An old-new tool for nuclear analysis: Time-of-Flight spectrometry

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The Time-of-Flight (ToF) technique can be used for mass identification, for separation of a specified mass or for measuring the energy of a given mass particle. The instrumentation required is simple and low in cost. The method features high yield, transmission efficiency is typically of 5 to 20%. Even with short flight paths (5 to 10 cm), ToF has adequate mass resolution (M/ΔM ~ 300 to 500) for identifying isotopic species. This paper examines the scope of ToF in nuclear science with examples in mass spectrometry, in mass separation and in kinetic energy measurements of fixed mass particles. An example of the latter is the energy determination of recoil nuclei. If a recoil is produced inside a solid, the residual recoil energy reveals the depth from which it originates. This approach is used for profiling nitrogen via $^{14}$N(n, p)$^{14}$C. The ToF measurement of the $^{14}$C recoil energies reveals the depth distribution of nitrogen with better than 50 Å resolution.

Introduction

The Time-of-Flight, ToF, technique has long been recognized as an inherently powerful concept for mass identification, for isotope separation or for measuring the velocity of a given particle. The performance of ToF depends on the means/instrumentation used for fast pulsing and for the time measurement. Progress over the last two decades, particularly the transition from microsecond to nanosecond measuring instruments, has dramatically expanded the applications of ToF. A telling example is that of mass spectrometry, where ToF has become the method of choice for large molecular mass analysis. The present paper addresses some application of ToF for the qualitative and quantitative assay of isotopic species: the analysis is based on the velocity and hence the energy of transmitted or backscattered ions or of recoiling nuclei from a nuclear reaction. Further a complementary yet potentially interesting application is also briefly examined: the use of ToF for radioisotope separation.

Methodology

It may be recalled that the ToF technique is based on the relationship between the mass, $m$, and charge, $e$, of an ion and its kinetic energy, $E$, acquired by acceleration through a known potential drop, $V$:

$$E = eV = \frac{1}{2}mv^2$$

(1)

where $v$ is the terminal velocity, and thus

$$v = \left( \frac{2eV}{m} \right)^{1/2}$$

(2)

The flight time for an ion of mass, $m$, over a distance, $D$, is then:

$$t = \frac{D}{v} = \left( \frac{m}{2eV} \right)^{1/2} D$$

(3)

The difference in flight times for ions of different mass-to-charge ratios can be used for isotope separation. Alternatively for ions of a given mass their kinetic energy can be determined from the flight time:

$$E = \frac{mv^2}{2} = \frac{m}{2} \left( \frac{D}{t} \right)^2$$

(4)

$$t = D \left( \frac{m}{2E} \right)^{1/2}$$

(5)

The above relationship is used to determine, from the experimentally measured $t$, the energies of backscattered ions or recoiling nuclei.

Isotope separation

The primary advantage of ToF over conventional electromagnetic isotope separation is the high transmission for ions. The term "transmission" denotes the percentage of the ions formed in the source of the
separator which are ultimately collected. Typically in ToF the transmission is in the range of tens of percent vs. a few percent for electromagnetic devices. Ion sources and collectors are common elements to all types of separators. Mass separation is in the case of ToF accomplished in two steps. A schematic outline is provided in Fig. 1. First a pulse or bunch of ions of multiple masses is produced. This may be accomplished by pulsing the ions from a continuously emitting ion source or by a pulsed mode of vaporization/ionization, using a pulsed laser for example. The ions are accelerated to the same voltage and then allowed to drift in a field-free region. They will drift at different velocities depending on their mass-to-charge ratios. Once they are separated in time and space, the mass of interest can be isolated by applying an appropriate voltage on a repeller/extraction grid across a pair of deflection plates. Obviously in this mode of operation only one isotope can be collected at a time. Figure 2 shows as an example the separation of $^{133}$Cs by ToF. The mass resolution ($M/\Delta M$) is over 400 with a transmission estimated at ~20%.\(^2\) It should be noted that these data were obtained more than four decades ago! The progress in fast timing electronics now allows this performance to be matched with a simple, low cost setup. Thus ToF isotope separation appears as an attractive alternative to conventional radiochemical separation of nuclides which are difficult to identify by virtue of their abundance or their decay characteristics. Two considerations will outline the scope of ToF-based radioisotope separation: (1) the species separated is recovered selectively as a shallow implant on a collector plate and is thus in a form suitable for high efficiency $\beta$-counting, and (2) the length of the separation time for maximizing the activity of the collected radioisotope depends on its half-life, $t_{1/2}$, i.e.:

$$A_t = A_0 \cdot t \cdot e^{-t/t_{1/2}}$$

where $A_t$ is the activity collected after a separation time, $t$, and $A_0$ is the activity at time zero. To estimate the separation time it is useful to note that ~80% of the activity is collected for $t = 0.7t_{1/2}$.\(^3\)