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# Concept design of a time-of-flight spectrometer for the measurement of the energy of alpha particles

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## HIGHLIGHTS

- Feasibility study of TOF detector for measurement of alpha particles energies.
- The main components of the system are described.
- The uncertainties that can be expected are discussed and estimated.
- A design is proposed.

## ARTICLE INFO

*Keywords:*
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## ABSTRACT

The knowledge of the energies of the alpha particles emitted in the radioactive decay of a nuclide is a key factor in the construction of its decay scheme. Virtually all existing data are based on a few absolute measurements made by magnetic spectrometry (MS), to which most other MS measurements are traced. An alternative solution would be the use of time-of-flight detectors. This paper discusses the main aspects to be considered in the design of such detectors, and the performances that could be reasonably expected. Based on the concepts discussed here, it is estimated that an energy resolution about 2.5 keV may be attainable with a good quality source.

## 1. Introduction

Knowledge of the energies of the alpha particles emitted in the radioactive decay of a nuclide is a key factor in the construction of its decay scheme. Following an intensive work of measurement and normalization of existing data carried out at BIPM, a catalog containing the energies of alpha particles for many radioactive nuclides was made available (Grennberg and Rytz, 1971; Rytz, 1991).

Virtually all existing data are based on a few absolute measurements made by magnetic spectrometry (MS), to which most other MS measurements are traced. From the side of semiconductor detectors, the pulse height defect prevents obtaining absolute measurements of the energies. An alternative technique based on cryogenic detectors, is being tested for high resolution alpha-particle spectrometry with good results (Leblanc et al., 2006; Horansky et al., 2008; Yoon et at, 2012), although the technique seems to be better adapted to Q spectroscopy of alpha decays (Jang at al, 2012).

An alternative solution based on time-of-flight (TOF) detectors is discussed in this paper. The main aspects to be considered in the design of such detectors are presented. First, some relevant numerical data are calculated, and then the basic elements of a TOF device including start and stop detectors and electronics setup are described. Effects that can limit the system performance, such as flight distance variation, source structure, transmission detector foils and Tandem effect are discussed. Finally, the performance that could reasonably be obtained is estimated. Based on data presented, an energy resolution in the order of 2.5 keV may be attainable.

Although TOF detectors are commonly used in many applications related to light or heavy ions, in particular for Rutherford Backscattering (RBS) (Döbeli et al., 1998) or Elastic Recoil Detection Analysis (ERDA) applications (Siketić et al., 2008; Yasuda et al., 2011; Laitinen and Sajavaara, 2014), only one precedent exists of the use of these devices for the accurate measurement of alpha-particle energies. It was built at VNIIM (D.I. Mendeleyev Institute for Metrology) by Frolov (1982), (1992) and applied to the measurements of the energies of a few radionuclides. Its configuration was slightly different from conventional TOF systems and will be described later.

## 2. Basic concept and some numerical data

The basic concept of a TOF system is depicted in Fig. 1. Alpha particles emitted by a radioactive source pass through the start detector, travel a known distance *d* and arrive at the stop detector. If the flight time, defined as the difference in time stamps generated by stop and start detectors, is accurately determined, the energy of the alpha particle can be determined in an absolute manner.

Alpha particles emitted by radioactive nuclides travel at velocities in the order of 5% of the speed of light in vacuum. Using the relativistic

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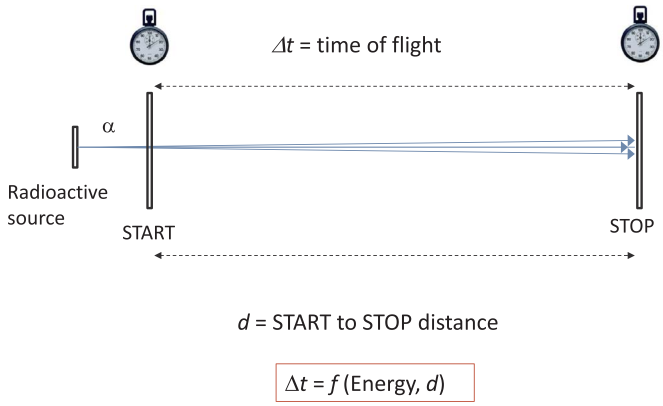


**Fig. 1.** Simplified scheme of a TOF device. Alpha particles emitted by a radioactive source cross the start detector, travel a known distance *d* and arrive to the stop detector. By combining timing information from both detectors, energies of the alpha particles can be calculated.

**Table 1**
Standard uncertainty in the energy determination as a function of the flight distance for alpha particles of 5 MeV assuming a timing uncertainty of 60 ps.

| Fight distance (m) | Flight time (ns) | σ (E) (keV) |
|---|---|---|
| 1 | 64.5 | 2.0 |
| 1.5 | 96.7 | 1.3 |
| 2 | 128.9 | 1.0 |
| 2.5 | 161.2 | 0.8 |
| 3 | 193.4 | 0.7 |

notation, $\beta = v/c$, values range from 0.046 for alpha particles of 4 MeV to 0.057 for alpha particles of 6 MeV. At that speed, a large flight distance is required in order to be able to determine, with enough accuracy, their energies. Table 1 presents flight times and estimated energy uncertainties for alpha particles of 5 MeV assuming a timing uncertainty in the order of 60 ps (Trzaska et al., 2002).

