THE IMPORTANCE OF PARTICLE ACCELERATORS

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As initial remark to this opening talk of EPAC2000 it can cursorily be said that particle accelerators are certainly important because the salaries and pension funds of the participants to this Conference depend on the existence, the running and the construction of accelerators. More seriously, it is useful to consider the three main uses of the primary and secondary beams produced by particle accelerators.

1. In a first type of application, beams of particles are employed as probes in the ***analysis of physical, chemical and biological samples***. Particle Induced X-ray Emission (PIXE) is a notable example.

2. In a second large family of application, beams of particles are used for the ***modification of the physical, chemical and biological properties of matter***. Sterilisation can be quoted here.

3. The most energetic beams of particles are today the main instruments for ***research in basic subatomic physics.*** These particles move close to the velocity of light and one should speak of 'massificators'.

In the next Section some applications belonging to the first two categories are presented. Accelerators of the next generations are the subject of Section 3, devoted to future applications, and of Section 4, where the requests made to accelerator-builders by the present status of subatomic physics are justified.

2 SAMPLE ANALYSES AND MODIFICATION PROCESSES

To a nice figure due to K. Bethge [1], I have added the leaves representing the many applications that continue to sprout from its various branches (Fig. 1). The roots of the trunk are in the nuclear physics of the thirties and the pull towards higher energies and beam currents comes still today from the study of the fundamental particles and their interactions. Some of the accelerator technologies mentioned in the figure became mature so long ago that they are not even discussed at large international conferences.

Already a cursory reading of the figure proves that particle accelerators are very important, because they give irreplaceable contributions to human life. The list of the fields of application goes from A to Z, i.e. from art to zoology. It is so long that I can only mention here some examples.

In the field of the ***arts*** one can consider the work done at the *Accélérateur Grand Louvre pour l'Analyse Élémentaire* (AGLAE) on a drawing made around 1450 and attributed to Pisanello. By means of the PIXE technique the attribution was falsified, since securely attributable drawings are characterised by much less copper than the amount observed [2].

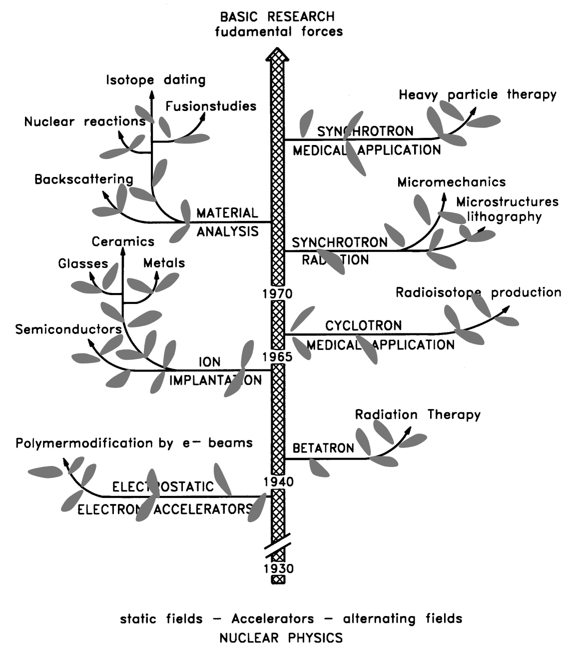

Figure 1: The *Time Tree* gives a pictorial view of the development of the applications of accelerators in both modification processes and sample analyses.

The next step in molecular ***biology*** - after the completion of the decoding of the human genome - is 'structural genomics', the understanding of the shape and the functioning of the proteins coded by each gene. X-ray diffraction of samples of crystallised proteins is at present the main tool in 'proteomics' and all suitable sources - in particular synchrotron radiation sources - will contribute.

Cyclotrons are used to produce the medical isotopes used for *Positron Emission Tomography* (PET) and *Single Photon Emission Computed Tomography* (SPECT). Still, in ***diagnostics***, about 80% of all examinations use isotopes (in particular Technetium 99m) produced at old reactors. It is high time to use for their production 100 - 150 MeV high-power cyclotrons instead of ageing reactors.

The most promising new technique in radiotherapy is ***hadrontherapy*** that utilises beams of light ions of atomic number around $Z = 6$. At variance with protons, which interact with the cells essentially as X-rays, light ions better control the slowly growing radioresistant tumours which represents about 20% of all the irradiated tumours. Since 1994 at HIMAC in Japan about 800 patients have been treated with carbon ions with satisfactory results. In 1998 the *carbon ion pilot project* was completed at GSI where about 50 patients have been irradiated. To increase this number a hospital-based therapy centre has been designed by GSI for the Heidelberg University [3].

