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**PRESENT AND FUTURE PROSPECTS OF ACCELERATOR MASS SPECTROMETRY**

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# PRESENT AND FUTURE PROSPECTS OF ACCELERATOR MASS SPECTROMETRY\*

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## Abstract

Accelerator Mass Spectrometry (AMS) has become a powerful technique for measuring extremely low abundances ( $10^{-10}$  to  $10^{-15}$  relative to stable isotopes) of long-lived radioisotopes with half-lives in the range from  $10^2$  to  $10^8$  years. With a few exceptions, tandem accelerators turned out to be the most useful instruments for AMS measurements. Both natural (mostly cosmogenic) and man-made (anthropogenic) radioisotopes are studied with this technique. In some cases very low concentrations of stable isotopes are also measured. Applications of AMS cover a large variety of fields including anthropology, archaeology, oceanography, hydrology, climatology, volcanology, minerals exploration, cosmochemistry, meteoritics, glaciology, sedimentary processes, geochronology, environmental physics, astrophysics, nuclear and particle physics. Present and future prospects of AMS will be discussed as an interplay between the continuous development of new techniques and the investigation of problems in the above mentioned fields. Depending on the specific problem to be investigated, different aspects of an AMS system are of importance. Typical factors to be considered are energy range and type of accelerator, and the possibilities of dedicated versus partial use of new or existing accelerators.

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## 1. Introduction

In a way, accelerator mass spectrometry (AMS) is just one of several different methods which make it possible to find a needle in a hay stack. Others are radioactive decay counting and laser resonance ionization spectroscopy (RIS). Although it has been demonstrated that RIS is capable of detecting a single atom under favorable conditions [1], counting atoms through their decay is to date the most sensitive method to measure a small number of atoms in a real experiment. The most famous example of this technique is the radiochemical detector of Ray Davis et al. [2], who for more than two decades measured the flux of solar neutrinos by detecting a few atoms of  $^{37}\text{Ar}$  ( $t_{1/2} = 35$  d), supposedly produced through the reaction  $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$  in 615 tons of  $\text{C}_2\text{Cl}_4$ . On the average, about 20 atoms of  $^{37}\text{Ar}$  are accumulated in this way in three months, which corresponds to a  $^{37}\text{Ar}$  atom concentration of about  $1 \times 10^{-30}$ . The combination of favorable chemistry and miniaturized low-level counting allows one to extract and count about 40% of these atoms [3]. This is an unparalleled sensitivity in detecting such a small number of atoms. However, decay counting is only efficient if the atoms decay in a reasonable time. For radioisotopes with much longer half-lives, it becomes more favorable to count the atoms directly rather than waiting for their decay. At present, AMS and RIS are the two most sensitive techniques of atom counting.

The main problem one has to solve in counting radioisotopes at extremely low concentrations is the background from stable nuclides. The advantage of AMS lies in its ability to eliminate molecular interferences by electron stripping and to separate a radioisotope from the stable isotopes of the same element with great discriminatory power. AMS can also reduce interferences from stable isobars. If one uses negative ions, as required for injection into

tandem accelerators, the interference of some stable isobars ( $^{14}\text{N}$ ,  $^{26}\text{Mg}$ ,  $^{36}\text{Ar}$ ,  $^{129}\text{Xe}$ ) is eliminated in measurements of the important cosmogenic radioisotopes ( $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{129}\text{I}$ ), since the former group does not form negative ions. (For  $^{36}\text{Cl}$  detection, however, one has to fight the remaining interference of  $^{36}\text{S}$ ). Also, one can sometimes use negative molecules, for which the formation probability of negative ions with the stable isobar is orders of magnitude suppressed as compared to those with the radioisotopes. The best example is the elimination of the  $^{41}\text{K}$  interference in  $^{41}\text{Ca}$  measurements by starting with  $^{41}\text{CaH}_3^-$  ions [4]. This feature made tandem accelerators by far the most powerful instruments for AMS measurements. In general, the problem with isobars is that the masses are so close to each other that for all practical purposes they are ion-optically identical. This makes them indistinguishable in the acceleration process and in magnetic and electric analysis. The property which allows one to separate isobars is the difference in nuclear charge. This can be utilized at ion energies in the multi-MeV range in three ways: (i) the rate of energy loss in matter is different; (ii) the mean charge state in matter is different; (iii) at sufficiently high energies the ions can be fully stripped, allowing in special cases ( $Z_{\text{radioisotope}} > Z_{\text{stable isotope}}$ ) a particularly efficient elimination of the stable isobar background. RIS, on the other hand, has a very high elemental selectivity, but a much lower power for isotopic discrimination. It seems obvious that the combination of AMS and RIS would lead to the ultimate in discriminatory power for atom counting and a realization of this dream may not be too far down the road.

Since its appearance in 1977 [5-7], AMS has developed into a field of large interdisciplinary scope. A recent review by Elmore and Phillips [8] gives an excellent status report of AMS in both technical achievements and areas of applications. Symposia on AMS have been organized every three years since

1978. Proceedings of these meetings [9-11] provide the best reference for the chronological development of the field. The most updated information on AMS will be available in the forthcoming proceedings of the 1987 AMS symposium [12].

In the present paper no attempt will be made to cover the large field of AMS in any detail. Rather, some general trends that developed in the past and present will be followed, with the goal to get some feeling of what may evolve in this field in the time to come.

## 2. Radiocarbon

There is little doubt that dating with  $^{14}\text{C}$  ( $t_{1/2} = 5730$  yr) is the best known application of AMS. Natural radiocarbon was detected [13] for the first time in 1947 and for 30 years thereafter has been used for numerous dating and tracing applications using beta-ray counting techniques. When AMS appeared in the field in 1977 one expected several important improvements: (i) smaller sample sizes; (ii) faster measurements; (iii) older ages. The first two have been fully met, whereas the last one turned out to be a much harder limit to push, partly for reasons not connected to AMS.

