Nuclear Instruments and Methods in Physics Research B 92 (1994) 213–216
North-Holland

NIM B
Beam Interactions with Materials & Atoms

The successful SINR mini cyclotron AMS for ^{14}C dating

Mao-Bai Chen *, De-Ming Li, Sen-Lin Xu, Guo-Sheng Chen, Li-Gong Shen, Ying-Ji Zhang, Xiang-Shun Lu, Wei-Yu Zhang, Yue-Xiang Zhang and Zong-Kun Zhong

Shanghai Institute of Nuclear Research, Academia Sinica, and T.D. Lee Physics Laboratory, Fudan University, Shanghai, China

The SMCAMS facility at SINR is the first successful one on which practically applicable mini cyclotron measurements on natural levels of ^{14}C have been produced. The results of the primary measurements on this facility are given. A series of new ideas and unique technical measures are summarized. The specifications and the analysing process of the machine are described.

1. Introduction

As is well known, particles of an analyzed sample in a conventional mass spectrometer will circle for less than one turn inside a uniform magnetic field. If the particles circle for more than 100 turns inside a magnetic field, then the resolution of the mass spectrometer will be significantly improved. Therefore, a cyclotron based upon resonance acceleration may be suitably employed as a super sensitive mass spectrometer. Historically, AMS made its first appearance on a conventional cyclotron in 1939 and then in 1977 [1]. However, present AMS work is mostly being carried out on existing tandem accelerators, and the nearly 40 laboratories which possess tandem accelerators in the world are engaged in AMS. Unfortunately, a major weakness of the tandem AMS is that its cost is too high to be popularized.

The mini cyclotron as a super sensitive mass spectrometer will keep the advantages of both tandem AMS and cyclotron AMS. (a) Like tandem AMS it possesses the capability of accelerating negative ions. Furthermore, the negative ions can be extracted directly for measurement without the need of stripping. If necessary, positive ions can also be analyzed. (b) The resonance analysis function of cyclotron AMS is retained. Moreover, the alternate acceleration of the ^{12}C and ^{13}C beams can likely be carried out for dating applications without the need of changing the magnetic field. (c) Because of its low capital and operating costs, and with no expenditure on shielding or special building arising from its small size, low energy, low magnetic field and low power consumption, it can be set up at any dating laboratory for practical applications. Therefore, the prospects are good for such a mini cyclotron AMS to be popularized.

The SMCAMS project was initiated in late 1985 and funded in early 1989. The first phase of the project has now been completed.

2. Results of the first measurement on SMCAMS

Fig. 1a shows the curve of the ^{14}C and ^{13}CH frequency response (counting vs frequency) for a carbon sample consisting of sugar. It shows that the ^{14}C rate is about 100 counts per minute, and the ratio of peak to valley on the curve reaches 3. Fig. 1b is the same curve for a blank sample. It is obvious that there are no counts at the frequency position corresponding to the peak of ^{14}C, which implies that the adjacent ^{13}CH ions have been totally suppressed. The background count rate for the blank sample indicates an abundance sensitivity of 10^{-15} on the SMCAMS. Fig. 2 shows the curve of the frequency response for $^{12}CH_2$ and ^{13}CH. It is apparent that the resolution of the SMCAMS approaches about 3000, which is much higher than required (about 1800) to discriminate between ^{14}C and ^{13}CH. Therefore, we can clearly see from these measurements that the SMCAMS facility is now able to serve the purpose of AMS.

3. Technical advances

In the fifties there was a fever to build small cyclotrons as mass spectrometers [2]. Nevertheless, all of them ended in failure to achieve an abundance sensitivity higher than 10^{-9} due to their very low beam intensity (10^{-15} A). Of course, they could not serve for AMS application for the simple reason that their particle acceptance (or beam intensity) was too poor to

* Corresponding author. Tel. +86 9530998 Cert. 213, fax+86 21 9528021, telex 30910 sinrs cn.

SSDI 0168-583X(94)00094-C

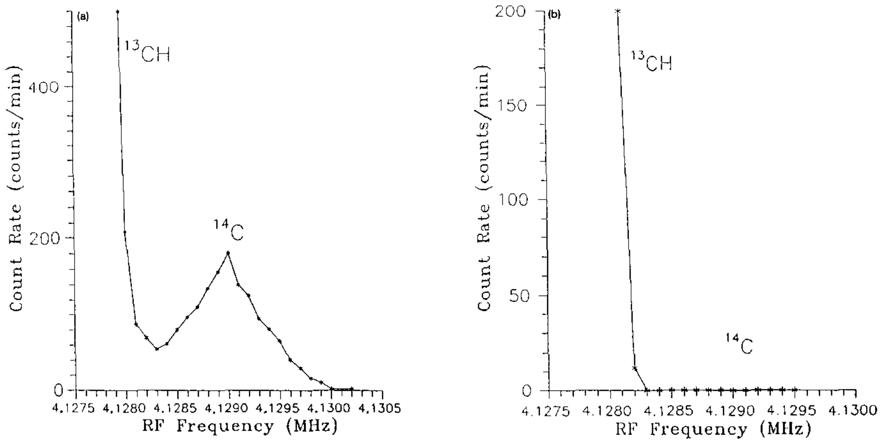

Fig. 1. (a) Curve of the ^{14}C and ^{13}CH frequency response for a carbon sample consisting of sugar. (b) Curve of the ^{14}C and ^{13}CH frequency response for a blank sample.

count ^{14}C. The same problem is true for modern small cyclotrons being built elsewhere for AMS use [3].

