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HIGH-ENERGY MASS SPECTROMETRY WITH LARGE TANDEM ACCELERATORS

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HIGH-ENERGY MASS SPECTROMETRY WITH LARGE TANDEM ACCELERATORS[+]

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ABSTRACT

The analytical properties intrinsic in a charged particle accelerator and its beam transport system permit the detection of rare atoms with original abundances perhaps 10^{-16} of the matrix. This method has been successfully applied to measure natural concentrations of long-lived cosmogenic isotopes. Principles and advantages of high-energy mass spectrometry are discussed with a particular emphasis on new systems employing large Tandems and combinations of Tandems and Post-accelerators. Some recent applications to geology, cosmochronology, archeology and fundamental nuclear physics are presented.

INTRODUCTION

A new analytical technique has been developed during the past seven years which employs a Tandem accelerator and its beam transport system as an ultrasensitive mass spectrometer. Its sensitivity is many orders of magnitude higher than that obtained with low energy mass spectrometers.

The technique consists of counting single atoms that have been ionized, then accelerated to energies of MeV/amu and finally identified with procedures typical of nuclear physics.

This method has been successfully employed in the analysis of long-lived cosmogenic radioisotopes present in natural samples with isotopic ratios in the range 10^{-9}-10^{-15} (Table I). The detection of these atoms with counting techniques is limited by the low specific activity, while the isobaric and molecular interferences thwart the use of low-energy mass spectrometry.

Mass spectrometric properties intrinsic in a particle accelerator were exploited for the first time in 1939 when Alvarez and Cornog discovered ^{3}He in nature using a cyclotron [1].

Only in 1977, about 40 years later, was the idea of using cyclotrons and electrostatic accelerators as analytical tools to count rare atoms considered again [2,3,4].

Presently, a number of laboratories are using accelerators, originally built for basic nuclear physics research, as ultrasensitive mass spectrometers [5]. Interdisciplinary research programs based on measurements of long-lived cosmogenic isotopes with Tandem Accelerator Mass Spectrometry (TAMS) involve different sciences like geology, archeology, cosmochronology, paleontology, hydrology (Table II). These radionuclides are used as tracers and chronometers of phenomena occurring over time spans ranging from several thousand years to several million years.

The wealth of information collected with such a sensitive and efficient technique can have a revolutionary impact on the cross-disciplinary fields. The main emphasis in the past has been on ^{14}C and ^{10}Be. These light nuclides can be measured using small Tandems with low terminal voltages. Some dedicated 3 MV Tandetrons [6] designed for mass spectrometry are already operat-

ing. Smaller ^{14}C dating systems based on 1.7 MV Tandem accelerators will be available in the near future [7].

Heavier long-lived isotopes (Table III) with important potential applications can be investigated only by using large accelerators with magnets adequate to transport the beam of isotopes under study. Furthermore, higher energies are necessary to resolve the rare nuclides from the isobaric and isotopic background.

Therefore, future developments of Accelerator Mass Spectrometry (AMS) are expected from new powerful machines like the 16 MV XTU of the Laboratori Nazionali di Legnaro, upgraded MP Tandems, DC accelerators coupled to superconducting cyclotrons, etc. An example of this "frontier" AMS is the recent use of the Unilac at GSI to accelerate ^{205}Pb ions to GeV energies for solar neutrino experiments.

TABLE I - LONG-LIVED COSMOGENIC ISOTOPES DETECTED WITH ACCELERATOR MASS SPECTROMETRY

ISOTOPE	HALF-LIFE (years)	INTERFERRING STABLE ISOTOPES	INTERFERRING STABLE ISOBARS	AMS DETECTION LIMIT a)	RANGE OF TERRESTRIAL CONCENTRATION a)
^{10}Be	1.6×10^{6}	^{9}Be	^{10}B	7×10^{-15}	10^{-8} - 10^{-14}
^{14}C	5.7×10^{3}	$^{12,13}C$	^{14}N b)	$.3\times10^{-15}$	10^{-12} - 10^{-16}
^{26}Al	7.2×10^{5}	^{27}Al	^{26}Mg b)	10×10^{-15}	$\sim10^{-14}$
^{36}Cl	3.1×10^{5}	$^{35,37}Cl$	^{36}S, ^{36}Ar b)	$.2\times10^{-15}$	10^{-12} - 10^{-17}
^{41}Ca	1.3×10^{5}	$^{40,42}Ca$	^{41}K	500×10^{-15}	10^{-15} - 10^{-16}
^{129}I	15.9×10^{6}	^{127}I	^{129}Xe b)	100×10^{-15}	$\sim10^{-16}$

a) Compared to the stable isotope of the same element.
b) These elements do not form stable negative ions.

