università di Padova
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy

Nuclear Techniques have been proposed to be an useful tool for detecting hidden explosives as the case of buried land-mines.

The official requirements in developing new instruments in this field have been set by UN and EC through the Geneva International Center for Humanitarian De-mining (GICHD). The requirements are:

1) Capability of detecting anti-personnel landmine (APL) buried up to 20 cm depth in any kind of soil with efficiency larger than 99 %.
2) Inspection time shorter that 60 s.
3) Low false-alarm rate.
4) Low Cost
5) Easy in field maintenance.

No single instrument in operation or prototype under development meets the above requirements that are to be considered as characterizing the complete de-mining system realized by the use of several tools (i.e. as a multi-sensor platform).

From a general point of view, the nuclear techniques used in the detection of explosive material are classified in 3 categories:

1) **Thermal Neutron Sensors**. The (n,γ) capture reaction on nitrogen nuclei is used to detect explosive material. Thermal neutron sensor have been tested in field by the Canadian Army within the ILDC (Improved Landmine Detection Concept) Project, demonstrating the capability of detecting easily the large Anti-Tank Landmine. Tests performed within the INFN EXPLODET projects demonstrated that this system is not viable to detect APMs.
2) **Fast Neutron Sensors.** Gamma-ray emitted from light nuclei (C,N,O) by inelastic scattering of 14 MeV neutrons have been used to identify explosive material by the yield ratio C:N:O. The PELAN system, based on a portable neutron generator and a single BGO detector has been developed by the West Kentuky University and is actually in the catalog of SAIC. Such system has been tested under the IAEA

Coordinated Research Program on Humanitarian Demining showing the possibility of detecting APM buried slightly under the surface of the soil in 5 minutes. A program of upgrading PELAN for the APM detection is sponsored by IAEA and is performed by European research groups. A system using the associated particle technique has been also developed by INFN and is now working at the Neutron Generator Laboratory of the Institute Rudier Boskovic in Zagreb, where the detection of APM will be studied under an INFN-IRM collaboration sponsored by NATO. At the same time, the development of a portable neutron generator equipped with the associated particle techniques is in progress within a collaboration involving INFN and EADS-Sodern (France), a primary European company leader in the field of portable neutron generators. Projects in the field of detection of explosives by using the associated particle method have been also proposed under the International Science and Technology Center (ISTC) by Russian institutes (JINR-Dubna and Radium Institute St. Petersburg).

3) **Neutron Back-scattering sensors**. The hidden explosive is also detectable in arid environment by detecting the low energy neutrons that are thermalized in the hydrogen contained in the explosive material. Such hydrogen anomaly detector is the only way to use nuclear techniques in hand-held systems, whereas both thermal and fast neutron sensors are usable only in vehicle mounted platforms. The Neutron Back-scattering sensors were studied first by SAIC that obtained first results from field tests. Research and development in this field was performed by several groups worldwide (Cape Town University (ZA), several groups in USA, Delft (N), Debrecem (H), INFN). In particular, two prototypes have been recently studies. The DUNBLAD detector designed by the Delft Group and the DIAMINE prototype studied under an EU founded research. DUNBLAD is an hand held system using commercial high efficiency ^{3}He counters. It is a quite heavy system (about 20 kg) and is used to scan directly the soil. It detect easily ATM but not APM. The DIAMINE prototype integrate a neutron detector based on MWPC in a commercial metal detector. The scan of the soil is performed with the metal detector and the neutron detector is used only to confirm the presence of the mine. This is a lighter system (about 2 kg). Limits in the application of the backscattering techniques have been studied under the DIAMINE project and are related to the hydrogen in the soil due to the moisture. Therefore, the use of this technique is limited only to arid country, were the soil moisture is lower than 10% in weight.

Application of Nuclear Techniques in the field of Civil Security

M. Cinausero, G. Viesti

Dipartimento di Fisica dell’ Università di Padova
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy

The goal of the proposed action is to overcome the current fragmentation of European research in the field of detection of threat materials by nuclear techniques, which make difficult to obtain realistic and timely progress as required by the societal needs. This action will contribute globally to integrating and straightening the ERA (European Research Area) in this specific field. Furthermore it will create a stable link between the fundamental research in Nuclear Physics and the applied research, to favour a fast transfer of new technologies and methods between the two worlds. Finally it will contribute to create a research/industry/user community common ground that will guide the research in line with the need coming from the users (International and National Agencies), through the validation of the interested industrial community. Such latter connection is believed to be absolutely necessary for a real fielding of new technologies.