To make the SMCAMS successful in obtaining a higher ^{14}C rate, we focused our attention upon increasing the ^{12}C beam intensity from two aspects – one, to improve the transmission efficiency in the acceleration region and, two, to improve the injection and extraction efficiency. This was done by a series of new ideas and unique technical measures which can be summarized as follows.

1) Adopting the triangular wave accelerating voltage rather than the usual sine-wave voltage for improving the particle acceptance of the mini cyclotron under high harmonic operation [4].

2) Configuring a differential dee electrode with wedge shape rather than the usual dee-dummy dee electrode for suitability of operation with high harmonics, and for elimination of the phase convergence and divergence effect.

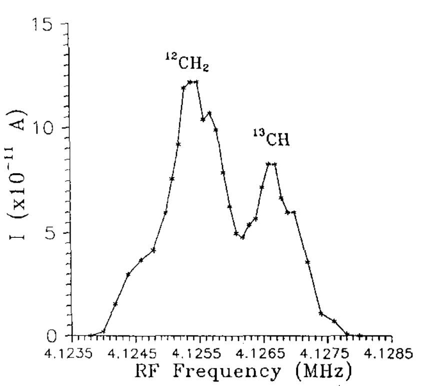

Fig. 2. Curve of the $^{12}CH_2$ and ^{13}CH frequency response for the sugar carbon sample.

3) Introducing the auxiliary electrode and width varied asymmetric electrode with "T" or "I" shape for obtaining a turn spacing wide enough for injection and extraction with minimal phase convergence and divergence [5].

4) Designing a pair of spherical electrostatic injection deflectors rather than the usual "mirror" or "spiral inflector" for increasing the axial injection efficiency.

5) Choosing a non-uniform magnet with high flutter and without trim coils rather than a uniform magnet in order to provide enough axial focusing and for simplifying injection [6].

6) Combining the yoke of the nickel-coated magnet with the vacuum chamber for cost-saving and simplicity.

7) Setting the prohibitive zone of background particles for thoroughly eliminating them.

8) Programming the analysed particle around the equilibrium phase for full use of the powerful function of the triangular wave voltage.

9) Adjusting electrical parameters while keeping the magnetic field unchanged for alternate acceleration of ^{12}C, ^{13}C and ^{14}C.

10) Adding the clearing deflector and measuring deflector for clearing away the residual particles during alternate acceleration and carrying out the sequential measurement.

11) Using a dynode-micro channel plate detector rather than the usual nuclear detector for counting ^{14}C [7].

All these measures are entirely different from those of conventional cyclotrons. In primary beam tuning we have observed a ^{12}C current of 350 nA, which is 10^8 times more than that of the small cyclotrons developed in the fifties and makes it possible for the SMCAMS to count ^{14}C as shown above. The axial injection efficiency has reached 60%, twice that in conventional cyclotrons. The transmission efficiency in the acceleration region has reached more than 20%. This implies that the acceptable rf phase width has reached more than 36°. The overall duty cycle of the minicyclotron under a high harmonic operation of 16 has reached 10%. It is really a great success in cyclotron technique.

4. Description of the SMCAMS facility

Fig. 3 shows the layout of the SMCAMS facility. The whole magnet is 40 cm in height and the yoke is 160 cm in outer diameter; its total weight is about 4.5 t. The gap between up and down sectors is 2.5 cm and the maximum magnetic field at the center of each hill is about 4 kG. The amplitude and frequency of the triangular wave voltage are $Vp\text{-}p = 1$ kV and $f = 4.8$ MHz respectively. The minicyclotron is operated at a harmonic of $h = 16$. The final ^{14}C energy after circling for 100 revolutions is about 50 keV. The total power consumption of the machine is only 12 kW.

Particles emitted from the Cs sputter negative ion source are first focused by a triple aperture lens, which can also adjust their injection energy to match the fixed injection condition, and then vertically injected into the vacuum chamber. After passing through the two injection deflectors, the ^{14}C ions mixed with $^{12}CH_2$ and ^{13}CH ions will obtain a turn spacing (6 mm) wide enough to clear the horizontal injector and begin to accelerate. In the central region their phase will be converged in the "T" shape electrode and diverged in the "I" shape electrode. The $^{12}CH_2$ and ^{13}CH ions will be accelerated and discriminated along the wedge dee electrodes for at most 67 turns up to $r = 42$ cm or so, where the 6 cm wide prohibitive zone begins. It is impossible for $^{12}CH_2$ or ^{13}CH to enter the prohibitive zone for the simple reason that they would have been decelerated inward before they approach this zone. The $^{14}C^-$ ions will continue to be accelerated outward up to $r = 48$ cm where the horizontal extraction deflector is located, and enter the extraction deflector with a turn spacing of 6 mm. If any unwanted particle emerges from the prohibitive zone, it will be suppressed by the extraction deflector (used as an electrostatic analyzer) due to its unsuitable velocity or incident direction. The extracted $^{14}C^-$ ions are focused by a triplet and deflected by the measuring deflector onto the surface of the dynode of the detector where each $^{14}C^-$ ions releases several electrons. These secondary electrons are aimed at the micro channel plate and recorded after having been multiplied by 10^8. The other particles (^{12}C, ^{13}C) when measured in turn aim straight at the neighbouring Faraday cup.