ADVANTAGES OF TAMS OVER DECAY COUNTING

For long-lived radioisotopes, TAMS is much more efficient than the radiometric methods. For example, if we consider ^{10}Be with a half-life of 1.6×10^{6} years, only a fraction 10^{-9} of the atoms in the sample decay each day. Low-level counting techniques are necessary, with long counting times (days) and large samples (grams). Furthermore, a complicated radiochemistry is needed to eliminate other soft beta emitters from the sample.

The overall efficiency of TAMS, where the atoms present in the sample are directly detected, is at least five orders of magnitude higher: sub-milligram samples can be measured in an hour or less. The additional advantage is that TAMS works for both, radioactive and stable isotopes.

TABLE II - SELECTED EXAMPLES OF TAMS APPLICATIONS

ISOTOPE	APPLICATION
^{10}Be	- Subduction of tectonic plates from ^{10}Be in volcanic lavas. - Growth of manganese modules from ^{10}Be profiles. - Origin of tektites. - Record of geomagnetic reversals in lake sediments. - Ice core record of solar modulations and climatic variations. - Origin of meteorites. - Variability of galactic cosmic-ray flux from ^{10}Be profiles in ocean sediment cores.
^{14}C	- Antiquity of homo sapiens. - Origins of early agriculture.
^{26}Al	- Origin of tektites and deep-sea cosmic spherules.
^{36}Cl	- Dating of groundwater. - Terrestrial age of meteorites.
^{129}I	- Irradiation histories of meteorites and galactic cosmic-ray constancy in the 10 - 100 Myr range.

ADVANTAGES OF TAMS OVER LOW ENERGY MASS SPECTROMETRY

The abundance sensitivity of the best low energy mass spectrometers is about 10^{-9}. The limitations of these instruments, where keV beams produced by specialized ion sources are separated in mass by combinations of magnetic and electric fields, are caused by: a) Interfering isobars (for ex. ^{10}B-^{10}Be mass difference is only few parts in 10^{5}). b) Interfering molecules (for ex. $^{12}CH_2$-^{14}C mass difference is only one part in 10^{3}). c) Scattering of ions from the walls and by residual gas. d) Charge exchange processes.

Many of the above limitations are eliminated or reduced when a Tandem is used as an element of the mass spectrometry system.

Isobaric interference. No general technique for the discrimination of isobars exists. Conventional mass spectrometry can solve the problem only with high resolution (low efficiency) systems. TAMS separates the isobars with a variety of methods:

(i) Source discrimination (ex.: ^{14}C-^{14}N, ^{26}Al-^{26}Mg). Rejection factor of 10^{6}.

(ii) Range separation (ex.: ^{10}Be-^{10}B). Rejection factor of 10^{10}.

(iii) Chemistry (ex.: ^{36}Cl-^{36}S). Rejection factor of 10^{6}.

(iv) Complete stripping followed by magnetic analysis (ex.: ^{36}Cl-^{36}S, ^{41}Ca-^{41}K). Rejection factor of 10^{10}.

(v) Energy loss. Multiple specific energy (dE/dx) measurements in a gas ion chamber produce a rejection factor of 10^{6} for elements up to Z=17. The energy loss in an absorber before a magnetic spectrograph removes most of the isobaric interference reaching the detector (rejection factor of 10^{6}).

Molecular interferences. Rejection of molecules is obtained by the stripping of 3 or more electrons at the high voltage terminal. Without outer binding electrons, molecules become dynamically unstable and break-up in

less than 1 μs.

Scattering and charge-exchange. Gas or wall scattering and low probability charge-exchange sequences bring unwanted particles to the detection system. Low energy mass spectrometry solves this problem with multiple magnetic analyses. With TAMS, this problem is alleviated by the use of negative ions and energies of MeV/amu.

TABLE III - NEW CANDIDATES FOR AMS

ISOTOPE	HALF-LIFE (years)	ISOTOPE	HALF-LIFE (years)
^{53}Mn	3.7×10^6	^{60}Fe	0.3×10^6
^{59}Ni	0.08×10^6	^{98}Tc	4.2×10^6
^{205}Pb	14×10^6	^{244}Pu	8×10^8
^{187}Re	5×10^{10}		

EXAMPLE OF TAMS SYSTEM: THE RUTGERS-BELL FACILITY

The Rutgers-Bell FN Tandem and its beam transport system are shown in Figure 1. This accelerator-based mass spectrometer is used to analyze ^{10}Be for applications to geology and cosmochronology [8].

