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# The Fission-Fragment Spectrometer VERDI

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**Abstract**

VERDI (VElocity foR Direct particle Identification) is a fission-fragment spectrometer presently under construction at the Joint Research Centre IRMM. It will allow measuring the kinetic energy and the velocity of both fission fragments simultaneously. The velocity information provide information about the pre-neutron mass of each fission fragment when isotropic prompt-neutron emission from the fragments is assumed. The kinetic energy, in complement of the velocity, will provide us with the post-neutron mass. From the difference between pre- and post-neutron masses the number of neutrons emitted by each fragment may be determined. Knowledge of this quantity as a function of the total kinetic energy will contribute to the understanding of how the available excitation energy is shared between both fission fragments at scission. The contemplated pre-neutron mass resolving power, A/ΔA, of at least 126 requires a time-of-flight (TOF) resolution better than 200 ps (FWHM) and an energy resolution, ΔE/E of 0.3% for a post-neutron mass. The VERDI spectrometer provides the best compromise between geometrical efficiency and time of flight. It consists of an electron detector located very close to the fissionable target and a double array of silicon detectors located 50 cm away on both sides of the target. Each silicon detector has an area of 450 mm$^2$ and is made from neutron transmutation-doped (NTD) silicon to reduce rise-time variation, to minimize pulse height defect and to reduce the plasma delay time. The intrinsic timing resolution of the electron detector was determined, using a $^{241}$Am alpha source ($E_\alpha$ = 5.49 MeV), against a previously characterized single-crystal diamond to $\sigma$ = 140 ps. The timing resolution of the NTD silicon detectors was determined using the spontaneous fission of $^{252}$Cf in conjunction with Monte-Carlo simulations to $\sigma_{NTD}$ = 150 ps. With the present timing resolution, $\sigma_{TOF}$ < 210 ps, VERDI is already close to the set goals. The excellent timing properties of VERDI will also permit studying prompt and delayed gamma-ray characteristics.


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## 1. VERDI - the need for a double-velocity, double energy spectrometer

In nuclear fission pairs of fission fragments with different mass and kinetic energy are produced (Wagemans, 1991). This process is accompanied by the emission of prompt neutrons and $\gamma$-rays from highly excited fission fragments (FF). The knowledge of the FF yield-distribution as a function of mass (A) and kinetic energy ($E_k$), Y(A, $E_k$), is a key

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input to fission models and important data to better understand the fission process as such. Fission-fragment properties after prompt-neutron emission form the excited fragments may be obtained by means of different techniques. First, chemical separation of fission fragments gives the mass yield after the FF has decayed to stable isotopes (cumulative yield) (Herrmann and Trautmann, 1982). Next, by measuring with a recoil mass separator (Mol eta l., 1977) or measuring the time-of-flight together with the kinetic energy (Oed et al., 1984), single fission fragment yields after prompt-neutron emission may be obtained.

Employing the double-energy (2E) method, fission-fragment yields after the instant of scission and prior to neutron emission, the so-called pre-neutron mass distributions, may be obtained, provided prompt neutron emission data are available for the iterative determination of the fragment mass (Budtz-Jørgensen et al., 1987; Vivès et al., 2000; Birgerson et al., 2009). Since from most actinide nuclei, even for uranium and plutonium isotopes, no or very limited neutron data is available, inter- or even extrapolation from the few cases, where those data exist, has to be used. This procedure may severely affect the quality of the obtained FF yield data (Al-Adili et al., 2012).

With the emerging new power reactor concepts of the $4^{th}$ Generation there is a call for new fission yield measurements in the fast-neutron energy region and for a more accurate assessment of correlations between fragment properties, with respect to e.g. mass yield and kinetic energy as well as prompt neutron and $\gamma$-ray emission.

One way to avoid ambiguities introduced in the data analysis by the applied neutron corrections is to measure not only the two fragment kinetic energies, but simultaneously the fragment velocities as well. Theoretically, from a double-velocity (2v) measurement both fragment masses before prompt-neutron evaporation may be obtained, provided the compound nuclear mass ($A_{CN}$) is known and isotropic neutron emission from fission-fragments is assumed. The subsequent measurement of the fragment energies, together with the measured velocity, provides the information about the fission fragment mass after prompt-neutron evaporation. The difference of pre- and post-neutron masses is just the number of evaporated prompt neutrons $\nu$. In such a way, those important neutron data need no longer to be introduced in the data analysis. Moreover, the emission yield may be directly deduced as a function of fragment mass and total kinetic energy, i.e. total excitation energy TXE.