For dating applications, the ratio of the detected radioisotope to its corresponding stable isotope, such as $^{14}C/^{12}C$ and $^{13}C/^{12}C$, must be measured sequentially. Therefore, ^{14}C, ^{13}C and ^{12}C must be alternately accelerated in a minicyclotron AMS in contrast to a conventional cyclotron, which is complicated even though without the need to adjust the magnetic field. Because the mass difference between ^{14}C and ^{12}C is as

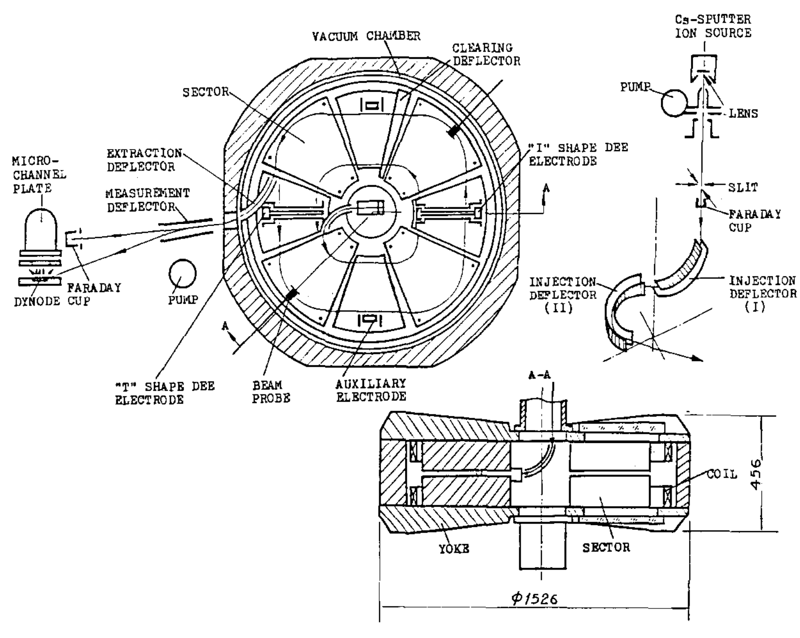

Fig. 3. Layout of the SMCAMS facility.

high as 15% and the magnetic field is fixed, most electrical parameters must be sequentially changed by about 15% according to the orbit similarity theory. In addition to this, the transmission efficiency of ^{14}C, ^{13}C and ^{12}C from the exit of the ion source to the detector must be calibrated all the time by a standard or known sample.

5. Further development

We have shown that the SMCAMS facility has been successful in obtaining ^{14}C identification without interference from ^{13}CH. This is a great breakthrough in the cyclotron AMS technique, and adds a new direction in the AMS technique.

However, the exact accuracy of dating with SMCAMS cannot be given at the present time, because the first phase of our project funded by the NSFC and Academia Sinica was just to certify the new ideas and unique technical measures put forward by us. For practical dating application, it is necessary to build the micro computer-controlled system for alternately accelerating ^{12}C, ^{13}C and ^{14}C, and to equip the Cs ion source with an optic fibre-controlled multi-sample device for sequentially changing various samples. With the complete system we would expect to obtain a dating accuracy of better than 1–3% for practical use. Of course, we still have to explore the correct method of alternate acceleration in the minicyclotron to achieve this.

Tandem AMS is now an advanced tool for AMS research after having been developed for more than a decade by many famous laboratories all over the world. In contrast, the SMCAMS is an exciting new development, which further improvements will make into a useful AMS tool.

Acknowledgements

We are indebted to Prof. Fujia Yang for his strong support and encouragement during the whole course of the project. Supported by the National Natural Science Foundation of China and Academia Sinica.

References

[1] R.A. Muller, Phys. Today, February (1979) 23.
[2] D.J. Clark, Proc. 10th Int. Conf. on Cyclotrons (1984) p. 534.
[3] J.J. Welch, Ph.D Thesis, LBL-21255 (1984); K.J. Bertsche, Ph.D Thesis, LBL-28106 (1989); Nucl. Instr. and Meth. B 52 (1990) 398.
[4] Mao-Bai Chen et al., Nucl. Instr. and Meth. A 278 (1989) 409.
[5] Mao-Bai Chen et al., Nucl. Instr. and Meth. A 297 (1990) 47.
[6] Mao-Bai Chen et al., Proc. 4th China–Japan Symp. on Accelerators (1990) p. 135.
[7] Yingji Zhang et al., Nucl. Instr. and Meth. A 302 (1991) 76.