Negative ions (BeO^-) are produced from a solid sample in the Cs sputter ion source and injected after a magnetic deflection of 17°.

The accelerator is operated at 6.2 MV and regulated by a GVM control to ±2 kV.

The BeO^- beam is dissociated at the high-voltage terminal by O_2 gas before stripping by a carbon foil. Positive ions are accelerated further to ground potential. Both ^9Be and ^{10}Be are analyzed in the 3^+ charge state. As the beam intensities differ by a factor of 10^9, different methods are used to detect these two isotopes. The ^9Be beam is transmitted only as far as the image position of the 90° analyzing magnet and is measured by counting particles Rutherford-scattered from a removable gold foil. The inflection and analyzing magnets, high-energy quadrupole and Wien filter are then adjusted to select ^{10}Be and the gold scattering foil is retracted. After the 90° analysis, ^{10}Be is transported to an Enge split-pole magnetic spectrograph. Isotopic and isobaric background must be reduced before final detection of ^{10}Be.

^{10}B mimics ^{10}Be in all acceleration and magnetic analysis steps. A carbon post-stripper, mounted downstream the image slits, strips the 3^+ ^{10}Be to 4^+ state. In subsequent transport, two switching magnets deflect the beam through a total of 120°. ^{10}B is stripped to 5^+ and is not able to match the change in rigidity required for further transmission.

More reduction in isotopic and isobaric background is obtained by passing the beam through an absorber located at the object position of the spectrograph. ^{10}Be, ^9Be and ^{10}B emerge from this foil with different energies. The magnetic field of the spectrograph deflects ^{10}B and ^9Be to miss the detector, except for the tails of the energy loss distribution. A position sensitive telescope will reject remaining interfering particles.

^9Be beam, injected into the accelerator as $BeOH^-$ (mass 26), can match the magnetic rigidity of ^{10}Be by charge exchange in the accelerator tubes.

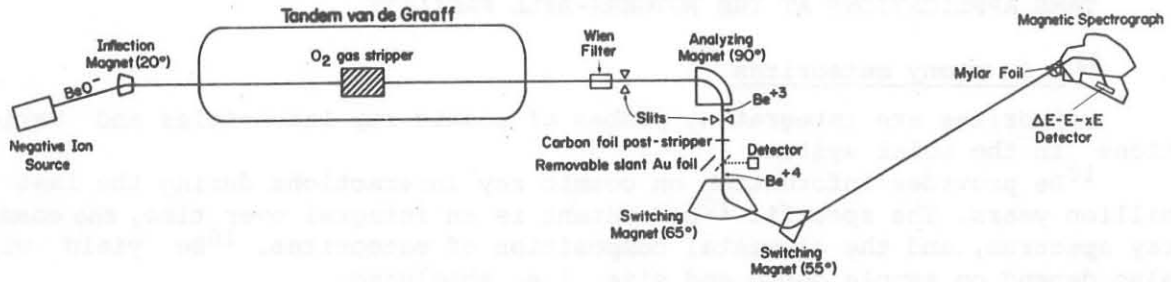

Figure 1 - The Rutgers accelerator mass spectrometry system.

A small part of this parasitic beam will reach the E-dE-X telescope in spite of the absorber-spectrograph analysis (Figure 2). A velocity selector, installed near the object position of the 90° analysing magnet, rejects this residual isotopic background (Figure 3).

A precise, absolute calibration of the relative detection efficiency of ^{9}Be and ^{10}Be is difficult. Therefore, the absolute number of ^{10}Be atoms per gram is obtained comparing the $^{10}Be/^{9}Be$ count-rate ratio of the sample with that of a standard of known isotopic ratio.

