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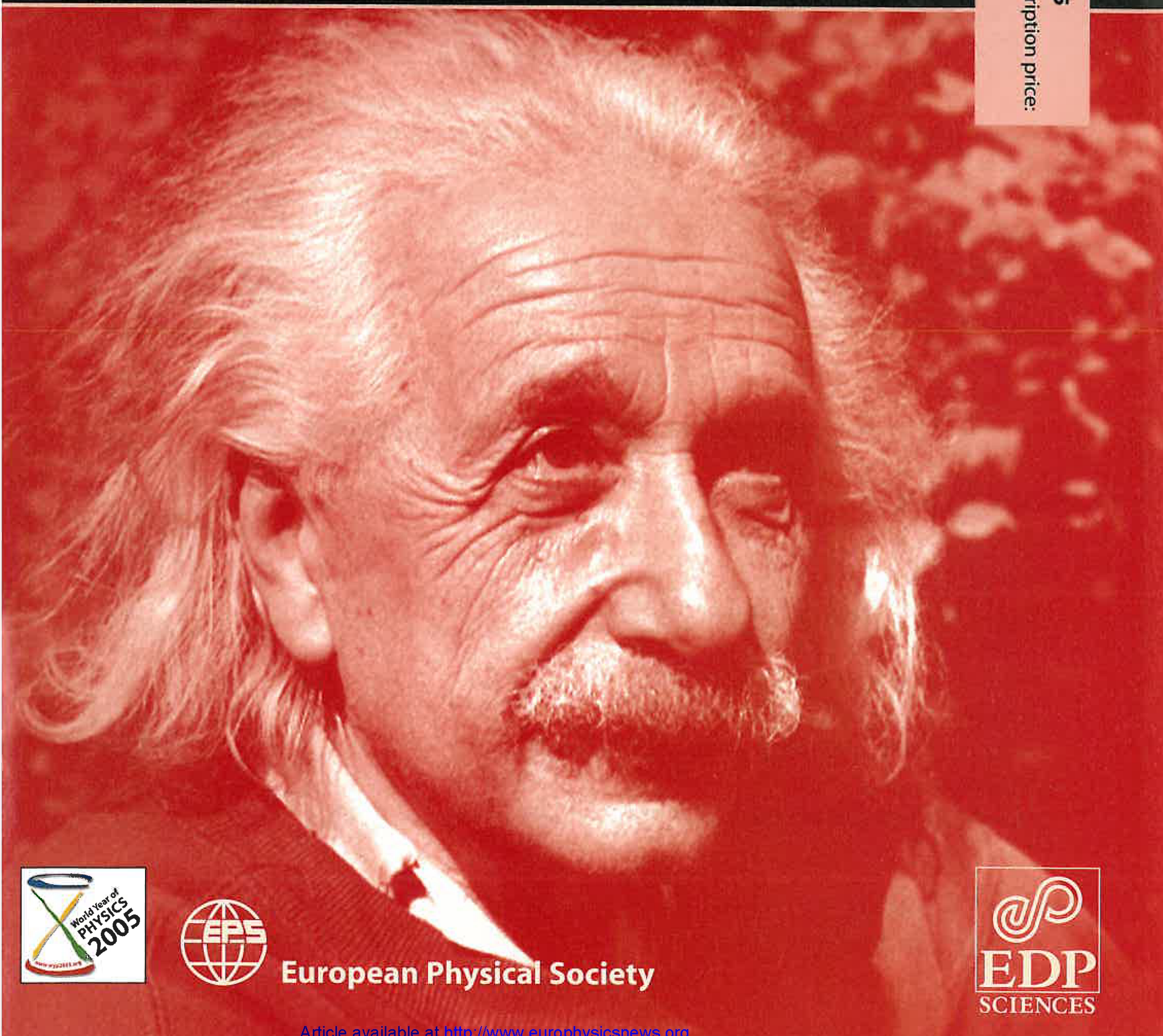
FEATURES ISSUE

Recent applications of Synchrotrons in cancer therapy

Einstein - from Ulm to Princeton

Einstein and the Nobel Committee

Doppler Tomography

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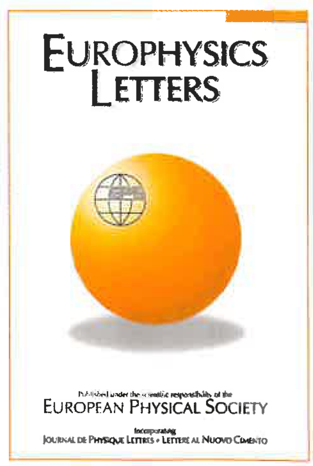


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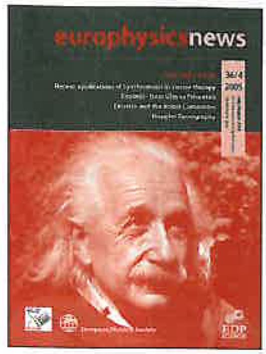


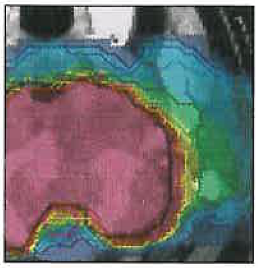

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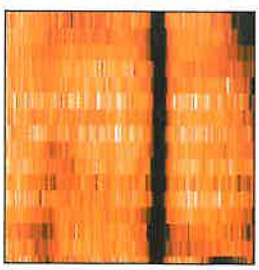

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# europhysicsnews

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# The Europhysics News challenge

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The European population of Physicists is the largest in the world, compared to Asia or to the North American continent. In spite of its size, this population has developed the feeling, during the last 50 years, that it constitutes a single community, certainly in parallel with the impressive political evolution towards unity that Europe has known along the same period. This is of course also true for Mathematics, Chemistry... The need for federal structures came up early and our fathers created the European Physical Society in September 1968. They had to involve the venerable and powerful National Societies: it was out of the question to replace them. Their role remains essential, even if only considering the variety of languages and of educational systems that they represent. However, a pure federation of National Societies was unacceptable and individual physicists or organisations had also to be recognised as members. This delicate balance was struck from the beginning and continues to this day. However, the consequence was to condemn EPS to remain relatively hard-pressed financially in spite of the large population of European physicists, simply because its financial needs came second to those of the National Societies.

Now, let us come to the EPN challenge. Among its duties, a structure such as EPS has to insure the diffusion of information within its population of physicists. The organisation of conferences and the sponsorship of journals are evident ways but the circulation of its own journal is essential as well. How else to communicate to members the recent progress and new questions in physics research and education, the highlights of recent European events and the purposes of forthcoming ones, the openings in teaching or research positions, the new instruments and machines and so forth, without it? So EPS needs a consistent and well-documented journal, interesting and useful to its members in addition to their National Society journals and, last but not the least, operating on only a small budget. This challenge has been successfully sustained over the years and I am sure that the readers of Europhysics News have appreciated the content and the presentation of the past issues.

Some changes are planned, however, starting from the next issue (36/5:September-October 2005). Most of you will have certainly noticed, when looking at the top of the fourth page of each EPN issue, how small is the team in charge of the practical preparation of the Journal. Presently everything rests on the shoulders of the Science Editor for the content and the Designer for the presentation. In more detail, the Science Editor has not only to interact with authors to obtain their papers, most often after he has required corrections, but also to package on time all the material, including EPS news, for each issue. This is a heavy job bringing maximum stress six times a year and no one should be expected to do it alone for long. The Executive Committee of EPS has recognized the achievements, even under pressure, of the present Science Editor, George Morrison, and has decided to lighten his workload by adding a new person to the EPN team. This new person, who happens to be the author of the present editorial, is expected to take on the position of an overarching Editor. The charge will be to call for and to collect on time all the material needed for each issue and to take it on to the publishers, freeing the Science Editor from the second part of his present tasks. The present Editor, whose primary job is that of Secretary General of EPS, will then become Executive Editor. The enlarged team will now have to show that it can still improve EPN without a budget increase! ■

Now, let me answer a few questions that you may have.

**Q: What will change in EPN?**
A: Wait and see! The time constant for the content is something like 5±3 months, so...

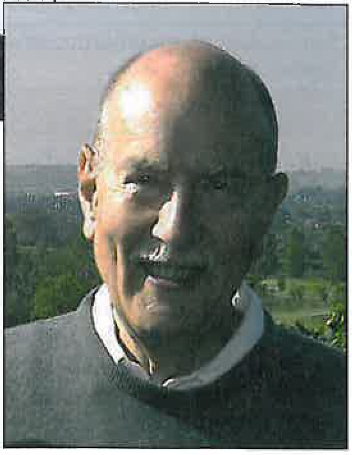
**Q: Who is the person that EPS has appointed?**
A: A semiconductor surface physicist, he was Head of the Solid State Physics Laboratory at Université Pierre et Marie Curie, Paris (1986-96)

**Q: What are his credentials regarding EPS?**
A: He was Vice Secretary of the Executive Committee (1994-98) then elected representative of IOMs at the Council (2001-03).

**Q: And regarding EPN?**
A: Presently a member of the EPN Editorial Advisory Board, he has completed in March 2005 a term of 8 years as Editor of the French Physical Society Bulletin.

**Q: How old is he?**
A: Old enough for the job.

▲ Claude Sébenne



▼ George Morrison

# Recent applications of Synchrotrons in cancer therapy with Carbon Ions

*Ugo Amaldi [1], Gerhard Kraft [2],*
*[1] University of Milano Bicocca and TERA Foundation*
*[2] GSI and Technical University, Darmstadt*

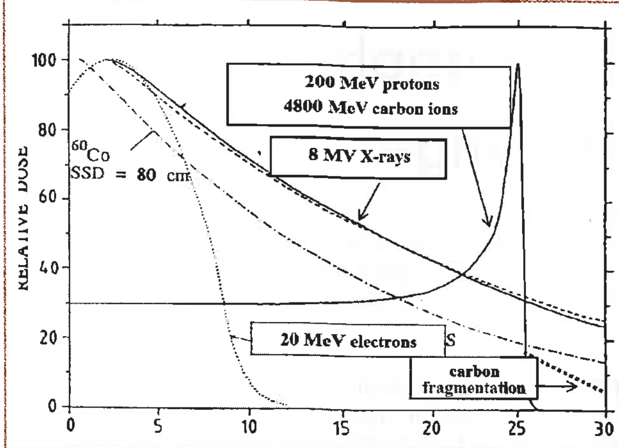
As shown in Table 1, accelerators originally designed for scientific research have found a large number of industrial and medical applications.

The main medical applications besides radioactive isotope production with cyclotrons are the electron linacs of a few MeV for radiotherapy of deep seated tumours. Every year in the developed countries about 40,000 people out of 1 million inhabitants are diagnosed as having cancer. About 50% of these patients are treated with radiation, mainly high energy photons produced by electron linacs. In 90% of the cases the electron beam is converted to Bremsstrahlung photons. These photon beams (called "X-rays" by medical doctors) have replaced the low energy X-rays and the $^{60}$Co gamma radiation because of a better depth-dose distribution (Fig. 1). Due to the fact that Compton-electrons go forward with a few centimetre range, the dose increases at the entrance (build-up effect) to a maximum value at 3-4 cm below the skin. This increase is followed by a shallow exponential decay for greater depth.

| Application | Number in use |
|---|---|
| High-energy accelerators for research (E >1 GeV) | 120 |
| Low energy accelerators for research (including biomedicine) | ~1000 |
| Synchrotron radiation sources | >100 |
| Medical radioisotope production | ~200 |
| Radiotherapy accelerators | >7500 |
| Accelerators for industrial processing and research | ~1500 |
| Ion implanters, modification of surfaces and matter in bulk | >7000 |
| TOTAL | >17500 |

▲ **Table 1:** World accelerators running in 2003 [1].

In the most advanced treatments the X-ray dose is given from many (5-10) ports by rotating the electron linac around the patient and modulating the shape and intensity of each port separately using computer-controlled multileaf-collimators. With this *Intensity Modulated Radio Therapy* (IMRT) the most conformal X-ray treatment can be given at the expense of a greater integral dose, which is nevertheless distributed to the normal tissues around the target.




▲ **Fig. 1:** Depth dependence of the deposited dose for different radiations.

As the induction of secondary tumours is rather a volume than a dose effect, a better cure with lower risk becomes possible when the physical properties of the radiation are changed. This is possible by the transition from X-rays to ion beams such as protons or carbon.

The depth-dose curves of proton and light ion beams are completely different from those of X-rays because these charged particles have little scattering in matter and give the highest dose near the end of their range in the 'Bragg peak' (Fig. 1). Often they are said to have an 'inverse' distribution of the longitudinal energy deposition with respect to X-rays. Protons and carbon ions were first proposed for radiotherapy applications by R.R. (Bob) Wilson in 1946 [2].

The energies for reaching deep-seated tumours (about 25 cm of water equivalent) are 200 MeV for protons and 4800 MeV for carbon ions, 24 times larger. Protons beams are obtained either from cyclotrons (normal or superconducting) or from synchrotrons having a diameter of 6-7 metres. Only synchrotrons are used to produce carbon ions of about 400 MeV per nucleon (400 MeV/u). Their magnetic rigidity of approximately 6 Tm is about three times larger than that of 200 MeV protons so that about 20 metre diameter synchrotrons are needed when fields in the range 1.5-2 Tesla are used. Superconducting cyclotrons are an option that is at present considered also for ion therapy.

For mono-energetic ions the Bragg peak, shown in Fig. 1, is very narrow, so that the energy of the particles has to be changed during the irradiation to cover the tumour depth. In cyclotrons the beam energy cannot be varied, so that movable energy absorbers and magnetic selection systems have to be used to adapt the range of the particles to the depth of the target to be irradiated. In synchrotrons it is easy to vary the energy of the extracted beam.

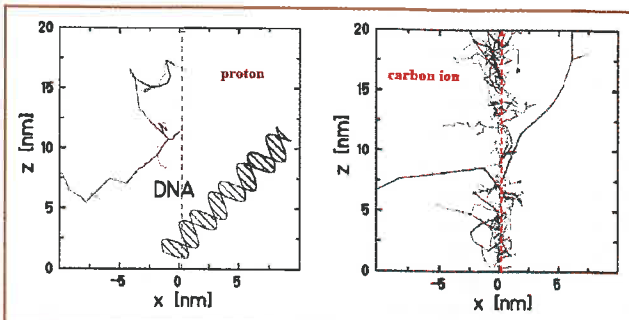
Until 1997 relatively simple 'passive spreading systems' have been used to produce a Spread Out Bragg Peak (SOBP) in all hadrontherapy centres. In this approach, a first 'scatterer' widens the pencil beam while their energy is adapted to the distal form of the tumour by using appropriate absorbers. Downstream of the single (and sometimes double) scatterer, the transverse form of the irradiation field is defined by collimators. Only in 1997 at GSI [3] and PSI [4] have the novel 'active spreading systems' been developed where the charged hadrons are magnetically guided over the treatment area and modulated in intensity (*Intensity Modulated Particle Therapy* = IMPT).

In this 'active spreading' technique the target volume is divided into slices of equal particle energy and each slice is divided into small volumes called 'spot' or 'voxels' (i.e. 3D pixels) that are treated separately by moving transversally the beam by means of bending magnets. When one slice has been treated, the energy of the beam is reduced for the next slice. In practice, the complete target volume consists of 10,000 – 30,000 voxels which are treated in 2-6 minutes. All recent hadrontherapy facilities have the possibility of using active systems. Most existing facilities still use protons delivered in fixed horizontal beam lines, combined with passive scattering systems.

From the end of the century the newly built protontherapy centres feature isocentric 'gantries' to improve the conformity of the treatment, avoiding high doses to healthy tissues by rotating the therapeutic beam around the patient as it is done in all X-ray treatments. The magnetic rigidity of 200 MeV protons is such that a standard magnetic channel capable of doing so has a typical radius of 4-5 m.

In a conventional treatment with X-rays a total dose of 60-70 Gy (1Gy= 1 J/kg) is deposited in a tumour target in typically 30 fractions over six weeks to give time for re-oxygenation of hypoxic – and therefore radioresistant – tumour cells and for the transition of tumour cells from radio-resistant cell cycle stages to more sensitive stages. In addition the unavoidably irradiated healthy cells have a chance to repair the radiation damage. Typically a proton treatment requires 20 fractions and allows higher doses to the tumour. It has to be remarked that a larger dose is beneficial because even a modest 10% increase of the dose deposited in a tumour gives typically an increased probability of local control of the tumour itself by about 20%. This implies that passing from 60 Gy to 66 Gy, for instance, the control probability increases from 50% to 60%, a not negligible gain. This fact is independent of any clinical trial and is the strongest argument in favour of protontherapy: since proton and X-rays beams produce practically the same biological effects on the irradiated cells, a better spatial distribution immediately translates either in a reduction of the side effects or in an increase of the tumour control probability.

Since good review articles on protontherapy have been recently written by E. Pedroni for *Europhysics News* [5] and by M. Goitein et al for *Physics Today* [6], here we limit ourselves to remark that – by the beginning of 2005 - about 40,000 patients had been treated with proton beams and that five commercial companies offer turnkey centres of proton therapy, two based on cyclotrons and three on synchrotrons, all of them featuring isocentric 'gantries': ACCEL, IBA, Hitachi, Mitshubishi and Optivus.




▲ Fig. 2: The structure of a proton and a carbon track in nanometre resolution are compared to a schematic representation of a DNA molecule. The density of ionizations and delta-rays are different because in each cell a carbon ion leaves 24 times more energy than a proton of the same range.

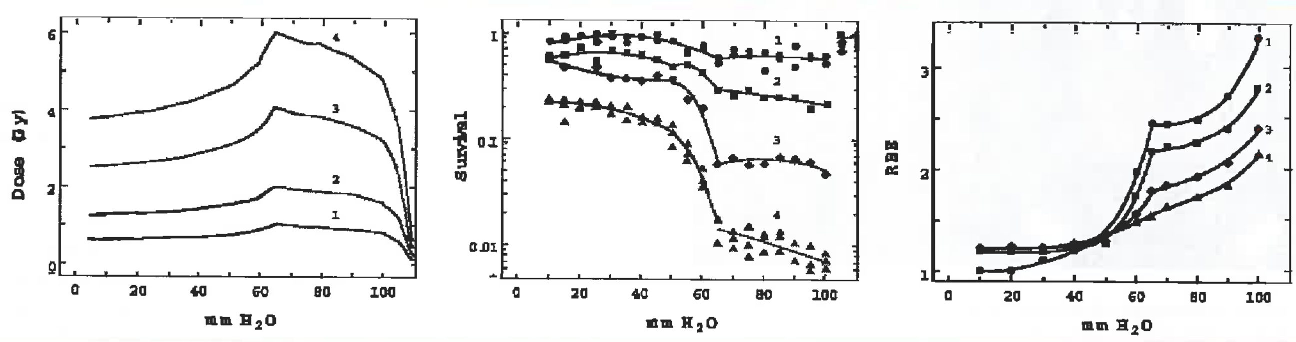
By the end of 2004 there were about fifteen hospital-based protontherapy centres running or under construction in the world [7]. This single number justifies the statement that protontherapy is booming.

## The rationale for Carbon Ion Therapy

Because of smaller scattering in both the lateral and the longitudinal direction, carbon beams exhibits dose gradients three times steeper than protons. But the main reason for the transition to carbon ions is the increased *Relative Biological Effectiveness* (RBE) in the last few centimetres of the carbon range. (RBE is defined as the ratio of the photon dose to the particle dose necessary to produce the same biological effect, e.g. inactivation of 90% of the irradiated cells.)