In parallel in the years 1996-1999 an AUSTRON-CERN-GSI-TERA Collaboration has carried out the *Proton Ion Medical Machine Study*, a study of a light ion synchrotron designed to produce a constant extracted beam [4]. This is an important feature for the scanning of tumours with pencil beams. PIMMS is the source of the proposals put forward by the Med-AUSTRON Project [5] and by the TERA Foundation [6] to their national authorities. Using PIMMS, preliminary proposals have also been prepared by TERA for the University Claude Bernard in Lyon and for the Karolinska Institute in Stockholm.

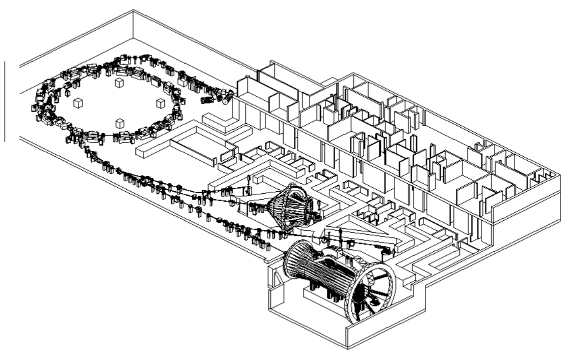

Figure 2: Proton and ion therapy Centre proposed by TERA and based on the PIMMS synchrotron.

In ***planetology*** small beams of low energy protons are used. At the *Heidelberg Proton Microprobe* the PIXE elemental mapping of micrometeorites is done with a spatial resolution of a few microns [7].

Coming to the letter Z, in the field of ***zoology*** one can quote the diffraction studies made at the European Synchrotron Radiation Facility of an isolated muscle fibre of a frog excited at a frequency of 25 Hz [8].

Already these few examples show the importance of particle accelerators in art, medicine and non-nuclear sciences. The argument becomes even stronger when the number of accelerators is considered. Table 1 shows that 55% of the 15000 accelerators running at present in the world are devoted to modification processes: ion implantation, surface modification and industrial applications (mainly sterilisation and polymerisation). Electron linacs for radiotherapy represent one third of all the existing accelerators. There are about 70 synchrotron radiation sources in the world, with the highest density in Japan, and more than 100 in subatomic physics. In 1994 the total number of accelerators was about 10000, so that one can conclude that the progression rate is about 15% per year.

Table 1: Accelerators in the world. The data of Ref. [9] have been updated for EPAC2000.

CATEGORY	NUMBER
Ion implanters and surface modifications	7000
Accelerators in industry	1500
Accelerators in non-nuclear research	1000
Radiotherapy	5000
Medical isotopes production	200
Hadrontherapy	20
Synchrotron radiation sources	70
Research in nuclear and particle physics	110
TOTAL	**15000**

3 NEW APPLICATIONS UNDER ACTIVE DEVELOPMENT

The past spin-offs are impressive. What about the future? **Spallation sources** are moving to the unexplored territory of high power beams on target. Europe has a very good record with ISIS at RAL and two new projects: the European Spallation Source and the AUSTRON project [10]. In the USA a new generation facility is well under way and is expected to be completed by 2006 [11].

A new application of great importance is the development of **X-ray emitting Free Electron Lasers**. The availability of these intense sources will allow even to ‘see’ moving microstructures of ångstrom dimensions. A project is under way in the USA [12] and another one is a parallel development of the work done for the TESLA linear collider centred at DESY [13]. In a long undulator, a 5 Hz electron beam of 15-50 MeV - formed of very intense (1 nC) and very short (80 fs) bunches – will radiate photons through the *Self Amplified Spontaneous Emission* (SASE) mechanism. At 1 Å wavelength the peak brilliances will be ten orders of magnitude larger than the best ones achievable today.

A recent development centres on Rubbia’s **energy amplifier**, a sub-critical lead-cooled fast fission reactor injected with the spallation neutrons produced by a powerful beam of 1 GeV protons. The main use would be the incineration of radioactive wastes, but the *Adiabatic Resonance Crossing* (ARC) technique, tested at CERN [14], is ideal for medical isotopes, so that an energy amplifier could substitute the ageing fission reactors in the production of Technetium 99m.

Finally one should not forget that the experiments on **inertial fusion** induced by laser beams performed in Japan, the USA and France suffer of the low efficiency of the lasers. Fusion reactors should rather use short and powerful ion bunches. The accelerator systems required are complicated but the components are based on reasonable extrapolations of existing technologies, as described in the Heavy Ion Driven Inertial Fusion report distributed by GSI [15].

