High precision mass measurement and LPT*

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Abstract A Penning trap, which can measure the atomic masses with the highest precision, is one of the most important facilities in nuclear physics research nowadays. The precision mass data play an important role in the studies of nuclear models, mass formulas, nuclear synthesis processes in the nuclear astrophysics, symmetries of the weak interaction and the conserved vector current (CVC) hypothesis. The status of high precision mass measurement around the world, the basic principle of Penning trap and the basic information about the LPT (Lanzhou Penning Trap) are introduced.

Key words Penning trap, super heavy, mass measurement, LPT

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1 Introduction

Mass is one of the most fundamental properties that can be obtained about an atomic nucleus. The precision mass data play an important role in the studies of nuclear models, mass formulas, nuclear synthesis processes in the nuclear astrophysics, symmetries of the weak interaction and the conserved vector current (CVC) hypothesis. Fig. 1 shows the importance of the atomic mass. To study different physics needs different mass resolution. A mass resolution of 1×10^{-7} is needed for the studies of such as testing mass formulas and nuclear theories, and a resolution of better than 1×10^{-10} should be satisfied for studying the fundamental constants.

Nowadays about 2300 isotopes are known and about 230 of them can be found in nature. In the AME2003 atomic mass evaluation[1] about 2200 nuclides have their mass data and 1158 of them have a mass resolution of $\leqslant10^{-7}$, 181 nuclides $\leqslant10^{-8}$, and only 24 nuclides $\leqslant10^{-9}$.

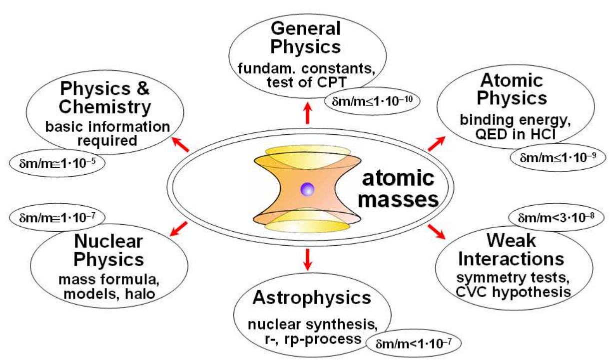

Fig. 1. Importance of the atomic mass.

Many techniques have been developed for the mass measurement and there are two main approaches. The indirect approach is based on the determination of Q-values measured in nuclear reactions and radioactive decays. The direct method uses mass spectrometers for both stable and unstable nuclides. A short comparison between different mass measurement techniques is shown in Table 1. The details of these techniques have to be omitted here because of

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Table 1. A comparison between different mass measurement techniques.

technique	typical m/δm	typical lower limit of $t_{1/2}$
α-decay	1×10^7	1 μs
β-decay	1×10^6	100 ms
nuclear reaction	5×10^6	1 μs
mass spectrometer	$200 - 1\times10^4$	1 μs
linear TOF	$4\times10^4 - 4\times10^5$	1 μs
cyclotron TOF[2]	2×10^5	50 μs
MISTRAL[3]	1×10^5	50 μs
storage ring (SMS)[4]	1.5×10^5	50 μs
storage ring (IMS)[5, 6]	7.5×10^5	10 s
penning trap	$10^7 - 10^8$	100 ms

lack of space. More details can be found in the review paper by Lunney, Pearson and Thibault[7]. Penning trap mass spectrometry is one of the direct methods and maybe the most accurate tool for the mass measurement. In fact, the most precise mass data in the world are obtained by using the Penning traps[1]. The mass precision measured by using Penning trap is so high that H. G. Dehmelt was awarded the Nobel Prize in 1989. At the same time W. Paul was awarded for his achievement in Paul trap and N. F. Ramsey for the atomic clocks.

2 Status of Penning traps

Table 2 lists all the existed and R&D projects on the Penning trap. The progress becomes very fast in the developed countries in Europe and American and Penning trap has become a standard facility in many outstanding nuclear laboratories around the world.

Table 2. Penning traps around the world.

stable isotopes	RIs* with low energy†		RIs* with medium energy‡		antihydrogen	others
running	running	R & D	running	R & D	R & D	R & D
Mainz-TRAP	ISOLTRAP[10]	MAFFTRAP[13]	CPT[17]	HITRAP[20]	ATHENA[21]	WITCH[23]
SMILETRAP[8]	JYFLTRAP[11]	TITAN[14]	SHIPTRAP[18]	LPT§	ATRAP[22]	RETRAP[24]
Seattle-TRAP	REXTRAP[12]	TRIμP[15]	LEBIT[19]			
MIT-TRAP[9]		MATS[16]				
		TRIGA-TRAP[16]				

∗ RI: Radioactive Ion; † Low energy: a primary energy of $\lesssim$100 keV; ‡ Medium energy: a primary energy of $\lesssim$100 MeV; § This work.

The first few Penning traps devoted to the mass measurement are concentrated on stable nuclei. Because the ions can be stored and measured for an extremely long time, the measured mass precision of some of stable nuclei has been better than 10^{-10}.

Most of the running Penning traps concentrated on radioactive ions are coupled to online isotope separators. Due to low production rate, short half-lives and the limitations from separators, only the nuclei not very far from the beta stability valley can be studied in the traps, and the measured mass precision has decreased rapidly for nuclei that are more and more unstable with respect to beta decay. By about 20 years hard working, the mass precision of these nuclei has become several orders higher. The successful running of these devices has also benefitted the optimum of the design and operation of new Penning traps.

Since accurate masses of rare isotopes far from the beta stability valley are requested for a better understanding of nuclear structure, several devices, such as the LEBIT[19] in MSU and the SHIPTRAP[18] in GSI, have been constructed to measure the masses of those isotopes produced by projectile fragmentation. The SHIPTRAP also hopes to measure the masses of the super heavy nuclei directly.