An early spectrum of  $^{14}\text{C}$  from a charcoal sample measured [14] with the Argonne FN tandem is shown in figure 1. Sample sizes are now down to 1 mg, with an overall efficiency of 1.5% for counting  $^{14}\text{C}$  atoms from the sample [8]. With a modern (pre-bomb) radiocarbon content of  $^{14}\text{C}/^{12}\text{C} = 1.2 \times 10^{-12}$  a sample of 1 mg carbon contains  $6 \times 10^7$  atoms of  $^{14}\text{C}$ . These are counted at a rate of approximately 50 per second. This means that for a one percent statistical accuracy a running time of only a few minutes is required. The fact that one has to wait 1.4 years to observe the same number of beta-decays (assuming 100%

detection efficiency) shows how far one has come with AMS. A critical point much debated since the early days of AMS is the precision of  $^{14}\text{C}/^{12}\text{C}$  ratio measurements. Assuming no other uncertainties, 1% precision of the ratio measurement translates into 83 years uncertainty in the age (1% of the mean life of  $^{14}\text{C}$ ). This status has now been reached at several dedicated AMS facilities, pioneered by the work of the Zurich group [15]. It is by no means trivial to perform AMS measurements with this precision, but fortunately this precision is not always needed. In particular, for old samples a precision of 10% (830 yr in the age) can be quite satisfactory. The problem of dating very old samples is complex and has little to do with the lack of precision in the  $^{14}\text{C}/^{12}\text{C}$  ratio measurement. The main problem is to avoid contamination with modern carbon in any of the steps leading from collection of the sample in the field to the final AMS analysis. In addition, the environment of an ion source seems to set dating limits at around 50,000 years, meaning that carbon samples which should contain no trace of  $^{14}\text{C}$  show  $^{14}\text{C}/^{12}\text{C}$  ratio in the  $10^{-15}$  range. The origin of the finite  $^{14}\text{C}$  content is not well understood, since it is difficult to separate a possible contamination prior to the AMS measurement from AMS-related background. Perhaps an extension to substantially older ages can only be achieved with isotopic pre-enrichment in a well controlled environment. Most promising in this respect seems to be Laser enrichment [16].

### 3. Other Radioisotopes

AMS opened the possibility to utilize radioisotopes produced by cosmic-ray interaction in the atmosphere whose half-lives are longer and/or concentrations are lower by several orders of magnitude as compared to radiocarbon. These include  $^{10}\text{Be}$  ( $t_{1/2} = 1.6 \times 10^6$  yr),  $^{26}\text{Al}$  ( $7.2 \times 10^5$  yr),  $^{36}\text{Cl}$  ( $3.0 \times 10^5$  yr) and  $^{129}\text{I}$  ( $1.6 \times 10^7$  yr). Limits for ratio measurements

are in the lower  $10^{-15}$  range, except for  $^{129}\text{I}$  where it is in the  $10^{-14}$  range. A vast range of applications has been implemented for these isotopes [8]. Only a few selected ones will be discussed here.

### 3.1 Icecores:

One of the most direct record of past atmospheric and climatic conditions on earth is preserved in ice from Greenland and Antarctica, where the deepest layers go back in time approximately 100,000 years and possibly more. Since annual layers can be counted (almost like tree rings) by following the seasonal variation of the  $^{18}\text{O}/^{16}\text{O}$  ratio [17], the measurement of cosmogenic radioisotopes gives a wealth of chronological information on their production and global distribution in the past. One of the most fascinating aspects is to find fingerprints of cosmic-ray variations through changes in the production rate of radioisotopes. However, before any such claim can be made with certainty, all the different processes influencing the atmospheric radioisotope concentrations must be disentangled. This can probably best be accomplished if all radioisotopes produced by cosmic-ray interaction in the atmosphere are measured. Some of them such as  $^{10}\text{Be}$  [18],  $^{14}\text{C}$  [19] and  $^{36}\text{Cl}$  [20] have already been measured to some extent, others, such as  $^{26}\text{Al}$ ,  $^{32}\text{Si}$ ,  $^{39}\text{Ar}$ ,  $^{81}\text{Kr}$  and  $^{129}\text{I}$  have not yet been measured in ice. For dating of ice it would be desirable to find two or more radioisotopes which behave identically after production, so as to use their ratio as a reliable signature for the time elapsed. Unfortunately, first measurements of  $^{10}\text{Be}/^{36}\text{Cl}$  ratios in ice from Antarctica show large variations [21]. Perhaps, better candidates would be ratios of noble gases such as  $^{39}\text{Ar}/^{81}\text{Kr}$  because of their inert chemical behavior. Noble gases, however, cannot be measured at tandem accelerators since they do not form negative ions (except for a metastable  $\text{He}^-$  ion). The

measurement of  $^{81}\text{Kr}$  in groundwater has been recently demonstrated with RIS [22] at a level of  $1200 \pm 300$  atoms of  $^{81}\text{Kr}$ , although with some difficulty because of the lack of discrimination against the stable isotope  $^{82}\text{Kr}$ . Current development of powerful positive-ion sources (see sect. 5) may well allow AMS to enter this field in the future.

An impressive example of anthropogenic activity measured in Greenland ice [23,24] is shown in figure 2, where the strong input of  $^{36}\text{Cl}$  from marine nuclear weapons testing during the fifties and sixties increased the natural  $^{36}\text{Cl}$  in the atmosphere by almost a factor of 1000. The effect of the nuclear test ban treaty in 1963 can clearly be seen by the removal of  $^{36}\text{Cl}$  from the atmosphere with an effective half-life of about 3 years. Similar results have been obtained in ice cores from a glacier in the Austrian Alps by the AMS group at the Munich tandem accelerator facility [25].