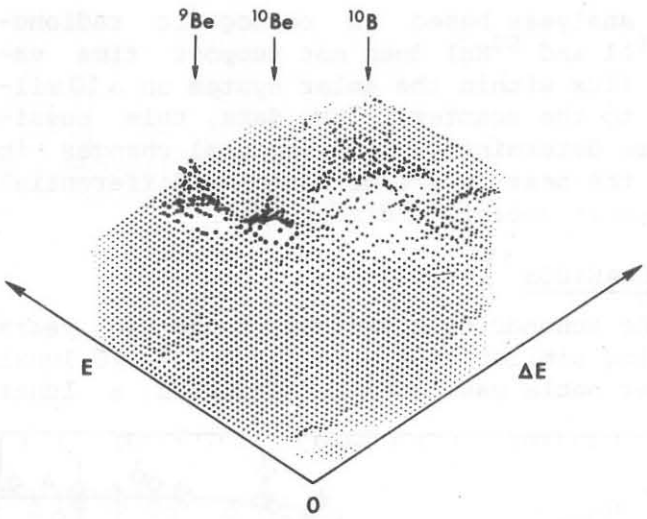

Figure 2 -

Particle spectrum obtained from BeO spiked with ^{10}Be; taken without Wien filter.

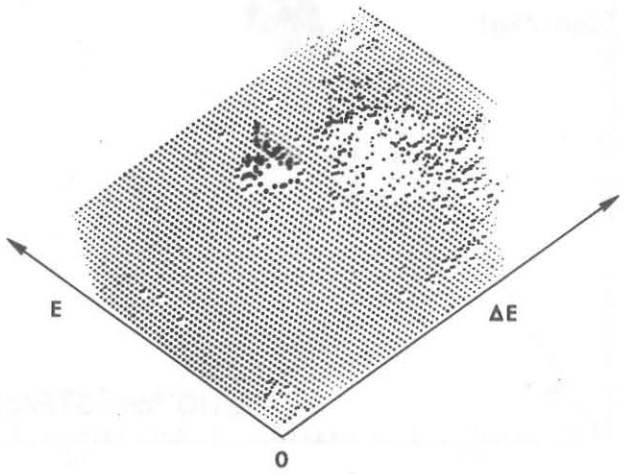

Figure 3 -

As above but with Wien filter.

TAMS APPLICATIONS AT THE RUTGERS-BELL FACILITY

^{10}Be in stony meteorites [9)]

Meteorites are integrating probes of cosmic ray intensities and variations in the solar system.

^{10}Be provides information on cosmic ray interactions during the last 10 million years. The specific ^{10}Be content is an integral over time, the cosmic ray spectrum, and the elemental composition of meteorites. ^{10}Be yield will also depend on sample depth and size, i.e. shielding.

On atmospheric passage, the surface of a meteorite is ablated, removing the effects of solar and other low-energy protons, and leaving the effects of high energy galactic protons and their secondaries. Most stony meteorites are recovered within a few hundred years of their fall, a time short compared to the ^{10}Be half-life, so that the ^{10}Be content measured reflects their cosmic ray exposure in space rather than terrestrial decay.

Stony meteorites begin to accumulate cosmogenic nuclides (e.g., unstable ^{10}Be and stable ^{21}Ne) when collisional breakup of a larger parent body exposes previously shielded material. For a constant cosmic ray flux, the plot of ^{10}Be versus ^{21}Ne for a suite of meteorites will fall on the growth curve $^{10}Be = {}^{10}Be_{sat}(1+\exp(-\lambda\ {}^{21}Ne/P_{21}))$ where λ is the decay constant of Beryllium-10 (Figure 4).

A least squares fit of this curve to a ^{10}Be-^{21}Ne data set yelds the cosmogenic ^{21}Ne production rate (P_{21}), a parameter used to calculate exposure ages of meteorites.

Comparison of our results with analyses based on cosmogenic radionuclides with different half-lives (^{26}Al and ^{53}Mn) does not support time variations in the galactic cosmic-ray flux within the solar system on a 10 million years time scale. However, due to the scatter in the data, this possibility is not ruled out. More precise determinations of temporal changes in the galactic cosmic ray flux may in the near future be based on differential measurements such as deposition rates in oceanic sediments[10)].

^{10}Be in the lunar meteorite ALHA81005 [11)]

The petrographic analysis of the achondrite ALHA81005, found two years ago in the Antarctica, showed striking similarities with the Apollo 16 lunar samples. The ratio MnO/FeO and higher noble gas content suggested a lunar origin for this meteorite.