VERDI will allow validating the 2E-method and the applied prompt-neutron correction to determine fission-fragment mass. It will contribute to the study of the sharing of excitation energy among the fission fragments by measuring the evolution of neutron multiplicities as a function of fragment mass and of the incident neutron kinetic energy.

Such a double time-of-flight and energy spectrometer had already been realized in the 1980s at the Institute Laue Langevin and was called Cosi-Fan-Tutte (Oed et al., 1984). The spectrometer was based on micro-channel plate (MCP) detectors as start and stop trigger devices and ionization chambers to measure fission fragment kinetic energies. With an impressive mass resolution $\Delta$A well below 1 mass unit, it suffered from a very small geometrical efficiency of about $4 \times 10^{-5}$ (Boucheneb et al., 1991). Therefore, correlated FF-yield measurements were strongly affected by the non-collinearity of FF emission due to prompt neutron emission. Today the spectrometer does no longer exist.

Presently, a double (v, E) spectrometer is being built at the Joint Research Centre IRMM (Oberstedt et al., 2010), which aims at a FF mass resolution $\Delta A < 2$ u in conjunction with a geometrical acceptance of at least $5{\times}10^{-3}$, i. e. with an about 100 times larger efficiency than Cosi-Fan-Tutte. In the following we explain the concept, the design and the characterization of the basic components of the spectrometer.

## 2. VERDI - the design

The determination of fragment masses created in neutron-induced fission is commonly performed by means of double-energy (2E) measurements with twin Frisch-grid ionization chambers. Such a device has several features that makes it very suited for neutron-induced reaction studies, such as high geometrical efficiency of nearly $2\pi$, high resistance to radiation and light weight. The general idea behind the data analysis is based on momentum conservation. However, with an ionization chamber it is not the velocity of each fragment that is measured but the kinetic energy after neutron emission. Unfortunately, many important approximations to correct for prompt neutron evaporation, and

the pulse-height defect in the counting gas, have to be done during the mass determination process, which results in a very limited mass resolution, typically not better than $\Delta A = 4$ u.

The best way to avoid neutron-emission corrections is to measure directly the time-of-flight (TOF), i.e. the velocity, of the two fragments. With the assumption that the average velocity of a fragment is kept after the emission of neutrons, it is then possible to directly apply momentum conservation to calculate the pre-neutron mass of both fragments:

$$A_1^* = \frac{v_2}{v_1 + v_2} A_{CN} \tag{1}$$

$$A_2^* = A_{CN} - A_1^* \,. \tag{2}$$

This approximation is valid as long as no scission neutrons are emitted, and the excitation energy of the compound nucleus remains below the neutron-emission threshold ($2^{nd}$ chance fission). If, subsequently, the kinetic energy of the fragments is measured, calculation of the fragment mass after neutron emission, the post-neutron mass, is possible as in any TOF spectrometer. As a bonus, since we know both pre-neutron and post-neutron mass, it is possible to calculate the average number of neutrons emitted by each fragments by computing the difference between the pre-neutron and post-neutron mass. The prompt neutron multiplicity can then be investigated event-wise as a function of fragment mass and kinetic energy, which is a measure for the total excitation energy of the fission fragments.

The design of VERDI is dominated by the timing resolution of the time pick-up and the pulse-height resolution of the energy detector, which are the primary parameters determining the mass resolution of the spectrometer:

$$\frac{\Delta A}{A} = \sqrt{\left(\frac{\Delta E}{E}\right)^2 + 4\left(\frac{\Delta t}{t}\right)^2 + 4\left(\frac{\Delta d}{d}\right)^2} \,. \tag{3}$$

For pre-neutron mass determination only the second term on the right-hand side of the equation contributes to the final mass resolution.