Dose is a macroscopic parameter that does not describes the microscopic structure of the energy deposition events. It is the spatial distribution of the ionizations around the particle trajectory – called the 'track structure' – that determines the biological effect. The relevant scale is the diameter of the DNA molecule, the main target of the radiation attack inside the cell nucleus (Fig. 2).

Because of its importance the DNA molecule is protected by an elaborate repair system that restores with high fidelity the base damages, the single- and most of the double strand breaks. In the tracks of carbon ions the local ionisation density and hence the density of severe DNA lesions becomes so high that repair fails (clustered multiply-damaged sites). Then the reproduction of the tumour cells is hindered and the tumour stops to grow. In many cases the cell internal program for its own destruction (apoptosis) is activated yielding a fast tumour regression.




▲ Fig. 3: Comparison of the physical absorbed dose (left panel) and measured cell survival of CHO cells (central panel) in a Spread Out Bragg Peak for various dose distributions. RBE values calculated from the measured cell survival are shown in the right panel. [8].

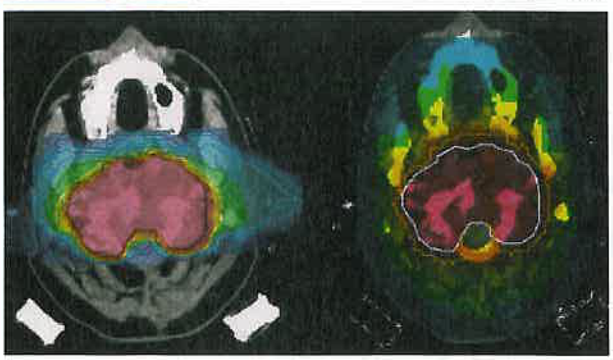
In the 'entrance channel' of a carbon beam, due to the plateau of the energy deposition, the density of severe lesions is lower and DNA damage can be mostly repaired as is in the case of X-rays and protons. Thus for carbon ions the increase in RBE is significant mainly over the Spread Out Bragg Peak (SOBP) (Fig. 3). Since the RBE varies along the SOBP the physical dose has to decrease towards the distal edge in order to achieve a homogeneous biological effect over the simulated tumour volume.

By contrast, for protons only over the last few micrometers is the RBE definitely larger than 1. For this one can state that protons have the same radiobiological effect as X-rays.

Because of the high effectiveness in suppressing the repair, heavy ion beams are most suited for slowly growing, well repairing tumours, which are precisely those tumours that are resistant to photons and protons. In these cases, the biological effect at the end of the range is increased 3 – 4 times compared to conventional radiations. In summary, carbon ion beams of about 400 MeV/u are indicated for treatment of deep-seated tumours, which are radio-resistant both to X-rays and to protons. These types of tumours are thus the elective targets in a carbon ion facility. Proton therapy is well adapted to the cases where a greater tumour dose is needed but where the tumour is not too close to organs at risk because protons have a dose gradient, always 3 times greater than carbon. These arguments are important since a proton therapy facility is about 30% cheaper than a combined proton / carbon ion centre, which requires a total investment cost of about 100 M€.

RBE is a complex function of the biological response to the microscopic structure of the radiation field, i. e. to the radiation quality. Consequently, RBE changes over the treatment area since the radiation quality changes (as indicated by the fragmentation tail of figure 1) and RBE is different for different tissues of different repair capacity. For a quantitative calculation of the RBE effects, a theoretical model, the *Local Effect Model* (LEM) has been developed at GSI [9].

In the LEM approach the individual RBE of the tumour to be treated (and the healthy tissues to be avoided) is not derived from in vitro data, but is determined from the intrinsic repair capacity as given by the dose response curve of the *same* tissue to photons. The very successful experience of the more than two hundred patients treated up to now at GSI using this treatment planning fully confirms the basic rationale of these calculations. The IMPT plan of Fig. 4 has been obtained by making use of a code based on LEM. In this case, and in most others, the advantage of an inverse dose profile, with the high dose and high LET at the end of the range, allows reducing the dose to the normal tissues outside the target volume by a factor of 2-3.



▲ Fig. 4: Comparison of treatment plans with 2 fields of carbon ion (IMPT – left panel) and with 9 fields of X-rays (IMRT – right panel). In both cases the conformity to the target volume is good but for carbon ions the dose to the normal tissues is much smaller.

A further advantage of particle beams, and especially of ions like carbon, is the 'in situ' production of positron emitters such as $^{10}C$ and $^{11}C$ and $^{15}O$. Because the stripping of one or two neutrons is a minor perturbation, the residual carbon ions form a maximum of $\beta^+$ activity close to the Bragg maximum of the stable carbon ions. By monitoring the positron emitting isotopes by a PET camera during and shortly after the beam application (Fig. 5), the actual stopping points of the beam can be controlled. PET control gives - for the first time in 110 years of radiotherapy - an 'in situ' control of the treated field that also checks all the calculations and calibrations of the energy losses used for treatment planning. The online PET technique has been developed by FZR (Dresden) [10].

## Clinical Results and numbers of potential patients

In 1994 the first patient was treated with carbon ions at NIRS in Japan where the construction of HIMAC (Heavy Ion Medical Accelerator in Chiba - www.nirs.go.jp) was promoted by Y. Hirao. At HIMAC the choice was made not to construct rotating gantries but to have a horizontal and a vertical beam in a single treatment room. The other two rooms feature horizontal beams. By 2005 more than 2,000 patients had been treated under the leadership of H. Tsujii and very promising results have been obtained [11].

Patients with early-stage Non-Small-Cell Lung Cancers (NSCLC) that could not be operated on have been treated with different dose-fractionation schedules: 18 fractions in 6 weeks, 9 fractions in 3 weeks and 4 fractions in 1 week. For the shortest one the local control rate was 73% at 3 years. At present a Phase I/II study is in progress by treating these patients with a single dose of 28 Gye delivered through four ports. Short schedules have also being studied for hepatocellular carcinomas: in the last phase II study the 3-year local control rate was 90% using a 4-fraction/1 week regimen. Finally, with 70 GyE in 16 fractions the local tumour control rate for bone and soft tissue sarcomas – which are very radioresistant tumours – was 88% after 3 years and the 3-year survival rate was 54%.

Almost 250 patients have been irradiated at GSI with a horizontal carbon beam and the active spreading system described above. Starting in 1988 one of us (G.K.), together with G. Gademann and G. Hartmann, proposed a two-step project: installation of an irradiation unit for experimental patient treatment at the new heavy ion accelerator SIS of GSI and, as a second phase, the construction of a dedicated heavy ion therapy unit at the Heidelberg clinic. In the summer of 1993 the construction of the therapy cave started and in December 1997 the first two patients were treated. In 2003 the construction of the Heidelberg Ion Therapy HIT was initiated.

At Darmstadt 3 year tumour-control rates for chordomas and chondrosarcomas, which were a subsection of the large variety of tumours treated at NIRS, are 100% and 84 % respectively [12]. These values are significantly better than reported for conventional radiotherapyand are also based on an accelerated fractionation scheme of 20 fractions in 20 days.

As far as the number of potential patients is concerned, detailed analysis have been made in Germany, Italy, Austria and France by groups of radiotherapists who have applied to the national data specific criteria for each tumour site. The results of these different approaches are very consistent. As an overall summary it can be stated that about 1% of the patients today treated with X rays must be irradiated with protons since the outcomes are definitely better than those of conventional therapy; about 12% of the X-ray patients would profit from a proton treatment but further clinical

▲ Fig. 5: The GSI horizontal beam has been used to treat mainly intracranial and head and neck tumours. The two white boxes, placed above and below the patient, contain the detectors for the on-line PET measurement of the stopping particles.

trials are needed to quantify, site by site, the clinical advantages; about 3% of the X ray patients would profit from carbon-ion therapy, but many more dose-escalation studies and clinical trials are needed.

Overall, 15% of the about 20,000 patients out of every 10 million inhabitants treated with conventional radiation would receive a better treatment with hadron beams. If the actual average recruitment rate could be as large as 50%, these figures would require a proton therapy centre (treating 1500 patients a year) for every 10 million people and a carbon ion centre for every 50 million people. This is indeed the conclusion reached by the Italian association for radiotherapy and oncology AIRO [13].

As far as costs are concerned, it has been said that proton treatment costs 2-3 times more than conventional treatment [14]. The economy of carbon treatment is different. The possible shortening of the treatment to less than 10 fractions is a great advantage for a very effective use of the costly infrastructures and – if confirmed by the ongoing clinical trials – will reduce the cost of the treatments and may become one of the main reasons behind the rapid diffusion of light ion therapy in the future. At present the German health insurance is negotiating 15, 000 to 20, 000 € per patient for particle treatment.

## European Carbon Ion facilities and enlight

Based on the successes of the pilot project, the Heidelberg Ion Therapy Centre HIT (Fig. 6) was approved in 2001 and the civil engineering work could start in November 2003 [15]. The total estimated cost of 90 M€ is shared equally between the federal Government and a bank loan of the Heidelberg hospital. The first treatment should take place in 2007.

HIT is an ambitious project that applies all the techniques and methods developed in the framework of the Darmstadt pilot project and features the first carbon ion gantry, which weighs about 600 tons.

At the end of 1995 one of us (U.A) - with the help of M. Regler - drew the interest of the CERN management to the design of an optimized synchrotron for light ion (and proton) therapy. PIMMS *(Proton Ion Medical Machine study)* was a collaboration of CERN, Med-AUSTRON (Austria), and TERA (Italy) [16].

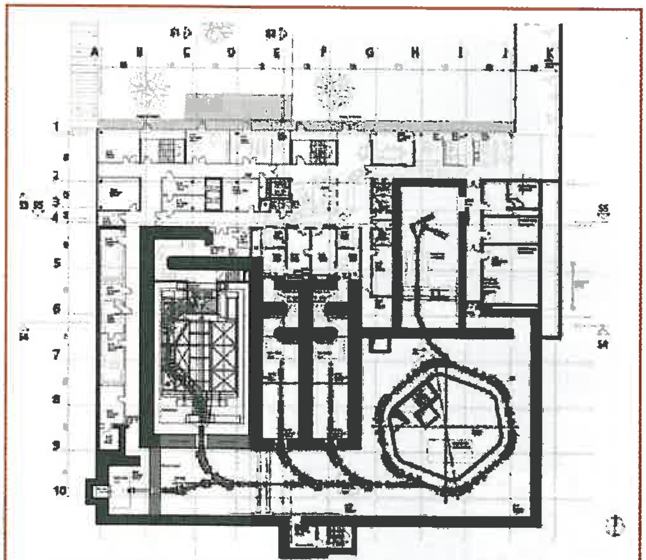
The second European centre is being built in Pave: CNAO (the *"Centro Nazionale di Adroterapia Oncologica"*) and has been designed by the TERA Foundation simplifying the PIMMS project. In the PIMMS/TERA design (Fig. 7) the sources are inside the ring together with a single 7 MeV/u injector of the GSI design [17].

In 2001 the Italian Government created the CNAO Foundation with five large hospitals of the Lombardy region and TERA as founders. In September 2003 TERA completed the technical drawings and the specifications, which have been worked out in collaboration with INFN, CERN and GSI. Since 2003 INFN is a participant of the foundation and has taken major responsibilities in the construction of the Centre. The facility is foreseen to be ready by the end of 2007.

In Europe the construction of other carbon ion centres are under consideration: Med-Austron in Wiener Neustadt, ETOILE in Lyon, ASCLEPIOS in Caen and a centre proposed by the Karolinska Institute for Sweden. These projects have adopted for their proposal the PIMMS/TERA design but the technical choices will be frozen when the financial framework is defined.

In 1998 the Med-Austron team presented to the Austrian authorities their project. At the end of 2004 the Austrian Government, the State of Lower-Austria and the town of Wiener Neustadt granted a substantial part of the required funding and initiated the creation of the organizational structure to advance the project. In 1998 the University Claude Bernard of Lyon commissioned a preliminary examination of a hadrontherapy centre based on the TERA design. A proposal centered on the health care and the economic aspects of the Lyon project was then issued. In 2004 ASCLEPIOS, a similar project at Caen, was proposed. In May 2005 the French Health Minister announced that the first French Ion Therapy centre will be built in Lyon.

The European projects (sited in Heidelberg, Pave, Wiener Neustadt, Lyon, Caen and Stockholm) have teamed with ESTRO (the European Society for Radiotherapy), EORTC (the European Organization for Cancer Research), CERN and GSI to form the *European Network for Light Ion Therapy.* In 2002 ENLIGHT was financed for three years by the European Union [18]. The work



▲ Fig. 6: The Heidelberg facility HIT (Heidelberg Ion Therapy) features three treatment rooms. One of them hosts a rotating carbon ion gantry of new design. A single 7 MeV/u linac injects in the synchrotron both protons and carbon ions.

done and the existence of this network, and of its potential successor, guarantees that the future of carbon ion therapy in Europe is on a good track and that the foreseen facilities will be run for the benefit of all European patients.

Finally it should be mentioned that the industry has meanwhile shown its interest in the forthcoming market of heavy-particle therapy. As stated above, five companies are selling proton therapy units. In the heavy-ion market Mitsubishi has designed a "micro HIMAC", a synchrotron for combined proton and carbon therapy and Siemens Medical Solutions has designed a combined proton - carbon facility on the basis of exclusive licenses of the GSI patents and know-how. IBA and ACCEL are studying superconducting cyclotrons for carbon ions and other companies are organizing themselves to enter this promising market. The strong interest of industrial companies in ion therapy indicates the large potential of this novel strategy for combating cancer. ■

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The authors share their interest in promoting ion therapy because of the expected benefit for many European patients.

## Acknowledgements

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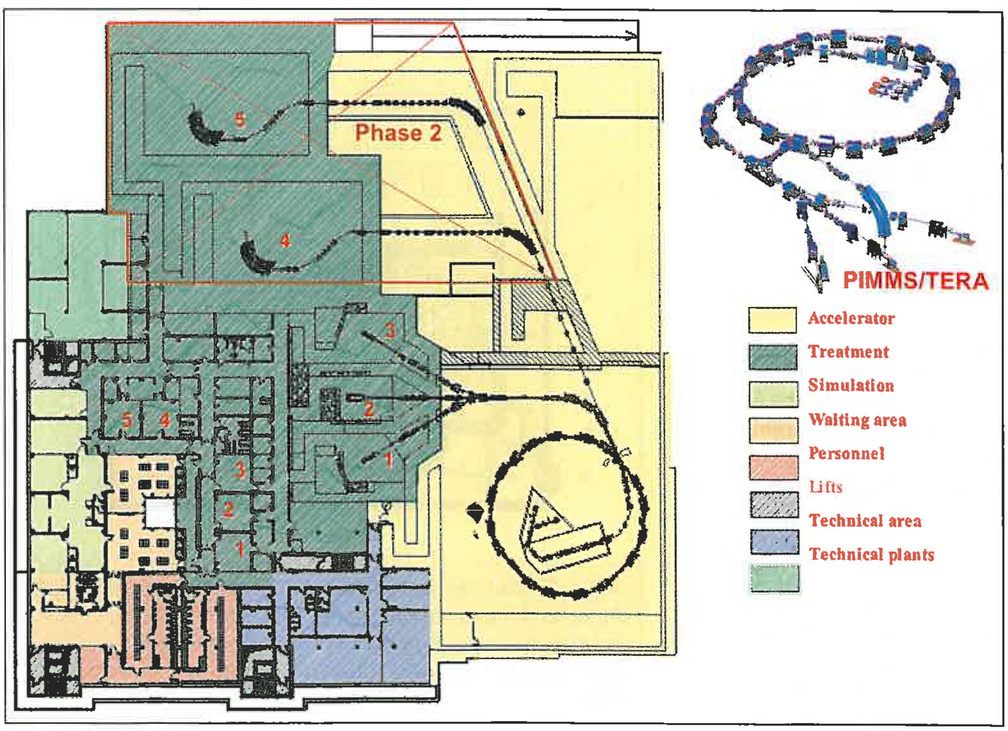


◄ Fig. 7: Layout of the CNAO underground floor. At the beginning the bunker will not feature the two very large gantry rooms that will be built and equipped with gantries at a later stage.

# Detection of buried landmines and hidden explosives using neutron, X-ray and gamma-ray probes

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It is estimated that more than 110 million active mines are a permanent threat in some 70 countries, resulting in about 2000 casualties per month, most of them being civilians. The anti-personnel mines (APM) and anti-tank mines (ATM) found in several affected countries are mostly buried, non-metallic or with minimum metal content; the most dangerous types are PROM_1, MRUD, PMR_3, and TMR_P6.

Using the classical technologies (metal detector, dogs, prodding) finding, localizing and identifying the landmines is a time consuming, expensive and extremely dangerous procedure. In addition, it will take a long time to de-mine the affected countries, mainly because the same tedious procedure has to be applied to all areas suspected to be contaminated with landmines. Mined areas are generally close to the battlefields, being consequently heavily infested by metal pieces from the explosions of different ordnances (explosion of an ordnance can result in more than 1000 small metal fragments). The presence of metal clutter produces a large number of false alarms in the metal detectors (MD) commonly used in de-mining. As a consequence, there is a need for a technological breakthrough in this field to solve definitively the land-mine problem.

Moreover, the threat of terrorist use of explosive devices and chemical, biological or radioactive agents has become realistic since the SARIN attack in the Tokyo subway system on March 20, 1995 and after the tragic events of September 11, 2001. The possibility of further terrorist actions against civil population is one of the most important issues on the international political agenda. An often evoked scenario implies the use of the so-called "dirty bomb": a sizeable quantity of radioactive material detonated by conventional explosive and dispersed in the environment. The illicit trafficking of explosives and fissile material through conventional commercial networks (air, maritime and terrestrial) represents therefore a real challenge to civil security for future years. Manual and visual inspection of large commercial payloads at terrestrial borders (trucks), seaports (containers) and airports (check-in luggage) would not be a viable solution both from efficiency considerations and for legal reasons. It is mandatory to realise standoff integrated inspection systems of cargo by means of imaging and analytical methods based on a sound technology to identify threat materials.

X-ray or gamma-ray based imaging is the only technique which enables a direct view of objects embedded or buried in soil. State of the art systems can give good precision density measurements with high-resolution three-dimensional images. The observed shapes and mechanical structure of detected objects may help to identify a particular mine type or at least to distinguish a mine from other buried objects such as metal scrap. Metal can be distinguished further by the available gross information about the elemental content of the inspected item (low Z vs. high Z discrimination).Two recent examples of systems under investigation are discussed below.

## Mine detection with neutrons

The key to distinguishing explosives from benign materials is, as for the detection of buried landmines, the use of the elemental analysis. Only neutron interrogation offers the possibility of measuring the elemental density of most elements in materials independent of their particular structure.

The use of neutron-induced reactions for non-destructive bulk elemental analysis is well documented. All neutrons, in particular fast neutrons, are well suited to explore large volume samples because of their high penetration in bulk material.

Nuclear techniques hinge on the fact that the explosives contain hydrogen, carbon, nitrogen, and oxygen in variable concentrations (for example, elementary compositions of some common explosives are: TNT - $C_7H_5N_3O_6$; RDX - $C_3H_6N_6O_6$; pentrite - $O_{12}N_4C_5H_8$; hexogen - $O_8N_8C_4H_8$; ammonium nitrite - $O_3N_2H_4$). The problem of explosive identification can be thus reduced to the problem of identification of light elements. Furthermore, the measurements of concentration ratios, especially carbon to oxygen and carbon to nitrogen, are very effective in discriminating explosives from the medium in which they are buried or hidden.

