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S. Pullanhiotan [a,b,*] , A. Chatterjee [a,c] , B. Jacquot [a] , A. Navin [a] and M. Rejmund [a]

[a] *Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM - CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen, France*

[b] *Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi, 110067, India and Dept. of Nuclear Physics, Andhra University, Visakhapatnam-530003, A.P, India.*

[c] *Nuclear Physics Division,Bhabha Atomic Research Centre, Mumbai, 400085, India*

Abstract

The VAMOS spectrometer at GANIL is a large acceptance magnetic spectrometer employing a trajectory reconstruction technique to identify the reaction products. The spectrometer when coupled with the EXOGAM clover array provides a powerful tool for the spectroscopy of very weak reaction channels. Parameters are reconstructed using a numerical procedure with a polynomial relationship between the measured final coordinates and the quantities of interest. The coefficients of this polynomial function are determined from a numerical fit to the data generated from ray-tracing calculations using the ion optics code ZGOUBI. To reconstruct each parameter, a single polynomial is used with a set of coefficients that are valid across the full accepted phase space of the spectrometer. To further improve upon the reconstruction method, we developed an alternate procedure for reconstruction based on selecting an optimum set of trajectories and interpolating the data within these trajectories. For each detected event, a set of coordinates lying close to the measured trajectory are selected from the database and the target parameters of interest are determined by polynomial interpolation. The results for the reconstructed parameters using the two methods are presented.

Key words: Magnetic spectrometer, trajectory reconstruction
PACS: 07.55.-w, 29.30.-h

1. Introduction

The VAMOS spectrometer is a large acceptance ray tracing spectrometer [1] used for selecting the reaction products from heavy ion reactions using both, the direct beams from the GANIL cyclotrons and the SPIRAL [2] beams. It consists of two large aperture quadrupoles, an $E \times B$ Wien filter and a large magnetic dipole configured to operate in different ion optical modes. Depending upon the kinematics of the reaction, the operating mode of VAMOS can be varied to optimize different requirements. In the mass dispersive mode operation, the spectrometer selects and separates the reaction products according to the momentum to charge($\frac{p}{q}$) ratio and their unique identification is achieved via event-by-event reconstruction of ion trajectories in magnetic fields. When operated as a velocity filter at zero degrees, the spectrometer physically separates the reaction products from beam backgrounds and transports them to the focal plane. The spectrometer has an angular acceptance ranging from -125 mrad to +100 mrad in horizontal plane and a momentum acceptance of $\pm 5\%$(at 25 msr solid angle). The main operational features of the spectrometer are listed in table 1 and detailed specifications can be found in Ref [1].

The large acceptance of the spectrometer induce significant image aberrations in the focal plane of the spectrometer making it practically difficult to resolve the mass spectrum by direct position measurement alone. It is essential to employ trajectory reconstruction to determine the particle momentum and scattering angles from the measured final coordinates. In VAMOS, event reconstruction is implemented using numerical methods that relate the final coordinates to the initial parameters by polynomial functions. The unique identification of reaction products is achieved by combining the reconstructed parameters (magnetic rigidity $B\rho$ and path length l) with measured quantities such as time of flight (TOF), energy (E) and energy loss (ΔE) obtained from focal plane detectors. VAMOS coupled with a high efficiency γ detector array EXOGAM [3], has been used in a recent experiment to identify the γ ray transitions belonging to very neutron rich nuclei produced in deep inelastic reactions [4]. Using kinematic reconstruction of the velocity and emission angle at the target, the

* Corresponding author
Email address: sugathan@iuac.ernet.in (S. Pullanhiotan).

Table 1
Operational features of VAMOS for dispersive mode operation

Horizontal Acceptance	−125 mrad to +100 mrad
Vertical Acceptance	±160 mrad
Momentum Acceptance	±5 %(at 25 msr)
M/q resolution	∼ 0.6 %
Maximum rigidity Bρ	1.6 T-m
Deflection Angle	0°- 60°(*variable*)
Flight Path length	760 cm
Linear Translation	40 to 120 cm
Angular rotation	0° to 60°

coincident γ-rays are Doppler corrected resulting in an improved resolution of the individual states in final nuclei.

