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Conference summary: Trends in AMS

Walter Kutschera *

Institut für Radiumforschung und Kernphysik, University of Vienna, Boltzmanngasse 3, A-1090 Vienna, Austria

1. Introduction

The conference summary is something like a punishment and an honor at the same time. It is a punishment because the person giving the summary should listen to all the talks and look at all the posters. On the other hand, it is a great honor because the organizers think that somebody could actually make sense out of this. Since the author believes that it is virtually impossible to cover the many interesting subjects reported at AMS-7 and the associated workshops, this summary will not attempt to report on individual achievements. Rather it will give reflections on listening to almost all the talks at AMS-7 and to all the talks at the four workshops associated with it. As a result, this summary is called "Trends in AMS", and in many ways represents a very personal view of the field.

2. Workshops

The first impression was the large number of workshops associated with AMS-7. There were two workshops at Lawrence Livermore National Laboratory entitled *^{129}I Studies of AMS and Biomedical ^{14}C Applications*. The third workshop took place at the Scripps Institution for Oceanography in La Jolla and concentrated on *Applications of AMS to Global Climate Change*. The fourth workshop took place at Tucson after the AMS-7 conference and discussed *Geological Applications of AMS*. Altogether, there were 4 days of workshops and 5 days of conference. This was a rather heavy load for those attending it all, nevertheless it was worth it. It clearly showed the enormous breadth of research utilizing AMS.

3. History

Can history teach us something? Perhaps. For AMS, there are two important historical events. The first happened during the early years of the Institut für Radiumforschung in Vienna, where Victor Hess was a research assistent from 1910 to 1920. In a series of daring baloon flights, Victor Hess carried sealed ionization chambers up to an altitude of 5000 m showing unambiguously in 1912 that the ionization increases with altitude [1,2]. In 1936 he was awarded the Nobel Prize in Physics for his discovery of cosmic rays. The connection to AMS is evident. Without long-lived cosmogenic radionuclides – the now familiar products of cosmic-ray interaction in the atmosphere and on the surface of the earth – AMS may not have evolved at all. The work of Hess was also a nice demonstration how to successfully perform field work, overcoming all the pitfalls of doing research outside a laboratory. In many applications of AMS, the quality of field work is an important part for the overall relevance of the AMS measurement.

The other historical event with large impact on AMS was the development of radiocarbon dating by Willard Libby at the University of Chicago [3,4]. In 1960 he was awarded the Nobel Prize in Chemistry for this achievement, which so dramatically changed our interpretation of the past. Clearly, radiocarbon measurements still dominate AMS, but the refinements in using it as a reliable chronometer are far from finished. It was apparent at AMS-7 that a detailed understanding of chemistry plays an important role for interpreting AMS measurements, but several other factors also matter. In his Nobel Prize Lecture Libby expressed very clearly how to deal with this complexity by stating something one might call the *law of radiocarbon dating*: "Radiocarbon dating is something like the discipline of surgery – cleanliness, care, seriousness, and practice" (Perhaps it was this clear understanding of difficulties which made him think that it would be problematic trying to date religious objects).

4. Universality

At AMS-7 and the associated workshops it was apparent – more than ever before – that AMS allows us to enter almost any field of science. In particular, AMS has become a universal tool for research in the environment at large. Table 1 lists the seven major domains of the environment where AMS measurements are being performed. AMS plays an important role in slowly unravelling the

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* Fax +43 1 31367 3502; email walterkv@pap.univie.ac.at

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complex processes governing these domains. Eventually, this will also contribute to a deeper understanding of the subtle interplay between the domains, which ultimately determines the fate of our environment.

However, we realized that a precise, and even an accurate, measurement of an isotope ratio in an ion beam is principally a "stupid" measurement. The value of the information it carries depends on a detailed understanding of every step from the original isotope material (natural, anthropogenic; naturally distributed or explicitly administered) to the final isotope composition we measure with AMS. We heard beautiful examples for the application of *Libby's law of radiocarbon dating* stated above, such as the use of advanced analytical techniques of (bio)molecular chemistry to disentangle complex forms of carbon compounds, or the various attempts to understand the contamination problem in graphitising ever smaller carbon samples.