Since it is not trivial to increase the charge state of the ions, only singly charged ions have been stored in most of the running Penning traps. Because using the highly charged ions can reduce the detection time and increase the precision of the measured masses, increasing the charge state of the stored ions has become a main characteristics in the newly R&D devices. In addition, letting the Penning trap work at the temperature of liquid nitrogen, even at liquid helium becomes an important factor to be considered in a few new projects.

Although a lot of Penning traps have been built in Europe and American, there is no similar device running in Asia. The LPT (Lanzhou Penning Trap) is the first one to concentrate on the high precision mass measurement by using Penning traps in China. However, other kinds of traps have been built in China. For example, two EBITs (Electron Beam Ion Traps) have been constructed at Fudan University and Lanzhou University, respectively. The EBIT can produce highly charged heavy ions and has become an important tool in both the atomic physics and the plasma physics. Paul traps have also been developed in Wuhan Institute of Physics and Mathematics, Chinese Academy of Science.

3 Basic principle of the Penning trap

A Penning trap is an electro-magnetic trap. The combination of an electrostatic quadrupole field $U(\rho,z)$ and a homogeneous magnetic field $\boldsymbol{B}=B\hat{z}$ allows a charged particle to be stored in a well defined volume. The potential $U(\rho,z)$ follows this formula:

$$U(\rho,z)=\frac{U_0}{4d^2}(2z^2-\rho^2),$$

where U_0 is the potential difference between the ring electrode and the endcaps. d is the characteristic trap dimension and defined by

$$d=\sqrt{2z_0^2+\rho_0^2}/2\ , \tag{1}$$

where ρ_0 is the inner radius of the ring electrode and $2z_0$ the distance between the endcaps.

If a charged particle with a charge of q and a mass of m moves in a pure magnetic field, it will rotate in a pure cyclotron motion with frequency

$$\omega_c=qB/m\ . \tag{2}$$

Due to the existence of the electric field, the pure cyclotron motion of the particle becomes a superposition of three independent harmonic motions. These motions are an axial oscillation with frequency

$$\omega_z=\sqrt{\frac{qU_0}{md^2}} \tag{3}$$

and two radial motions with frequencies

$$\omega_\pm=\frac{\omega_z}{2}\pm\sqrt{\frac{\omega_c^2}{4}-\frac{\omega_z^2}{2}}\ . \tag{4}$$

It is easy to see that the sum of both radial frequencies is equal to the cyclotron frequency

$$\omega_c=\omega_+ + \omega_- \tag{5}$$

of an ion in a pure magnetic field. By direct determination of this sum frequency and consideration of the known q and B, the mass of the stored ion can be calculated according to the formula (2). Practically, in order to reduce the influence of the instability of the magnetic field, the masses of the ion of interest and a reference are measured alternatively.

Figure 2 shows two Penning traps with different electrode structures. The advantage of the hyperbolic Penning trap is that the variation of the electrode potentials will not change the shape of the equal-potential planes, thus the precision of the measured mass will be relatively higher compared to the cylindrical one. Its disadvantage is that the hyperbolic electrodes are very difficult to machining. For the cylindrical Penning trap, its advantages are firstly easily machining and secondly giving a possibility to perform precise spectroscopy in the traps due to the open structure. Because the shape of equal-potential planes in the trap will be easily changed with the varying potentials of the electrodes, power supplies with very high stability have to be applied to achieve high precision mass measurement.

A real Penning trap is much more complicated than an ideal one. The precision of the mass measurement will be decreased by the defects of electric field, magnetic field, machinery, assemble, the cross effect of ions in the trap and so on. The achievable highest precision of the mass measurement in a Penning trap will be determined by the control of these defects.

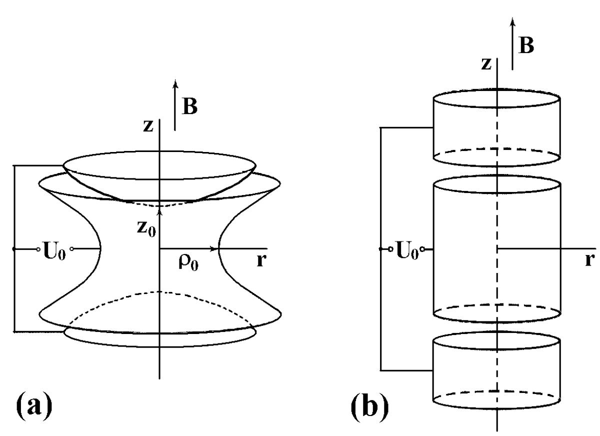

Fig. 2. Penning traps with (a) hyperbolic and (b) cylindrical structures.

4 LPT

In order to start the high precision mass measurement in China, the LPT (Lanzhou Penning Trap) is under construction. Its main objective is to perform direct mass measurement of the fusion-evaporation residues and if possible for the heavy isotopes. Fig. 3 shows the schematic setup of the LPT. The fusion-evaporation residues will firstly be injected into the RFQ cooler and buncher RFQ1L to be cooled and stored, then transported to the purification trap to get rid of the unwanted ions, and finally transported to the measurement trap to perform the mass measurement. RFQ1L[25—29], a necessary device for the LPT, is now under the test. The design, simulation and optimum of the two traps and the beam transfer line are also on the way.

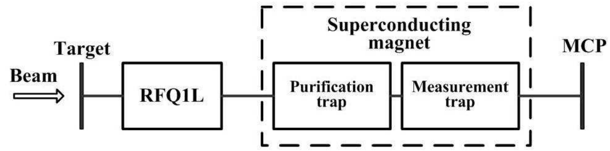

Fig. 3. Schematic setup of the LPT.

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