▲ Fig. 1: Test of the thermal neutron sensor prototype in the laboratory

We present three different neutron based techniques for applications to the landmine detection and cargo inspections. The first is based on the so-called Thermal Neutron Analysis where fast neutrons from a radioactive source are thermalized in a moderator and then sent onto the inspected area where they are eventually captured by the elements that characterize the investigated volume [1]. In this technique the search is for an anomalous concentration of nitrogen that is characteristic of most explosives. The second is based on the Neutron Backscattering Technique where fast neutrons from a radioactive source are sent directly onto the investigated area and the flux of thermal or epithermal neutrons scattered backward is proportional to the inverse atomic number of the elements contained in the inspected volume. In this way materials with a high hydrogen content (such as the explosive in a landmine and the plastic case as well) are detected if the background has an average higher atomic number [2]. The third is the so-called Associated Particle Technique where one produces neutrons by the d + t reaction that yields a neutron of 14 MeV and an alpha particle of 3.5 MeV energy emitted back-to-back in the center of mass of the compound system. The possibility of detecting with high efficiency the $\alpha$ particles allows a determination of the direction and the time of production of the associated neutrons. In this way one can direct a beam of "tagged" neutrons onto the area to be investigated and measure the characteristic gamma radiation originating from the neutron induced reactions on several elements highly reducing the "environmental" background [3].

### Thermal Neutron Analysis

A picture of a thermal neutron sensor prototype, as assembled for laboratory tests is shown in Fig. 1. A $^{252}$Cf neutron source ($1.10^7$ neutron/s) in a spherical lead shield (inner radius 1.5 cm, outer radius 4.5 cm) is housed in a high density polyethylene cylinder of 28 cm diameter and 26.5 cm height. The stand-off distance of the sensor is about 20 cm from a sand box with 1 m$^3$ volume. The moderator geometry is selected after an experimental study devoted to the optimisation of the thermal neutron flux in the soil. It is certainly mandatory to increase the thermal neutron flux at the typical depth where landmine are buried, i.e. up to 20 cm, the moderation capability of the bare soil being too low to allow measurements of the neutron capture reaction on nitrogen nuclei in realistic time. Four large scintillation detectors serve in this set-up to detect the characteristic gamma rays. The relative detection probability of chemicals containing nitrogen was determined as a function of the burial depth and of the soil moisture to investigate the capability of the method in different conditions (i.e. depth and soil moisture).

Results demonstrate that it is still possible to detect a sample of about 800 g of the explosive simulant Melamine even in the presence of relatively high soil moisture (up to about 20 % in weight). The increase of the burial depth causes a sizeable decrease of the signal from the explosive simulant due to the solid angle effects. In the measurements shown here the stand-off distance is about 20 cm (see Fig.1). In this condition, the presence of a buried object can be identified up to burial depths of about 15 cm. For deeper burial depths, the signal-to-noise ratio for Melamine samples up to about 2 Kg makes the detection very difficult.

About 20 minutes measurement time is needed for a Melamine sample at a depth of 15 cm in order to distinguish the explosive from the background. This suggests the use of such a sensor only for Anti Tank Mines. In the case of a common ATM, such as the TMA3, the TNT charge is about 6 kg. Considering a source of $2 \times 10^7$ neutrons/s and increasing the number of detectors from 4 to 8, the confirmation time for such a mine buried up to 15 cm would be less than 2 minutes, making realistic the use of such sensor.

### Neutron Backscattering

The principle of the technique is very simple: when a fast neutron source (such as $^{252}$Cf ) is used to irradiate the soil, the yield of thermalized, backward scattered neutrons depends on the hydrogen content of the irradiated volume. Therefore, to confirm the presence of the mine, a Neutron Backscattering (NB) sensor will verify the presence of anomalous hydrogen concentration in the target point, previously identified by using, for instance, a common tool such as the MD. From an operational point of view, it is mandatory to have a unique hand-held system that integrates a NB probe inside a MD.

One possible Neutron Backscattering detector design makes use of a large area ($20 \times 20$ cm$^2$) Multi-Wire Proportional Counter (MWPC) as a neutron detector. The detector consists basically of 3 parallel electrodes: a plane of wires as anode and the two cathodes coated with a 3 $\mu$m thick $B_4C$ layer, 97% enriched in $^{10}$B. The anode wires are grouped to obtain 10 independent portions having an area of $2 \times 20$ cm$^2$. In this system, the efficiency for low energy neutrons is determined by the conversion via the $^{10}B(n,\alpha)$ reaction which is estimated to be about 16% .The detector electrodes are light (700 g) and have been specifically designed to minimize the metal content, so that the performance of a standard MD is not lowered when it is integrated with the NB sensor. Laboratory tests with the NB sensor working in stand-alone mode, in a configuration where the MWPC electrodes are enclosed in a gas-tight, sealed G-10 box operated at atmospheric pressure with a mixture of Ar (85%) and $CO_2$ (15%) show that a steady gas charge will allow operation during an 8 hours shift without showing a significant deterioration of the signal size.

An example of a portable system realized by the group of Prof. Carel W.E.Van Eijk of Delft University (The Netherlands) is shown in fig. 2.

▲ **Fig. 2:** Portable Neutron backscatter system in operation

## Associated Particle Technique

In the last few years a prototype of the Tagged Neutron Inspection System (TNIS) was developed using tagged beams of 14 MeV neutrons with suitably defined beam profile, produced by the d+t reaction. Recent studies on this technique point to the development of a portable sealed neutron generator with the neutron-tagging detector embedded into the system.

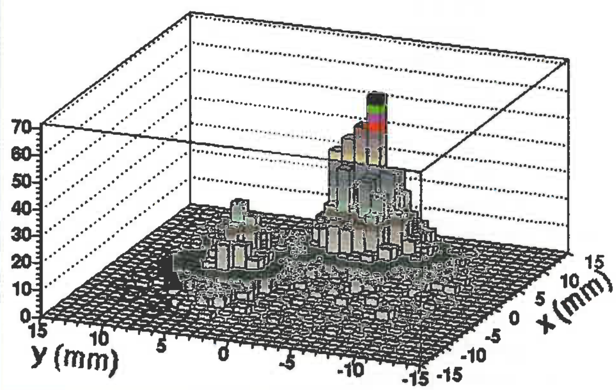
A possible design for the alpha-particle detector for this application has been tested at the Neutron Generator Laboratory of the Ruder Boskovic Institute (IRB) in Zagreb, Croatia. The experimental system now in operation at the IRB contains a neutron tagging detector made of a 40 mm diameter, 0.5 mm thick YAP:Ce scintillator placed inside the reaction chamber at approximately 5.5 cm from the target, 90° with respect to the beam direction and at an azimuthal angle of 45°.

As a test to measure the effectiveness of the method on the signal-to-noise ratio a graphite sample of 5x5x5 cm$^3$ located at about 90 cm from the source of neutrons is used. The detection of the 4.4 MeV gamma rays emitted by the $^{12}C$ first excited level populated by neutron inelastic scattering by means of a 4 inch x 4 inch NaI scintillation detector is used to determine the improvement of the spectrum quality. The results of the irradiations are shown in fig. 3: on the left-hand side is shown the gamma-ray spectrum detected without requiring a strict coincidence between the alpha particle and the associated neutron hitting the sample. One can see a peak between 5 and 6 MeV due to neutrons hitting directly the NaI counter, and the 4.4 MeV and "first escape" peaks associated to the decay of $^{12}C$ in the sample. On the right-hand side is shown the same spectrum but with a strict condition on the alpha-gamma coincidence time.

One can notice a dramatic improvement of the signal-to-noise ratio due to both the "geometrical" and "timing" related reduction of the background contribution. Such improvement can be of up to two orders of magnitude in the case of a pure mono-elemental sample.

Another important property of a system based on fast neutron elemental analysis is the "granularity" of the tagging system that determines the number of neutron beams that can be produced and their maximum transversal dimension. In other words the position resolution of the alpha particle tagging system determines the "imaging" properties of the associated neutron beams.

With the use of two small (5x5x5 cm$^3$) graphite samples placed at about 6 cm distance from each other on a plane at 90 cm from the neutron source, the usual gamma-ray line at 4.4 MeV is used to confirm that a neutron has hit one of the two samples. The "image" of such a double-sample system as determined in the associated alpha-particle detector is shown in fig. 4 below.



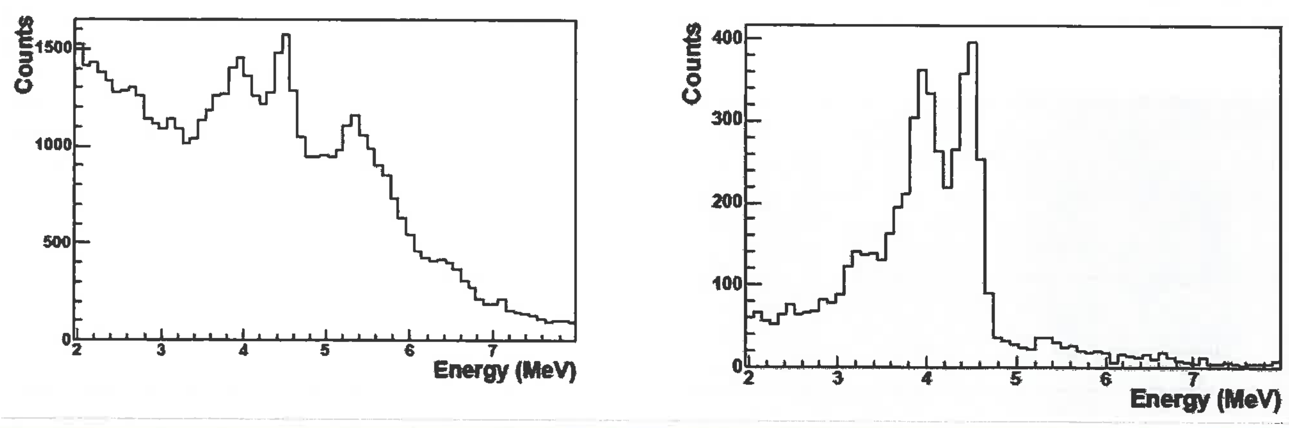

▲ Fig. 4: Position resolution demonstrated with two graphite samples 6 cm apart.

The distribution of hits on the 40 mm diameter YAP:Ce alpha counter is determined in this case by the "centre-of-gravity" method of the signal amplitudes recorded by a multi-anode photomultiplier tube. One can see in the figure the capability of one such system to create an "image" of a given element (in this case $^{12}C$). Extending the method to different elements or mapping directly the elemental ratio one can envisage obtaining a "chemical map" of the area under investigation.

## Mine detection with photons

As discussed earlier, neutron activation may cause gamma rays with characteristic energies to be emitted by land mine constituents. The second, rather promising approach to employing photons in the landmine detection process is photon scattering. Compton scattering is dominant in most materials at photon energies below several hundred keV. In this process, photons collide incoherently with the atomic electrons, thereby loosing part of their energy. The scattering probability is dependent on the electron density, and consequently the mass density, of the medium. Therefore, Compton scattering can provide a density map, which can be used as an indicator that an anomaly falls in the range of explosive materials.

The intensity of photons scattered by an object embedded in soil is proportional to i) the intensity of the photons emitted from a source towards the object, ii) the attenuation of the photons before they scatter, iii) the probability of scattering in the back direction and iv) the attenuation of the photons as they pass back out of the object and traverse the soil on the way to the photon detector.




▲ Fig. 3: Neutron activation spectrum without (left) and with (right) alpha particle coincidence (see text).

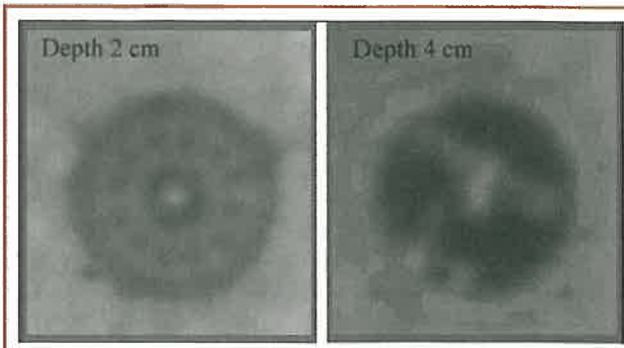
features

Sources of photons can be either high power x-ray generators capable of producing x-rays ranging in energy up to 300 keV and more, or gamma sources containing radioactive isotopes such as $^{137}Cs$ or $^{22}Na$. The photons emitted in the direction of the soil and the objects therein are partly removed by side-scattering or absorption in the material. Back-scattered photons travelling towards the detector are again partly removed by further scattering or absorption. Organic material and in particular explosives are characterized by a low effective atomic number, resulting in a high scattering probability and low absorption probability. Dense, metallic material on the other hand readily absorbs low energy photons (x-rays), while for higher energy gamma-rays the remaining Compton scatter probability together with the high density may yield a stronger backscatter signal compared to organics and soil. The combination of density and atomic number can therefore be characteristic for explosives, metal debris or other material.

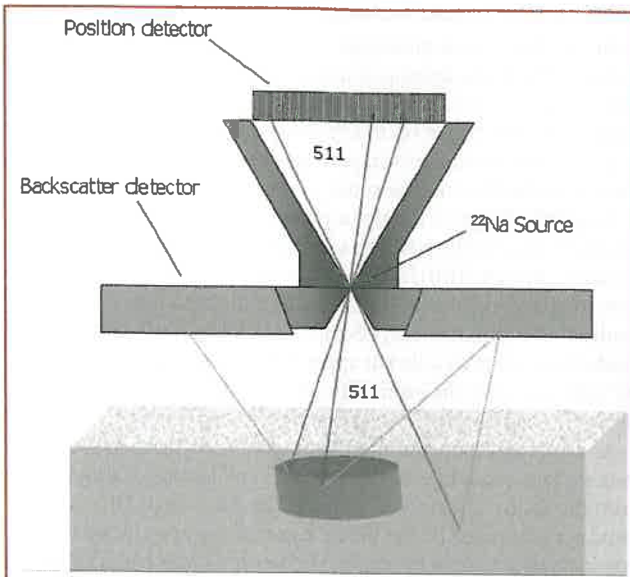
The photon backscatter techniques aim at mapping the effective atomic number and the density of a given soil area. An image of the backscatter distribution may thus reveal irregularities in the soil enabling one to distinguish metallic clutter from land mines by geometry and scatter probability. Generally a position resolution of 2 mm to 4 mm is sufficient for the identification of APMs, whereas for ATMs 1 cm may still be adequate.

In conventional systems collimation of the employed x-ray or gamma-ray beam and its scanning movement is required to map a suspicious surface area. Appropriate beam geometry is achieved by means of a suitably shaped channel in a dense and heavy absorbing material such as lead or tungsten alloys. Good image resolution generally requires a small beam profile, thus the usable fraction of radiation emitted by the photon source is often very small in the range of 0.001 to 1 percent. Rather high source activity is required to obtain the necessary radiation dose at each scanning position in a short time span. Otherwise the total time to generate an image would be impractibly long.

Devices can for instance be mounted on a remote-controlled vehicle, with only the detectors suspended over the minefield by a cantilever arm. To produce an undistorted image the speed of the vehicle would need to be either regulated or accounted for. The backscatter system might be applied as the second stage of a two-stage process in which the first stage identifies suspect objects, and backscatter imaging verifies each threat. For example, a metal detector and a neutron detection system could be used in the first stage.




▲ Fig. 5: X-ray images of a buried PPM-2 APM.




▲ Fig. 6: Principle of the annihilation radiation imaging method.

## X-ray imaging

X-ray imaging is a mature technology with the advantage of very high image contrasts and good position resolution. In contrast to transmission technologies such as radiography a backscatter image normally is obtained pixel by pixel. A scanning mechanism for a pencil-like x-ray beam is used to generate images. The attenuation of low energy x-rays in soil and explosives is tremendous. Depending on the soil composition and density the total probability for an x-ray to penetrate through the soil to a mine, be backscattered by the mine material and to travel through the soil back into the detector may be of the order $10^{-8}$ at 10 cm mine depth. Therefore the highest possible x-ray energies and intensities are required to achieve good contrast in a reasonable scanning time.

An example is the prototype scanner ComScan450 developed by the company YXLON to detect land mines (W. Niemann et al., YXLON International X-Ray GmbH, Hamburg [4]). All the components of the system are mounted on a trailer. A high flux 450 kV x-ray tube and a multi-channel x-ray detector system are the major components. The largest and heaviest part of the system is the power generator for the x-ray tube.

ComScan450 has been in use on military test sites several times. Tests were made at varying soil conditions such as humus, sand, gravel etc. Tests were also made with varying conditions of vegetation and of wetness. In the following example in fig. 5 images of a buried PPM-2 APM are shown. The diameter of the mine is approximately 12 cm, layers are shown at depths of 2 cm and 4 cm, respectively. In the first layer, structures of the top lid are clearly visible. No non-mine object in the soil (such as stones, sand, vegetation) would reveal structures like this.

## Backscatter imaging with gamma rays

Recently a novel backscatter imaging technique has been introduced, which uses the source of gamma rays very effectively by avoiding any collimation. Therefore the required source activity can be several orders of magnitude below conventional systems. Fig. 6 illustrates the principle of the new method. A point-like $^{22}Na$ positron source emits pairs of 511 keV positron annihilation gamma rays directed 180° to each other. One gamma ray may be registered in the Position gamma detector. The active detection area of this detector defines the beam shape of the correlated 511 keV gamma rays intended to probe the object to be examined. Its spatial resolution determines the image resolution. The Backscatter gamma detector detects gamma rays scattered from the object. The backscatter probability depends on the amount, density and element composition of the object. To distinguish between gamma rays belonging to the probing beam and other gamma rays emitted by the source or by other natural or artificial radiation sources, time coincidence of the signals of both detectors is demanded.

Currently a detection system is being developed at GSI Darmstadt by its technology transfer partner company GFE mbH, aiming particularly at the detection of land mines in soil. It incorporates a $^{22}$Na source of 10 MBq activity in a massive tungsten alloy shielding. The position detector has nine position sensitive LYSO scintillator block elements. The elements form a shell segment covering a solid angle of about 5% of $4\pi$. Each element is coupled to a position sensitive photomultiplier which, together with the subsequent electronics circuitry, produces x and y position as well as time information for each gamma ray detected.

The Backscatter detector consists of 8 plastic detector elements read out by three photomultiplier tubes each, forming a 5 cm thick disc with ca. 50 cm outer diameter and a rectangular centre hole. The 511 keV gamma rays emitted by the source illuminate the object of inspection through this hole. If a 511 keV gamma ray is detected at a certain position of the Position detector its 180° counterpart may be scattered off an object in front of the set-up. For a given range of scattering angles this scattered gamma ray may be detected in the Backscatter detector and generates a coincidence trigger. An image of the matter distribution in the field of view –defined by the active area of the Position detector and the source to matter distance– is obtained by incrementing an image data array in the data acquisition computer.

Fig. 7 shows as an example the image of a metal object and of a small candle of 5 cm diameter in sandy soil. The enhanced backscatter probability of the metal allows it to be discriminated from the candle with its reduced probability, which resembles the scattering behaviour of a plastic mine with 511 keV gamma rays. Depending on the soil type and the volume of the mine the layer thickness that can be penetrated is 10 to 40 cm.

The presented imaging device may help to verify mines found e.g. by metal detectors and may considerably speed-up the clearing of mine fields by avoiding time consuming treatment on harmless metal objects. Moreover, for APM detection in shallow depths a handheld system may be realized since the efficient use of the gamma source with this new method allows for low activity and, hence, lightweight protective shielding.