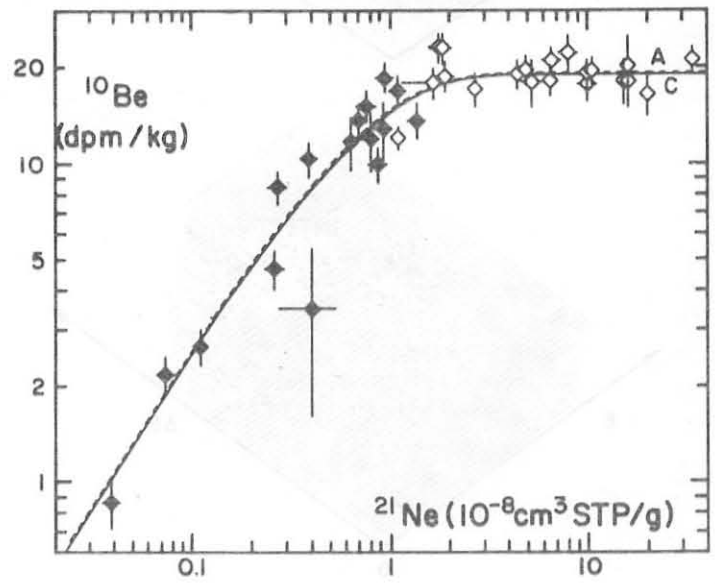

Figure 4 -

Abundances of ^{10}Be vs ^{21}Ne in stony meteorites.

The recent irradiation history of a meteorite can be reconstructed from an analysis of its cosmogenic radionuclide contents. An analysis of this kind for ALHA81005 was based on measurements of its ^{10}Be (measured at Rutgers) and ^{26}Al (measured at Battelle P.N.L.) contents. Calculations based on one-step irradiation models imply that the time spent by this object in space is shorter than that spent by most 'asteroidal' meteorites. On the other hand the results are readily consistent with a lunar origin.

Measurements of ^{53}Mn and ^{36}Cl may be hepful in defining more closely the irradiation and decay history of ALHA81005.

^{10}Be and the origin of tektites [12]

Two of the lasting mysteries of geophysics are where and how tektites formed. The field of possibilities has narrowed through time. No known meteorite group has the composition of tektites. Lunar surface samples have the wrong isotopic signatures. Most workers now endorse an origin involving the hypervelocity impact of a meteorite on terrestrial sedimentary material. Perhaps the most persuasive evidence for this conclusion consists of (1) the observation of certain high-temperature, high-pressure minerals in tektites, and (2) the presence in some samples of iron-nickel rich spherules widely believed to come from meteorites. Few groups support the hypothesis that a lunar volcano spewed the tektites to earth. Calculations show that material from any other planet would take millions of years to reach earth, during which time the tektites would accumulate certain products of cosmic ray interactions; these products are not observed. Terrestrial sediments, both marine and continental, typically contain appreciable amounts of ^{10}Be. The formation of tektites from such material would introduce ^{10}Be in a natural way.

We therefore began a series of ^{10}Be measurements in tektites with the aim of constraining more narrowly the hypotheses of tektite origin.

The youngest tektites, the 0.7 Myr-old australites, should have lost by decay the smallest fraction of any ^{10}Be present in their parent material at the time of formation. We found $0.8\text{-}1.4\times10^{8}$ atom/g of ^{10}Be. A content of 0.3×10^{8} atom ^{10}Be/g was measured in the older (1.5 Myr) tektites from the Ivory Coast.

Several possible sources were considered for ^{10}Be, including meteoritic contamination, adsorption from rainwater, and neutron-induced reactions at the earth surface. None of these seem adequate. We believe that the ^{10}Be measured was indigenous to the precursor material of the australites.

The $^{26}Al/^{10}Be$ ratios recently measured by Raisbeck, Middleton and co-workers in several australites is consistent with a terrestrial origin. Their result limits the fraction of lunar and chondritic material in Australasian tektites, but does not rule out an iron meteorite as the source of ^{10}Be [13].

Measurements of $^{53}Mn/^{10}Be$ in australites by the Rutgers-Koln collaboration show that the iron meteorites supplied less than 1% of the ^{10}Be found in the australasian samples studied [14].

TAMS WITH THE XTU ACCELERATOR OF THE LABORATORI NAZIONALI DI LEGNARO

The XTU Tandem Van de Graaff of the Laboratori Nazionali di Legnaro [15] is shown in Figure 5 with the -50^{o} beam line dedicated to ultrasensitive mass spectrometry.

The characteristics of the XTU which are relevant for TAMS are:

(i) Beam transport system with high magnetic rigidity ($B\rho$ = 3.3 T.m., corresponding to a mass-energy product of $\sim$500).

(ii) Double focussing 90^{o} inflection magnet with mass resolution 1:100 and mass-energy product 9.6.