### 3.2 The Age of the Dead Sea through Accumulation of $^{36}\text{Cl}$

Since ancient times the Dead Sea has aroused the curiosity of man. Located at the lowest point on earth with the highest salinity of any sea water, one of the most natural questions was how the salt originated. Since the Dead Sea is a terminal lake in a highly arid region, it was conjectured that the influx of salt with fresh water and the subsequent evaporation resulted in the high salt content. Therefore a detailed budget of the salt in the water system of the Dead Sea should lead to an estimate of an 'accumulation' age. Such an estimate was performed in 1961 [26] with a resulting age range of 12,000 to 70,000 years, with the lower end being more probable. Since the sources of salt input are highly complex, stable salt is difficult to trace in the accumulation process.



In an AMS program at the Rehovot tandem accelerator,  $^{36}\text{Cl}$  was measured in the Jordan River-Dead Sea water system in an attempt to use it as a new hydrological tool [27]. Figure 3 demonstrates what can be learned from such measurements. In essence,  $^{36}\text{Cl}$  traces salt that originates from precipitation, because it contains the cosmogenic radiochlorine. Salt leached from rocks, which contains negligible amounts of  $^{36}\text{Cl}$  can thus be distinguished from the former as one follows the water system from the sources to the Dead Sea. In this way, evaporation rates along the water system can be better understood, which is of paramount importance in a country where water is one of the most precious natural resources. An accumulation age of the Dead Sea can now be calculated from a  $^{36}\text{Cl}$  budget alone. The result is an age range of 19,000 to 25,000 years, which narrows down the previous estimate based on the stable salt budget.

### 3.3 Radiocalcium Dating

One of the most difficult objects to date with  $^{14}\text{C}$  are bones. On the other hand, they are the only direct remains from our early ancestors and a reliable date is of great interest. Great progress has been made with AMS because little carbon is needed for a measurement and bone-specific carbon fractions can be used (e.g., amino acids specific to collagen, the main organic constituent). As a result, some of the dates obtained with more indirect methods and more global carbon fractions had to be revised substantially [28]. Notwithstanding this important improvement, the practical age limit for radiocarbon dating lies at about 50,000 years (10 half-lives) for reasons described in sect. 2. It is well known that the earliest appearance of man goes back much further in time, which asks for a radioisotope with a correspondingly longer half-life. To be useful for dating it must be specific

to bone and must exist in a measureable abundance. In addition, a known equilibrium concentration in living bone must exist, which after death changes only due to radioactive decay. The only viable candidate seems to be  $^{41}\text{Ca}$ , which has a half-life of 100,000 years. Radiocalcium dating with  $^{41}\text{Ca}$  has been proposed some time ago by Yamaguchi [29] and more recently by Raisbeck and Yiou [30]. The big questionmark was the very low  $^{41}\text{Ca}/\text{Ca}$  ratio estimated [28] to lie between  $10^{-14}$  and  $10^{-15}$ . Figure 4 illustrates that the main process of production is thought to happen through neutron capture in  $^{40}\text{Ca}$ , induced by cosmic-ray secondaries. Decay counting at the expected concentration of  $^{41}\text{Ca}$  is virtually impossible, since  $^{41}\text{Ca}$  decays by electron capture to the ground state of  $^{41}\text{K}$  leaving only soft X-rays and Auger electrons around 3 keV as detectable radiations. However, AMS was also considered marginal, mainly because of the great difficulty to produce a good Ca beam at tandem accelerators. Therefore, in a recent experiment at Argonne [31], we decided to utilize a  $^{41}\text{Ca}$  enrichment procedure prior to the AMS measurement. Calcium extracted from a cow bone was enriched in a Calutron isotope separator at Oak Ridge by approximately a factor of 150. The  $^{41}\text{Ca}/\text{Ca}$  ratio was then measured with AMS at ATLAS, the Argonne Tandem Linac Accelerator System. The value found was  $^{41}\text{Ca}/\text{Ca} = (3.0 \pm 0.6) \times 10^{-12}$ , which corresponds to an original ratio of  $(2.0 \pm 0.5) \times 10^{-14}$ . This value established the first measured information on the natural  $^{41}\text{Ca}$  concentration in a contemporary bone material.

Despite this very encouraging result, it is quite clear that there is a long way to go before a radiocalcium dating method is established. The distribution of  $^{41}\text{Ca}$  must be studied in quite some detail to find out whether the above mentioned conditions for dating can be met. What is needed most is an AMS system which allows one to perform  $^{41}\text{Ca}$  measurements without prior

enrichment. This most likely leads to AMS with positive ions, since those can be produced in sufficient intensity to make a direct  $^{41}\text{Ca}$  measurement at natural concentration feasible. Prospects for this possibility will be discussed in sect. 5.

#### 4. Fundamental Physics Application

AMS has the potential to be used for a number of fundamental physics applications including searches for free quarks, anomalously heavy isotopes and superheavy elements, nuclear cross section and half-life measurements, and solar neutrino detection experiments. A summary of this more nuclear-physics oriented use of AMS can be found in ref. 32.

Perhaps one of the most significant outcomes from this type of application are the persistent negative results of searches for fractionally charged particles using a variety of different experimental approaches [33-35]. No effect has been seen down to concentrations of  $10^{-19}$  fractional charged particles per normal atom [34]. Since this is at present the limit of sensitivity one can reach with AMS for this type of measurements, the famous fractional charges observed on superconducting niobium spheres [36] (which implied a possible free-quark concentration of  $2 \times 10^{-18}$ ) will remain a mystery and unchallenged until a better technique is developed.

However, the dream goes on to use AMS for detection of solar neutrinos. Although it is at present not possible to detect 20 atoms as required in the  $^{37}\text{Cl}$  experiment described in sect. 1, feasibility studies to detect the very heavy radioisotope  $^{205}\text{Pb}$  ( $t_{1/2} = 1.5 \times 10^7$  yr) have been performed at the UNILAC accelerator of the GSI Darmstadt [37]. This radioisotope has been proposed some time ago [38] as a possible candidate to measure the essentially

model-independent flux of low-energy neutrinos from the pp reaction, integrated over millions of years in a suitable thallium mineral. Estimates of the  $^{205}\text{Tl}(\nu, e^-)^{205}\text{Pb}$  reaction rate lead to an accumulation of approximately  $10^5$  atoms of  $^{205}\text{Pb}$  in 1 kg of lorandite ( $\text{TlAsS}_2$ ). Although a "mountain" of difficulties must be overcome before an actual experiment can be started, the AMS part looks promising, assuming that a very efficient way of ion-beam production and acceleration can be found.