5. ^{14}C calibration

Another interesting question in connection with radiocarbon dating is the extension of the calibration beyond the tree-ring curve, which currently reaches back to about 11400 years [6]. Several attempts were reported, using cross calibration with U-Th dating on corals, or varved sediments. There is indication from these measurements that large fluctuations of atmospheric ^{14}C may have occured during the end of the last ice age. This may be coupled to the large temperature fluctuations observed with δ^{18}O measurements in ice cores going back in time beyond 11000 years. Although information on climatic changes is increasing especially for periods of focussed interest (Younger and Older Dryas, see e.g. Ref. [7]), there is a lot to be done before one will be able to assess its influence on the atmospheric ^{14}C budget. It is clearly a challenging and important task to establish a reliable abso-

Table 1
The seven domains of the environment

Domain	Examples of AMS applications [a]
Atmosphere	chemistry, transport, origin of trace gases: CO, CO_2, CH_4 (^{14}C) transport and origin of biomass burning aerosols (^{14}C) cosmic-ray production of radionuclides (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{81}Kr)
Biosphere	radiocarbon dating in archeology and other fields (^{14}C) in-vivo tracer studies in animals and humans (^{14}C, ^{26}Al, ^{41}Ca) radiocarbon calibration studies with tree rings (^{14}C)
Hydrosphere	groundwater dating (^{14}C, ^{36}Cl, ^{39}Ar) extension of calibration curve with varved lake sediments (^{14}C) and with ocean corals (^{14}C–U/Th comparison) dating of benthic and planktonic foraminifera (^{14}C) for paleoclimatic studies
Cryosphere	studies with ice cores from glaciers and polar ice sheets: dating of ice with CO_2 of trapped air (^{14}C) paleoclimatic record (^{10}Be, ^{14}C) bomb peak (^{36}C, ^{41}Ca, ^{129}I) variation of cosmic ray intensity (^{10}Be) in situ production (^{14}C)
Lithosphere	exposure dating and erosion studies of rock surfaces for geomorphologyical studies (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl) paleoclimatic studies through dating of loess (^{10}Be) characterization of vulcanism (^{10}Be) mineral studies (trace elements, e.g. platinum group elements)
Cosmosphere	galactic cosmic-ray record in meteorites (^{10}Be, ^{14}C, ^{26}Al ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{129}I) solar cosmic-ray alpha particle record in lunar rocks (^{59}Ni) terrestrial age determination of meteorites (^{14}C, ^{36}Cl, ^{41}Ca) geochemical solar neutrino detection (^{97,98}Tc, ^{205}Pb) search for exotic particles (superheavy elements)
Technosphere	semiconductor material (trace element concentration) radioactive waste disposal (^{36}Cl, ^{129}I) neutron flux of Hiroshima bomb (^{36}Cl, ^{41}Ca) characterization of fission material (^{239,240,242,244}Pu)

[a] The radionuclides used in the specific area are given in parenthesis.

Table 2
Summary of facilities for accelerator mass spectrometry (status 1996) [a]

County	Number	Location
North America		
Canada	2	Chalk River Laboratories (TV = 14 MV)
		University of Toronto (2.5)
USA	8	University of Arizona, Tucson (2.5)
		Lawrence Livermore National Laboratory (9.5)
		Michigan State University, East Lansing (cycl.) [b]
		Naval Research Laboratory, Washington (3) [b]
		University of North Texas, Denton (3)
		University of Pennsylvania, Philadelphia (9)
		Purdue University, West Lafayette (9)
		Woods Hole Oceanographic Institution (3)
Europe		
Austria	1	University of Vienna (3) [c]
Denmark	1	University of Aarhus (6)
England	1	University of Oxford (2.5)
France	1	National Scientific Research Center, Gif-sur-Yvette (2.5)
Germany	4	University of Erlangen-Nuernberg (6), University of Kiel (3) [c]
		Technical University and University of Munich (14),
		Forschungszentrum Rossendorf (3) [b]
Israel	1	Weizmann Institute of Science, Rehovot (12)
Italy	1	University of Napels (3) [b]
Netherlands	2	University of Groningen (3)
		University of Utrecht (6)
Sweden	2	University of Uppsala (6)
		University of Lund (3)
Switzerland	1	ETH Zurich (6)
Asia		
China	4	China Institute of Atomic Energy, Beijing (14),
		Peking University, Beijing (6),
		Shanghai Institute of Nuclear Research (6),
		Shanghai Institute of Nuclear Research (cycl.) [c]
Japan	5	Kyoto University (8) [b]
		Nagoya University (2.5)
		University of Tokyo (5),
		University of Tsukuba (12) [b],
		National Institute for Environmental Studies, Tsukuba (5) [c]
India	1	Institute of Physics, Bhubaneswar (3) [b]
Australia and New Zealand		
Australia	3	Australia Nuclear Science and Technology Organisation, Sydney (8)
		Commonwealth Scientific and Industrial Research Organisation, Sydney (2.5)
		Australian National University, Canberra (14)
New Zealand	1	Institute of Geological & Nuclear Sciences, Lower Hutt (6)
South America		
Argentina	1	Atomic Energy Commission, Buenos Aires (20) [b]
Brazil	1	University of Sao Paolo (9) [b]

[a] Except for two (MSU and Shanghai), all AMS facilities are based on tandem accelerators. For the latter, the nominal terminal voltage in MV is given in parenthesis.