The novel methods employing neutron and gamma ray probes for mine detection reveal very promising results in the laboratory and in field trials. Therefore we believe that instruments based on these techniques may soon become available to detect land mines in a much safer way and much faster compared to current approaches.

## About the authors:

**Dr. Jürgen Gerl** is physicist specialized in experimental nuclear structure research. Besides pure science he was always interested in the development of novel instrumentation and its application for "practical" purposes outside science.

**Dr. Giancarlo Nebbia** is a physicist with a two decades of experience in accelerator-based experimental nuclear physics. Since 1996 he has been working on the application of nuclear techniques to humanitarian demining and civil security issues. ■

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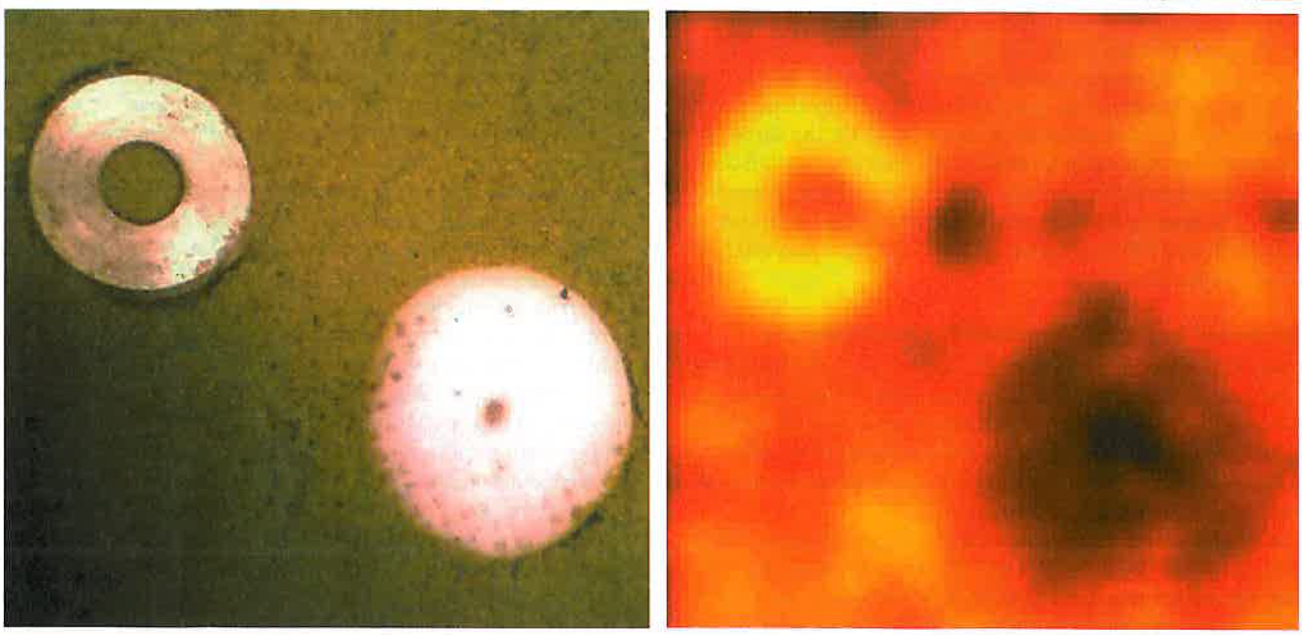

▲ Fig. 7: Image of a metal object and a candle.

features

# Einstein - from Ulm to Princeton

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Last year, the University of Ulm, the City of Ulm, and the German Physical Society celebrated the $125^{th}$ birthday of Albert Einstein, who was born in Ulm on 14 March1879. Being fully aware of the multitude of events expected to happen at many places during the "World Year of Physics 2005", it was felt appropriate to commemorate Einstein at his birthplace already in 2004. This followed a long tradition in Ulm, where previously Einstein's 70th and 100th birthday had been celebrated in 1949 and 1979, respectively.

The celebration in Ulm consisted of a large number of events during a period of nine months. To bring Einstein's work, ideas and life to a broad audience, a series of a dozen of public lectures [1] were given by physicists and historians that met with great response. An "Albert-Einstein-Schülerwettbewerb" (competition for students at secondary schools) was organized, and a new "Einstein Opera" commissioned by the City of Ulm was performed at the Ulm Theatre. Furthermore, an "Einstein Exhibition" was installed which saw many visitors over several months.

On Einstein's birthday, 14 March 2004, the Mayor of the City of Ulm held a "Festakt" in Ulm's Einstein Hall in the presence of the President of the Federal Republic of Germany and the Prime Minister of Baden-Württemberg. In the evening of the same day, the opening ceremony of the Spring Meeting ("Frühjahrstagung") of the German Physical Society took place at the University of Ulm. The scientific and cultural highlights were the magnificent "Einstein Lecture" delivered by the Nobel Laureate, Chen Ning Yang [2], and the sensitive interpretation of the E minor Mozart Sonata (K304) by violinist and Einstein's great-grandson Paul Einstein. Let us cite from Yang's talk [2]: "Einstein was the greatest physicist of the 20th century, and with Newton the two greatest physicists of all times. His work is characterized by depth, scope, imagination, persistence and independence. Of the three great conceptual revolutions in fundamental physics in the 20th century, he was responsible for two, and had decisively shaped the third." The three revolutions referred to by Yang are of course special relativity (1905), general relativity (1915), and quantum theory (1900-1925).

### Genius isn't always immediately recognized [3]

Albert Einstein's ancestors were of Jewish origin and had lived in southern Germany for centuries. His father Hermann served a merchant's apprenticeship in Stuttgart and arrived in the late 1860s in Ulm where several of his relatives had already settled. In 1870 he joined the feather-bedding firm of Israel and Levi. In 1876 Hermann Einstein married Pauline Koch.

Albert Einstein's younger sister Maria Winteler-Einstein (1881-1951), called Maja, wrote in 1924 about her brother [4]: "At his birth his mother was shocked at the sight of the back of his head, which was extremely large and angular, and she feared she had given birth to a deformed child. But the doctor reassured her, and after a few weeks the shape of the skull was normal... Otherwise, he developed slowly in childhood, and he had such difficulty with language that those around him feared he would never learn to speak... His early thoroughness in thinking was also reflected in a characteristic, if strange, habit. Every sentence he uttered, no matter how routine, he repeated to himself softly, moving his lips. This odd habit persisted until his seventh year."

▲ **Fig. 1:** Albert Einstein with his sister Maja, ca. 1885.

In June 1880, the Einstein family moved to Munich. "Had Hermann remained in Ulm," wrote Maja [4], "his son Albert would also have been granted a more carefree youth." This remark does not allude to the fact that legend has it that Einstein was a "poor pupil", but rather refers to the economical situation of the family in Munich. After some success with an electrical firm which produced large-scale dynamos, arc lamps and telephone systems, the firm liquidated and the family moved without their son Albert to Milan in 1884 and a year later to Pavia.

Although later, Einstein commented only very negatively on his school days in Munich ("The teachers at primary school appeared to me as sergeants and the teachers at the Gymnasium as second lieutenants" [5]), he actually had been a good student. When at the age of 15, he abruptly left the Gymnasium in Munich without asking his parents and went to Milan, he got a certificate from a Gymnasium teacher, praising his "mathematical knowledge and abilities." (CP1, p.lxiv) Naturally, the parents were alarmed by his high-handed behaviour but he most adamantly declared that he would not return to Munich. However, he told his parents he would prepare himself for the entrance examination to the Polytechnikum in Zurich. And in fact, in October 1895 he received an exceptional permission to take the examination even though he was two years under the regular admission age of eighteen. The examination consisted of two parts: one testing general knowledge, the other testing specialized scientific knowledge (arithmetic, algebra, geometry, physics and chemistry) (CP1, p.10). Although he passed the examination with the best outcome in the second part, he failed in the first, and therefore he was advised to attend the final year at a Swiss secondary school. Thus he entered in October 1895 the Cantonal School in Aarau.

In October 1896 he received in Aarau the Matura (graduation certificate) as the best of his class which enabled him to enter the Mathematical Section of the Polytechnikum at the age of 17 1/2. Here he met his first wife Mileva Mariç (1875-1948) who was the only female student in his section. She was born in Titel, a Serbian village near Novi Sad.

In his eighth semester, he wrote a Diploma Thesis on heat conduction and obtained in July 1900 at the age of 21 his Federal Diploma for Specialist Teachers of Mathematics and Physics. However, his hopes to get a position as an assistant at a university in Switzerland, Germany, Holland or Italy were not fulfilled, and thus he worked temporarily as a supply teacher in a private school. After his move to Bern in February 1902, he even put an advertisement in a local newspaper offering private lessons in mathematics and physics – first lesson free of charge! At last, in June 1902 he got a position as III.Class Technical Expert at the Swiss Patent Office in Bern and was promoted there in 1906 to become a II.Class Expert – after he had already published his revolutionary papers of 1905.

It was a big surprise, when in 1986 the love letters of Albert Einstein and Mileva Mariç written during the years 1897-1903 were discovered [6]. The letters show us the young man fallen in love and his relation to his first wife. They give us deep insight into his intellectual development during the years shortly before he published his epochal scientific papers that made him world-famous. Already in these letters we recognize a characteristic feature which he kept through all his life: absolute independence in scientific and political issues, be it with respect to people or institutions, the "suspicion against every kind of authority" [7]. Until the discovery of the love letters, the world did not know that in January 1902 Mileva had given birth, out of wedlock, to their first child, a daughter named Lieserl. The mystery surrounding Lieserl remains unsolved; probably she was put up for adoption. In January 1903, Einstein married Mileva who gave birth to two sons: Hans Albert (1904-1973) and Eduard (1910-1965).

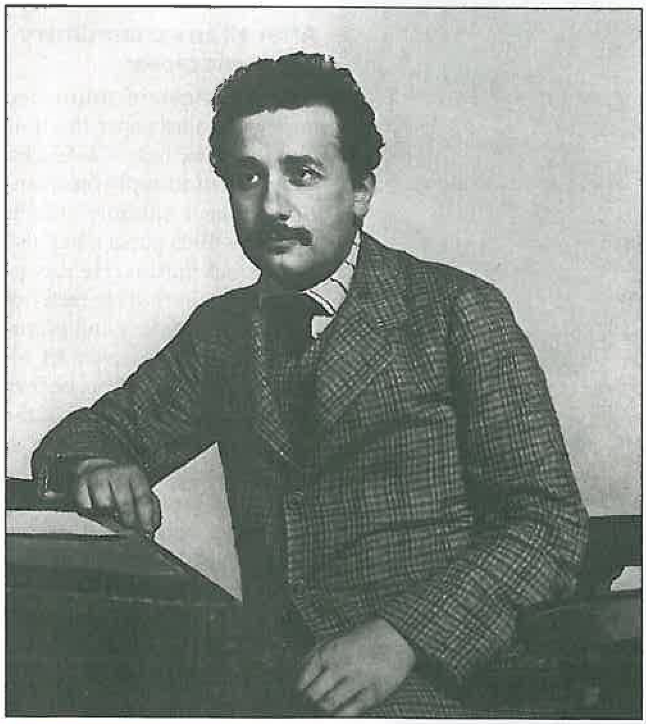
## The annus mirabilis 1905

In 1905, Einstein's annus mirabilis or wonder year, the 26-year old patent clerk submitted five fundamental papers to the "Annalen der Physik" during the incredibly short period between 17 March and 27 September. For the first of these papers, and not for the Theory of Relativity, the Nobel Prize in Physics for 1921 was awarded to Einstein in 1922. In this paper, he developed a completely novel theory of light by introducing a new elementary particle, the light quantum or photon (c.f. Friedman's article, this issue). With the second and third paper, he became one of the most important advocates of the then still heavily disputed hypothesis on the existence of atoms. The fourth paper contains the foundation of the Theory of Special Relativity, and finally in the fifth and last paper of the annus mirabilis he derives his legendary formula $E=mc^2$.

In a letter to his friend Conrad Habicht (written on 18 or 25 May 1905), which is a typical example of his strong sense of humour, Einstein wrote: "So, what are you up to, you frozen whale, you smoked, dried, canned piece of soul, or whatever else I would like to hurl at your head, filled as I am with 70% anger and 30% pity! You have only the latter 30% to thank for my not having sent you a can full of minced onions and garlic after you so cravenly did not show up on Easter. But why have you still not sent me your dissertation? Don't you know that I am one of the 1 1/2 fellows who would read it with interest and pleasure, you wretched man? I promise you four papers in return, the first of which I might send you soon, since I will soon get the complementary reprints. The paper deals with radiation and the energy properties of light and is very revolutionary, as you will see if you send me your work first. The second paper is a determination of the true sizes of atoms from the diffusion and the viscosity of dilute solutions of neutral substances. The third proves that, on the assumption of the molecular theory of heat, bodies on the order of magnitude 1/1000 mm, suspended in liquids, must already perform an observable random motion that is produced by thermal motion; in fact, physiologists have observed <unexplained> motions of suspended small, inanimate, bodies, which motions they designate as 'Brownian molecular motion'. The fourth paper is only a rough draft at this point, and is an electrodynamics of moving bodies which employs a modification of the theory of space and time; the purely kinematic part of this paper will surely interest you." (CP(c)5, p.20)

It is remarkable that Einstein calls only his first paper, in which he explains the photoelectric effect, "revolutionary", and not the two papers on relativity. How revolutionary this paper really was, can be seen from an interesting document. It shows that even Max Planck, who had introduced the notion of quantum in 1900, criticized Einstein's light quantum hypothesis even still in 1913.

At the beginning of the year 1913 Fritz Haber had proposed that Einstein be brought to Berlin as a member of the Kaiser Wilhelm Institute of Physical Chemistry and Electrochemistry. By late spring, Max Planck and Walther Nernst had modified Haber's



▲ Fig. 2: Albert Einstein at the Patent Office in 1906.

proposal, combining the idea of Einstein's membership in the Prussian Academy of Sciences with the prospect of his directorship of a Kaiser Wilhelm Institute of Physics. (CP5, p.29) On 12 June 1913 Max Planck read aloud to the physical-mathematical class of the Academy a proposal for Einstein's membership in the Prussian Academy of Sciences which was signed by him, Nernst, Heinrich Rubens, and Emil Warburg. We read in this proposal: "In sum, it can be said that among the important problems, which are so abundant in modern physics, there is hardly one in which Einstein did not take a position in a remarkable manner. That he might sometimes have overshot the target in his speculations, as for example in his light quantum hypothesis, should not be counted against him too much. Because without taking a risk from time to time it is impossible, even in the most exact natural science, to introduce real innovations. At the moment he works intensively on a new theory of gravitation; with what success, only the future will tell." (CP(c)5, p.337)

## After all an extraordinary academic career

In 1907 Einstein published another seminal paper, this time on the specific heat of solids. He was the first to apply the quantum concept not only to light (as in his 1905 paper), but also to normal matter. He recognized the universal character of the quantum theory and postulated that the energy of all vibrational phenomena, be they the oscillations of light or of the atoms in material bodies, has to be quantized. With this paper he established the quantum theory of solids with its far-reaching practical applications later on.

Einstein worked at the Patent Office until May 1909 when he accepted his first academic position as Associate Professor at the University of Zurich. Two months later, at the age of thirty, he was granted together with Marie Curie and others his first honorary doctorate in the physical sciences by the University of Geneva on the occasion of the University's 350$^{th}$ anniversary celebration. In 1910 Einstein moved to Prague where he accepted a Full Professorship at the German University. There he occasionally visited the salon of Bertha Fanta where he met Max Brod and Franz Kafka. In 1911 he was invited to attend the first Solvay Conference in Brussels and was given the honour of being the final speaker. The title of his talk was: "The Current Status of the Specific Heat Problem." At Brussels he met the leading physicists of the time, among them Marie Curie, Paul Langevin, Hendrik Antoon Lorentz, Henri Poincaré, Ernest Rutherford and the Berlin physicists, Max Planck and Walther Nernst. At Prague he obtained offers from the University of Utrecht and the ETH Zurich, and in 1912 he returned to Zurich to become a Full Professor at the ETH where he had studied several years before.

We have already cited from the proposal for Einstein's membership in the Prussian Academy of Sciences. In July 1913, Nernst and Planck visited Einstein in Zurich and offered him a well-paid position as a member of the Berlin Academy and director of the planned Kaiser Wilhelm Institute of Physics. Einstein accepted and moved in April 1914 to Berlin. He was now 34 years old and had an extraordinary position. In a letter to his first coworker Jakob Johann Laub he wrote: "On Easter I leave for Berlin as an Academy-man without any obligations, like a living mummy in a way. I am very happy about such a difficult career!" (CP(c)5, p.344)

From Einstein's correspondence we know now that he was attracted to Berlin not only by the famous physicists there and the excellent position, but also by his cousin Elsa Löwenthal-Einstein (1876-1936). Already from Prague he had written to her: "I can't even begin to tell you how fond I have become of you during these few days." (CP(c)5, p.291) And in July 1913 he wrote: "I rejoice at the thought that I will soon be coming to you. (...) Seeing you regularly will be the nicest thing that awaits me there!" (CP(c)5, p.343). Shortly after Mileva had joined Einstein in Berlin, it became clear that their marriage was ruined and Mileva returned with the two sons to Zurich. They got divorced in 1919, and a few months later Einstein married Elsa.

## General relativity

Already in 1907, when most physicists still struggled with special relativity, Einstein sought a generalization. "So far we have applied the principle of relativity, i.e., the assumption that the physical laws are independent of the state of motion of the reference system, only to nonaccelerated systems. Is it conceivable that the principle of relativity also applies to systems that are accelerated relative to each other?" [8]

Between 1907 and 1915, Einstein wrote numerous papers attempting to generalize special relativity. For this purpose, he had first to find out that the required mathematics is Riemannian geometry and the absolute differential calculus developed between 1896 and 1900 by Elwin Bruno Christoffel, Gregorio Ricci, and Tullio Levi-Civita. Already in Prague he had realized that gravitational fields are equivalent to a curvature of space-time which can be described by a Riemannian metric. This idea led him in 1911 to the prediction that light waves should be bent near a heavy body like the sun.

In November 1915, which can be called "Einstein's wonder month", he gave four talks at the weekly plenary meetings of the Prussian Academy in Berlin. It is only at the last session on 25

◄ Fig. 3: Albert Einstein in Princeton with Chen Yang's son Franklin Yang.

November that he could present the complete gravitational field equations which form the basis of general relativity. "General relativity was a singularly profound creation of Einstein's. In originality and boldness I believe it has no equal in the history of physics." (C.N.Yang, [2]).

In Einstein's General Theory of Relativity space and time are no more rigid but rather become dynamical entities which are determined by matter. Already on November 15, when he did not yet have the correct equations, Einstein presented a crucial test of his new theory. "In the present work I find an important confirmation of this most radical relativity theory, showing that it explains qualitatively and quantitatively the secular rotation of the orbit of Mercury (...), which was discovered by Le Verrier and which amounts to 45 sec of arc per century. Furthermore, I show that the theory has as a consequence a curvature of light rays due to gravitational fields twice as strong as was indicated in my earlier investigation." [9] In al letter to his friend Paul Ehrenfest he wrote: "Imagine my delight at realizing that general covariance was feasible and at finding out that the equations yield Mercury's perihelion motion correctly. I was beside myself with joy and excitement for days." (CP(c)8, pp.177) "This discovery was, I believe, by far the strongest emotional experience in Einstein's scientific life, perhaps in all his life. Nature had spoken to him. He had to be right." (A.Pais, [10])

A few months later, Karl Schwarzschild found the exact solutions to Einstein's field equations for a spherically symmetric mass distribution. His by now famous solution provides the fundamental model of a black hole. Recently, it could be demonstrated using modern methods of infrared astronomy that there exists a massive black hole at the center of our Milky Way (e.g., H.Genzel in [1]).