## 5. New Developments

Progress in science is often advanced by merely improving on technical methods. AMS is no exception. As AMS turned into a truly applied field, the technical advances were driven to a large extent by the needs of the fields it was applied to. This is, of course, desirable and good examples are the improvements in sensitivity, precision, sample sizes and through-put. There is no question that such demands can best be met by dedicated AMS facilities. One of the standard instruments for this purpose is the tandemron accelerator [39] operated at a terminal voltage between 2 and 3 MV. An interesting trend in recent years goes towards smaller and smaller facilities, circumventing the increasing difficulties with background rejection by a number of technical improvements in ion source and particle detection, and to a large extent simply by very thorough chemistry of sample preparation. The most extreme of this miniaturization trend is a 'pocket-size' cyclotron developed at Berkeley [40], which aims at  $^{14}\text{C}$  dating with 35-keV ions. The driving force in these developments is the possibility of constructing an inexpensive table-top instrument which one could even consider for AMS measurements in the field. While this is certainly a very desirable goal, the required sensitivity has not yet been reached due to the low output of the

internal negative ion source. However, there is hope [40] that this problem will be solved in the future with an external ion source.

The world-wide capacity of AMS measurements is substantial and is probably close to about 10,000 samples per year (A more precise estimate will be available shortly [12]). The bulk of these measurements are done at dedicated facilities and include only five isotopes:  $^{14}\text{C}$ ,  $^{10}\text{Be}$ ,  $^{36}\text{Cl}$ ,  $^{26}\text{Al}$  and  $^{129}\text{I}$ , in rapidly decreasing order of use. Although these radioisotopes are the most important ones for a large number of fields, they only constitute a small fraction of what nature is offering us for a potential use with AMS (see figure 5). It seems evident that the large untouched area of radioisotopes offers an exciting challenge to AMS for developments in both technological and applied fields.

Embarking into new areas might be one of the prime purposes of AMS at accelerators mainly used for other fields such as heavy-ion nuclear physics, because of the availability of higher energy and of expensive and potentially useful equipment such as magnetic spectrographs. The price one generally has to pay is the complexity of AMS measurements on a non-dedicated system and the lack of time on the machine, which makes the measurement of a large number of samples, usually required for truly applied fields, quite impossible. An example of such a new development is the use of a gas-filled spectrograph for isobar separation [41], first applied to eliminate a very strong isobaric  $^{60}\text{Ni}$  background in the search for  $^{60}\text{Fe}$  ( $t_{1/2} = 1.5 \times 10^6$  yr) in meteorites [32], and later in the detection of  $^{41}\text{Ca}$  in bone [31] to discriminate against  $^{41}\text{K}$  background. A good example of the power of this technique is shown in figure 6, where in a recent experiment the isobars  $^{124}\text{Te}$  and  $^{124}\text{Sn}$  were separated after acceleration to 508 MeV in the ATLAS accelerator at Argonne. The goal

of this experiment is to measure a more accurate value of the half-life of  $^{126}\text{Sn}$ , presently estimated [42] to be about 100,000 years. Eventually, measurements in the environment of this poorly studied long-lived fission product will be of interest for nuclear waste storage problems.

The ultimate goal in AMS is to count an ever smaller number of atoms, such as required for measuring the present-day solar neutrino flux (sect. 1). The biggest obstacle to reach this condition is the poor efficiency of ion sources used for AMS. Even in the currently best case of the detection of  $^{14}\text{C}$ , the number of carbon atoms from the sample converted into negative ions are only a few percent [8]. On the contrary, it is well known that some elements like alkaline metals can be ionized to singly charged positive ions with 100% efficiency (by surface ionization). Most other elements can also be ionized with high efficiency using a number of different techniques. Unfortunately, acceleration to high energies is difficult with singly charged positive ions. There are developments under way at GSI to accelerate singly charged heavy ions of medium mass and doubly charged ions of all masses in an RFQ (Radio Frequency Quadrupole) injector suitable for further acceleration in the UNILAC linear accelerator. However, this involves stripping to higher charge states after the RFQ with some loss in detection efficiency. At Argonne, there is a project under way to replace the tandem as injector for ATLAS by a positive-ion injector [43] consisting of an ECR (Electron Cyclotron Resonance) ion source and a superconducting low-beta rf structure, similar in concept to the existing linac. The ECR source produces highly charged positive ions in a magnetically confined plasma through the impact of rf powered electrons. The conversion of sample atoms into usable ions should be very high, around 10% or better, depending on the mass and charge state of the ion. Further stripping is not required, which means that it is not unreasonable to expect that in

favorable cases overall efficiencies of more than 10% can be achieved. This might allow one to study such interesting candidates for solar neutrino detection as

$^{81}\text{Kr}$  ( $t_{1/2} = 210,000$  yr), currently proposed to be detected by RIS [44].

One possibility of avoiding the necessity of high energy for isobar separation might be a suitable combination of RIS and AMS. For example, one could consider an ion source based on laser resonance ionization [45] coupled to a low energy linac working with singly charged positive ions, such as commercially available for ion implantation [46]. With such a facility a very effective isobar separation could be accomplished in the ion source and an equally effective isotope separation in the velocity focussing linac combined with some magnetic analysis system after acceleration. Thus, a relatively small machine with unprecedented discriminatory power might be in the cards.

## 6. Summary

AMS has become a very powerful technique to probe the composition of matter at a level of sensitivity never achieved before. More than twenty AMS facilities are in operation world-wide, with roughly half of them fully dedicated to AMS and turning out thousands of sample measurements per year. Applications seem to be touching almost every field of science, although some interesting ones such as biology and medicine have yet to get involved. Despite this impressive range of applications, a large body of long-lived radioisotope has not yet been utilized by AMS at all. Therefore, the field seems to be open to many new developments, some of them being indicated in the present paper. As a truly interdisciplinary field AMS might eventually combine its forces with other powerful techniques such as RIS to deliver an analytical tool of utmost

versatility.

