A CYCLOTRON AS A MASS SPECTROMETER

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ABSTRACT

Taking advantage of the system of coupled cyclotrons at GANIL, we have developed a method for mass measurements with a cyclotron. The secondary nuclei are produced in a target located between the two separated sector cyclotrons by the interaction of a beam coming from the first cyclotron. They are subsequently accelerated in the second cyclotron. The prior tuning of this cyclotron for those very low intensity is accomplished using a beam having the same q/A ratio at the right velocity. For fine tuning, we have developed a probe inside one sector of the cyclotron. This new probe is described and first results will be presented.

1. INTRODUCTION

Mass measurements provide information on one of the most fundamental properties of the nuclide, its atomic mass. Number of techniques have been used for such measurements. Masses of radioactive nuclides are traditionally determined through reaction Q-value measurements, or through measurements of the energy released in α or β decays. Direct mass measurements of nuclides far from stability are available by coupling a high resolution spectrometer to a production facility for radioactive isotopes[1,2,3]. More recently mass measurements of radioactive nuclides have been done using recoil mass spectrometers, SPEG[4] at GANIL and TOFI[5] at LAMPF. Precision of 100-500 keV has been achieved. The cyclotron resonance mass spectrometer at CERN[6,7] has the potential of mass measurement of 1 keV level. We have developed at GANIL a new method for mass measurement using a cyclotron as mass spectrometer. The present paper describes the technique used for this measurement and gives some of the results obtained.

2. PRINCIPLE OF THE METHOD

GANIL consists of a system of three coupled cyclotrons (fig. 1). Highly stripped ions from the ECR ion source are accelerated by a compact cyclotron, k=30 (C0) before being injected in the first of two identical separated sector cyclotrons (CSS1 and CSS2). In normal operating mode, the accelerated ions emerging from CSS1 are stripped of electrons in a thin carbon foil before being injected into CSS2 for their final acceleration. If the stripper foil is replaced with a thicker target, then secondary ions produced in this target, rather than the ions of the primary beam, may be accelerated in CSS2.

2.1. Coupling relation between two cyclotrons

In the following the index 1 and 2 will refer to CSS1 and CSS2 respectively.

The fundamental relation for the cyclotron is,

$$B\,q = m\,\omega/h \qquad 1)$$

where B is the magnetic field, q the charge, m the mass of the ion, ω the radio frequency and h the radio frequency harmonic.

Since the two cyclotrons are operated at the same radio frequency, we obtain easily the relation governing the coupling between two cyclotrons,

$$\omega = \left(\frac{q_1}{m_1}\right) B_1 h_1 = \left(\frac{q_2}{m_2}\right) B_2 h_2 \qquad 2)$$

The velocity can also be expressed in term of the frequency ω and the mean radius of curvature, so we have the following relation,

$$\omega = \left(\frac{v_1}{\rho_1}\right) h_1 = \left(\frac{v_2}{\rho_2}\right) h_2 \qquad 3)$$

where v_1 and v_2 are the velocity at the ejection of CSS1 and at the injection of CSS2, ρ_1 and ρ_2 are the ejection and injection radius, h_1 and h_2 are the harmonic number of CSS1 and CSS2 respectively.

The ratio ρ_1/ρ_2 of the GANIL cyclotrons is 2.5 and since the velocity in normal use is the same between the ejection of CSS1 and the injection of CSS2 then the harmonic number ratio must be equal at 5/2. And since $h_1 = 5$, in normal operating mode, then h_2 must be equal 2.

Given that the production of secondary nuclei by nuclear reaction, between CSS1 and CSS2, will invariably be associated with a velocity loss, we must consider other solutions for which $v_2 < v_1$. The most favorable case is $h_2=3$, for which $v_2/v_1=2/3$. Other combination are of course possible as long as h_1 and h_2 are integer numbers.