In general, micro-channel plate (MCP) detectors are used when the focus is put on a high timing resolution as it was done in Cosi-Fan-Tutte (Oed et al., 1984). However, back then those detectors had been placed outside the well-collimated thermal neutron beam for reducing the possible risk of radiation damage to the MCP and, as a consequence, also limiting strongly the geometrical efficiency. Another limitation to the geometrical efficiency came from the use of an ionization chamber as energy detector, which requires a thin and highly uniform entrance window. This is very difficult to obtain for areas larger than a few square centimeter, heaving led to the limitations of Cosi-Fan-Tutte as discussed before. In order to achieve a higher efficiency for such a design the energy-loss and straggling in two emissive foils and the entrance window may contribute to the deterioration of the mass resolution.

During the design study for VERDI an attempt is made to find an optimum compromise between the different parameters. In order to allow for a larger opening angle, first the time pick-up device, which triggers the instance of fission, should be placed as close as possible to the target under investigation. In VERDI such a time pick-up is realized by using the support foil of the actinide deposit itself as electron-emissive foil. The energy detector will serve also as time pick-up for TOF determination relative to the instance of fission. As a consequence one fission fragment loses energy only in the residual target layer (usually $< 120\ \mu g/cm^2$) and the entrance window of the energy detector. Here we opt for neutron-transmutation doped silicon detectors with a dead layer smaller than 500 Å. For the complementary fragment additional energy loss and straggling will come only from the arial density of the polyimide backing ($\approx 33\ \mu g/cm^2$) and the gold layer of $50\ \mu g/cm^2$, deposited for electrical conductivity. The flight path length is 50 cm, and the fragments will travel in vacuum at a pressure of $10^{-7}$ mbar.

The NTD silicon material used for energy and time measurement provides a higher homogeneity of the dopant, which allows applying a substantially higher electrical field. This should serve for a better charge separation and for minimizing the so-called plasma effect created by highly ionizing particles like fission fragments. An intrinsic timing resolution well below 200 ps may be expected (Canberra, 2014) together with a pulse height resolution better than 0.5%.

The left-hand side of Fig. 1 shows a simulated pre- (post-)neutron mass distribution from the spontaneous fission of $^{252}$Cf, that may be expected to be measured with VERDI assuming a coincidence timing resolution of 200 ps and

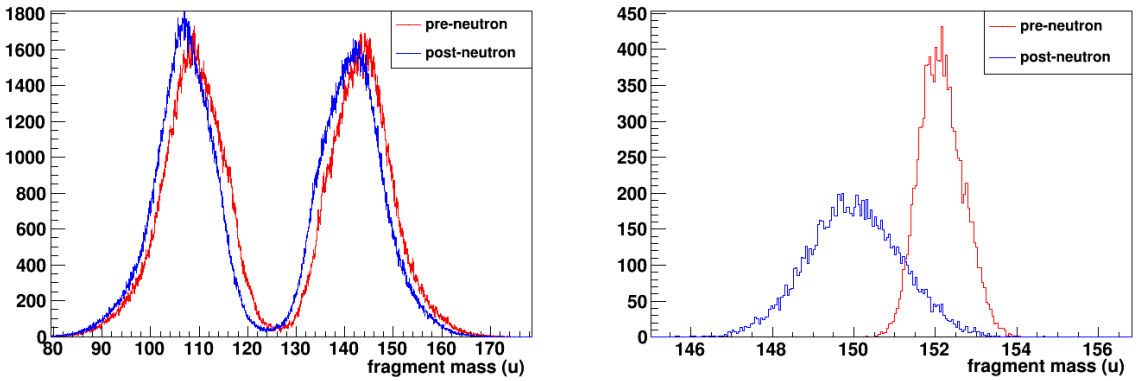


Fig. 1. (Color online) Left: Simulation of pre- and post-neutron fission fragment mass distribution of $^{252}$Cf, depicted as red and blue lines, respectively; Right: Simulated distribution for A = 152, only (red), and the corresponding post-neutron distribution (blue) simulating event-wise prompt-neutron evaporation into account. For further details see text.

a pulse-height resolution of 0.3%. The right-hand side depicts the same simulation for fragments with mass A = 152 u, only. The pre-neutron mass resolution $\Delta A$ = 1.2 u (FWHM) and the post-neutron mass resolution $\Delta A$ = 3.2 u (FWHM), taking event-wise prompt-neutron evaporation into account.