In 1916 Einstein derived another fundamental prediction of his theory: the existence of gravitational waves. When more than 60 years later Russel A. Hulse and Joseph H. Taylor discovered a new type of pulsar, they used it for an indirect confirmation of the existence of gravitational waves. (For this work they received the Nobel Prize 1993).

At a solar eclipse in May 1919, two British expeditions confirmed Einstein's prediction of the bending of light. The results were presented in a memorable joint meeting of the Royal Society and the Royal Astronomical Society in London on 6 November 1919. The president of the Royal Society, Sir Joseph John Thomson, said in his summary: "This is the most important result obtained in connection with the theory of gravitation since Newton's day, and it is fitting that it should be announced at a meeting of the Society so closely connected to him."[11] The next day an article appeared in "The Times" (London) with the headlines "Revolution in science. New theory of the universe. Newtonian ideas overthrown." This was the birth of the Einstein legend (e.g., [10], pp. 306). Einstein himself accepted to write a guest article in "The Times" of November 28. "After the lamentable breach in the former international relations existing among men of science, it is with joy and gratefulness that I accept this opportunity of communication with English astronomers and physicists. It was in accordance with the high and proud tradition of English science that English scientific men should have given their time and labour (...) to test a theory that had been completed and published in the country of their enemies in the midst of the war." (CP(c)7, 213).

## Cosmology and Einstein's "biggest blunder"

In February 1917, Einstein presented another epochal paper in which he applied his theory of gravitation to the Universe at large [12]. He introduced what we call today the Cosmological Principle that assumes that the large-scale structure of the Universe is homogeneous and isotropic, on average. With this paper he founded modern cosmology by constructing a model of the Universe fully compatible with observations at that time. He wrote to his friend Ehrenfest: "I have (...) again perpetrated something about gravitation theory which somehow exposes me to the danger of being confined in a madhouse." (CP(c)8A, 390).

The Einstein universe is closed. In describing the beings in it, Einstein wrote in his popular book: "The great charm resulting from this consideration lies in recognition of the fact that *the universe of these beings is finite and yet has no limits.*" [13] For reasons which were also metaphysical, Einstein wanted a static, eternal universe, i.e., without a Big Bang to use the modern term. He encountered, however, a problem because his field equations did not allow solutions unchangeable in time. As a way-out, he therefore modified his equations by adding an additional term containing a new fundamental constant, the so-called cosmological constant (in full agreement with general covariance). The Einstein universe possesses positive curvature, and its spatial shape is that of a three-dimensional hypersphere. Assuming that the universe is filled only with "dust" having constant density and zero pressure, he was able to calculate the "radius of the universe" which turned out be completely given in terms of the cosmological constant. When the observations by Vesto Melvin Slipher and Edwin Hubble clearly showed that the Universe is expanding, Einstein rejected the cosmological constant and remarked that its introduction "was the biggest blunder he ever made in his life". [14]

That Einstein did not realize that his field equations are not compatible with a static universe (with or without a cosmological constant), is one of his greatest "missed opportunities". Nevertheless, it may turn out in the future that his "biggest blunder" is actually one of his greatest achievements. Since a few years, it has been known that the Universe is filled with a mysterious, unknown energy, called dark energy, with negative pressure which is responsible for an accelerated expansion of the Universe at the present epoch. It turns out that all existing data are consistent with the assumption that the dark energy is identical with Einstein's cosmological constant!

During his Berlin time, Einstein made two important contributions to quantum theory. In 1917 he formulated a statistical theory for the interaction between photons and atoms which 40 years later was applied in the maser. In 1925 he predicted the Bose-Einstein condensation which 70 years later was achieved in dilute gases of alkali atoms by E.A.Cornell, W.Ketterle and C.E.Wiemann (Nobel Prize in 2001).

## At Princeton, and the "obsession" with unified field theory

In 1932, Einstein received an offer to work at the newly founded Institute of Advanced Study in Princeton. At that time, he did not intend to leave Germany for good, but agreed to spend half of his time in Berlin and half in Princeton. In December 1932 he visited CALTECH. In January 1933, Hitler came to power, and on March 10 Einstein declared publicly his decision not to return to Germany. On March 28, he resigned from the Prussian Academy. After a stay in Belgium and England, Einstein arrived with his wife Elsa in New York on October 17. For his remaining 22 years he never went back to Europe again.

Einstein's work in Princeton is often considered as unimportant with the exception of his Einstein, Podolsky and Rosen paper [15] that in recent years has been recognized as a stimulating source of ideas. This is particularly so since "EPR-states", and, in general, "entangled states" can now be realised experimentally. Furthermore, it is well known that the EPR-paper led Schrödinger to his famous paper on the "Schrödinger cat" [16].

In Princeton Einstein continued his work on a unified field theory which he had already started in Berlin. His efforts in this direction were not successful. His search for the basic principles of physics became an "obsession". "Assessing today Einstein's insistence on unified field theory, I would say, yes, it was an obsession. But what a grand obsession! It gave direction to later theoretical research, and its influence on fundamental physics will extend well into the 21st century." (C.N.Yang, [2])

During his whole life Einstein had two hobbies: sailing and music, but music had a particular emotional importance to him. He had played the violin since his sixth year. His preferred composers were Vivaldi, Bach, and Mozart. Paul Einstein wrote

▲ Fig. 4: Paul Einstein in Ulm on 14 March 2004 in front of a picture of his great grandfather (showing Albert Einstein in Berlin in1921).

recently: "It's a fine line with Mozart between sensitivity and aggression, between line and colour. Besides, Mozart was a bit like Albert Einstein, a sharp-tongued intellectual, with powerful, outspoken ideas." (Letter to the author.)

On 18 April 1955 Einstein died of an aneurysm of the aorta at Princeton Hospital. ■

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# Einstein and the Nobel Committee: Authority vs. Expertise

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For his contributions to relativity and gravitation theory, Albert Einstein never received a Nobel Prize. And in spite of a popular misconception, spread especially through Abraham Pais' oft-cited but flawed account, Einstein did not receive a prize for his theory of the photoelectric effect. On September 6, 1922 the five Swedish members of the Nobel Committee for Physics proposed to the Royal Swedish Academy of Sciences that Einstein be awarded the previously reserved prize for 1921 for *his discovery of the law of the photoelectric effect*. In this year of celebrating Einstein, how should we reflect upon this paradox? An institution that is commonly accepted as a short-hand for supreme excellence in science ignored some of the most momentous accomplishments in the history of physics. Rather than rationalizing and seeking excuses, we might, in the spirit of Einstein, adopt a willingness to question established authority through reflection and insight.

## Committee Experimentalist Bias

In the early decades of awarding the Nobel Prize, Swedish physicists with a strong experimentalist bias dominated the committee. They held precision measurement as the highest goal for their discipline; they favored candidates whose work mirrored their own orientations. Just as an experimental bias in the committee benefited some candidates, it also worked to the detriment of others. In 1911 new committee member Vilhelm Carlheim-Gyllensköld protested the minimal representation theoretical physics had received through the Nobel Prize. He stressed the neglect was not due to an absence of nominations for, since the beginning, prominent representatives had, in fact, been proposed, including Ludwig Boltzmann, Oliver Heaviside, Lord Kelvin, Max Planck, Henri Poncaré, and J. H. Poynting. Nevertheless, the committee continued to disregard the growing number of nominations for Planck and other theoretical physicists. Indeed the eventual prize to Planck in 1919 – the previously reserved 1918 prize – represented more a desire to acknowledge the leader of German science at a time of national tragedy than an embrace of early quantum theory. Some members of the committee at first proposed giving Johannes Stark the reserved 1918 prize and then the 1919 prize to Planck in order to underscore the greater importance of precision experiment over theoretical speculation. Of course the chronology of their respective achievements dictated otherwise.

For the Academy's scientists the emerging post-World War I era posed multiple hazards. The threat of socialism if not bolshevism, and a break-down in international relations within science were but some of the monsters swimming in this uncharted sea. The problematic hydra-headed beast of quantum and relativity theories that threatened what the Nobel committee frequently called "the common sense foundations of physics" continued to gain in strength during and immediately after the war. First the committee had only Planck to contend with, but increasingly others entered the list of nominees enjoying serious support from nominators, such as Niels Bohr, Arnold Sommerfeld, and Einstein. Einstein's new general theory of relativity added yet further challenges to established modes of conceiving physical thought that began in 1905 with his special theory of relativity.

Those in the know understood the situation in Sweden was decidedly negative toward the latest advances in physics. The embarrassing delay in awarding Planck was but one indication. Apostles of the new physics who visited Sweden in 1919 noted little sympathy among senior scientists. Committee members Allvar Gullstrand and Bernhard Hasselberg could not follow much of the new physics based simply on their lack of training as well as disposition. Carlheim-Gyllensköld may have been sympathetic, but lacked skills to master the new. Gustaf Granqvist was too overwhelmed with work to follow the new developments for which he nevertheless had little enthusiasm. In contrast to the committee majority, Svante Arrhenius had no prior prejudice against theory taking an upper hand in the advance of science, but on matters that were at the limits of his understanding he frequently allowed calculation of interests and signals from his international contacts to dictate his position. The problem of recognizing the radical achievements in physics was not merely a question of individual beliefs and tastes, at the time committee members were also concerned with the image of physics, among other disciplinary issues. How the committee and Academy reacted to Einstein became a drama in several acts.

## 1920: A Surprise

On November 6$^{th}$ 1919 at a joint meeting of the Royal Society of London and Royal Astronomical Society, the retired Cambridge physicist J. J. Thomson announced the results of the now-famous British eclipse expeditions. Thomson declared Einstein the winner. The ever so minute bending of starlight by the sun's mass was recorded on the photographic plates; the effect was declared real and not the result of random experimental error.

Sensational media coverage quickly transformed Einstein into a celebrity. In a Europe still recovering from the horror of world war and perplexed over the political and social upheavals in its wake, news of a revolutionary theory that claimed to overthrow the foundations of physics riveted media attention. Einstein himself was a sufficiently unorthodox figure in appearance, manner, and belief that the cult of relativity – and its sworn enemies – gained yet further momentum from the man. Naturally many observers wondered whether Einstein would soon receive a Nobel Prize.

Einstein was no stranger to the Nobel committee. He had been nominated in 1910 when Wilhelm Ostwald proposed him for the special theory of relativity. In the years just before the war, Einstein received annual modest support from nominators. No doubt, nominators who might have been favorably disposed toward him were still trying to open the Nobel doors to theoretical physics with Planck. The committee merely claimed that Einstein's work needed to be followed to see if it possessed significance for physics.

Following the news of the eclipse results, nominators began to register the first aftershocks. Although still modest in number, nominations for Einstein dominated the sparse 1920 list. From the committee's perspective, the nomination from Niels Bohr might have been seen as one revolutionary thinker advocating the work of another intellectual radical, but others who proposed Einstein could scarcely have been more respectable. The elderly Berliner Emil Warburg, whose nominations frequently won committee respect, was one. Others included three Dutch laureates H. A.

features

Lorentz, Heike Kamerlingh Onnes, and Pieter Zeeman. It is also possible that the revulsion scientists in Allied nations felt toward the German sweep of science prizes in 1919 – Planck, Stark, and Fritz Haber – prompted some nominators to turn to non-German candidates. Einstein heard rumors that he should not expect a prize in 1920 for political reasons.

Regardless, in its 1920 general report the committee dismissed Einstein, making but a minimal gesture in his direction. In a special report on the degree to which relativity theory had been confirmed, Arrhenius claimed that the British eclipse results cannot be admitted as evidence as questions remained about their degree of exactness. Arrhenius followed the skeptics' line that the margin of possible experimental error was larger than the effect that was to have been measured. Although acknowledging general relativity's success in accounting for the eccentricities in Mercury's orbit, he noted researchers' inability to find a shift toward the red end of the solar spectra. Arrhenius's report was decidedly tilted toward the negative opinions and interpretations in circulation. He duly noted J. J. Thomson and Arthur Eddington's points of reservation, but he did not include their widely quoted positive remarks. It seems he was trying to take cues from German scientists but which ones? He included the opinions of laureate Philipp Lenard, who along with Stark and other ultranationalists, were already endeavoring to discredit Einstein and relativity theory. For them, Einstein's wartime internationalist and pacifist stance was treason. His so-called Jewish-manner of practicing physics, based on flights of fantasy and self-promotion, threatened true German physics, grounded in experimental fact. This less-than-comprehensive report took little notice of what the nominators found valuable in Einstein's work. In fact, from the start it would seem the committee wanted the Nobel Prize in physics for 1920 to go to Charles-Edouard Guillaume.

Guillaume was the Swiss director of the French-based International Bureau of Weights and Measures. Guillaume devoted his career to improving the precision and reliability of standardized measurements. He had accidentally discovered a nickel-steel alloy that, unlike virtually all materials, was relatively unaffected by changes in its environment. He received but one nomination. His work and that of the bureau was of course valuable for science and its practical applications.

But in 1920, when the world of physics had entered upon an intellectual adventure of extraordinary proportions, it was remarkable to find Guillaume's accomplishment, based on routine study and modest theoretical finesse, recognized as a beacon of achievement. Even those who opposed relativity theory found Guillaume a bizarre choice. As one anti-relativist remarked to a Swedish colleague, whatever may be said about Einstein, he made his mark *on* physics; whereas Guillaume at best was marked *by* physics. Others, such as Sommerfeld, expressed disbelief. What then was going on?

Hasselberg, the Academy's professor of physics and member of the Nobel committee since its start in 1901, had been seriously ill for several years and was now about to retire. Hasselberg had previously championed works that reflected his own preference for precision measurement as the essential path to new insight in physics. After having maneuvered the 1907 prize to A. A. Michelson for his metrological work (basing the international meter on a natural constant), he asked like-minded colleagues abroad to nominate Guillaume. Not many others agreed with him. In 1920, the Swiss physicist, Charles Eugene Guye, nominated his countryman.

The bed-ridden Hasselberg wrote to the committee that he would be very happy to see Guillaume receive the prize. The

▶ **Fig. 1:** Allvar Gullstrand, **Uppsala** University, **member of the Nobel Committee for Physics, 1911-1929.**

committee and then the Academy's vote delighted Hasselberg and of course Guillaume, who was as surprised as the rest of the world.

### 1921: Allvar Gullstrand vs. Albert Einstein

In 1921, Einstein's place in physics received unambiguous confirmation. Nominations from England, Finland, France, Germany, Holland, and Sweden gave him broad international support. Einstein's position in the world of physics was portrayed by some nominators as being that of a giant, the likes of which had not been seen since Newton. Both theoreticians and experimentalists proposed Einstein, especially for his work on relativity and gravitation theory. Some claimed that it would be difficult to consider other candidates without first seeing Einstein recognized. No other candidate enjoyed anything resembling a mandate such as Einstein received.

When the Nobel committee for physics began assessing the nominations for the 1921 prize, Swedish Einstein-mania was in full bloom. As elsewhere, Einstein and relativity theory were emblematic of the new age of anxiety. Radicals proclaimed relativity as liberation from social, cultural, and intellectual traditions. Philosophers and cultural commentators feared that Einstein's theories implied a relativity of values. A few physicists borrowed the tone of the German attacks that began in earnest in 1920, but in contrast rarely invoked anti-Semitic slurs, at least in public. Of course, the snap, crackle, and pop of media noise need not have had any direct effect on the Nobel committee. But it seems that most committee members could scarcely conceive this bushy-haired, political and intellectual radical, who seemingly did not conduct experiments, crowned as the pinnacle of physics at a Nobel ceremony.

In 1921 Allvar Gullstrand took it upon himself to report on Einstein's contributions to relativity and gravitational theory. Gullstrand, who was one of the most distinguished members of the Academy, simply did not understand Einstein's work. Gullstrand embodied the best and worst of Uppsala's academic culture. In 1911 the physics committee was poised to award him its prize for his work on physiological optics, but the medical committee gave its prize to him first. Although a medical doctor by training, Gullstrand demanded and received a personal professorship as both ophthalmologist and physicist. In his path-breaking studies on the optics of the eye, and on astigmatism, Gullstrand

◄ Fig. 2: Carl Wilhelm Oseen, Uppsala University/Nobel Institute for Theoretical Physics, co-opted member of the Nobel Committee for Physics, 1922 and member thereafter, 1923-1944.

developed his own intricate methods of analysis. When new advances in mathematics offered tools to simplify analysis, Gullstrand remained unmoved. His command of higher mathematics and theoretical physics was at best limited. Still he endeavored to join the physics committee. The Uppsala contingent in the Academy ensured Gullstrand's election.

Gullstrand demanded as much of himself as of others. He was fond of saying that: "a professor whose hands do not shake from exhaustion by the end of the academic year has not performed his duties properly." In a small, isolated but locally prestigious academic environment, arrogance, like mold in a damp cellar, tends to thrive. Arrogance prompted him to confront Einstein; to prove to the committee, the Academy, and Swedish society that relativity theory was of little significance. In the Academy, as elsewhere, titles and authority sometimes are mistaken for expertise.

Gullstrand had no intention of admitting relativity theory into the comprehensible world of physics. The theory's broader implications were troubling: Where is God in the fourth-dimension? Gullstrand insisted that the theory contained numerous errors. But his own critiques, both published and private, were shown to rest on mistaken understanding. No matter, he returned again and again with new objections.

Gullstrand's exceptionally long, fifty-page special report might appear at first glance to be comprehensive, but it was written from a basic premise: Einstein cannot be right. Gullstrand mobilized any negative claim, any article that was published in a scientific journal that provided alternative interpretations to those advanced by Einstein. His own analyses aimed at defusing those aspects of Einstein's theory that called for an overhaul of the "common sense foundations" of mechanics. According to Gullstrand that which remained once Einstein's errors and unproven assertions were eliminated, could best be treated successfully by classical mechanics. The British results were useless. Regardless, he rejected the suggestion that the bending of starlight by the sun can be regarded as a critical test for the theory, even if successfully demonstrated. Gullstrand maintained that classical aether physics might also explain this phenomenon. He concluded Einstein's theories did not possess "the significance for physics for which an awarding with a Nobel Prize can come into question."

Gullstrand had no trouble convincing his colleagues. No member had been convinced that the eclipse experiment yielded valid evidence. The remaining strong experimentalist core of the committee, Granqvist and Hasselberg, had little sympathy for Einstein's forceful use of theory. Hasselberg wrote from his sick bed, "it is highly improbable that [Alfred] Nobel considered speculations such as these to be the object of his prizes."

For the most critical Swedish opponents of Einstein, Hasselberg and Granqvist were seen as a bulwark keeping the Nobel Prize from promoting the further spread of the "diseased movement" of relativity. Hasselberg was not alone in expressing concern about the eroded foundations of European civilization; Bolshevism was a danger, poised to eradicate what was left of the prewar order. Einstein and his theory exemplified the erosion of past certainties; Dadaism in science standing in direct opposition to Truth, Beauty, and Goodness rooted in western civilization's classic Greek heritage.

When Gullstrand presented his report to the committee, nobody dissented. All agreed that no candidate could be identified as worthy; and therefore proposed to the Academy that the prize should be reserved until 1922.