4 STATUS OF SUBATOMIC PHYSICS AND ITS FUTURE ACCELERATORS

Subatomic physics covers two subjects: nuclear physics and particle physics. The former is concerned with systems having baryon number much larger than 1 and naturally subdivides in two chapters. The phase diagram of ***high-temperature nuclear physics*** belongs to the first one (Fig. 3).

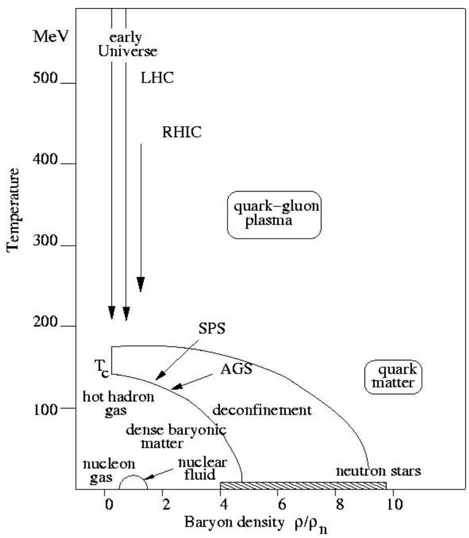

Figure 3: The expected deconfinement (or parton-hadron) transition is shown together with the phase space regions experimentally studied at the AGS, the SPS, RHIC and LHC.

The horizontal axis represents the baryon density. On the vertical axis, the temperature of the nuclear system is plotted in terms of the kinetic energy of its components (100 MeV $\cong 10^{12}$ kelvin).

The problem here is the experimental study of the deconfinement transition predicted by the Standard Model description of the baryons in terms of quarks bound by the exchange of gluons. The oblique arrows indicate the approximate paths of the non-equilibrium baryonic systems studied by colliding heavy ions with heavy fixed targets at the AGS and at the SPS. Recently the physicists working at the SPS have put together the results of different experiments reaching the conclusion that a new state of matter has been observed.

The results expected from RHIC should bring very clear information on the deconfinement transition, starting from temperatures which are about two times larger than the transition temperature. The lead-lead collisions to be studied with the ALICE experiment at the LHC will start with much higher temperatures, thus reproducing even more closely what happened in the early Universe. So, if other phase transitions are not discovered, LHC could be the ultimate ion-ion collider to study these phenomena.

Fig. 4 is the introductory chart of the chapter devoted ***low-temperature nuclear physics***.

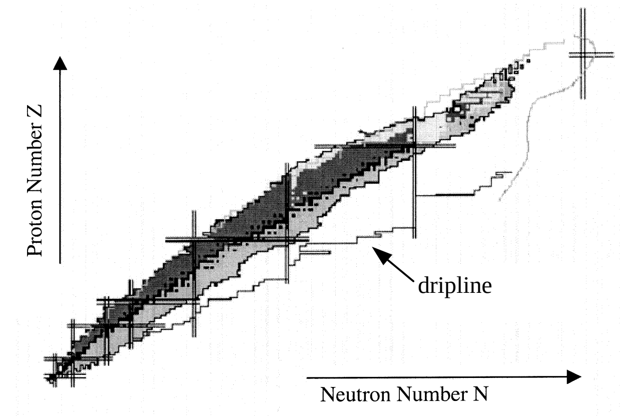

Figure 4: Below the dripline the nuclei are not bound. The crosses indicate the magic nuclei.

The dark and shaded area covers the well-studied stable and unstable nuclei. Below, one sees the area of neutron-rich nuclei that can be produced only by accelerating and colliding unstable nuclei with fixed targets. The frontier instruments of low-temperature nuclear physics are thus *accelerators of radioactive nuclei*. The phase space to be explored is very large, as indicated by the extension of the unknown white area lying above the dripline. The importance of these experiments comes also from the fact that here the so-called '*r-process*' takes place, i.e. the rapid neutron capture happening in supernovae and leading to the creation of many elements heavier than iron.

In summary, at least two nuclear physics subjects are important for astrophysics: the transition from the quark-gluon plasma phase to the hot hadron gas and nuclear reactions (e.g. the r-process mentioned above) taking place in ordinary stars and supernovae. The links between subatomic physics and astrophysics are even stronger. Indeed all that one learns on the second subject of subatomic physics – i.e. 'particle physics' - is crucial for solving the first of the *three really important scientific problems*: the origin of the Universe, the origin of life and the origin of consciousness.