## 3. VERDI - characterization of its components

In the following we describe the characterization of both the MCP-based FIssion Electron Tof Start detector (FIETS) and the NTD silicon detector.

### *3.1. The electron time pick-up detector*

The FIssion Electron Time-of-flight Start detector (FIETS) uses electrons ejected from an emissive foil when passed by a fission fragment. Here the target/backing acts as the emissive foil itself. The electrons are accelerated and deflected by an electrostatic mirror into the micro-channel plate (MCP). The signal created and amplified in the MCP provides the time reference for the TOF measurement.

In order to minimize the velocity speed of the ejected electrons the target is biased to - 3000 V. A grid at ground potential is place at a distance of 4 mm on each side of the target. The electrons, when crossing the grid have a mean energy of about 3 keV and an average velocity vector normal to the target surface. The grids are composed of 50 $\mu$m tantalum wires with a pitch of 1 mm giving a transmission of 95%. The target and the grids are held together by ceramic pieces ensuring electrical insulation, mechanical stability and low outgassing. The target holder also includes a screen to avoid direct emission of fission fragments or $\alpha$-particles in the direction of the MCP. Another component of the detector is the electrostatic mirror. It is used to bend the electrons into the direction of the MCP located perpendicular to the detector axis, 40 mm downstream and 65 mm away from the axis. It is composed of two parallel grids similar to those used for the acceleration of the electrons. The grids have a diameter of 115 mm and are separated by 20 mm. They are inclined by an angle of 45° relative to the detector axis and have a transmission of 86%. The electrons are finally detected by a DDL40 MCP detector and read out by a double delay-line provided by Roentdek (RoentDek, 2014). It allows determining the emission position of the electrons and their arrival time.

The timing resolution was first tested relative to a previously characterized single-crystal CVD diamond detector, with an intrinsic timing resolution of $\sigma_{int}$ = 100 ps (Frégeau et al., 2015), using $\alpha$-particles from a ultra-thin $^{241}$Am source. The source was placed 12 mm behind a PI film with an areal density of 33 $\mu$g/cm$^2$ and a gold deposit of 50 $\mu$g/cm$^2$. The $\alpha$ particles had then to cross the foil before being detected by the diamond detector 50 cm

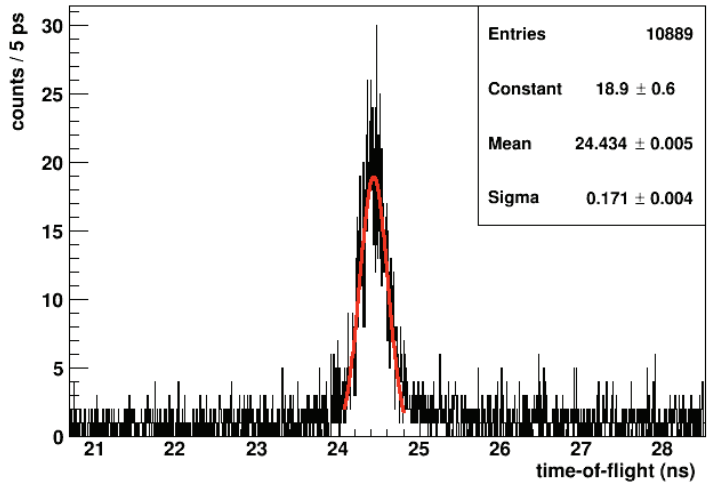


Fig. 2. (Color online) Time-of-flight measurement with the FIETS detector in conjunction with a single-crystal diamond detector at a distance of 50 cm. The peak corresponds to the TOF of an $\alpha$-particle with energy $E_\alpha$ = 5.5 MeV from a ultra-thin $^{241}$Am source (black). The TOF resolution is determined with a Gaussian fit (red).

away. This test setup, except that the radioactive source is not deposited on the emissive foil, corresponds to the contemplated configuration of VERDI. The resulting time-of-flight spectrum is depicted in Fig. 2. The coincidence timing resolution, FIESTS and diamond detector, was determined by a Gaussian fit (red line) to $\sigma_{conic}$=170 ps. After quadratic subtraction of the intrinsic timing resolution of the diamond detector we obtain the corresponding intrinsic timing resolution for the FIETS detector, $\sigma_{int}$ = 140 ps.