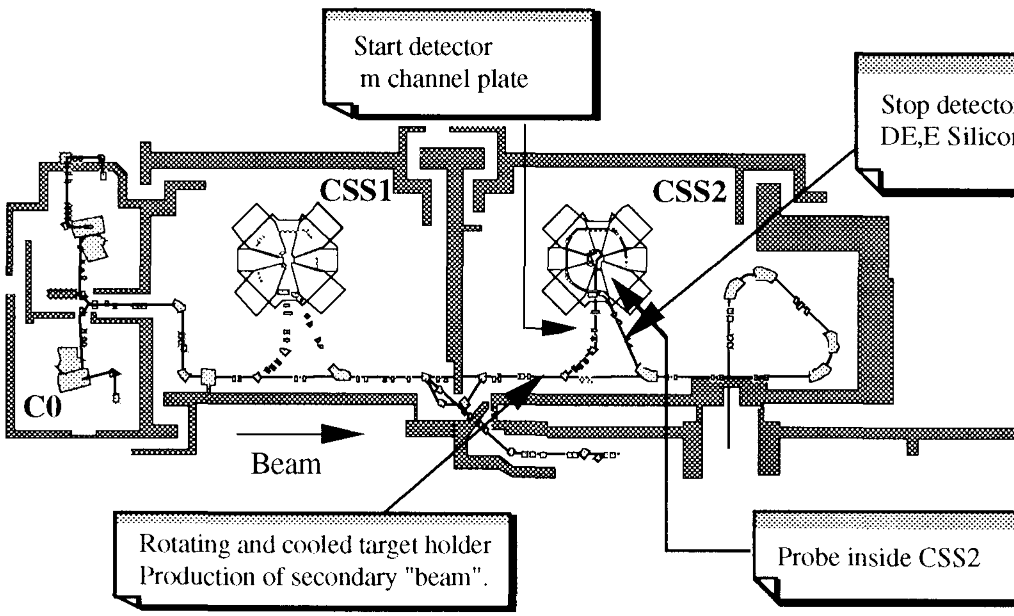

Fig. 1 Schematic view of the GANIL cyclotron facility. The principal component locations used for the mass measurements are indicated.

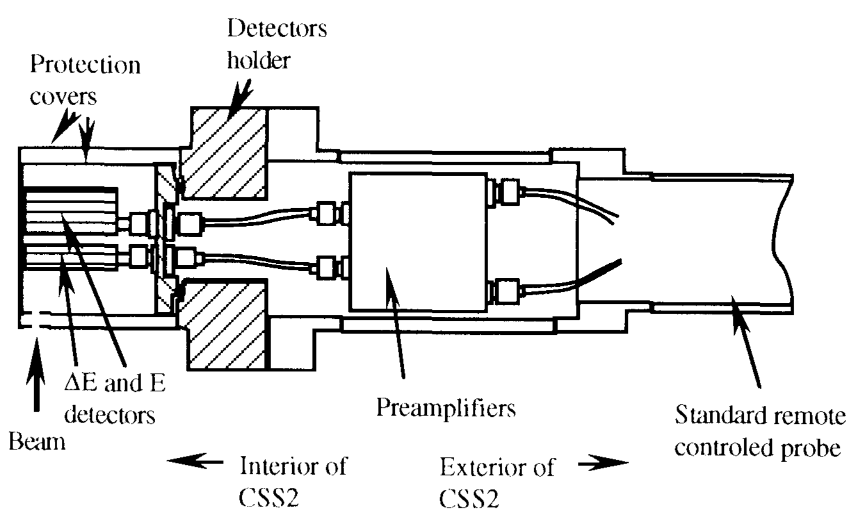

Fig. 2 Schematic of the probe installed in one sector of the CSS2.

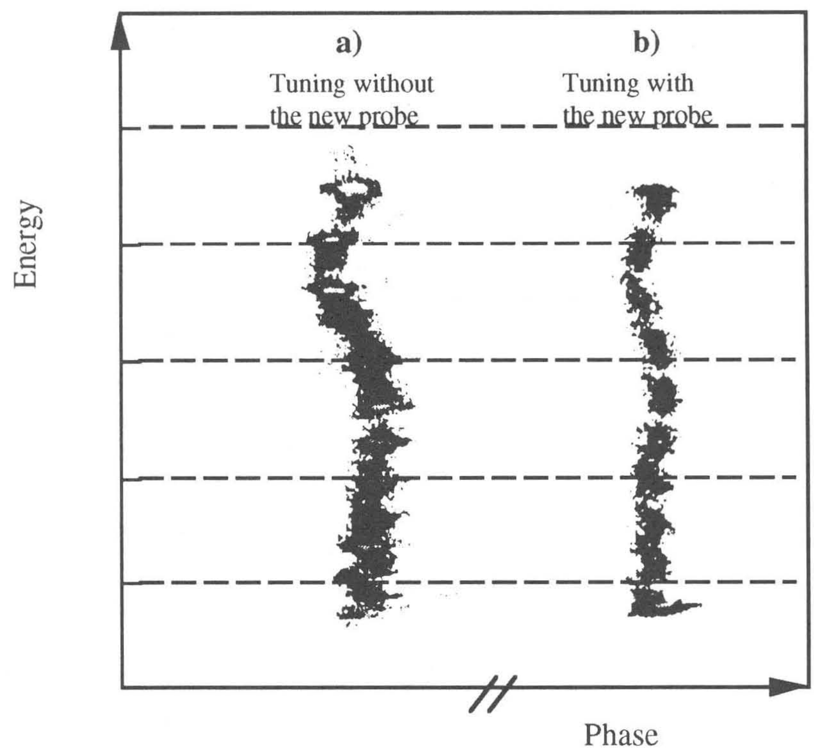

Fig. 3 Phase space diagram of the particles in the cyclotron. Fig. 3a shows the phase space obtained just after the prior tuning using a particle having the same A/q ratio as the nuclei of interest. Fig. 3b shows the final phase space using this detector for the fine tuning of the magnetic field.