Recently a new approach has been attempted in VAMOS to further improve upon its reconstruction results. The reconstruction methods and its application to identification of reaction products from experimental data is presented in this paper.

2. Focal plane detector setup for VAMOS

The VAMOS spectrometer has a versatile detection system suitable for both light fast particles having energy around 2-20 MeV/u (direct reactions) and heavy slow particles having energy less than 2 MeV/u (fusion reactions). The focal plane detector system consists of a pair of two dimensional position sensitive tracking detectors, followed by multi segmented ionization chamber and an array of Silicon detectors measuring the particle coordinates(x,y), energy loss(ΔE) and energy(E) respectively. Two kinds of position sensitive detectors are used in VAMOS. For light ($Z < 15$) ions with high energy ($E > 2$MeV/u), low-pressure drift chambers are used. The drift chambers have a x and y position resolution of 0.3 and 1 mm (FWHM) respectively. For heavier and slower ($E < 2$ MeV/u) ions, position sensitive detectors based on secondary electron detection (SED) [5] are used.

Fig. 1 shows a typical focal plane detection setup used in dispersive mode operation. A pair of identical drift chambers [6] separated by 1 m measure the horizontal (x) and transverse (y) position of the particles passing through it. The measured x, y coordinates in two planes are used to compute the angle of the trajectory and its projection onto an "image plane" located between the two detectors. A large area SED detector mounted between the drift chambers is used to obtain fast timing and trigger signals. The second drift chamber is followed by a 30 cm deep segmented anode ionization chamber which measures the differential energy loss(ΔE) of the particles. An array of silicon detectors mounted behind the ion chamber is used to stop the particles, giving residual energy(E) and an additional time measurement. The charge Z identification is achieved by the standard method of combining the differential energy loss and residual energy from the detectors. The time

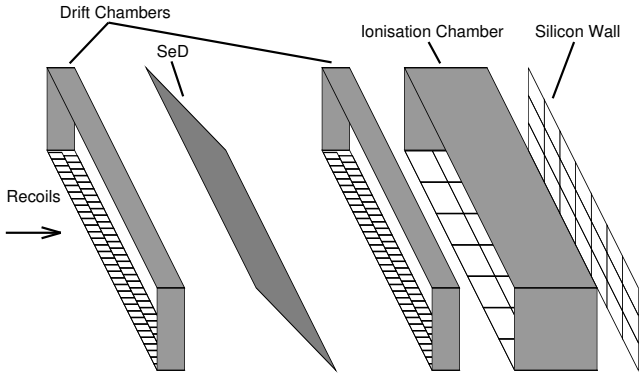

Fig. 1. Schematic of VAMOS focal plane detection setup used in Deep inelastic transfer reactions.

of flight (TOF) is recorded between the beam pulse radio frequency(RF) and the SED as well as between the SED and silicon. In experiments where low energy heavy recoils are to be detected, the two drift chambers are replaced by a pair of identical SED providing x, y position and time of flight signals.

3. Event Reconstruction in VAMOS

VAMOS is a "software spectrometer" employing trajectory reconstruction technique [7,8] to determine the momentum and scattering angles of detected particles. The reconstruction method used in VAMOS is based on two independent steps: trajectories simulation and reconstruction algorithms.