Gullstrand may have won the backing of the Academy's physicists, but he had not proved Einstein wrong. When the full Academy met to vote on the 1921 science prizes, a few solitary members questioned Gullstrand's evaluation. As usual no official account of the meeting exists, but a number of archival sources provide insight into the event. The Academy's discussion revealed gaps in Gullstrand's command of physics, as well as his prejudice. Some members understood that Einstein was more prominent than the Nobel Prize. Would it not be an embarrassment for the Academy not to recognize the man who had become the greatest scientific celebrity since Newton?

A decade earlier Gullstrand had compared each Nobel Prize to a Swedish flag that is visible to the entire world. For Gullstrand and many conservative members of the Academy the issue entailed whether the yellow and blue Swedish colours should be draped around a media-created sensational yet scientifically dubious theory? Gullstrand remarked privately, Einstein must never receive a Nobel Prize even if the whole world demanded it. In time he expected the theory and the mass-hysteria to fade away.

If the issue was simply Gullstrand's faulty evaluation, then in principle, the Academy was free to act once this was brought to light. But most members of the Academy had little inclination to give Einstein a Nobel Prize, and especially not for relativity, and no desire to slight its own esteemed member, Gullstrand. It mattered little that leading international physicists had praised Einstein as the greatest living representative of their discipline, and had declared his accomplishments in relativity theory to be among the most significant in the history of science. Local 'expertise' had spoken; the Academy guarded its own authority and its own right to assess and judge. The Academy voted not to award that year a Nobel Prize in physics.

### 1922: Enter Oseen

The Academy of Science had once again made a statement. Those invited to nominate candidates for the two available physics prizes to be given in 1922 had to reflect on the meaning of this obvious rejection of Einstein. Could the Academy be persuaded to recognize Einstein, or would a proposal for him be a wasted nomination? Not sure how to second-guess the Academy's recent decisions, some nominators suggested a choice of alternate candidates. Einstein and his contributions to relativity theory still received overwhelming support.

Some also proposed Einstein for his contributions to quantum theory including the theory of the photoelectric effect. But, as in

1921, one lone nomination specified Einstein's discovery of the law of the photoelectric effect. The nominator, Carl Wilhelm Oseen, theoretical physicist in Uppsala, chose his words with care. He had a clever strategy that just might defuse the ticking Einsteinian bomb without unleashing its theoretical shock wave, and at the same time rescue Bohr from committee bias.

The law of the photoelectric effect emerged in connection with Einstein's 1905 paper "On a Heuristic Point of View Concerning the Production and Transformation of Light," where suggested that light behaves at times as discrete, individual particles. What began as a hypothesis, Einstein soon developed into a firm theory.

Very few physicists accepted Einstein's claim for the particulate nature of light. When in 1916 Robert Millikan painstakingly accumulated experimental data with which to disprove Einstein's theory, he was shocked to find Einstein's law beautifully confirmed. But this did not convince him, or most other physicists, to accept the "bold, if not to say reckless hypothesis," of light-quanta. The law held, but what was the physical reality behind it? Einstein's light-quanta remained controversial until Arthur Compton's experiments showing X-rays acting as particles with momentum a few years later was.

The committee met in late winter to assign reports. Gullstrand accepted the responsibility of updating his evaluation of relativity theory. The committee accepted the need to recruit Oseen.

Once again, Gullstrand axed relativity. This time he took particular aim at the special theory of relativity. The many books on the subject did not give the reader a critical examination of the underlying assumptions: "dogma... are mistaken for facts." Gullstrand insisted that "the question of the special (and with that also the general) theory of relativity's justification is a matter of faith." He again asserted that Einstein could not receive a Nobel Prize for relativity.

Oseen knew what he was after. Once he joined the committee, Oseen insisted on maintaining a clear demarcation between his nomination and those that specified the theory of the photoelectric effect. As odd and perhaps incomprehensible as this surgical procedure might appear to a physicist today, in the context of physics in 1922 and especially in the context of the Academy, it reflected unusual insight. Oseen's strategy entailed underscoring that the law relating discrete absorption and emission of energy to the frequency of light is a meticulously proven fundamental law of nature independent of the theory from which it was derived.

Oseen wanted Einstein to receive a prize, but not for relativity, with which he was increasingly dissatisfied. Equally significant, he wanted Bohr to receive a prize. For Oseen, Bohr's quantum model of the atom and its unexpected successes were "the most beautiful of all the beautiful" in recent theoretical physics. Previously the Nobel committee rejected Bohr on the basis that his model of the atom was "in conflict with physical reality." Oseen understood the Academy's prejudices. In one brilliant strategic stroke, he saw how to meet the objections against both Einstein and Bohr.

First, by restricting the motivation for the prize to just the law, he could safeguard the proposal against charges that the existence of Einstein's light-quantum was still disputed. Second, in his special report, he noted that Einstein's many different achievements in physics appealed to different types of researchers. Here he could counteract the objection made in 1921 against his nomination that it would appear strange to reward Einstein for a less prominent achievement than relativity. Oseen identified a variety of scientific orientations; each might consider a different one of Einstein's contributions to be the most significant. So, for example, theoretical physicists might be drawn to Einstein's work on quantum theory. And for "the measuring physicist" – the type of physical scientist most admired in the Academy – no work of Einstein's can compete in significance with the discovery of the law of the photoelectric effect.

Appealing to the committee's convictions about the nature of physics, Oseen also opened the door for Bohr. By emphasizing, if not exaggerating, the very close bond between Einstein's thoroughly proven fundamental law of nature and Bohr's atom, Oseen masterfully defused the charges of speculative theory.

When the committee came to vote, there was hardly a whisper of dissent. Gullstrand knew that Oseen mastered theoretical physics; he did not protest. For his part, Arrhenius was already transformed into an enthusiastic supporter. He had met Einstein in Berlin. He witnessed the great respect and affection afforded Einstein by members of the Berlin scientific establishment. He also appreciated that Lenard and Stark were now held in contempt by most prominent German physicists. The committee, followed by the Academy, accepted Oseen's recommendations for the 1921 and 1922 prizes respectively for Einstein and Bohr.

◄ **Fig. 3:** Einstein holds his Nobel lecture on a very hot July 11, 1923 in the Congress Hall of Liseberg Amusement Park at the 17th Scandinavian Natural Scientists' Meeting in Gothenburg. King Gustav V is sitting in the first row center with head in hand.

## Einstein's Triumph

Humility ultimately vanquished arrogance, this time. Einstein might not have received the prize for his contributions to relativity theory, but he was soon able to have these celebrated in spite of the Academy. Einstein learned of the Academy's decision in a telegram that reached him while he was en route to Japan. He was relieved to receive the prize. He had been counting on it since 1918. At a time of decreasing value of the German Mark, he needed a hard currency to make alimony payments in Swiss Francs for his ex-wife and children living in Zurich. But he also was tired of being asked by journalists and others why he had not already received a Nobel Prize. It was the money that attracted him. Although he never expressed any special reverence to the Nobel Prize, Einstein later told a Swedish journalist that the prizes brought about a "social regulating" of age-old injustices. "Through the prizes scientists finally can harvest dividends from their work just like businessmen." And that made him happy.

Providentially, his trip to Japan would keep him away from the formal ceremonies of December. He could avoid the stiff formalities and media attention, both of which he loathed. Einstein undoubtedly found amusing the instructions informing him that when he delivered his Nobel lecture, he must lecture on the topic for which he has been awarded the prize: viz., no relativity. He arranged to hold his Nobel lecture the following summer. And he went not to Stockholm and the Academy, but to Sweden's second city, Gothenburg, where he addressed the 17th Congress of Scandinavian Natural Scientists. Not being a formal Nobel ceremony, Einstein felt free to choose the topic for his lecture, or simply did not care. He spoke on recent developments in relativity theory. Sitting in the front row of the audience was one most attentive spectator who let it be known that he very much wanted to learn something of relativity theory: King Gustav Adolf V th . On later occasions when Einstein drew up lists of his most important honours, he did not include the Nobel Prize. ■

## About the author

**Robert Marc Friedman** is professor of history of science at University of Oslo. He acknowledges support from the National Science Foundation for research on the Nobel prizes. His publications include Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology and The Expeditions of Harald Ulrik Svedrup: Contexts for Shaping an Ocean Science. His play "Remembering Miss Meitner" was performed at Gothenburg Theatre, Swedish Broadcasting's Radiotheatre, and elsewhere, including at the 2004 International Nuclear Physics conference in Gothenburg. Another play, "Becoming Albert Einstein" opens in August in Bergen.

## Further Reading

Full references to archival documents used in this summary can be found in:

Robert Marc Friedman, "Nobel physics prize in perspective", Nature, 292 (1981), 793-98.

Friedman, "Text, context, and quicksand: Method and understanding in studying the Nobel science prizes", Historical Studies in the Physical Sciences, 20 (1989), 63-78.

Friedman, The Politics of Excellence: Behind the Nobel Prize in Science (New York: Freeman/Times Books, 2001), Chapter 7.

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# Doppler Tomography

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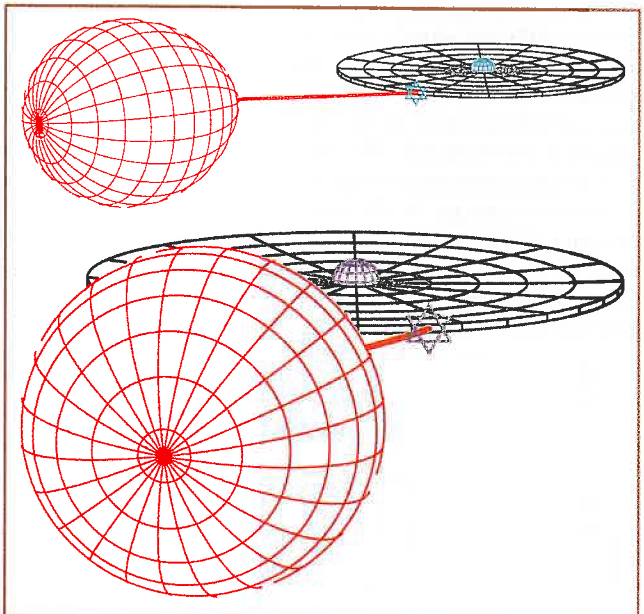
Flattened disc-like structures are common throughout the Universe whenever matter has accumulated, for instance in the formation of stars and galaxies. Studies of these discs and related structures have benefited over the past two decades from an indirect imaging technique based upon medical Xray imaging called Doppler tomography. As will be described, this allows us to probe physical scales far below the reach of even the largest current telescopes.

## Accretion

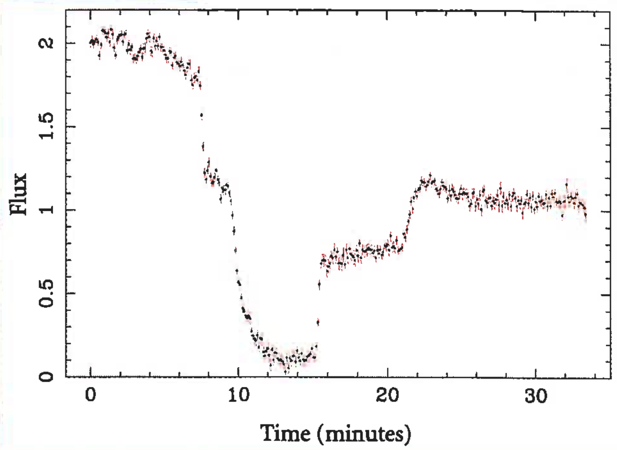
The Earth and other planets will continue to orbit the Sun until the Sun itself becomes a red giant some 7,000 million years hence. The outer planets and possibly the Earth too will survive beyond even this point as the Sun evolves to its final state as a small, dense star called a white dwarf. Although attracted towards the Sun, the planets never fall into it because they have angular momentum, and there is nothing, short of a passing star, that can remove it[1]. How then can the Sun and other stars ever have formed given that they had to coalesce from rotating clouds originally much larger than the Solar system?



▲ Fig. 1: Schematic pictures of a mass-transferring binary star with an accretion disc. A cool, tidally-distorted star (red) loses mass at the saddle-point in potential between the two stars. The gas forms a disc around the small hot, companion (blue). The compact star, the disc and the spot where the transferred matter hits the disc dominate the luminosity of these systems. The entire system shown here is comparable in size to the Sun; they have orbital periods which range from 10 minutes to 10 days.

[1] This is not quite true: gravitational radiation removes angular momentum, but so feebly as to be negligible over the lifetime of the Sun.

features

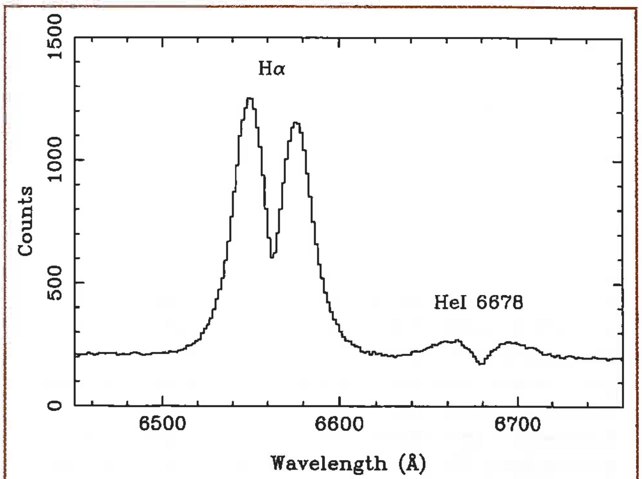



▲ Fig. 2: The brightness versus time during the eclipse of an accreting binary star shows two sharp drops as first the accreting star (a white dwarf) and then the impact region of the gas stream and disc are eclipsed, followed by sharp rises as the white dwarf followed by the bright-spot emerge from eclipse [3].

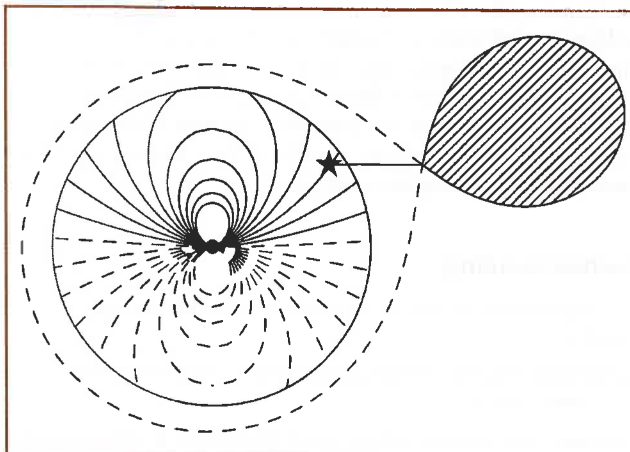
The problem is one of the re-distribution of angular momentum which needs to be removed before matter can accrete onto a compact object whether it be a forming star or a black-hole. Nature's solution, in many, although not all, cases is an accretion disc, a flattened structure in which material orbits on near-circles around the central object. Interaction between different annuli, traditionally ascribed to "viscosity", although in fact it is probably the result of magnetohydrodynamic turbulence [1], allows angular momentum to be transported outwards in the disc while causing the matter to execute a slow in-spiral. This allows accretion to occur, and as a by-product generates energy from the release of gravitational potential energy. In the case of accretion onto the most compact objects of all, neutron stars and blackholes, 10% or more of the rest mass energy of the accreted material can be released as radiation (by comparison, nuclear fusion in stars liberates only ~1% of the rest mass). Accreting black-holes in our Galaxy can produce over a million times the power of the Sun, with most of the energy coming from the inner few tens of kilometres of the disc, and almost entirely radiated at X-ray and $\gamma$-ray wavelengths. Accretion onto the super-massive black-holes, $10^8$ or more times the mass of the Sun, that sit at the centres of many galaxies powers sources another factor of a million or more brighter still. Many millions of such sources, enshrouded in dust, are thought to produce the X-ray "background" that is seen from all parts of the sky.

Some of the most easily studied examples of accretion discs are to be found in close pairs of stars in which material flows from one star to its companion (Fig. 1). The discs in these binary systems are small, having outer radii ranging from 0.1 to 10 solar radii, compared to the several thousand solar radii of proto-planetary discs and those surrounding the super-massive black-holes. This makes the "viscous time-scale" on which the disc responds to variations in the mass supply rate accessible to observation. The viscous time-scale at radius $R$ in a disc is given by $t_V = R^2/\nu$, where the kinematic viscosity $\nu = \eta/\rho$ is the ratio of the viscosity $\eta$ to the density $\rho$ of the material of the disc. Rather general arguments [2] suggest that the kinematic viscosity has an upper limit given by $\nu < c_s h$, where $c_s$ is the sound speed and $h$ is the thickness of the disc, which for discs supported by gas pressure is given by $h \sim (c_s/v_K)R$, where $v_K$ is the Keplerian orbital speed at radius $R$. Thus the viscous time-scale is subject to the limit $t_V > (v_K/c_s)R/c_s$; observed values are typically at least a factor of 10 higher than this limit. In the region of the disc from which the Earth formed $v_K \sim 30\text{kms}^{-1}$, $v_s \sim 1\text{kms}^{-1}$ and $R \sim 1.5\text{x}10^8$ km, leading to $t_V > 100$yr, while in the outer parts of a disc in a close binary $v_K \sim 600\text{kms}^{-1}$, $v_s \sim 10\text{kms}^{-1}$ and $R \sim 5 \times 10^5$ km, giving $t_V > 1$ month. Thus in close binary discs it is possible to see complete cycles of changes, for instance between faint and bright states, and it is the study of these discs that has driven many theoretical developments in the field.

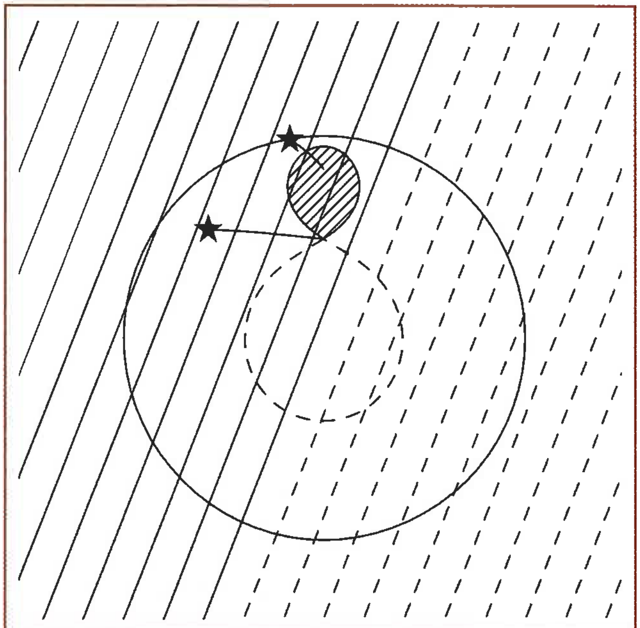
The accessible time-scales in close binary stars come at a heavy price: they are not directly resolvable. Nearby examples are about 200 light-years away and are comparable to the Sun in size (~ $10^6$ km). They therefore subtend ~$10^{-4}$ seconds-of-arc at the Earth. To resolve them well would require a




▲ Fig. 3: Atomic emission lines from an accretion disc. The lines are very broad (equivalent to ~ 4000kms$^{-1}$) owing to Doppler shifting from the surface of the disc. The two peaks come from the outer disc and are a classic signature of emission from discs.