(iii) High terminal voltage (16 MV).
(iv) High intensity ion source (GIC model 860 sputter ion source).

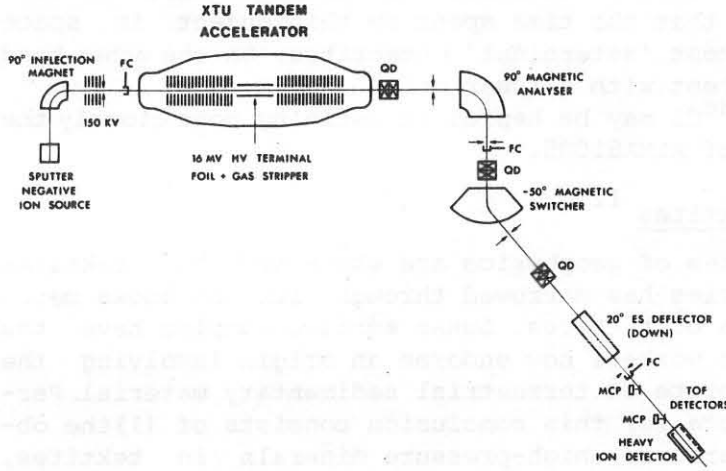

Figure 5 - The ion beam transport system of the XTU tandem used as an ultrasensitive mass spectrometer.

The XTU-based mass spectrometry system is being completed with the following mass filtering and detection elements:

a) A 20° high-resolution electrostatic analyzer (Figure 6).
b) A gas ionization chamber of the Rochester type (Figure 7).
c) A couple of TOF detectors for analysis of elements with A≥50. These detectors use michrochannel plates to measure electrons produced in carbon foils mounted across the ion beam.
d) A removable precision Faraday cup with electron suppression, mounted in front of the final detection system to measure the macroscopic beam.

Some potential TAMS applications with the XTU Tandem are discussed in the following sections.

Origin of ^{244}Pu in nature

The existence of ^{244}Pu ($T_{\frac{1}{2}} = 0.8 \times 10^8$ y) as an extinct radioactivity was postulated to explain the xenon isotope ratios observed in meteorites[16]. The presence of this isotope in nature was in fact observed directly in Precambrian minerals with conventional mass spectrometry [17].

A convincing explanation about the origin of ^{244}Pu has not yet been found. Hoffman and co-workers suggested that the detection of this isotope in younger minerals ($<<0.8 \times 10^8$ y) could be useful to discriminate between a primordial and cosmic-ray origin.

The features of the XTU tandem are suitable to attempt more ^{244}Pu measurements on samples of minerals of different ages.

^{187}Re - ^{187}Os dating of meteorites

^{187}Re decays to ^{187}Os with a half-life of 5×10^{10} years. The Re - Os system has been proposed as a cosmochronometer of the early hystory of the solar system.

Age T_o of meteorites is obtained from the chronometric equation for a closed system:

$$(^{187}Os/^{186}Os)_{today} = (^{187}Os/^{186}Os)_{T_o} + (^{187}Re/^{186}Os)_{today} \ (e^{\lambda T_o} - 1),$$

where λ is the decay constant of ^{187}Re.

The results obtained with low energy mass spectrometry on some iron and stony meteorites [18] are shown in Figure 8.

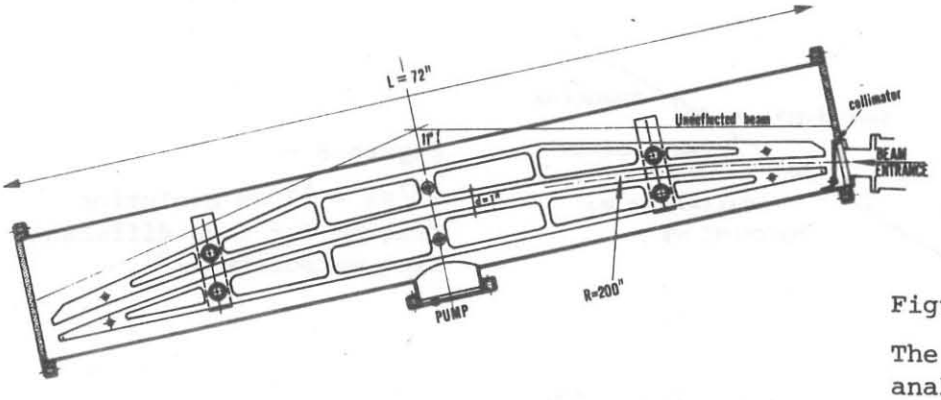

Figure 6 -

The XTU 20° ES analyzer.