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### Figure Caption

- Fig. 1 Three-dimensional display of the first  $^{14}\text{C}$  spectrum from a natural carbon sample, measured in the focal plane detector of the split-pole magnetic spectrograph after acceleration in the Argonne FN tandem accelerator [24]. The background from  $^{12}\text{C}$  and  $^{13}\text{C}$  stems from  $^{12}\text{CH}_2^-$  and  $^{13}\text{CH}^-$ , respectively, injected into the tandem as mass-14 ions together with  $^{14}\text{C}^-$ . The intensity of these background ions is reduced by about eight orders of magnitude due to the break-up of the molecules in the terminal stripper. In modern  $^{14}\text{C}$  facilities the background is further reduced by an electrostatic deflector which disperses the isotopes due to their different energy.
- Fig. 2 Profile of the  $^{36}\text{Cl}$  concentration in an ice core from Greenland [23,24], showing the time period when a substantial increase in atmospheric  $^{36}\text{Cl}$  occurred due to the marine nuclear weapons testing program. The production mechanism are thought to be the  $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$  and  $^{37}\text{Cl}(n,2n)^{36}\text{Cl}$  reactions in the salt of the sea water. The arrow indicates the Nuclear Test Ban Treaty (NTBT) of August 1963.
- Fig. 3 Systematic variation of  $^{36}\text{Cl}$  levels in waters from the Jordan River/Dead Sea system, arranged in downstream order [27]. The distances along the horizontal axis are arbitrary. The vertical extension of the data boxes reflect the uncertainty of the measurements. Also shown are a rock salt sample from a 2,000-m-deep core in the Mount Sedom area and a brine sample from the hypersaline Ashlag spring which is believed to be representative of the sub-

lacustrine saline springs: (a)  $^{36}\text{Cl}/\text{Cl}$  isotopic ratios measured by accelerator mass spectrometry; (b)  $^{36}\text{Cl}$  concentrations in waters obtained from the  $^{36}\text{Cl}/\text{Cl}$  ratios and measurements of the stable chloride concentrations. The monotonous downstream enrichment is attributed mainly to evaporation.

- Fig. 4 Schematic of radiocalcium dating as proposed by Raisbeck and Yiou [28]. Important for dating of bone is that they are shielded by at least 3 m of overburden from the cosmic ray neutrons to guarantee negligible in situ production of  $^{41}\text{Ca}$ .
- Fig. 5 Display of all radioisotopes with half-lives longer than one year as a function of isotope mass and half-life. Only the five radioisotopes marked with circles are currently used for applied AMS work.
- Fig. 6 Demonstration of the effect of a gas-filled magnetic spectrograph on the separation of isobars. The yield of ions is plotted as a function of the position along the focal plane of the spectrograph. In (a)  $^{126}\text{Te}$  ions of 508 MeV energy are dispersed by the different charge states they attain after passing through a  $150\ \mu\text{g}/\text{cm}^2$  gold foil in front of the spectrograph. In (b) and (c) the spectrograph was filled with nitrogen gas of 8 torr pressure. In (b) the charge state distribution of (a) collapsed into a single line. In (c) a pair of stable isobars,  $^{124}\text{Te} - ^{124}\text{Sn}$ , was accelerated and clearly separated due to their different mean charges in the gas.