The use of neutron induced reactions for non-destructive bulk elemental analysis is well documented [1]. All neutrons, and in particular fast neutrons, are well suited to explore large volume samples given their large penetration depth in bulk material. Fast neutrons can be produced efficiently and economically by natural radioactive sources, small accelerators (portable electronic neutron generators) or portable repetitive Plasma Focus devices, making possible the use of neutron based techniques for in-situ analysis. Gamma-rays produced by irradiating the sample allow to identify the elemental composition of the material. Moreover, knowing the nuclear cross-sections and estimating the self-absorption factors in the different materials, it is possible to perform a quantitative analysis of elements in the sample even in depth. In some cases with the use of "tagged" neutrons it is possible to determine also the local distribution of some elements inside the sample volume.

The threat of terrorist use of chemical weapons was rising after the SARIN attack in the Tokyo subway system on March 20, 1995. After the recent tragic events of September 11, 2001, the possibility of a further use of the chemical warfare (CW) agents (the so called “poor man’s atomic bomb”) is one of the most terrifying scenarios for future terrorist attacks against civil populations. The second scenario often evocated is the use of the so-called "dirty bombs": a sizeable quantity of radioactive material detonated by conventional explosive and dispersed in the environment.

It is well known that many CW agents can be reliably detected when in use by conventional methods, nevertheless these substances are virtually impossible to detect while being stored in a sealed container. Radioactive material can also be detected by measuring its decay products detection by "passive" radiation methods. However, the specific decay products that mark the presence of a given radioactive species may be absorbed by shielding materials or masked by using a second stronger radiation source. Therefore the combination of radioactive material with explosives needs a specific multi-elemental analysis. Neutron interrogation would help in solving the difficulties in both situations.

As an example, chemical weapons can be identified by their particular ratio of elements as H,C,N,O and from the presence of some particular elements such as Cl and S for MUSTARD GAS or P and F for SARIN [2]. Each of these elements is characterized by their own gamma-lines thus allowing an unambiguous identification of the element itself, a further quantitative analysis of the sample composition allows the identification of the compound or, at least, shows its particular fingerprint.

Nuclear systems have been extensively used in the program NSCMP (Non-Stockpile Chemical Material Program) by the US Army to identify the content of unexploded ordnance (UXO). Reported results demonstrate 98% proper identification for 105 mm heavy ammunition, whereas for lighter 75 mm ammunition the system performances are no better than 28% of valid identifications. The sensitivity of the technique then depends on the sample dimension, and is drastically decreased for smaller objects as the 75 mm shells. This demonstrates the limits of the commercially available nuclear systems that are all from US based industries.

The European Union must plan a huge program to ensure the capability of security and safety within its border, for the public but also to prove to the world that the European Union has the means to respond to any kind of terrorism [3]. So, there is a strong need of surveillance and means of radiation protection for security warning in public sites. The development of advanced technologies will therefore enhance the EC capabilities in the countermeasures to terrorist actions, improving the civil security and decreasing the risks connected to the use of mass destruction weapons.

In the perspective of an anti-terrorist application, it is extremely important to enhance the capability of detecting small quantities of chemical agents and radioactive materials.

Furthermore, it is also needed to study a system that can be efficiently used, in full agreement with the EC rules for radiation hazard.

The starting point of this action is the expertise already present at EU level in several Research institutes that have been working in the last years in the field of explosive detection in connection with Humanitarian De-mining programs at national as well at EU levels [4].

It is important to stress that, in targeting this specific application, it is necessary to develop modern technologies in the field of:

1) portable neutron generators;
2) in-situ detection of neutron and gamma-rays employing advanced tools;
3) modern front-end electronics and DAQ systems;
4) advanced software for automated analysis and decision taking.

This latter point is of paramount importance in view of future real-time application of such technologies.

References

[1] G. Vourvopoulos and P.C. Womble, Talanta 54 (2001) 459 and references therein.

[2] P. Bach, J.L. Ma, D. Froment, J.C. Jaureguy Nucl. Instr. and Meth. B 79 (1993) 605

[3] see: http://europa.eu.int/scadplus/leg/en/lvb/l28001.htm

[4] see for example IAEA Reports on the Coordinate Research Program on Humanitarian De-mining. IAEA/PS/RC-799-2.

The SIMPLE Experiment

L. Cosentino, P. Finocchiaro
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy

Two techniques for microscopic particle beam imaging and current measurement, both based on scintillators, are being developed at the INFN-LNS. The imaging device, named μ-SFOP (Scintillating Fiber Optic Plate), is meant to produce 2D live images of the micro-beam, with high accuracy. It is based on a scintillating plate made of a bundle of Terbium-glass scintillating fibres, with diameter of 10 μm each, and a compact CCD camera watching it. The device called μ-SBBS (Scintillator Based Beam Sensor) has been used for very high precision current measurements. It basically consists of a scintillator, optically coupled to a compact photomultiplier, used in current and pulse mode in order to perform self calibration procedures. We have proved the possibility of spanning from single beam particles counting up to several nA, with beam sizes of less than 50 micron. Their surprisingly good performance makes them suitable candidates to be used in Deep Lithography with Particles (DLP), exploited to produce micro-opto mechanical structures with high aspect ratios, for optoelectronics applications.