3.1. *Step 1: Trajectories Simulation and Tracking codes*

The modeling of ion trajectories in an optical systems is generally realized by two approaches. The first approach relies on a transfer map calculation which relates the initial coordinates to the final coordinates of a trajectory. The corresponding transfer map may be represented with a Taylor series of given order computed for some predefined optical object (TRANSPORT [9], GIOS [10]). Codes using a differential algebraic method even allow the computation of the transfer map up to an arbitrary order(COSY INFINITY [11]). The second approach uses multi-particle tracking codes based on the numerical integration of Newton-Lorenz equation for individual particles in a set of analytical field models (ZGOUBI [12], RAYTRACE [13]). In the case of VAMOS spectrometer, the complexity of the quadrupoles (a pole shim in Q2 induces field corrections up to fifth order) prevent the usage of the standard and predefined field model proposed in most of the codes. The precise computation of trajectories can only be done with a very accurate field model. The trajectories in VAMOS are reconstructed using the field maps obtained during the magnet design(generated with the 3D electromagnetic computation code TOSCA [14]) in combination with the ZGOUBI multi-particle tracking code. ZGOUBI offer different op-

tions for the treatment of field maps including both 2D and 3D lattices of field values. The accurate description of the VAMOS spectrometer in a given mode is simulated by ray-tracing a set of 20000 trajectories covering the full acceptance and storing their initial$(\delta, x_i, \theta_i, y_i, \phi_i)$ and final coordinates $(x_f, \theta_f, y_f, \phi_f, l)$. For a given trajectory the parameters x and y corresponds to the two transverse distance from the reference trajectory, θ and ϕ refers to the inclination angle in horizontal and vertical planes. The parameter $\delta = (p - p_0)/p_0$ defines the fractional momentum deviation from the reference momentum and l, the difference in path length between the given and the reference path. The subscripts 'i' and 'f' here refer to the parameters corresponding to initial and final space respectively. In all calculations, the nominal image plane considered is an arbitrary plane normal to the reference trajectory and located midway between the two drift chambers. The four parameters $x_f, \theta_f, y_f, \phi_f$ are determined on this image plane by projecting the position and angle measurement from two drift chamber detectors.

3.2. *Step 2: The reconstruction algorithm*

In a spectrometer, generally the determination of momentum(or mass) is directly obtained from the particle position, recorded with a detector in the dispersive focal plane. In a large acceptance spectrometer such as VAMOS, the non-linearity make the extraction more involved. The particle momentum is to be reconstructed from the measured four final coordinates (two position x_f, y_f and two angles θ_f, ϕ_f) using mathematical transformations. The reconstruction algorithm employed in VAMOS uses a numerical procedure that calculates a polynomial relationship between the four final coordinates and the quantities to be reconstructed (δ, l, θ_i, ϕ_i) [15]. For each detected particle, the parameters that are to be be reconstructed are expressed as the following set of polynomial functions:

$$\begin{aligned}
\delta &= F_1^N(x_f,\ \theta_f,\ y_f,\ \phi_f) \\
\theta_i &= F_2^N(x_f,\ \theta_f,\ y_f,\ \phi_f) \\
\phi_i &= F_3^N(x_f, \theta_f, y_f,\ \phi_f) \\
l &= F_4^N(x_f,\ \theta_f,\ y_f,\ \phi_f)
\end{aligned} \tag{1}$$

where N is the order of polynomial(7^{th} order in the present case). As an example, the expression for δ is written as:

$$\delta = \sum_{i,j,k,l=0}^{i+j+k+l=7} C_{ijkl}\ x_f^i \theta_f^j y_f^k \phi_f^l \tag{2}$$

where the coefficients C_{ijkl} are related to the transfer map of the spectrometer. These coefficients are determined off-line, from fitting polynomials to the set of trajectories computed by ZGOUBI. Due to the mid plane symmetry in the magnet, the coefficients in Eq. 2 are null for odd values of $k+l$ and only the remaining relevant coefficients are considered for reconstructing the δ parameter. This method of reconstruction uses a universal set of coefficients to reconstruct all trajectories across the full acceptance window of the spectrometer. It is difficult to get a clear idea, if these polynomials have sufficient precision over the full region of phase space. The merit function χ^2 gives only a feeling of the quality of the fit on an average.