The Standard Model has its foundations in the existence of two groups of particles: the *force-particles*, mediators of the four fundamental interactions, and the *matter-particles*, that are either leptons or quarks. The ***sector of the force-particles of the Standard Model*** is the most relevant to the origin of our Universe. We are concerned here with the probability of emission of a virtual mediator.

Such elementary emission and absorption processes determine all the collision and decay phenomena and are governed by the numerical value of α^{-1}, the *inverse of the coupling*.

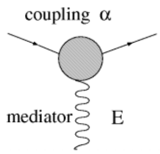

Figure 5: Emission and absorption of a mediator by a matter-particle, either quark or lepton.

The reason is that for every interaction (strong, electromagnetic and weak) α^{-1} equals the number of times one has to observe the matter-particle before finding a virtual mediator close to it. If α^{-1} is larger than 1, one has to wait a long time before finding a mediator close-by and the interaction is weak. If α^{-1} is of the order of 1, the matter-particle is always surrounded by a mediator and the force is strong.

The important point is that the value of α^{-1} depends upon the energy (or the momentum) E of the virtual force-particle. Indeed, when a blob of energy E surrounds a matter-particle, all particle-antiparticle pairs of energy smaller than E can be created for a very short time. They influence the interaction between the mediator and the matter-particle and change the value of α^{-1}. For instance, a virtual photon of momentum larger than 10 GeV is exchanged between two passing-by electrons, the couplings are modified by the momentary creation of beauty/anti-beauty quarks, each having a mass of about 5 GeV. Quantum field theory allows precise calculations of the energy dependence of all couplings, once their values at a given energy are known together with the masses of all the particles that can temporally be created.

In 1991 the new accurate LEP measurements of the three fundamental couplings performed at E ≅ 100 GeV allowed for the first time their precise extrapolation [16[. A fact suspected for a few years became a certainty in the Standard Model: the forces do not unify at high energy (top panel of Fig. 6).

But unification is obtained if a theoretically more satisfactory model is adopted, the *Supersymmetric (SUSY) Model* in which there is *full symmetry* between the matter-particles and the force-particles. In such a model - as in other less simple ones - new 'superparticles' are predicted at energies just above the about 100 GeV explored till now. Their existence would modify the energy dependence of the couplings, bending them towards a unification point at 10^{16} GeV, as shown in the lower part of Fig. 6.

Simple thermodynamic considerations connect the universal time t with the energy E available in the collisions of the particles forming the primordial soup:

$$t_{\text{microseconds}} \cong 1/\,E^{2}_{\text{GeV}}$$

It is enough to rotate by 180° the lower image of Fig. 6 - transforming the energy scale in a time scale - to visualise the events which, in this model, happened during the 'first' second.

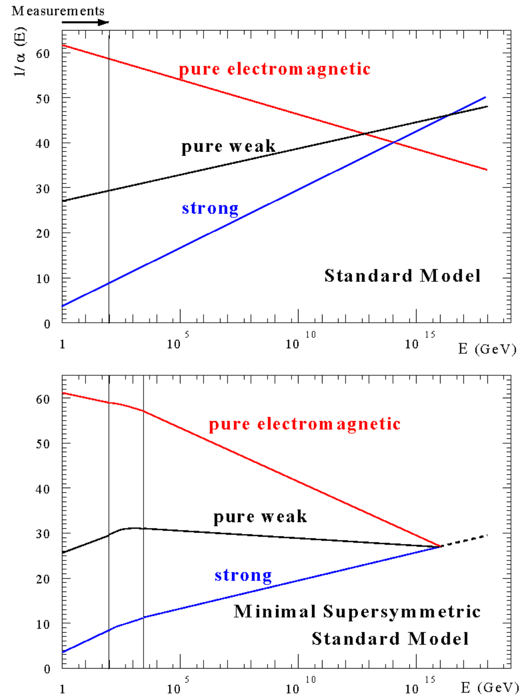

Figure 6: In the Standard Model there is no unification, but this can be obtained in models with new particles of masses larger than 100 GeV.

