A proposed method to measure relativistic kinetic energy of electrons in Penning Trap

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Introduction

Penning ion trap is a versatile tool which serves as a storage device for sub-atomic particles using a combination of quadrupolar electric potential for axial confinement and a strong magnetic field for radial confinement. Trapped particles have three oscillatory motions: 1) axial motion, along the direction of the magnetic field with frequency ω_z, 2) the trap-modified cyclotron motion at a higher frequency ω_+, 3) slow magnetron motion with frequency ω_-, where $\omega_- < \omega_z < \omega_+$. The cryogenic Penning trap has so far been used for various precision measurements like the measurement of (g-2) parameter of electron and positron [1] and several other similar studies.

In this work, we propose a new method of measuring the shape of a beta spectrum by high precision measurement of the relativistic kinetic energy of the electrons using a cryogenic Penning trap. Using this method, it might be possible to measure the shape of the end-point of a beta spectrum with a high precision enabling the mass measurement of electron-neutrino.

Present work

The axial oscillation frequency of a trapped electron with relativistic mass m and electric charge q in the purely harmonic potential region of a trap is given by [2]

$$\omega_Z = \sqrt{\frac{q\,V_0}{m\,d^2}C_2} \qquad (1)$$

where V_0 is the applied voltage between the ring and the end-cap electrode, C_2 is the quadrupolar coefficient of trap potential and d is the characteristic length of the trap. The relative values of the relativistic masses of the electron trapped with different kinetic energies can be obtained by measuring their respective axial frequencies. The relative values of the kinetic energies of the electrons and the corresponding shape of the electron spectrum can then be obtained from their relative values of the relativistic masses. However it is generally not possible to trap a high energy electron in a Penning trap, because there are practical difficulties of applying more than ~500V between ring and electrodes with high stability. Since it is necessary to trap the electron in the purely harmonic potential region (central region) of the trap for high precision mass measurement, the electrons with only axial energy in the range of tens of eV or lower can be used. So in order to trap a high energy relativistic electron, it must be injected in the trap making an angle close to 90˚ with the trap axis (magnetic field axis). The beta sources emitting electrons with energies greater than 10 keV can be used for testing the proposed method. The source can be placed outside the Penning trap in a metal enclosure with a tiny hole cut at an angle close to 90˚ with respect to the magnetic field **B**. The electrons will follow a spiral path with cyclotron radius

$$r = \frac{m\,v}{q\,B} \qquad (2)$$

and thus, electrons of different energies will have different radii. A narrow band of energies can be selected by placing an appropriate annular slit in front of the source. For example: In a magnetic field of 5T, a circular slit having inner diameter(ID) of 90 micron and outer diameter (OD) of 100 micron as shown in Figure1. placed at a distance of 10 micron away from the source will allow electrons of energy from 18500 eV to 20500 eV to come out and enter the trap. The presence of these electrons in the trap can be identified by their image current on the end-caps and they can be trapped by raising the voltage of the end-cap, as they would come close to the center of the trap. By analyzing the image current of the electrons, it should be possible to determine both the axial and cyclotron frequencies of the trapped electrons and their relativistic masses can be determined with high precision. In order to determine the relativistic masses with 0.001% level accuracy, no more than 4-5 electrons should be trapped at a time and ~1 ms of measurement time is required. However trapped high energy electrons will emit radiation at cyclotron frequency and lose their energies. If the cyclotron frequency lies outside the line-width of the natural frequency of Penning trap cavity, the emission of radiation is greatly inhibited [3] and it would be possible to measure the kinetic energy of such trapped high energy electrons within a time period of ~1 ms with negligible loss of energy.

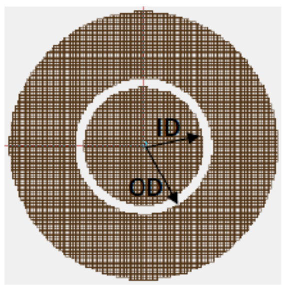

Figure1. Annular slit for selecting energy band of electrons.

Simulation

We have selected a trap of inner radius r=3.29 mm, Z_o=3.04 mm , C_2=0.65202 and d= 2.7068 mm and carried out simulation for this trap using SIMION8 [4]. The electrons of all energies are emitted from the source in the angular region from 88˚ to 89˚ with respect to the magnetic field and electrons of kinetic energy ranging from 18500 eV and 20500 eV will pass through the annular slit placed in front of the source. According to the simulation, these electrons can be trapped in the quadrupolar potential region of the Penning trap by applying a potential difference of 500V between the end-cap and ring. The axial frequencies obtained from the simulation agree well with the theoretical values as shown in Table 1.

Table 1. Axial frequency

Kinetic Energy(eV)	Theoretical value (GHz)	Simulated value(GHz)
18500	0.4376	0.4369
20500	0.4368	0.4360

The accuracy of the simulated values is limited by the error in fitting a sine function. The wavelength of cyclotron radiation of these electrons in 5T magnetic field are 2.2 mm which is not integer multiple of the trap inner radius, so the emission of cyclotron radiation will be greatly inhibited.

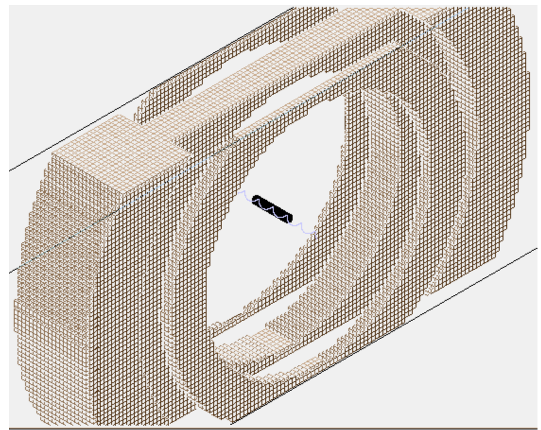

Figure2. Sectional view of trap centre where electrons of energy 18500 eV emitted at 89˚ are trapped (shown in black colour) and other electrons emitted at smaller angles escape (shown in gray colour).

Discussion

We have proposed a method to determine the spectral shape of electron spectrum by measuring the relativistic masses of the electrons in a Penning trap with high precision. Simulations using SIMION8 have been carried out and the simulations support the possibility of such a measurement. We are now looking at other possible practical problems of implementing this idea.

References

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