▲ Fig. 4: The figure shows the dipole-field pattern made by lines of equal radial velocity over a disc in Keplerian rotation with $v \propto R^{-1/2}$. The observer is assumed to be located on the right-hand side of the figure. Solid lines represent material moving away from Earth while dashed regions move towards it.



▲ Fig. 5: The figure shows the equivalent of Fig. 4 in velocity rather than position coordinates. The lines of projection become straight. Since by the definition of the coordinate axes the mass donor star moves in the positive y direction, in velocity coordinates it appears on the positive y axis. Emission from the disc appears outside the circle which represents the outer edge of the disc; the inversion is a result of Keplerian $v \propto R^{-1/2}$.

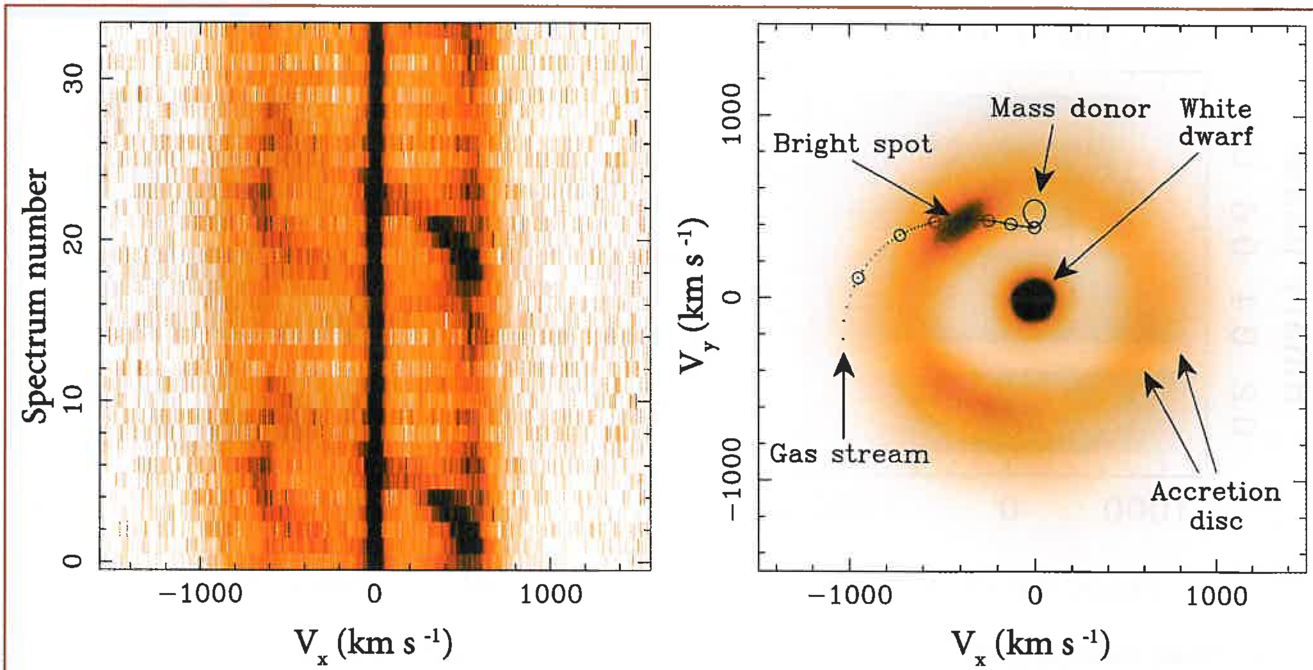
diffraction-limited optical telescope of about 10km diameter, beyond the wildest dreams even of astronomers. We have then had to turn to indirect imaging techniques for trying to unravel the nature of the discs and other structures within these stars.

## Eclipse Mapping

The principle behind indirect imaging is to exploit information upon the spatial distribution of emission that may be encoded within the spectra or light curves (brightness versus time) of the systems. The right-hand panel of Fig. 1 suggests one such method. When suitably oriented, binary stars may eclipse, and during the eclipse the accretion structures may be eclipsed. For instance when the accreting star is eclipsed, sharp edges appear in the light curve because it is small (see Fig. 2). For a given geometry one can readily deduce the location within the system of the sources of the sharp drops, which for instance can allow one to measure the ratio of the stellar masses from dynamical arguments about the flow of the transferred matter. This can be extended by modelling the brightness distribution over the disc as a 2D array of delta functions, with the light curve serving to fix the relative contribution of each point source. This is the principle of the "eclipse mapping" method developed by Keith Horne [4].

## Doppler Tomography

The main contribution of eclipse mapping has been to measure the temperature distribution versus radius over discs, providing a fundamental test of theory because the temperature distribution is largely determined by energy conservation. Eclipse mapping is however limited for imaging. A useful way to see why this is so is to consider the nature of the information available: as one enters eclipse, over a short interval of time a thin strip of disc along the leading edge of the occulted region goes into eclipse causing a drop in flux. During a whole eclipse we therefore effectively measure a series of line integrals of the brightness. On emerging from eclipse, another series of projections is obtained at a different angle. Such series of line integrals are called "projections". In this case the 1D derivative of the light curve contains two projections at different angles of the 2D brightness distribution of the disc. A series of projections can be used to reconstruct the higher dimensional distribution that they originated from using a




▲ Fig. 6: The left panel shows spectra plotted in row-by-row with time running upwards over one cycle of an accreting binary. The right-hand panel shows the equivalent Doppler image in velocity space with features marked. Dots along the stream mark steps on 1% of the distance from the accretor to the start of the stream; circles mark steps of 10% (courtesy Danny Steeghs).

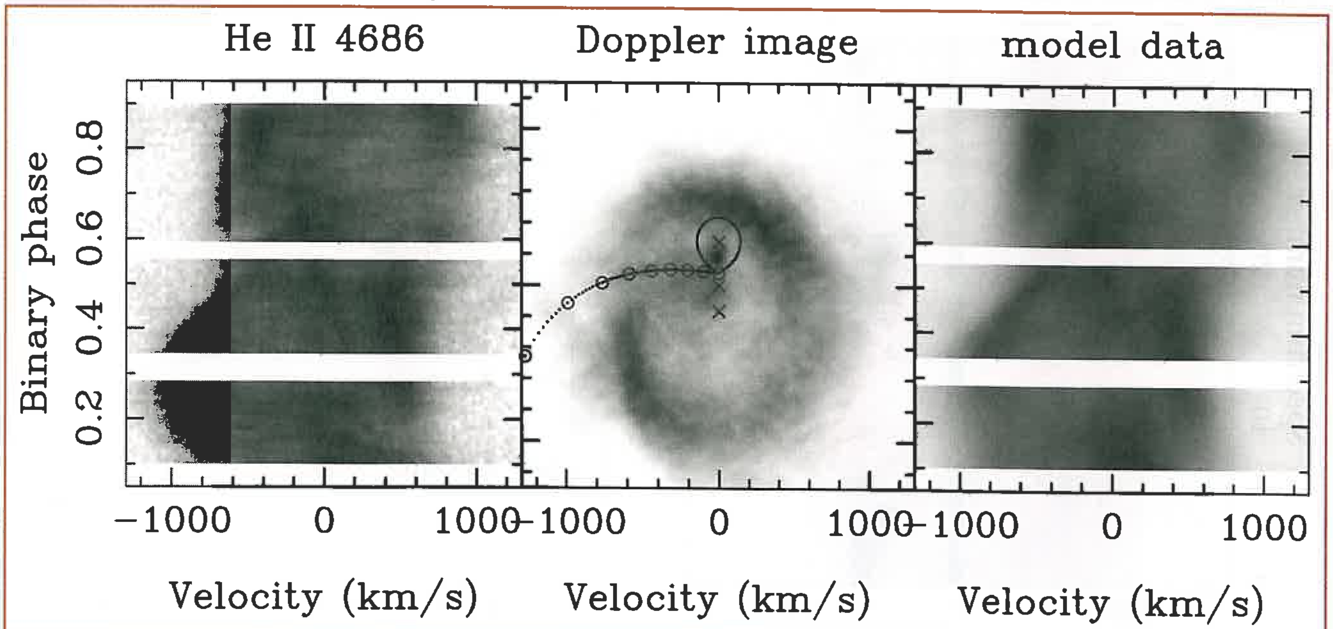
process known as "tomography" (see the special box on tomography). Eclipse mapping is a case of "limited-angle tomography" and with just two angles, we cannot hope to obtain perfect reconstruction.

Doppler tomography is an alternative indirect imaging method based upon atomic line emission such as Balmer series lines which are emitted strongly by accretion discs (Fig. 3). In this case we can obtain many angles and reliable images can be obtained. The bulk flow speeds in discs, which range from 600 kms$^{-1}$ in the outer disc to over 2000 kms$^{-1}$ in the inner disc, are greatly in excess of other broadening mechanisms such as thermal broadening (~ 10 kms$^{-1}$). This means that the line profile retains an imprint, albeit scrambled, of the distribution of emission over the disc. For instance, emission 2000 kms$^{-1}$ from line centre can only come from the inner disc. The formation of the line profile is in fact another form of projection, with the 2D atomic emission distribution giving a 1D profile as a function of radial velocity (component of velocity along the line-of-sight). To see why, consider Fig. 4 which shows lines of equal radial velocity at a particular point in the orbit of a binary. Regions of the disc which lie between adjacent radial velocity contours all have a similar speed along the line of sight $v$, and therefore they contribute to a single part of the line profile at wavelength $\lambda \approx \lambda_0(1+v/c)$ where $\lambda_0$ is the rest wavelength and $c$ is the speed of light. For instance the two peaks of Fig. 3 come from the largest complete crescent-shaped regions of Fig. 4, i.e. the largest regions unaffected by the outer edge of the disc. Therefore the atomic line profiles are effectively the result of integration over the curved strips of Fig. 4. This process is what is meant by a projection.

Fig. 4 shows just a single phase in the orbit. At other phases, the binary rotates but the dipole-like pattern stays locked in the observer's frame. Relative to the binary, the lines of projection rotate, and so by observing multiple orbital phases, we obtain the equivalent of the multiple projection angles used in medical tomography. The analogy with computerised tomography can be made even more plain with a transformation of coordinate system. Fig. 5 shows the equivalent of Fig. 4 as seen in velocity rather than spatial coordinates. Viewed in these coordinates, the lines of projection become straight. Velocity coordinates do not rely on assumptions such as the flow being Keplerian, and it is standard to use them.

## Tomography

Tomography refers to the process of constructing a spatial distribution of physical quantity given measurements that are essentially line-integrals ("projections") through the distribution. This crops up in many different fields. For instance, the travel-times of seismic waves, $t = \int dl/C_s$ where $C_s$ is the sound speed, is used in "seismic tomography" to map the sound speed within the Earth, which can help identify changes in composition. Perhaps most famously, in medical tomography, the absorption of X-rays by a specimen is directly related to the line integral of the opacity through it because if a beam has initial intensity $I_0$, then it will emerge with intensity $I = I_0 \exp(-\tau)$ where $\tau$ is given by the line integral $\tau = \int \kappa(x)dx$ and $\kappa(x)$ is the absorption/unit length at position $x$ along the path of the X-rays. If this is measured over a series of parallel lines at each of a series of angles, a 2D slice of the specimen can be built up, the trick being to use the multiple measurements of $\tau$ to determine $\kappa$ over the two dimensions of the slice. This is the idea behind CAT scanning. Fig. 9 illustrates how projections can reveal something about the nature of the higher-dimensional distribution 5 from which they originate. In this example there are just three projections, but they nevertheless reveal useful information about the object. One generally requires many (>20) angles to build up an accurate image. The mathematical inversion goes under the name of the "Radon transform".



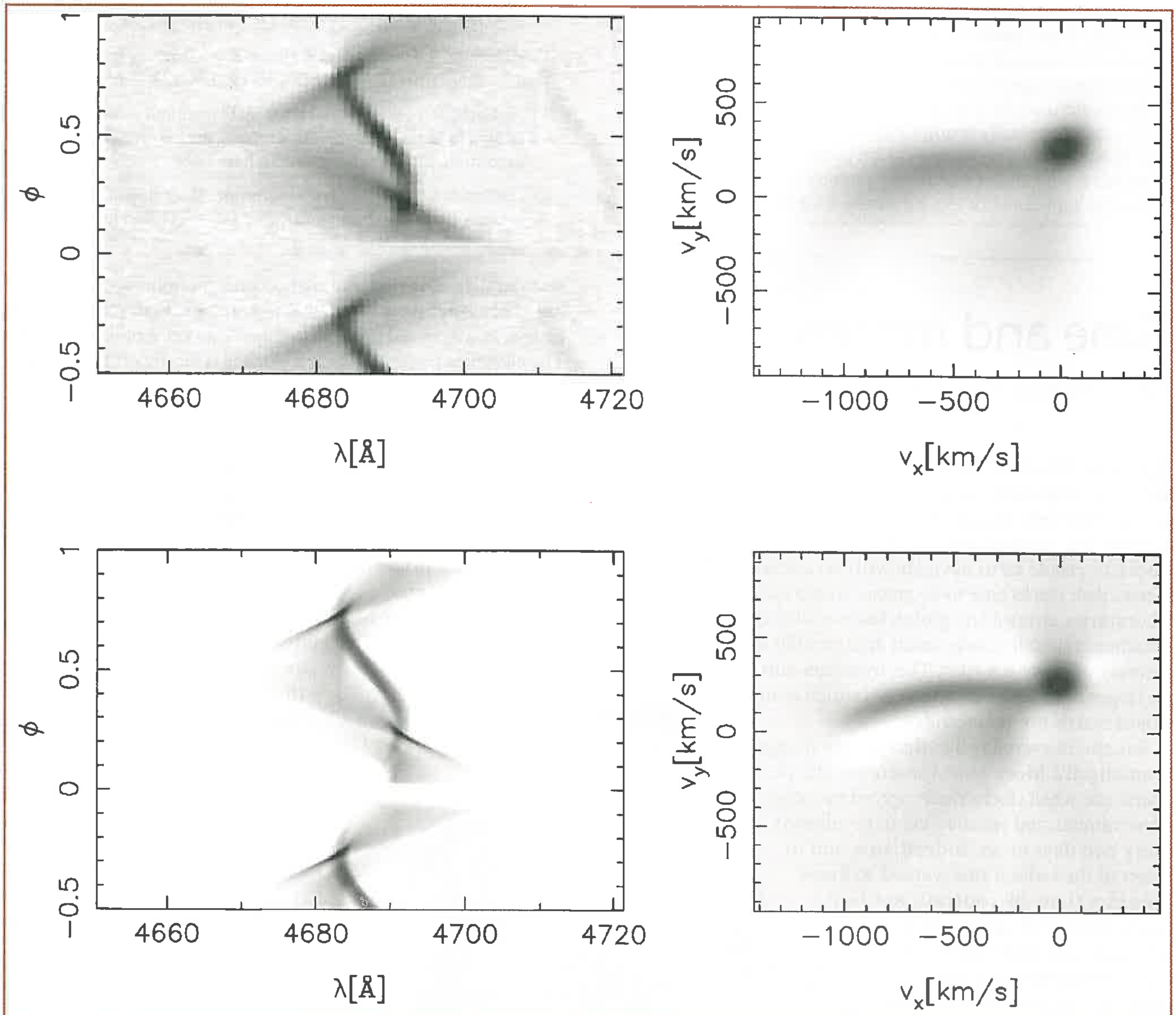

▲ Fig. 7: The left panel again shows spectra plotted row-by-row with time running upwards over one cycle of an accreting binary. The middle panel shows the equivalent Doppler image in velocity space. Apart from the strong narrow emission from the inner face of the mass donor, the most obvious feature is the very asymmetric background from the disc which takes the approximate form of a loose two-arm spiral. The right panel shows artificial data computed from the middle panel showing the recovery of many of the peculiar features seen in the data. Figure from [7].

Fig. 6 shows a real Doppler image of a system that shows several features in a clear form. The disc appears as the smooth ring with a radius of ~ 600 $kms^{-1}$, representing the orbital speed in the outer disc. An intense spot is seen at one location on the ring that corresponds to the impact of the stream of transferred material with the disc. Its location shows that the disc extends 70% the distance from the white dwarf to the point where the stream leaves the mass donor. Somewhat unusually, this system displays emission from the accreting white dwarf, seen as the almost-straight line running upwards in the left panel and as the strong central spot in the right panel. Plotted over this image are the predicted locations of emission from the mass-transfer stream and the mass donor which, as we will see, is sometimes visible in Doppler images.

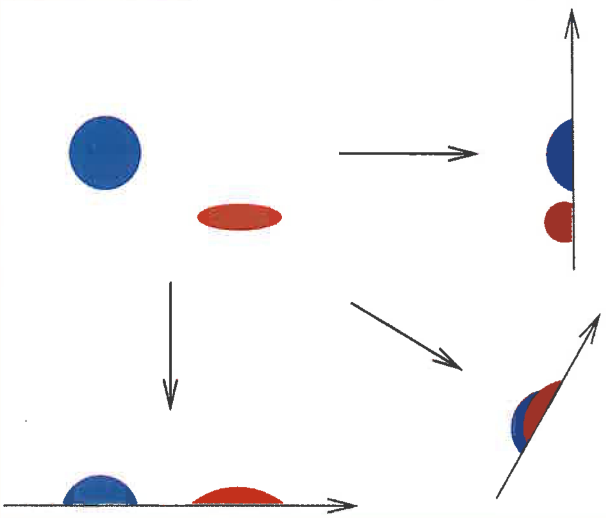
Since the method of Doppler tomography was presented [5], it has been applied in over 200 papers. Doppler tomography has elucidated the dynamics of the interaction between the mass transfer stream and disc and the distribution of line emission over the disc. Perhaps the major discovery that Doppler tomography made possible was the discovery of spiral structures in accretion discs [6] (Fig. 7) While there had been theoretical speculation about spiral structure in discs in the 1980s, they had never been recognised in data. In this case Doppler tomography proved essential in unravelling the complex changes in line profiles that the spiral structures cause. Although they undoubtedly owe their origins to tidal effects, the precise nature of the spiral structures in these discs remains controversial.

Doppler tomography has also proved useful in systems in which a strongly magnetic white dwarf (surface field ~ 5000 T) prevents the formation of any disc at all, resulting instead in magnetically-controlled streams of matter. Fig. 8 show a beautiful example which can be modelled as a free stream of matter gradually being stripped of material as itapproaches the accretor and the magnetic field becomes ever more dominant.

The exciting prospect for future application of Doppler tomography is to build up "time-lapse" movies to study how discs change over the viscous time-scale. This is primarily an observational challenge, but the first steps are being taken towards achieving it. ■




▲ Fig. 8: The top-left panel shows spectra from a system dominated by the magnetic field of the accretor, plotted over 1.5 orbits. The top-right shows the Doppler image. The lower panels show an empirical model in which mass is stripped from the mass transfer stream as it nears the accretor. The bright spot in the images is from the X-ray irradiated face of the mass donor. Figure from [8].



▲ Fig. 9: The process of forming projections is illustrated with a simple object consisting of two discrete parts, blue and red. Three angles of projections are shown. Knowing the projections angles and the projections, one could deduce the positions of the blue and red objects and that the red one was horizontally elongated. This is an elementary form of "tomography". The identification of the positions of these objects is very analogous to the location of the small sources that the light-curve of Fig. 2 makes possible.

## About the author

**Tom Marsh** received his PhD from the University of Cambridge in 1986. He is now the holder of a PPARC Senior Fellowship and Professor of Experimental Physics and head of the Astronomy & Astrophysics group at the University of Warwick.