In order to reduce the complexity of the problem it is possible to decompose the full acceptance of the spectrometer into N smaller bins and use a set of piece-wise lower order polynomials locally. We have tested a different algorithm for reconstructing trajectory parameters in VAMOS using a third order polynomial interpolation within a subset of trajectories selected close to the region of interest. The method of reconstruction is implemented through the following steps.

a) For each detected particle, the measured data $(x_m, \theta_m, y_m, \phi_m)$ in the image plane is compared with the set of trajectories from ray-tracing calculation to select an optimum number (~ 125) of nearest trajectories. The criteria for selecting the nearest trajectories is based on the minimum squared distance D to the points where $D^2 = \alpha_1(x_m - x_f)^2 + \alpha_2(\theta_m - \theta_f)^2 + \alpha_3(y_m - y_f)^2 + \alpha_4(\phi_m - \phi_f)^2$. The choice for the number of trajectories and weight factors α_i are optimized empirically by determining the best χ^2 fit for the reconstructed parameters with least computation time.

b) Only those selected nearest trajectories are used to obtain the coefficients of local third order polynomial functions for δ, θ_i, ϕ_i and l independently.

c) The required reconstructed parameters are then obtained using Eq. 1.

This method has the advantage of avoiding the global fitting procedure involving several hundreds of coefficients. Coefficients of these piece-wise polynomials can be stored, or can be recomputed for each trajectories on event by event basis.

For a complete identification of the reaction products, the following basic relations between $B\rho$, measured energy (E_{tot}) and particle characteristics(mass number M, velocity v and atomic charge state q) are used.

$$\begin{aligned}
\frac{M}{q} &= \frac{B\rho}{3.105 \times \beta} \\
M &= \frac{2E_{tot}}{931.5 \times \beta^2}
\end{aligned} \tag{3}$$

where E_{tot} is total energy in MeV, $B\rho$ in T-m, and $\beta = v/c$.

Fig. 2 shows a comparison of the reconstructed m/q spectrum using the two approaches: a global fitting procedure using 7^{th} order polynomials (a) and the reconstruction procedure using a local third order polynomials whose coefficients have been adjusted for the nearest trajectories. The data shown here correspond to quasi-elastically scattered target like recoils in the reaction $^{238}U + ^{58}Ni$ at 1.3 GeV energy [16]. Though the second method is computationally

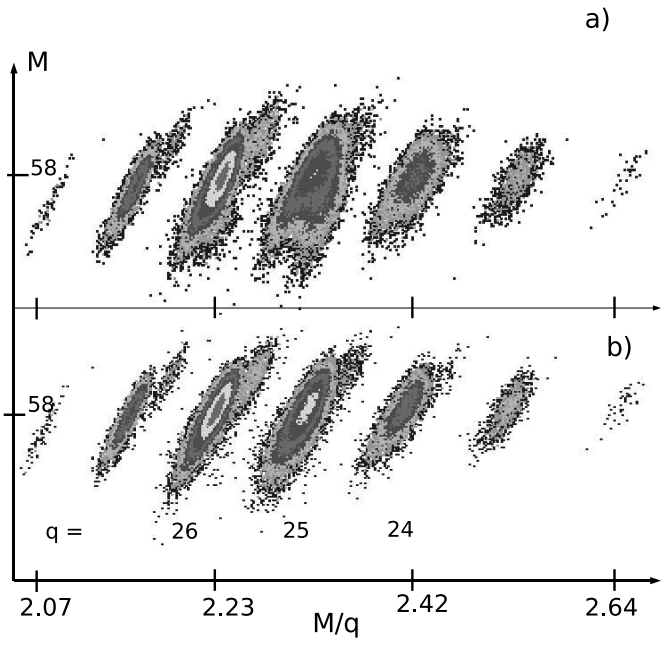

Fig. 2. The M (mass) of the recoils plotted as a function of $\frac{M}{q}$ for different charge states. a) using a 7^{th} order polynomial function with set of coefficients obtained using data across the full phase space; b) using a local third order polynomial for a selected set of trajectories. (See text).