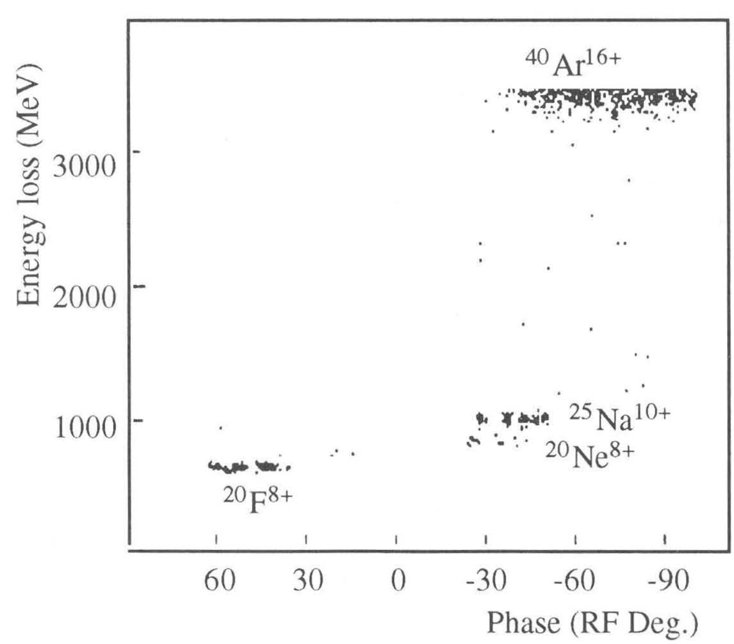

Fig. 4 Two-dimensional spectrum of data from the silicon showing both $^{40}Ar^{16+}$ ions and accelerated secondary ions produced between the two cyclotrons.

2.2. PRECISION OF THE METHOD

Consider two nuclei with slightly different masses, m and m+δm. During the acceleration process the heavier of the two will lag behind the other.

From the expression 1 we easily obtain

$$\frac{\Delta m}{m} = \frac{\Delta B}{B} - \frac{\Delta \phi}{\phi} . \qquad 4)$$

We can neglect the variation of the magnetic field during the time of measurement. Thus, we obtain the simple relation,

$$\frac{\Delta m}{m} = \frac{\Delta \phi}{\phi} . \qquad 5)$$

After N turns at harmonic h the total phase is

$$\phi_{total} = 360 \text{ h N}. \qquad 6)$$

Taking typical values of h = 3 and N = 250 we obtain,

$$\frac{\Delta m}{m} = \frac{\Delta \phi}{\phi_{total}} = 3.7\ 10^{-6}\ \Delta\phi . \qquad 7)$$

A timing resolution of 250 ps is readily attainable and corresponds to a resolution of 1.2° in the phase difference at ω = 13.MHz. Hence the mass resolution attainable is

$$\frac{\Delta m}{m} = 5\ 10^{-6} . \qquad 9)$$

3. TUNING THE CYCLOTRON

In the case of an arbitrary m_2/m_1 there is no simple general method for the prior tuning of CSS2. Since secondary beam intensity are very low compared to those of stable beams, standard diagnosis are not useable for the tuning. However, in the special case where a charge state of the incident beam leading to the same value of A/q exists, this charge state can be used to tune the magnetic field in the cyclotron using standard beam tuning diagnosis within the cyclotron.

But, often it is not possible to achieve the tuning as precisely as desired, because the mass difference between the tuning mass and the mass of interest is too large. So, it is useful to tune the magnetic field and the injection system using a tuning mass having the same magnetic rigidity.

For the fine tuning it is necessary to use an apparatus able to detect very low intensity, typically from 10 to 10000 pps. Also, this detector must give the following informations: total kinetic energy, atomic number and have a very good timing. A telescope composed of silicon detectors can fulfill these specifications. We have developed and installed such a detector in one magnetic sector of the cyclotron.

4 DESCRIPTION OF THE PROBE

Silicon telescope detectors have been mounted on the normal remote control probe inside one sector of the cyclotron. It can be moved along a radius in the median plane. Fig. 2 shows a schematic view of this probe, it is composed of a ΔE of 300 µm and a E detector of 3.6 mm tick.

Two shielding protect the silicon detectors from the rf and other perturbations. This has the effect that there is a dead zone where no particle are detected for a given radial position. The width of this dead zone is about 2 mm and has no importance since the radial dimension of a pulse in CSS2 is between 5 mm and 10 mm.

In a cyclotron the energy is a function of the radius, $E(r)= dE_0N_t$, where dE_0 is the energy gain per turn and N_t is the number of turns. Fig 3. shows the difference in the phase space of the particles in the isochronous field obtained without this new probe and using it. Fig. 3a shows the phase space obtained just after the prior tuning using a particle having the same A/q ratio as the nucleus of interest. Fig. 3b shows the final phase space using this detector for the fine tuning of the magnetic field.

The precession effect of the beam in the cyclotron combined with the motion of the probe leads to discontinuous spectrum in energy. This effect can be observed in the phase space spectrum of the fig. 3. At given energy there is no count.

5. ESTIMATION OF MASSES

Despite the complexity of the spectra of the secondary ions, they are sufficiently similar from one species to the another that, using one as a calibration, it is possible to estimate the masses of the others. This is clearly visible in fig. 4. Assuming the mass of one nuclei as the reference we are able to derive the masses of the others.

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