The table shows that, in order to achieve a standard uncertainty in the order of 1 keV, flight distances in the order of meters are required. That, in turn, implies that solid angles subtended by source and detector would be very low, and long counting times will be required to reach the desired counting statistics.

## 3. Basic TOF elements

As depicted in Fig. 1, the basic constituents of a TOF detector are the start or zero timing detector and the stop detector. They must be complemented by an electronic setup which generates the time stamps from which the flight time will be determined.

### 3.1. Start detector

While the structure of the stop detector is subject to many variables depending on the particular application of the spectrometer, start detectors follow, in most cases, the original design from the transmission device proposed by Busch et al. (1980). Light or heavy ions pass through a thin foil (typically made from carbon) and knock out electrons with typical energies of a few eV (Arnold et al., 2014) which are then accelerated in order to be able to produce a valid signal. An electrostatic reflector directs them to a timing device such as a Microchannel Plate (MCP) from which a start signal can be derived. A diagram of the disassembled device is presented in Fig. 2.

Being an essential component of a TOF device, the characteristics of transmission detectors have been thoroughly studied in the literature. Critical aspects are, among others, the composition of the foils, the so-called Tandem effect, the design of electrostatic reflectors and the

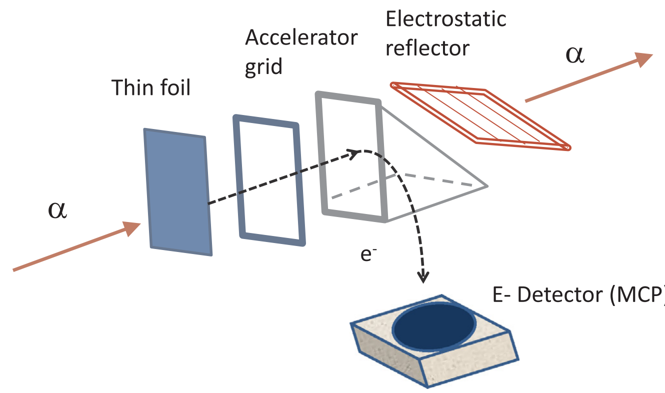


**Fig. 2.** Diagram of a transmission detector, based on the ideas proposed by Busch et al. (1980). As alpha particles go through the C foil, low energy electrons are produced and accelerated. They are then deflected to the microchannel plate detector, from which a timing signal can be obtained.

performances of the electron detectors such as MCPs.

#### 3.1.1. Foil structure and characteristics

The preparation, composition and properties of the foils has been discussed in detail by many authors (Arnold et al., 2014; Laitinen et al., 2014; Yasuda et al., 2011; Ma et al., 2011; Liechtenstein et al., 2002, 2006; Shima et al., 2001). As a general rule, diamond-like or graphite foils are preferred. In some designs, supporting grids with high transmission characteristics have been used (Kottler et al., 2006), but self-supporting foils are generally chosen (Ma et al., 2011).

As Ma et al. (2011) point out, foils can be manufactured by a variety of techniques, such as sputter deposition, pulsed laser ablation, ion beam deposition and plasma enhanced chemical vapor deposition. Shima et al. (2001) describe a complex procedure to produce carbon foils of 2 μg cm$^{-2}$ starting by an evaporation step followed by addition of a layer of polyvinyl formal, later blown away to get the self-supporting carbon foil. Ma et al. (2011) highlight the advantages of using the filtered cathodic vacuum arc procedure for the synthesis of highly transparent and self supporting films. Liechtenstein et al. (2006) describe the preparation of foils as thin as 0.6 μg cm$^{-2}$ by glow discharge sputtering of graphite in a low-density krypton plasma. Ultra-thin foils with dimensions up to 50 × 69 mm are available (ACF-METALS, 2017).

For the reasons that will be discussed next, thinner foils are not necessarily better for the application discussed in this paper. They produce minimum energy loss and straggling to the alpha particle beam, but homogeneity and robustness are also important factors to be considered in the design (McDonald et al., 1999; Ma et al., 2011).

An important effect related to the transmission detectors has been pointed out, among others, by Döbeli et al. (1998) and Laitinen et al. (2014). It is called the “tandem-effect” and refers to the flight time and energy spread caused by the change of the charge state of the particle in the start foil and the resulting variation in the acceleration or deceleration in an electrostatic field. According to Döbeli (1998), this effect can limit the energy resolution of the spectrometer for any kind of ion. Although keeping the whole ion path at a constant electrical potential or grounding the foil potential can make the problem negligible, its effect on alpha particles must be carefully evaluated for the final design of the start detector.

In Armstrong et al. (1965) published a complete study on the equilibrium charge-state of helium ions in carbon. According to their experiments, after a large number of collisions, a homogeneous helium beam becomes “charge equilibrated”, that is reach a definite value for the fraction of helium beam in each charge state. He beams of several energies were scattered by carbon foils and the resulting He ions analyzed to determine their charge state. According to their findings, “charge-state equilibrium is established in traversing the last few fractions of μg cm$^{-2}$ of a real density”. Their measurements also showed