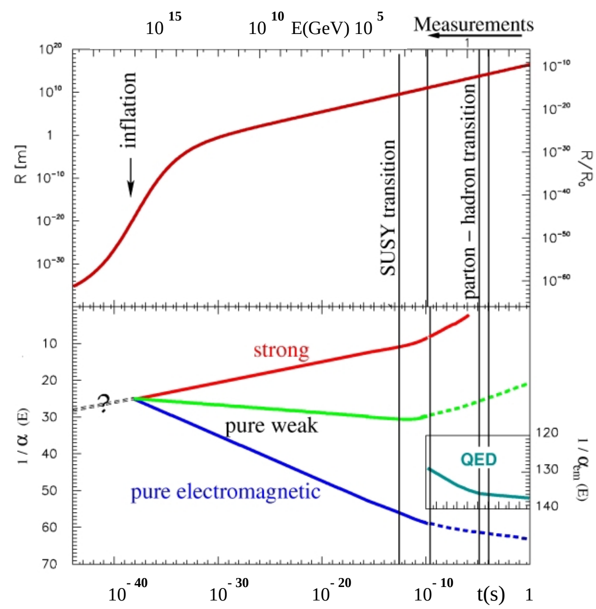

Figure 7: The lower graph shows the SUSY and the quark-gluon plasma transitions. The upper panel represents the *inflation* of the early Universe, that probably happened at the time of divergence.

Fig. 7 shows that in this model the couplings diverged, at 10^{-38}s, and at 10^{-12}–10^{-10} s a transition took place, during which all the superpartners of the known particles decayed and could not be created any longer for the lack of energy in the collisions. (It is however possible that the lightest neutral superparticles did not decay and form today the so-called 'dark matter'.)

Also other models of the events before 10^{-10} s are fashionable today. Anyway we know that around that time all the weak bosons W and Z bosons decayed and since then the pure weak and pure electromagnetic forces are mixed together to form the usual weak and electromagnetic forces (inset of Fig. 7).

As indicated by the arrows ‘measurements’ in Fig. 6 and 7, the only way to probe the possible SUSY transition is to study collisions at energies larger than 100-200 GeV. This will be the domain of LHC.

The ***matter-particles of the Standard Model*** are the second hot issue in particle physics. For the quarks the phenomenology is quite well known. In the collisions processes, the down, strange and beauty quarks are produced, but in the decay processes linear combinations of them - indicated as d', s' and b' – give the observed effects. The Cabibbo-Kobayashi-Maskawa matrix connects them.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.9740 \pm 0.0010 & 0.2196 \pm 0.0023 & \mathbf{0.0040^{+0.0006}_{-0.0007}} \\ 0.224 \pm 0.016 & \mathbf{0.91 \pm 0.16} & \mathbf{0.0402 \pm 0.0019} \\ < 0.010 & \simeq 0.0400 & 0.99 \pm 0.29 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Figure 8: The CKM matrix connecting the quarks is given by neglecting the CP violating phase. A parametrisation of the neutrino matrix is also shown.

The top matrix of Fig. 8 summarises more than forty years of experiments and further improvements require higher luminosities, an important line of development for future colliders.

A similar phenomenon is expected to happen with the three neutrinos. We know already the order of magnitude of some non-diagonal elements of the lower matrix of Fig. 8. Much better measurements will allow to falsify any ‘theory of everything’, but by sure more than fifty years will be needed.

Quark mixing can be studied at colliders because all heavier quarks decay within a few millimetres. Neutrinos, being the lightest of all particles, do not have enough energy to decay and thus, once produced, travel for ever. Their mixing can be observed only as the appearance of a different neutrino in a beam of neutrinos of a well-defined type. Such ‘oscillation experiments’ done in controlled conditions require very intense neutrino beams and long flight-paths. These are the arguments that have prompted the design of *neutrino factories*. They will become widely required accelerator complexes to be built together with the more standard hadronic and leptonic colliders in our accelerator centres, eventually sending beams to far away underground laboratories in a possible *World Wide Neutrino Web*.

This field is in full development while the future of lepton and hadron colliders is well defined. Precise experiments on the quark sector will continue at quark factories and possibly at a new Z-factory. As far as the high-energy frontier is concerned, while LHC experiments will be running, at least one high-energy electron-positron linear collider will have to be built to study in detail the new energy domain explored with the wide-band but less precise proton-proton processes. The energy attainable should be as large as feasible; the results obtained at LEP, Tevatron and LHC will indicate the optimal initial energy. Muon colliders are for later, when neutrino factories will have opened the way to intense muon sources.

5 CONCLUSIONS

Particle accelerators are and will be important for the arts, the other sciences, medicine and high-tech industries. They are crucial for the understanding of the origin of our Universe and of the formation of heavy nuclei, without which the Earth could not exist. Moreover they give the information needed to falsify any new ‘theory of everything’. Thus, the trunk of the Time Tree is strong and developing, the old leaves are green and new leaves are sprouting. If the accelerator specialists continue to invent and labour as in the past, their salaries and pension funds are secured.

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