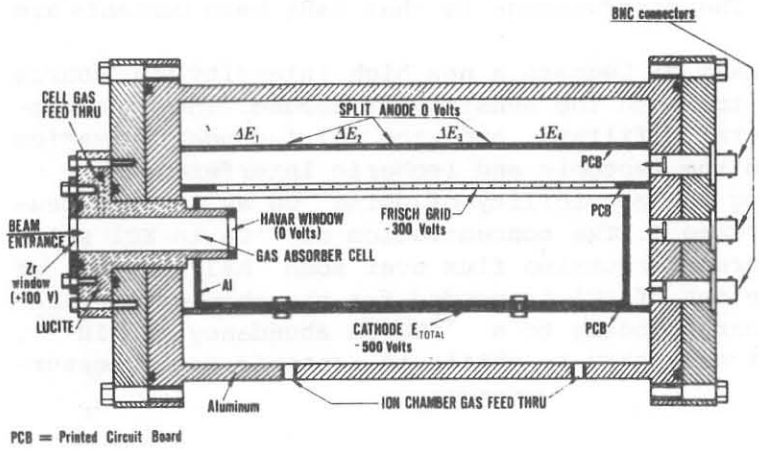

Figure 7 -

The XTU heavy ion detector with gas absorber cell.

It has been suggested that accelerator mass spectrometry is a suitable technique to measure the isotopic ratios appearing in the chronometric equation.

TAMS will improve the precision and sensitivity of Re-Os measurements in the following way: 1) Elimination of molecular interference at the high voltage stripper, 2) Elimination of isobaric interference at the source, where Os/Re negative ions are discriminated.

Detection of ^{41}Ca

^{41}Ca ($T_{\frac{1}{2}}$ = 130,000 y) is produced at the surface of the earth by capture of secondary cosmic ray neutrons in ^{40}Ca. Raisbeck suggested the use of this isotope to extend dating of paleontological interest to the million year time scale [19]. An interesting application could be the study of Plio-Pleistocene hominid fossils found in Hadar (Etiopia) [20]. That collection of skeletons suggests that Homo and Australopithecus coexisted as early as 3 Myr ago. The dates inferred by radiometric K-Ar measurements of the Basalts are not very precise. An alternative direct dating of the bones would be of fundamental importance.

An equilibrium concentration $^{41}Ca/Ca = 10^{-14}-10^{-15}$ is expected in natural samples [19].

The best detection limits obtained with TAMS are $10^{-12}-10^{-13}$ [21,22,23]. The main obstacles to the measurement of natural concentrations of ^{41}Ca derive

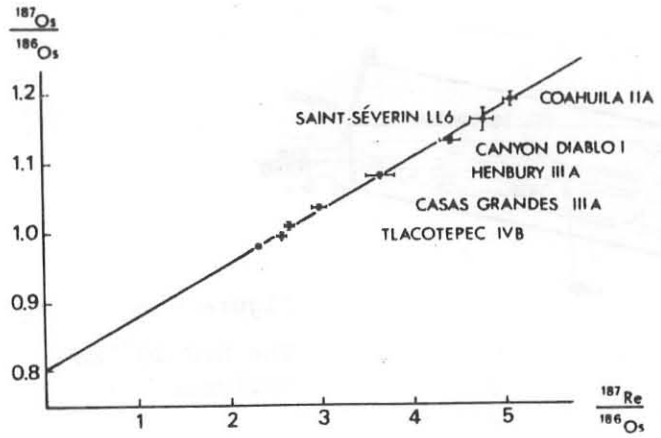

Figure 8 - ^{187}Re - ^{187}Os evolution diagram for five different iron meteorites [18].

from the ^{41}K background and the low calcium output from the sputter source. The acceleration of CaH_3^- has been suggested [24] to eliminate ^{41}K, since KH_3 does not from negative ions. The disadvantage is that CaH_3^- beam currents are very low.

At the Laboratori Nazionali di Legnaro a new high intensity ion source is available and we can hope to reach the sensitivity needed. The high resolution magnetic and electrostatic filters and the multi-anode ionization chamber can resolve ^{41}Ca from the isotopic and isobaric interferences.