### *3.2. The silicon detector array*

The silicon detectors are located at 50 cm from the target on a holder having the shape of a portion of a sphere centered on the target ensuring that every detector is located at the same distance from the target. Each single detector is a circular neutron transmutation doped (NTD) timing-optimized PIPS detector (Canberra, 2014) with a surface of 450 mm$^2$. This diameter introduces an uncertainty on the TOF distance of less than 0.12% and may be neglected.

With the compact design of our FIETS detector up to $2 \times 32$ energy detectors may be used providing a geometrical efficiency of almost 1%, i. e. more than 100 times higher than with Cosi-Fan-Tutte (Boucheneb et al., 1991).

A first test of the timing resolution achievable with the NTD PIPS detectors was perform with a $^{252}$Cf source evaporated on a 250 nm thin nickel foil and mounted, with a distance of only 1.8 mm, very close to the diamond detector, discussed in the previous section. The fragment detected in the diamond was used as a stop for the TOF measurement. The complementary fragment was detected by the silicon detector located 87 mm away from the spontaneous-fission source. The corresponding TOF spectrum is shown by the the black points Fig. 3, while the colored lines represent TOF distributions calculated by means of Monte-Carlo simulation. The simulations are based on experimental data for the mass and energy distribution of fission fragments, obtained by the 2E-technique (Hambsch and Oberstedt, 1997), and Gaussian broadening to simulate the effect of the timing resolution. The timing resolution of the diamond detector was fixed, $\sigma_{CVD}$ = 100 ps, while the timing resolution of the silicon detector, $\sigma_{NTD}$, was varied in the different simulations.

By means of $\chi^2$ minimization between experimental and simulated data the best reproduction is achieved when assuming a intrinsic timing resolution $\sigma_{NTD}$ = 150 ps. Due to a non-negligible time jitter caused by the TOF difference

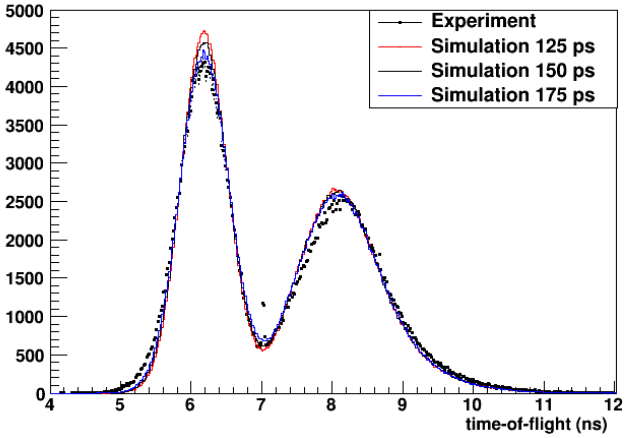


Fig. 3. (Color online) Time-of-flight distribution for the fission fragments from the spontaneous fission of $^{252}$Cf measured by a diamond detector and a silicon detector. The Monte-Carlo simulations were used to estimate the timing resolution of the detector (see text for details).

of fission fragments detected by the diamond detector, it was not possible to evaluate pulse height defect and the contribution of the plasma-delay.

## 4. Conclusion

The main components of the VERDI fission-fragment spectrometer are now constructed and their properties characterized. The timing resolution of the FIETS detector was determined to $\sigma$ = 140 ps, and the neutron-transmutation doped silicon detector shows a similar performance, i.e. $\sigma$ = 150 ps. An improved signal-to-noise ratio might lead to further improvement. The present timing resolution of VERDI is $\sigma$ = 205 ps. This timing resolution is very close to the design specifications as presented in our simulations (cf. Fig. 1). It may, therefore, be expected to achieve a pre-neutron mass resolution close to 1 amu (FWHM), which will allow benchmarking the 2E-technique. First 2E-2v measurements on the spontaneous fission of $^{252}$Cf with 16 silicon detectors on each TOF section will be performed during the first months of 2015. In the ultimate configuration, with a slight increase of the TOF distance, the number of detectors may be increased to 64, covering almost 1.5% of $2\pi$.

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