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RECENT CHARCOAL SAMPLE

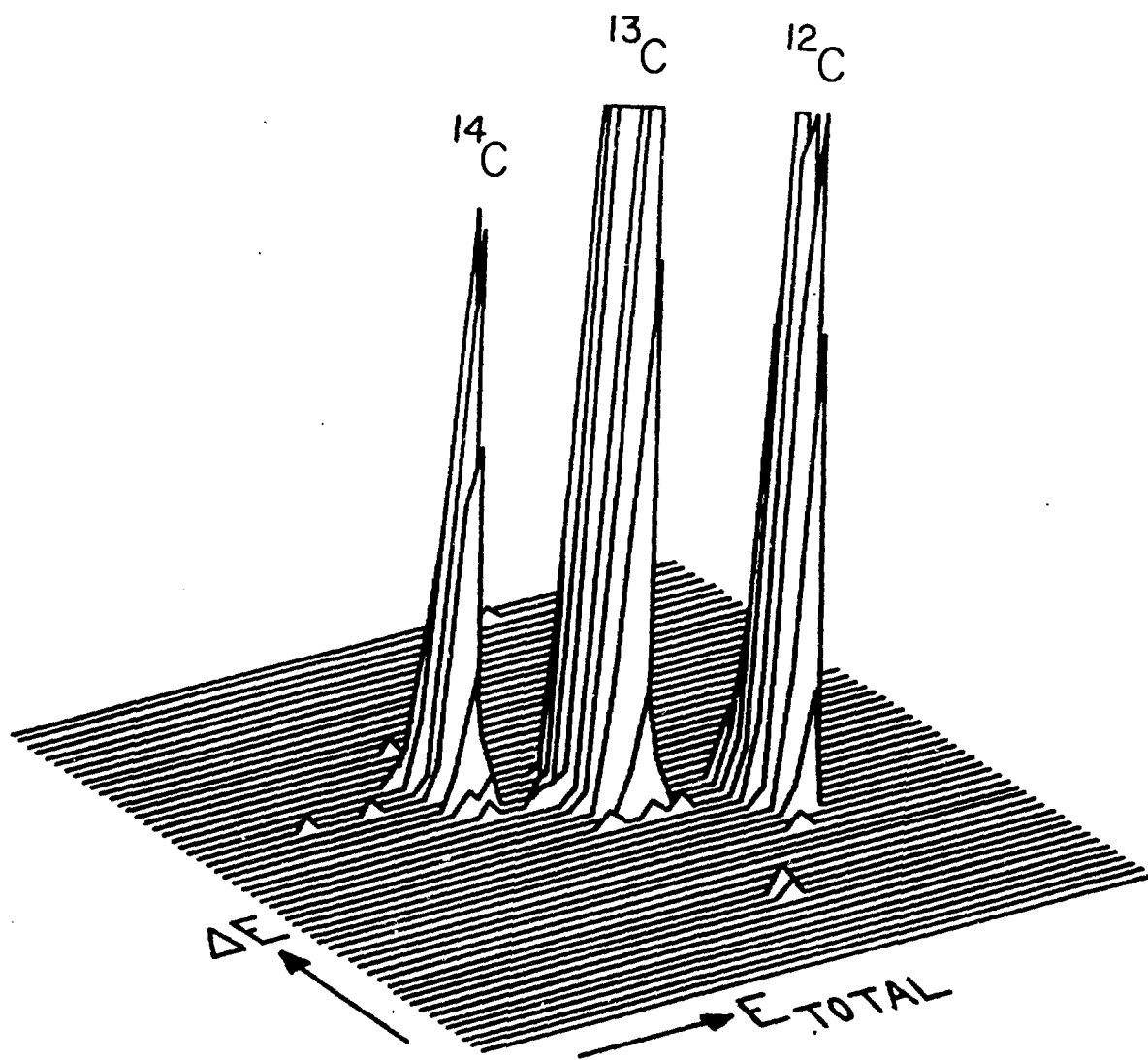


Fig. 1

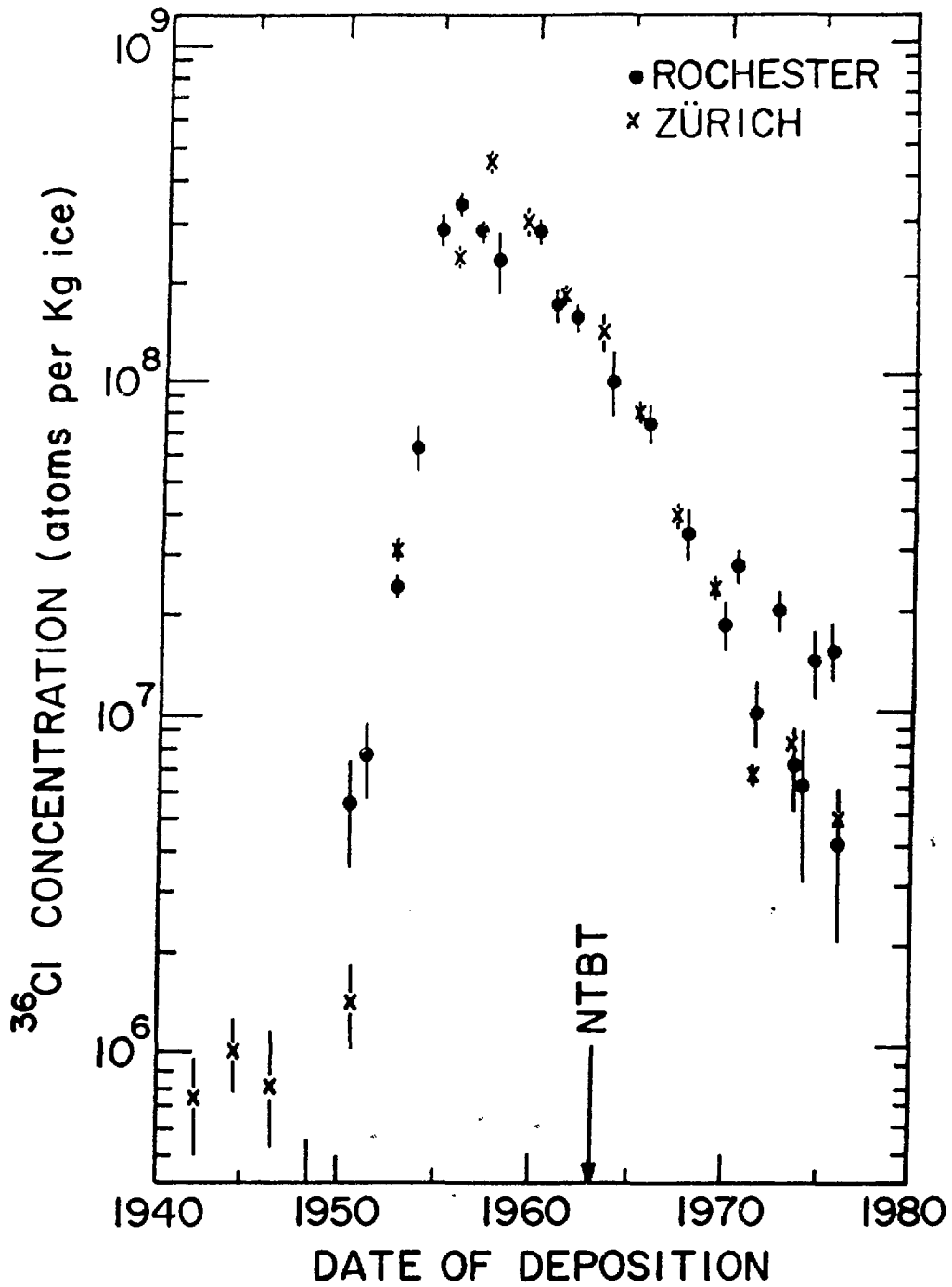