We are also investigating the possibility of using ^{41}Ca as a solar neutrino detector ($^{41}K+\nu \longrightarrow {}^{41}Ca+e^-$). The concentration of ^{41}Ca in KCl salts has been suggested as a measure of neutrino flux over some half-lives of ^{41}Ca (few million years). One ton of KCl is needed for the chemical separation of 10^4 atoms of ^{41}Ca, corresponding to a $^{41}Ca/Ca$ abundancy of 10^{-21}. An isotopic pre-enrichment is necessary to obtain an isotopic ratio measurable with TAMS.

HIGH ENERGY AMS SYSTEMS

The main problem in Accelerator Mass Spectrometry of rare heavy radioisotopes is the reduction of the interfering stable isobar with lower atomic number. The separation of the isobaric couple is based on the energy loss of ions in matter and is more effective for ion velocities above the maximum in the energy loss curve. Furthermore, if ions have velocities above the 'Bohr energy', they can be fully stripped in their passage through matter. A Magnetic element will then deflect the abundant isobar to miss the detector. Raisbeck demostrated the validity of the complete electron stripping method for ^{26}Al-^{26}Mg and ^{41}Ca-^{41}K, at the heavy-ion facility of Orsay [25,26]. High energies to reduce the isobaric background were later applied at Argonne [27], Munich [28] and recently at the GSI of Darmstadt [29] (Table IV).

The high energy necessary to apply the above-mentioned techniques is available only at the new-generation heavy-ion facilities. A complete review about status and prospects of these machines is given in Reference 30. A combination of Tandem accelerator followed by superconducting cyclotron will be available in few years at Catania.

The main disadvantage of these AMS systems is the instability with the 'ghost' beam corresponding to the rare atoms. Precise measurements of isotopic ratios for interdiscipinary applications are very difficult. Nevertheless, important results have been already obtained.

It's worth mentioning the recent measurements on ^{60}Fe at Argonne. The improvement in the half-life determination of this isotope with accelerator

TABLE IV - HIGH-ENERGY AMS SYSTEMS

LABORATORY	ACCELERATOR	ISOTOPE	INTERF. ISOBAR	ENERGY (MeV)
Orsay	Linac+Cyclotron	^{26}Al	^{26}Mg	200
		^{41}Ca	^{41}K	310
Munich	Tandem+Linac	^{36}Cl	^{36}S	155
Argonne	Tandem+Linac	^{59}Ni	^{59}Co	328
		^{60}Fe	^{60}Ni	360
GSI-Darmstadt	Unilac	^{205}Pb	^{205}Tl	2300

mass spectrometry is the first step for future applications in cosmochronology. In fact, cosmogenic ^{60}Fe in meteorites will reveal their exposure histories in a time scale of a few million years.

The largest AMS system is the Unilac of Darmstadt. Work at GSI is aiming to detect ^{205}Pb at concentrations $^{205}Pb/Pb = 10^{-14}$. The motivation is the use of ^{205}Pb as a solar neutrino detector ($^{205}Tl + \nu \longrightarrow {}^{205}Pb + e^-$). First measurements at 2.3 GeV show that rejection of isotopic and isobaric background is adequate. The major problem comes from the low efficiency of the source.

CONCLUSIONS

A variety of accelerators of all sizes are being employed for ultrasensitive analyses that are useful in different disciplines like geology, archeology, hydrology, cosmochronology.

The main effort of small dedicated and semi-dedicated Tandems is presently devoted to improving sensitivity and accuracy in the measurement of light cosmogenic isotopes (^{10}Be, ^{14}C, ^{36}Cl). For example, a precision of 0.1% in ^{14}C measurements was recently obtained at the ETH dating facility of Zurich.

The last generation of Tandem accelerators (XTU, upgraded MP, etc.) and more complex systems (Tandems followed by linacs and superconducting cyclotrons), intensitively used for fundamental nuclear physics research, are involved part-time in 'frontier' AMS projects. They are mainly used in the detection of heavier long-lived radioisotopes not measurable with smaller facilities.

The high sensitivity of AMS to detect radioactive and stable isotopes is going to be exploited in material sciences, medicine and biology to complement and extend other techniques like Neutron Activation Analysis, Proton Induced X-Ray Emission and Rutherford Back-scattering Spectrometry.

AMS could have an important impact on basic nuclear and particle physics. For example, an all-electrostatic AMS system is being used at Rochester for a quark search in nature. The Argonne AMS system is used to measure small cross sections and nuclear half-lives. There are already programs where AMS is employed for the study of rare fundamental processes (duble beta decay, proton decay and solar neutrino interactions) with the geochemical method.

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