[b] AMS development at existing accelerators.

[c] New AMS facilities in test operation.

lute time calibration over the full range of radiocarbon dating.

6. Complexity

The growing complexity and interdisciplinarity of AMS sometimes leads to a Babylonian mix of scientific jargons, particularly when biomedical AMS results are discussed. For example, it seems difficult for a nuclear physicist or any scientist not particularly well-trained in chemistry to make sense out of an expression like 2-amino-3,8-dimethylimidazo [4,5-f]quinoxaline, commonly known as MeIQx [5]. We also have to get used to plots of biomedical results, where one axis could be labeled in units of MeIQx DNA adducts per 10^9 nucleotides. For this, it is good to remember that the human genome consists of about 3×10^9 nucleotides.

In a different area (agriculture), slowly being entered by AMS, complexity was demonstrated during the outing to the beautiful Arizona-Sonora Desert Museum near Tucson. Here, in a display about desert soil, one could read: "All life depends on what happens here – in the rhizosphere, or root zone." This was followed by listing the impressive content of one gram of soil: 10^9 bacteria, 10^9 actinomycetes, 10^6 fungi, 10^5 protozoe, 10^4 algae, and an unknown number of viruses (because one cannot see them). The failure of man to reproduce this complexity of life was clearly demonstrated by the visit to Biosphere II. Although an extremely impressive project, it tells us vividly how complex the natural biosphere is and how much we have to learn to come anywhere close of simulating it. It may well be that future research with Biosphere II (now under scientific guidance of Columbia University) will use AMS to solve some of the most interesting questions on Earth. Biosphere II is an excellent example of the domain of our environment we might call the *technosphere*.

7. AMS facilities

Another sign of the liveliness of AMS is the increasing number of AMS facilities around the world summarized in Table 2. AMS activities at these facilities range from small fractions at nuclear physics facilities to fully dedicated AMS systems. In general, dedicated facilities occupy the lower energy range. Interesting reports about very small AMS facilities were presented at AMS-7. There are several proposals and projects for the detection of ^{14}C with table-top tandem accelerators at terminal voltages between 0.5 and 1 MV. The message one got from the various ideas presented was this: it may actually be feasible. The mini-cyclotron idea is also still alive, and pursued with some hope of developing in a useable instrument for radiocarbon dating.

8. New isotopes, trace elements, micro beams, and electron affinities

The number of long-lived radionuclides used in AMS is increasing. Besides the traditional radionuclides used in AMS, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{129}I, developments for AMS measurements of a number of other radionuclides are under way: ^{3}H, ^{53}Mn, ^{55}Fe, ^{60}Fe, ^{59}Ni, ^{63}Ni, ^{79}Se, ^{81}Kr, ^{90}Sr, ^{126}Sn, ^{135}Cs, ^{236}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{244}Pu. There are many promising features evolving in the applications of these radionuclides. Particularly encouraging is the notion that even small tandem AMS facilities with terminal voltages in the range from 2 to 3 MV should be capable of measuring the heaviest radionuclides – provided they have magnets strong enough to bend them.

Trace element AMS would be very important for the analysis of clean materials such as semiconductors, and the direct analysis of mineral objects. Both stable nuclide background and matrix effects seem to be still considerable hurdles to overcome. There were also several reports on micro-beam AMS in connection with this field. They are good examples for the fact that usually things get more complex the closer one looks. This seems to be particularly true for the study of mineral phases at the micron level. In general, it seems that the field is still wide open for challenging developments.

Another interesting use of AMS in connection with stable isotopes is the measurement of electron affinities for very weakly-bound negative ions such as the alkaline earths, lanthanides, and actinides. Here, AMS is used to identify the isotope of interest and is then combined with some means of measuring the electron affinity (e.g. by laser detachment).

Finally, the author would like to conclude with a few words about **Linas Kilius**, who died so untimely by a heart attack on 28 January 1996 while he was enjoying skiing in a resort near Vienna (a tribute to his life and work is given in Ref. [8]). The Vienna AMS group had the privilege to spend the last few days of Linas' life together with him during his visit to the VERA lab in Vienna. As always, Linas was full of ideas and interested in everything connected to science. It was particularly interesting to hear about the fascinating idea of using the release of fissiogenic ^{129}I from reprocessing plants – something usually considered to be only a bad thing – as a new means to study ocean circulation patterns on a global scale. This work, which was started in collaboration with the Orsay AMS group [9] near the major sources of release (La Hague, France and Sellafield, England), should help to understand basic question such as the North Atlantic Deep Water Formation and circulation patterns in the Arctic Ocean. The exciting discussions with Linas gave us a glimpse about his innovative and pioneering spirit which drove his life. Most importantly, perhaps, he left us a legacy which we value highly: Science is fun – and especially AMS.

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