more intensive, it yields improved results as seen in Fig. 2. An improvement of the experimental $\frac{M}{q}$ resolution(8% improvement in FWHM) could be achieved in the present data. The advantages of the second method are of operational interest, since it is clear that the first method (a) could be improved by selecting the coefficients more carefully or/and improving the quality of the fit with a bigger set of computed trajectories. However a systematic checking of the quality of large order polynomials over the whole acceptance of the spectrometer could be difficult. The second method, appears to be well adapted in the context of the flexible operation of the spectrometer and can improve the VAMOS resolution when required. Further improvements may be obtained by employing alternative methods for the reconstruction as proposed in the literature [17–19].

Apart from determining the particle momentum, the initial angles of the particles are also determined by reconstruction methods. Fig. 3 shows the results of reconstruction applied to determine the initial angles of well defined trajectories using a sieve slit (1 mm thick collimator) placed in front of the magnetic aperture of first quadrupole(Q1) of VAMOS. The slit contained a pattern of pin holes (11 x11) defining a set of well defined trajectories with known angles (37 mrad between holes) in θ, ϕ. Elastically scattered ^{58}Ni passing through the slit were detected in the focal plane detectors and their final coordinates at the image plane were determined from the drift chamber measurements. For each scattered particle passing through individual sieve-holes,

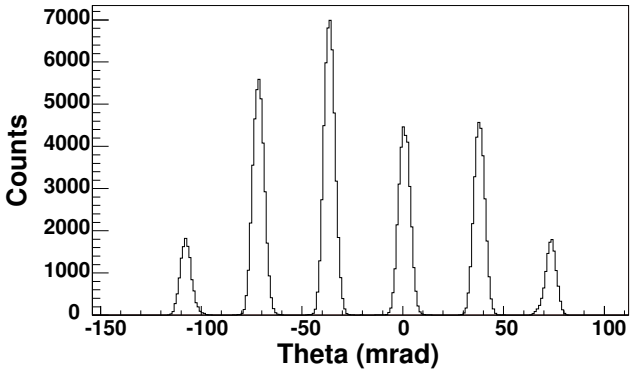

Fig. 3. The reconstructed horizontal angle θ of holes in sieve slit. The slit contained a pattern of pin holes separated by an angle of 37 mrad.

its initial angles were reconstructed from the measured final positions and angles and compared with the calculated angle of the trajectory. The figure shows the reconstructed angle θ (horizontal plane) for the trajectories through the collimator. The results shows a close agreement between the reconstructed angles and the real angles of the sieve-holes suggesting that the reconstruction method can be applied to determine the scattering angles of the particles to reconstruct the kinematics of the reaction.

4. Experimental Results

In this section we illustrate the application of trajectory reconstruction and identification method using the first approach (using 7^{th} order polynomials) to the identification of nuclei formed in deep inelastic transfer reactions. The experimental setup consisted of the VAMOS spectrometer coupled to the high efficiency γ-detector array EXOGAM.

The experimental data shown are taken from Ref [4] using a ^{238}U beam at 1.3 GeV energy bombarding an isotopically enriched 1 mg/cm^2 thick ^{48}Ca target. The resulting target-like recoils from deep inelastic transfer processes were detected and identified in the VAMOS spectrometer. The spectrometer was rotated at 35°(around the calculated grazing angle) with respect to the beam direction. VAMOS was operated in the mass dispersive mode with magnetic fields set for mass $M = 52$ with charge state $q = 19^+$ and energy $E = 430$ MeV optimizing the yield for ^{52}Ca like products. At the image plane the reaction products were characterized by an event by event measurement of the final coordinates$(x_f, \theta_f, y_f, \phi_f)$, energy loss ΔE, energy E and time of flight TOF

For each detected particle, the magnetic rigidity $(B\rho)$, path length (l) and initial angles (θ_i, ϕ_i) were determined by reconstruction method and reaction products were identified using the values of $M, M/q$, v and energy loss (ΔE)