L.Cosentino et al.,
Ion micro-beam diagnostics with photodetectors, Nucl. Ins. & Meth. in Physics Res. sect.B, in press

Radioactive probe techniques

Ulrich Wahl

I have sent out the questionnaire shown below to 40 colleagues working on "Nuclear Applications" and received response from some 20 people. The colleagues I addressed are mainly out of the field of solid state physics with radioactive probes, but I also received some answers on medical physics, synchrotron-based techniques, and ion beam physics. However, for these I do not feel competent and I will limit myself to the answers I received for **radioactive probe techniques**.

Those who have responded to the questionnaire have mentioned the following "Nuclear Application" techniques which they assume will play a major role in the next 10 years.

Techniques mentioned:

- Perturbed Angular Correlation (PAC)
- Mössbauer Spectroscopy (MS)
- Emission Channeling (EC)
- Beta Nuclear Magnetic Resonance (β-NMR)
- Muon Spin Rotation (μSR)
- Low Temperature Nuclear Orientation (LTNO)
- Positron Annihilation Spectroscopy (PAS)
- Radiotracer Deep Level Transient Spectroscopy (DLTS)
- Radiotracer Photoluminescence(PL)
- Radiotracer Hall Effect
- Radiotracer Diffusion
- Nuclear resonant scattering of synchrotron radiation
- Density Functional Theory (theoretical approaches with DFT codes)

Among the systems to be studied, the following were named, the ones in bold several times.

Systems:

- **Semiconductors:** point defects, the physics of impurities in general, Frenkel pairs, vacancies and interstitials and their agglomerates, and complexes formed with dopant or contaminating impurities; more specific

    - Si (to be considered most important semiconductor for next 10 years)
    - Emerging wide band gap semiconductors (GaN, ZnO, SiC, diamond).
    - Ion implantation-related questions, “defect engineering”
    - Optical dopants in semiconductors
    - Magnetic semiconductors
- **Opto-electronic and optical materials, Ferroelectrics**
    - doped perovskites ($BaTiO_3$, $LiNbO_3$, $KTaNbO_3$, etc.)
- **Magnetic systems**
    - Colossal Magnetoresistance materials
    - Giant Magnetoresistance materials
    - Semimagnetics
    - Ferromagnets
    - Spintronics
    - Rare earth magnetism
    - Magnetic multilayers
- **Superconductors**
- **Surfaces and interfaces, multilayers**
- **Nano-sized materials and low-dimensional systems**
- Materials modification by single ion tracks

The most-welcome substantial improvements mentioned were as follows.

Improvements:

- **easier access to nuclear probes** (the ideal would be having an isotope separator such as GPS-ISOLDE with several beam lines, available for nuclear-probe technique based collections)
    - improvement of **on-line** access to RIB facilities for radiotracer-based techniques such as diffusion, photoluminescence etc.
- **production of new radioactive probe beams with the necessary energy, intensity and purity**
    - tunable energies some keV to 10 MeV
    - soft landing on surfaces
    - further improvements of chemical selectivity, especially isobaric separation, development of laser ion sources for specific elements
    - general improvement of yields

    - some requested isotopes: ^{3}H, ^{8}B, ^{11}C, ^{16}N, ^{15}O, ^{19}O, ^{31}Si, ^{33}P, ^{35}S, ^{100}Pd
- development of low-energy muon beams
- new high-intensity low-energy positron beams, based either on electron Linacs, or on nuclear reactors, desirable positron fluxes are 10^7 - 10^9
- sub-micron positron beams (positron microscope), desirable spot size is of the order of the positron diffusion length (<150 nm).
- **improved position-sensitive detectors for charged particles** (β^-, CE, β^+, α):
    - faster detectors for use with short-lived isotopes
    - better energy resolution
    - increased energy range
    - larger detectors (10x10 cm^2)
- small detectors with energy resolutions around 1 keV for energetic ions (1 MeV/amu).
- for Time-Differential PAC, detectors with both high time resolution (like BaF_2 scintillators) and high energy resolution (like HPGe detectors)
- ultrafast photomultipliers for scintillation detectors and faster scintillators, overall timing resolution of FWHM <50 ps
- **theory**:
    - a full theoretical first principles description of probe atom parameters in solids, biological materials etc. as determined by nuclear methods like Moessbauer spectroscopy, PAC, channeling
    - new theoretical tools for calculating positron parameters in insulating materials, and for modelling
    - simulation codes for positron channeling
    - reliable calculations of magnetic hyperfine fields of noncubic systems
- **complementary approaches** by combining several techniques (EXAFS + EC, PAC + DFT), especially by combining theory with experiment
- automated data analysis capable of on-line analysis, and eventually of automated control of the experimental conditions (simulated annealing, Bayesian inference, and artificial neural networks)
- new signal digitising PC-cards with 5-10 GHz digitising rates, with flexible and high data throughput, in order to allow for digital lifetime spectrometry

Finally, I would like to resume this and add some personal comments.