Fig. 2

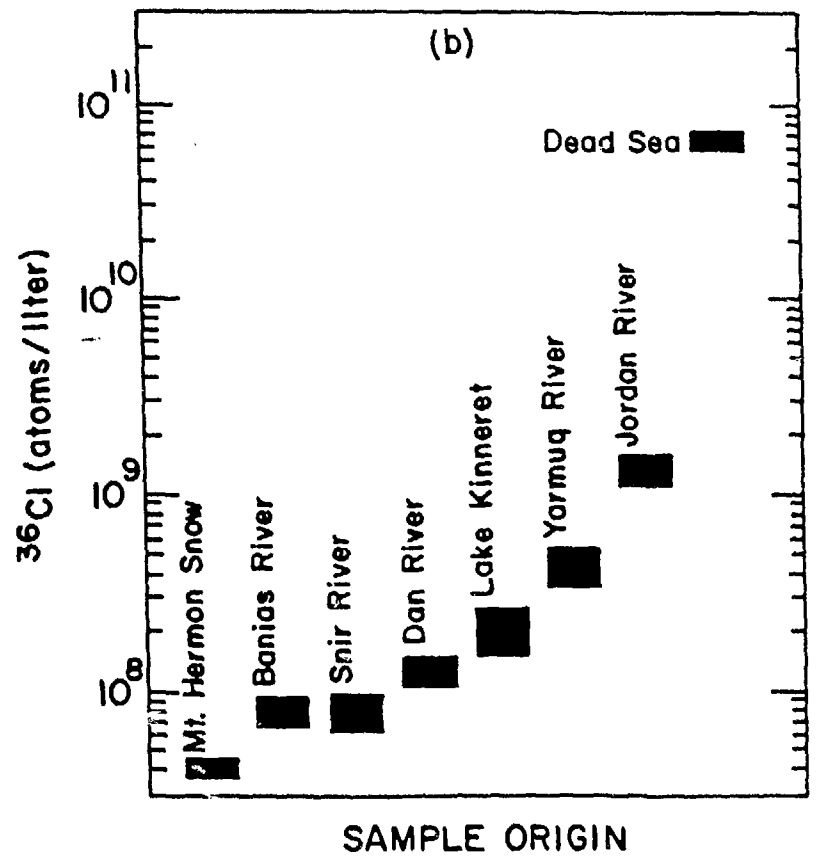
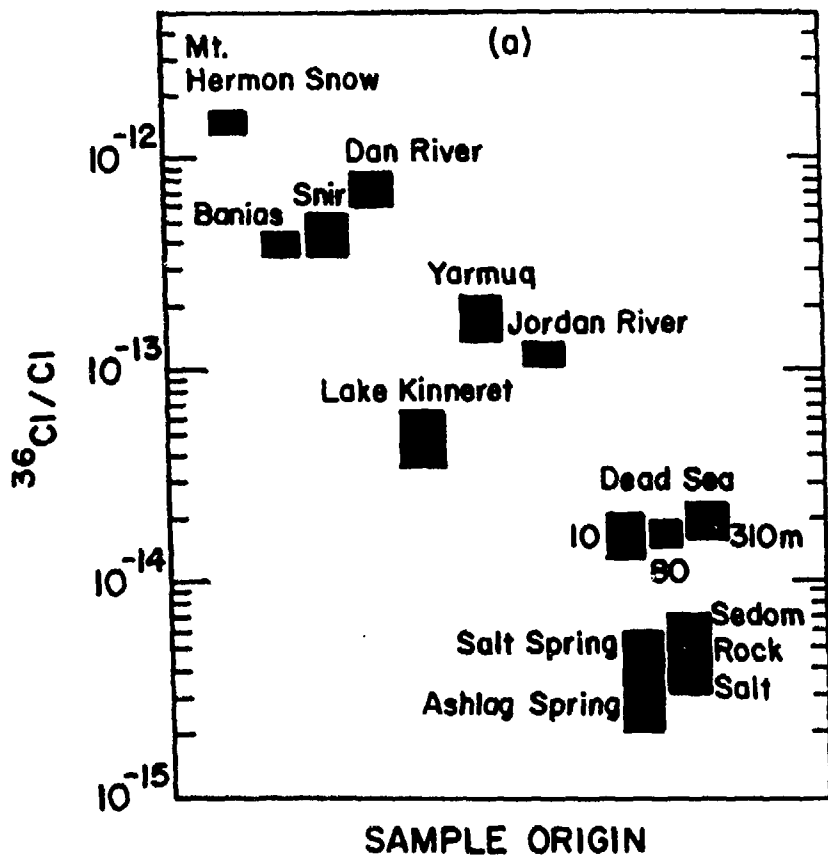


Fig. 3



RADIOCALCIUM DATING  
(after Raisbeck and Yiou)