The resulting identification spectra is shown in Fig. 4 which displays the two dimensional image of the energy loss (ΔE) plotted as a function mass over charge 'M/q'. As seen in the figure, unambiguous identification of target like

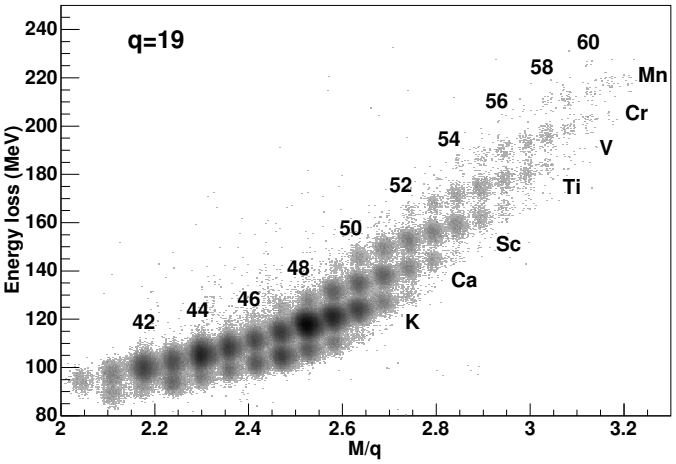

Fig. 4. Identification plot displaying ΔE plotted as a function of M/q, showing an unambiguous identification of the products. The spectrum shown here is generated by gating on the charge state q = 19.

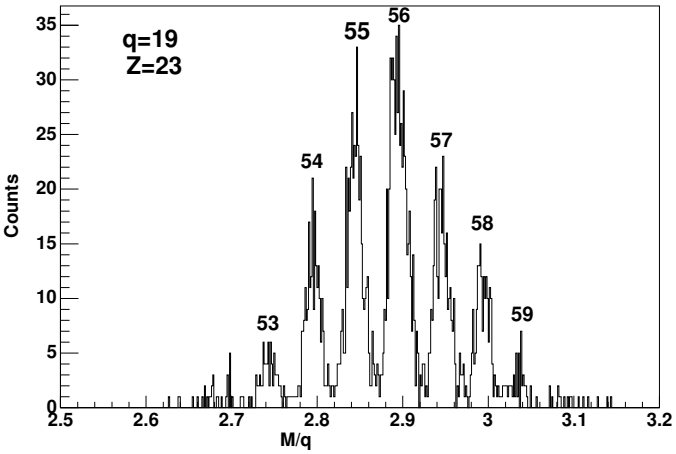

Fig. 5. The reconstructed mass spectrum of the Vanadium isotopes.

residues with $Z \geq 19$ could be achieved by gating on charge state q =19. The data shown here are selected by a particular silicon detector covering only a small region of the focal plane. By software gates on a particular Z, the corresponding mass spectra are generated as shown in Fig. 5 which shows the mass spectrum belonging to *Vanadium* isotope (Z=23). All these measurements were done with a TOF resolution of ~ 2 ns mainly limited by the time resolution of the beam pulsing. More details on the experimental results are given in Ref [4].

5. Conclusions

The VAMOS spectrometer is now fully operational at GANIL and uses trajectory reconstruction method for complete identification of the reaction products. Two different algorithms have been developed and compared for trajectory reconstruction. The method using polynomial interpolation using a subset of selected trajectories shows improved resolution compared to that using a single polynomial across the full phase space. Results from recent experiments showed that the reconstruction and identification procedures used in VAMOS are capable to unambiguously identify products. High sensitivity and selectivity of the spectrometer coupled with the EXOGAM detector array proved successful in identifying and assigning gamma ray transitions in exotic nuclei.

6. Acknowledgment

The authors are thankful to the GANIL team for their excellent support in operating the facility. They would also like to thank various colleagues for help and insightful discussions. This work has been founded by the European Commission under contract 506065 (EURONS/INTAG).

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