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# Time and money

*L.J.F. (Jo) Hermans, Leiden University, The Netherlands*

Back in 1905, when Einstein was working on relativity in which 'time' plays such an important role, he would have never guessed that time would be measured with such an astonishing accuracy just a century later. As an example, think of GPS satellite clocks: to enable us to navigate with accuracies on the order of meters, their clocks have to be precise within nanoseconds. And in laboratories around the globe, laser-cooled Cesium and Rubidium fountain clocks reach an incredible fractional accuracy of about $6 \times 10^{-16}$. This translates into errors no larger than 20 ns in one year (which contains almost exactly $\pi \times 10^7$ seconds).

But also in everyday life, things have changed dramatically. Most of us remember the pre-quartz era, when clocks rarely agreed to within a few minutes, and watches had to be adjusted every two days or so. Indeed, one had to resort to the radio if one wanted to know the exact time. By contrast, modern quartz clocks and watches routinely have accuracies better than 1 in $10^6$: some 30 seconds in a year. And, except for the switch-over to daylight saving time, adjustment is rarely necessary.

At what cost, in terms of kWh and Euros, do we read our daily time so accurately? The electrical energy consumption, even for an analog clock operating on 230 V in our home, is very small of course, as we can tell from the negligible amount of heat released. The electrical power for such a clock is typically on the order of 1W, and since a year has about $10^4$ hours, it consumes about 10 kWh per year. In terms of money, that's about a Euro per year.

Now let us look at our digital watch. It typically operates on a silver oxide battery of 1.55 V having a charge of roughly 25 mAh. If we assume that the battery runs for at least two years, a back-of-the-envelope calculation shows that the watch operates on a power of less than 2 microwatt. That is very little indeed: it is six orders of magnitude more efficient than an analog clock connected to the mains.


What about the cost? Such batteries cost, typically, 2 Euros, or a Euro per year of operation. Now lo and behold: isn't that what the analog counterpart in our home would cost?

The conclusion is simple. Digital watches are very accurate and extremely efficient. But the energy in their battery is extremely expensive, of the order of 50 000 Euros/ kWh. And whatever type of clock we use for knowing the time as accurately as we do, the cost is 1 Euro at most for an entire year. If Einstein were alive today, he would probably agree: that's a lot of time for very little money. ■

# Italy's new Number Cruncher gears up to study Quarks.

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Since early this year, physicists in Rome have started testing the prototype of a massively parallel supercomputer, the ApeNext. Optimised for huge lattice simulations, the machine is directly competitive with other state-of-the-art parallel-processor machines developed in the US and Japan.

The success of the "standard model," the comprehensive theory describing the properties and interactions of fundamental particles, is mainly based on analytical calculations--pencil and paper. Quantum electrodynamics (QED), which studies the interaction between electrons and photons (which carry the electromagnetic force) is amenable to this approach because the photons that are exchanged are neutral and don't interact with each other. However, the situation with quarks and gluons - the gluons carry the strong force - cannot be tackled in any meaningful way with analytical methods because the gluons are not neutral but carry one of three types of "colour charge." Therefore they interact with each other as well. The requirement that all particles made up of quarks and gluons have to remain colour-neutral adds another complication, leaving numerical lattice simulations as the only method for predicting the properties of these particles – a subdivision of the standard model known as quantum chromodynamics (QCD).

Lattice QCD or LQCD is now the frontier of the standard model. In this approach quarks, placed at the interstices of a crystal-like structure – the lattice, interact with each other by exchanging gluons. Since the gluons interact with each other as well through their colour charges, the situation quickly becomes very complex and simulations require huge numbers of number-crunching steps in order to predict values that come close to the ones obtained experimentally.

Particle physicists performed the first simulations on a space-time lattice during the 1970s, but soon it became clear that substantially increasing the computing power was the key to making LQCD successful. The problem was not only the time it took to perform the simulations on the existing supercomputers, but the hardware cost per megaflop, which could amount to several hundreds of dollars on the existing supercomputers. And as a large LQCD simulation might now require 5 teraflop/s-years, their cost is prohibitive. (A gigaflop/s-year is the number of floating-point operations a gigaflop computer will perform during a year of continuous operation at that rate). A third problem was that the architecture of available supercomputers was not really optimal for performing LQCD simulations, and their efficiency was typically a few percent.

Both in the US and in Europe, theoretical physicists quickly understood that massive parallel processing with nodes optimised for LQCD calculations was the solution.

Started more than two decades ago, several research groups began developing massively parallel computers, linking up large numbers of processors. In Italy, Nicola Cabbibo and Giorgio Parisi initiated a program of dedicated multiprocessing computers during the 1980s. A similar research program started around the same time at Columbia University in New York, and other research groups started building large parallel systems from PC clusters. Although PC clusters are also a cheap alternative, their reliability decreases rapidly with larger numbers of nodes because of malfunctioning PCs.

The ApeNEXT is the fourth generation of a series of parallel computers developed at Italy's National Institute for Nuclear Physics (INFN), with the collaboration of DESY in Germany and the University of Paris-Sud in Orsay. The first one, appeared in the 1980s, when a group of Italian physicists at INFN, led by Nicola Cabibbo of the University of Rome, set out to develop a line of computers for computations in particle physics. "These machines had the same performance for lattice quantum chromodynamics that you could have with a supercomputer, but at the fraction of the price," says Raffaele Tripiccione, international spokesperson for the APE consortium and a physicist at the University of Ferrara. Three generations of computers appeared, the one-gigaflop APE, which had the computing power of a modern PC, the APE100 and APEmille, the numerals indicating the increase in computing power. These machines allowed Italian particle physicists to make numerous breakthroughs. "Those machines, for 20 years, have been responsible for generating key data sets on which a lot of the work in QCD has been based", says Richard Kenway of Edinburgh University.

The INFN physicists realised early during the APE project that if they really wanted to optimise the computers for large-scale lattice simulations, they had to take a big step. "Starting with APE100 we decided to build our own processors rather than using commercial ones, and by putting into those processors only the things that we really needed, essentially floating-point operators, we were able to get a price performance ratio of a factor 10-20 better than you would get by a standard processor," says Tripiccione. The APEmille computer costs 1.5 Euro per megaflop; this will be reduced to 0.5 Euro for the ApeNEXT.

At the core of ApeNext is a new processing unit or node that contains the computing engine, the interface with the memory and the interface with the network in one VLSI chip, explains Piero Vicini of INFN and leader of the technical development of the ApeNext computer at Rome 1 University. These processing units are mounted on boards containing 16 units, which in turn are mounted in towers. The nodes are connected in a three-

▲ Fig. 1: An ApeNext board carrying 16 nodes

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▲ Fig. 2: Piero Vicini (right), the leader of the technical development of the ApeNext computer and Alessandro Lonardo who is responsible for developing the software, both of INFN, Rome.

dimensional toroidal clustering with about 500 nodes in a tower. A prototype single tower has been completed in Rome, and is going through a testing phase that started in January. The development cost in terms of expenditures, not researcher's salaries, was very low, about two million Euros. The cost was shared between 60 % INFN, 30 % DESY and 10 % Orsay. The building of the production units will start this summer, and a network of 6000 nodes delivering about 10 teraflop will be installed on the campus of Rome 1 University, and will cost INFN about five million Euros. The twelve towers will be combined dynamically to form smaller or larger computers. DESY is now building a prototype tower as well, and will install a three-tower machine in Zeuthen, Germany.

The APE team is now also transporting the software developed for the Apemille onto the ApeNext computer. The TAU dynamic language developed for ApeMille now works, as well as a real C-compiler, reports Tripiccione.

"Surprisingly enough, our C-compiler is almost as efficient as the TAU compiler, and my feeling is that all new programming will be done in C," says Tripiccione.

This will be especially true for the so-called "unquenched LQCD", or "complete LQCD" that will be run on the ApeNext computer. This type of simulation includes certain loops that increase the accuracy of the results, but also require a huge amount of computing power, says Vicini. He expects that some of these simulations will probably take several months on a 10-teraflop configuration of ApeNext.

According to Tripiccione, the results with ApeNext and other machines is showing that cheap pentaflop machines could become a reality in about five years. However, the technical challenges are daunting, and although there is expertise and leading-edge technology available in the computer industry, it is now difficult to interest industry in becoming involved in machines for very specialised applications. "The way out would be a world-wide collaboration. We would ask for a set of machines large enough to command enough attention that some computer company might be willing to come into the game" says Tripiccione. ■

### About the author

Alexander Hellemans is a science writer, based in Naples, Italy. In the past he has been the book review editor at Physics Today (then in New York). He is now Contributing Editor for IEEE Spectrum Magazine (NY) and contributes to Physics World, Science, New Scientist, Nature and occasionally to Scientific American.

# IBA-Europhysics Prize 2005 for « Applied Nuclear Science and Nuclear Methods in Medicine »

*Christiane Leclercq-Willain*
*President IBA-EPS Selection Committee*
*Université libre de Bruxelles, B 1050 Bruxelles.*

The Executive Committee of the EPS has approved the recommendation of the Nuclear Physics Board according to the proposal of the IBA-EPS prize selection Committee to award the IBA-Europhysics Prize 2005 to:

Prof. Dr. Werner Heil,
Johannes Gutenberg Universität Mainz,
Germany

And
Dr. Pierre Jean Nacher
Laboratoire Kastler Brossel, ENS Paris,
France

The Prize is attributed with the citation:

" For the development of spin polarized $^3$He targets by optical pumping and their applications in nuclear science and medicine: nuclear physics, neutron low temperature physics and medicine."

The two winners are pioneers in the art of polarizing $^3$He by the method of metastability exchange optical pumping (MEOP) and applying it to several fields (electron scattering on polarized $^3$He targets, polarization of neutron beams, contrast agent for NMR tomography).

Powerful techniques of polarizing $^3$He have been developed in the past for fundamental experiments in nuclear and neutron physics. The basis for an important application in medicine was prepared, the use of polarized $^3$He as a contrasts agent to image the airspaces of the lungs and to check lung functions.

The IBA-Europhysics prize is sponsored by the IBA (Ion Beam Applications) Executive Committee, Chemin du Cyclotron, 1348 Louvain la Neuve, Belgium.

It will be delivered during the XIX Nuclear Physics Divisional Conference *"New Trends in Nuclear Physics Applications and Technology"* in Pavia, Italy from September 5 to 9, 2005. ■

# EuroPhysicsFun – on the very frontier of science edutainment

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"I enjoy doing experiments more than before and overall it's more fun to take physics classes than before."

The above quote is from a 14 year old girl who had seen a performance by the Danish Physics Show a few months before. This quote – and many more like it – illustrates that "*show physics*" is a direct and effective form of science communication. The EuroPhysicsFun project now aims at expanding these activities throughout Europe.

## Birth of EuroPhysicsFun!

The idea of EuroPhysicsFun came up in 2002 when the Danish Physics Show participated in the "Physics On Stage 2" conference in The Netherlands. Among 100 other projects the show won a bronze award for "*teaching excellence, stimulation and motivation of young people*", and the conference participants found the show to be characterized by high speed, professionalism, humour, and enthusiasm, and we received much encouragement to initiate an international physics show project.

The organizers suggested to us that similar shows should exist at universities all over Europe and this made us believe that the success of the Physics Show contains aspects from which universities all over Europe could benefit. This was the very beginning of the EuroPhysicsFun project.

When starting an ambitious project like EuroPhysicsFun, it is crucial quickly to establish an international network of contacts at universities, physical societies as well as teaching and outreach organizations. For the project to be successful, we simply need to advertise our existence to as wide a European audience as possible.

For this purpose, we have during 2005 been represented at the World Year of Physics Launch Conference in Paris, at physics student conferences in Bergen, Norway, and Ankara, Turkey, and at the International Conference of Young Scientist in Katowice, Poland. Our participation in these conferences has met with great response and has been extremely fruitful for the EuroPhysicsFun project, and we expect to participate in further conferences in Switzerland (EPS13), The Netherlands, Finland, and Portugal during the remaining part of 2005.

## Background: The Danish Physics Show

The Physics Show at the University of Aarhus was initiated in 1998 during the Danish Science Festival where several students from the Faculty of Science had prepared a stand involving a 15-minute programme supported by several small and simple experiments. Due to the huge success of this venture, the students at the physics stand decided to make a permanent group which could travel all over the country and give demonstrations of physics at primary and high schools, science museums, libraries, and other public places. The Danish Physics Show was born, and the Faculty of Science quickly decided to fund transportation, materials, and salary for the students involved.

Despite the name, the Physics Show is definitely not just an entertaining *show*. The educational part is equally important, and we normally use the term "edutainment" to describe our activities. We thus always explain the underlying physics of the experiments presented. However, experience has taught us that people will not learn much if they are shown an experiment only and then presented with the explanation.

Explanations of the experiments at the show are instead presented through questions to the audience; *"What do we expect?"*, *"Why does this happen?"*, *"How does this relate to the other experiments?"* A perfect show is the one where the experiments presented are explained and carried out by the audience themselves with only little guidance from the show performers. Keeping in mind the famous saying of Confucius: *"Tell me and I listen, show me and I will understand, involve me and I will learn"*, the more involved the audience is in the actual experiments, the better. Often, experiments are passed around, and several members of the audience will be asked to participate in them in front of the audience.

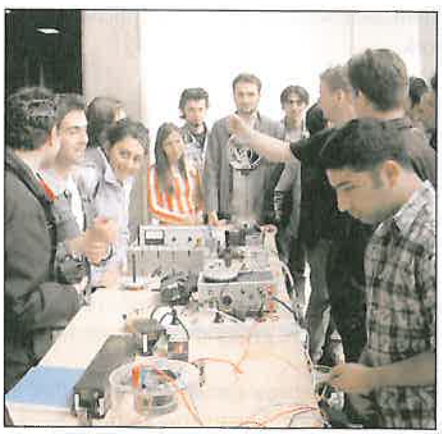
To get in touch with all members of the audience we prefer not to perform in front of more than one school class of perhaps 25 to 30 people. A show can simply be considered a complete flop if the audience does not learn anything!

## Benefits all over the place

The advantages of the show edutainment form described above are many: the intensive use of experiments and the close proximity with the audience stimulate the attention paid to the explanations given in connection with the experiments. We have for example succeeded in giving a 140 minute show without intermission to a high school class without loosing their attention!

Using enthusiastic physic students, the show is able to dispense with the public's stereo-typical image of the physicist. The audience relates and identifies more easily with the show physicists who furthermore express themselves in a youthful manner, not as some fusty old scientist. This appeals to the young and - in recruiting terms –particularly important target group.

Physics students are little used in the field of science communication, although they are closer to the educational level of the ordinary audience and hence understand more easily the difficulties that the audience may have in comprehending the subject matter. Last but not least, physics students are moreover a low-cost resource.



◄ Fig. 1: Curious students gather around the table wanting to try some of the experiments themselves after a EuroPhysicsFun presentation in Ankara, Turkey.

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The use of physics students also inspires the students themselves. They have fun and learn more about their own subject by teaching it to others, thus continually developing their pedagogical, experimental and professional skills and as a show physicist, one continuously becomes aware of the growing number of explanations and experiments needed in order to be able to demonstrate and explain problems in a professional and educational way - and at the same time also be able to appreciate the ideas, suggestions and feedback from the audience during the show.

The outcome is a large number of excellent ambassadors of physics, who - regardless of their future career - will benefit from the communication skills obtained in an outreach group.

## The EuroPhysicsFun Network

We know that several groups similar to our Physics Show exist in many places in Europe. Our first task is thus to find and contact these groups and invite them into the EuroPhysicsFun Network, which to our knowledge is basically the first ever international network of its kind.

In Denmark, show physics has existed at several universities for many years, and presently five Danish groups are members of EuroPhysicsFun. A completely new group is currently being formed under the guidance of EuroPhysicsFun at the University of Aalborg. Each group consists of 5-10 students, and has contact to more than 20.000 people from the general public each year.

The shows have never cooperated much with each other, but the groups are now, due to EuroPhysicsFun, starting to meet at conferences and public science event, e.g. the National Danish Day of Research on 12 May 2005, where all Danish shows for the first time ever was gathered and presented demonstration experiments at stands placed all over the Copenhagen Central Railway Station. We foresee a future where events like this are visited by groups from all over Europe, thus improving the professional teaching skills of each individual group member and addressing a broad range of the public.

At present, we are in contact with two outreach groups outside Denmark. Creative Group Quark from Katowice in Poland is a group of high school students who present a wide range of physics demonstration experiments and physics toys, while RINO *("Reizende Informanten Natuurwetenschappelijk Onderzoek")* from the University of Leiden in The Netherlands is a group of physics students who perform a show based primarily on liquid nitrogen experiments.

Two members of RINO have already visited the Danish Physics Show in Aarhus, and an evening was spent in a very rewarding exchange of experiences and demonstration experiments. The meeting proved beyond any doubt that a network like EuroPhysicsFun is an excellent idea, which will be a great benefit to all members of the network.

## Workshops

EuroPhysicsFun is not only about joining existing shows into a network. The project is equally about setting up completely new shows at European universities. All the above-mentioned travelling is necessary, but when EuroPhysicsFun gets more well-known and the network is established, we would prefer to cut down on foreign shows and concentrate instead on organizing workshops in Denmark to which interested universities can send students to learn about show physics, and where group members get together to share experiences.

Our experience shows that starting a similar activity to that in Denmark has different bottlenecks. The purpose of our workshops is to offer a shortcut through them. Specifically, funding is an issue, understanding the problems of the audience in comprehending the topics, making a curriculum and getting accustomed to it are some of these bottlenecks.

We are now setting up a series of workshops, which will include a lot of hands-on experimenting, and the participants will go home with detailed knowledge about a large number of demonstration experiments. They will experience an actual physics show, but they will also try many of the experiments themselves. During the workshop, they will practice performing in front of a large audience, and they will be evaluated through video analysis. The workshops for example include a talk by the director of the Street Circus Academy, Aarhus on performing and a didactics expert about learning processes. Fund raising and individual business plans for each show will also be on the agenda.

The participants are expected to pay travel expenses and a workshop registration fee of EUR 250. We believe that many European universities will be interested in sponsoring the participation of one or two students, and we encourage interested students to discuss this with their local administration.

## Future plans

As already mentioned above, the future will bring our show to more physics conferences, where we will work on extending our contact network and trying to inspire local universities to start up shows similar to the Danish Physics Show.

Our first four-day workshop will be held in July 2005. Physics students from all over the world will be travelling to Denmark to learn the basics of show physics. It appears so far that we are not restricted to a focus on Europe only – students from many countries (including Ghana, Nigeria, Iran, and Pakistan) have already registered, and we all are looking forward to a remarkably productive event.

## Further information

EuroPhysicsFun can be contacted by email: mail@EuroPhysicsFun.org

We would very much appreciate any information on existing European outreach groups similar to the Danish Physics Show, whom we could invite to join the EuroPhysicsFun Network!

Also, we would appreciate letters of recommendation to be used for raising financial support beyond December 2005.

At the website www.EuroPhysicsFun.org, you can find our discussion forum, pictures, calendar, demonstration experiments, and planned workshops. Further information on the Danish Physics Show can also be found at this site, where one can also sign up for the EuroPhysicsFun Newsletter.

For more information on the RINO group in Leiden, visit www.physics.leidenuniv.nl/rino.

EuroPhysicsFun is funded by the Danish Ministry of Science, Technology and Innovation, the Danish Research Council and the Villum Kann Rasmussen Foundation. This covers activities and 1.5 full-time employees for one year. ■

◄ Fig. 2: The Danish Physics Show perform in the Danfoss Universe science park.