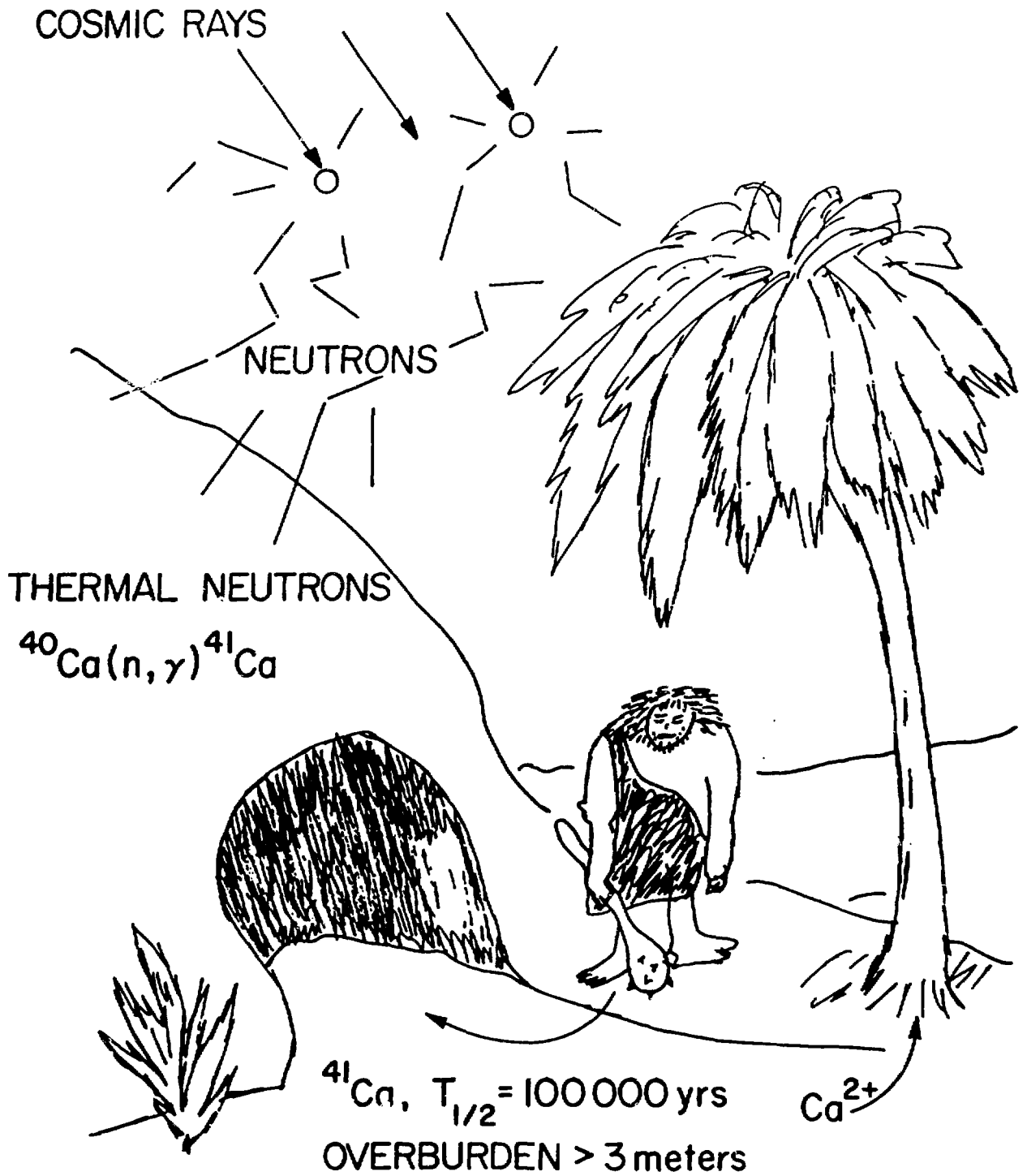


Fig. 4



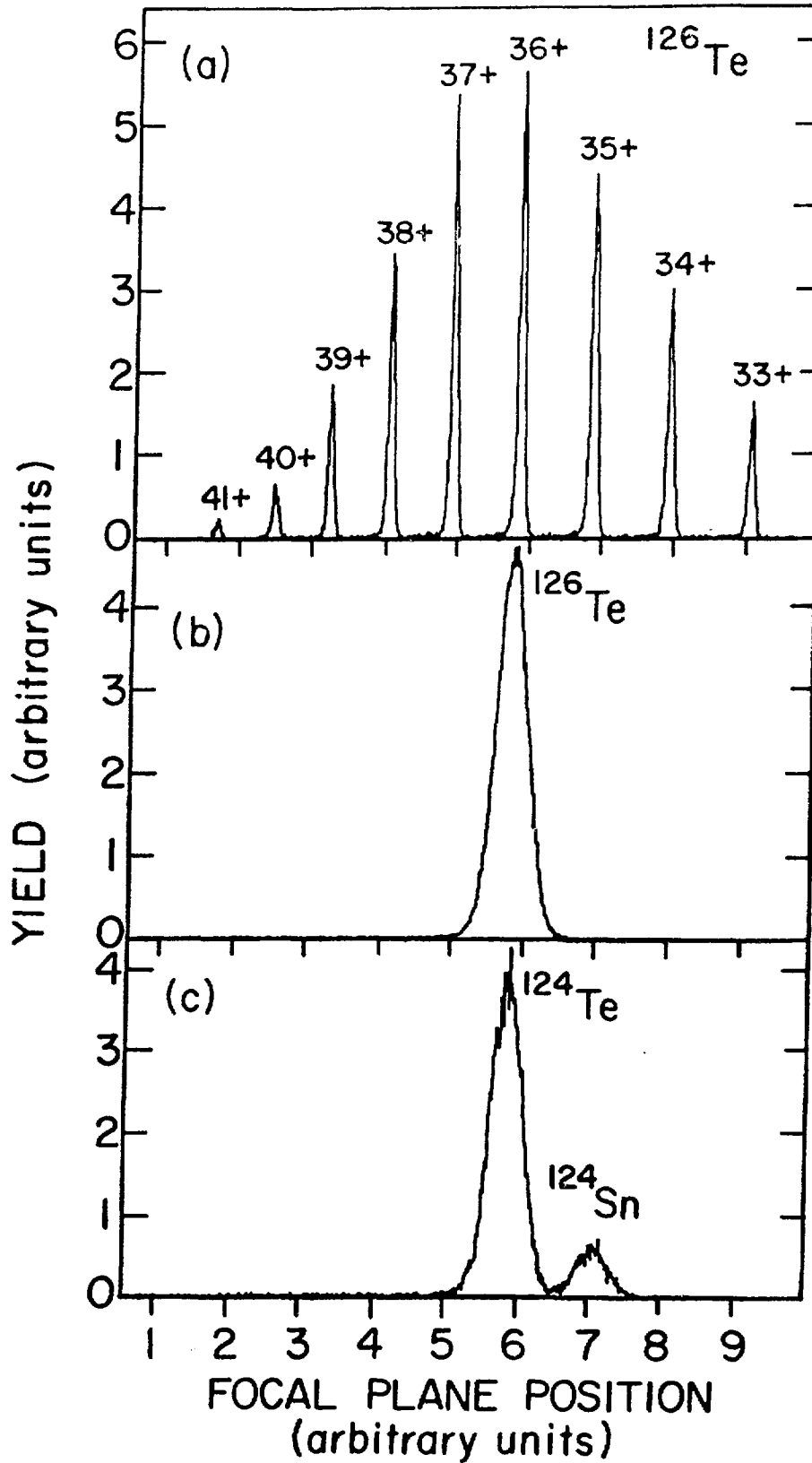


Fig. 6