It is clear that Nuclear Applications with respect to radioactive probe techniques are currently a mature field of physics, meaning that there exist a number of well-established techniques that have been thoroughly explored from the nuclear physics point of view. At the moment there is no revolutionary new approach in sight, as has been, e.g., the discovery of the Mössbauer, PAC, or channeling techniques in the 50s and 60s. However, significant progress is to be expected from interdisciplinary approaches.

Without doubt, one of the greatest challenges will be to correlate the effects observed by Nuclear Techniques with predictions from ab-initio studies of solid state theory. In this respect, radioactive probe techniques often offer the unique possibility of providing **critical benchmarks** for the theoretical models. More and more solid state theorists are realizing this and have undertaken the effort to understand the nuclear physics techniques and adapt their calculations in order to predict specific parameters measured with nuclear methods, such as electrical field gradients, magnetic hyperfine fields, lattice sites, positron lifetimes, muon rotation frequencies, etc.

Another fruitful perspective for the future is the further development of **radiotracer** techniques. This approach, which basically aims at using a radioactive probe atom's characteristic half life in order to identify the chemical origin of a signal obtained by a conventional solid state physics technique such as PL, DLTS, Hall effect, EPR, has a long history. However, more widespread use of these methods has been hampered by

- the "interdisciplinary" approach that they require, i.e. experts in conventional solid state physics techniques have to learn how to master the handling of radioactive samples, comply with radiation safety aspects, etc.
- overcoming the barrier for solid state physics experiments to work in nuclear physics neighbourhoods, both from the point of view of the nuclear physics community being open to such proposals, and from the solid state physicists to request access to such facilities.

As has been always the case in the past, progress in the field of **nuclear instrumentation** has been promoting further development in Nuclear Applications. At the moment, there is certainly a need for improved sensors. Mentioned most often in that respect are the further developments of position-sensitive detectors, compact charged particle detectors with better energy resolution, and faster sensors for timing applications. It seems as if scientists working in Nuclear Applications are readily waiting for progress in these technical fields in order to immediately transform it into new and exciting experiments.

There is a clear trend for **on-line** charged particles beams, either accelerator- or reactor-based, to become the main source of nuclear probes for research purposes. Obviously for some nuclear probes such as muons or short-lived isotopes, this is the only way of supply. In other cases, especially for long-lived radioisotopes, on-line ion beams offer an increased safety aspect in comparison to the handling of open radioactive sources and radiochemical procedures. In any case this trend stresses the future role of central beam facilities, where nuclear probe techniques are applied in a controlled, secure and user-friendly environment.

On the other hand, certainly the development of **improved or new probe beams** will have a profound influence on the field of Nuclear Applications. One aspect concerns expanding the energy range of existing beams, for instance low-energy positron or muon beams, the soft-landing deposition of radioactive probe atoms on surfaces, or high-energy radioactive beams for deep implantation. A second aspect considers beam intensity and purity. In many cases, basic nuclear physics studies are able to work with a very small number of nuclei and can tolerate some contamination, but often these are limiting factors for applied nuclear techniques. Here new techniques such as laser ion sources or high mass-resolution isotope separation may help to improve yield and/or purity. A third aspect is, that there exist for instance many radioactive isotopes with properties that would make them excellent probe atoms for applications, however, they are not easily available as particle beams. Great potential in that respect have radioactive beams of light elements such as ^{3}H, ^{8}B, ^{11}C, ^{16}N, ^{15}O, ^{19}O, ^{31}Si, ^{33}P or ^{35}S. Developing safe and convenient methods to produce intense beams of these isotopes could certainly spark applications for which there already exist “Gedankenexperimente”.

Generally, easier access to nuclear probes is still something that prevents the more widespread use of Nuclear Applications. Very often, in order to carry out solid state physics, condensed matter or medical research, systematic studies with a large number of samples and hence access to nuclear probes on a regular basis is needed. This need is further enhanced by the fact that obtaining research funding and providing a secure basis for PhD students both requires the perspective to carry out experiments on a regular basis during time scales of several years. In that respect, for instance the development of future radioactive beam facilities in Europe is most welcome within the nuclear probe community.