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CAMAC-controlled system for the measurement of ion mobilities

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Abstract An electronic measuring system to determine ion time-of-arrival spectra in drift tubes is described. The system consists of a CAMAC crate interfaced to a minicomputer. An instrument with a great adaptive power, wide range of acceptable drift times and very short dead time has been realised. The circuitry and computer program used to perform the measurement are described, as well as the performance of the system.

1 Introduction

Although ion mobilities and ion–molecule reactions in the gas phase have been studied extensively in the past, the interest in this field has grown due to the importance of these phenomena for atmospheric physics and chemistry. Several experimenters (McDaniel 1970, McDaniel and Mason 1973, McFarland *et al* 1973) working in this area use the well developed techniques of drift tubes, which are described mainly by McDaniel (1970, 1973). In such experiments, measurements are made of the time-of-arrival spectrum of an ion swarm, which moves under the influence of a uniform electric field through a gas at pressures of the order of some micrometres of mercury to several Torr (some tenths of a pascal to several hundred pascals).

For the measurement of the time-of-arrival spectra, either commercial multichannel analysers (in the multichannel scaling (MCS) mode) or specially designed time-of-flight systems (Albritton 1967) are used. Commercial multichannel analysers have the disadvantage of limited resolution (typical minimum dwell time per channel is 10 μs) and also represent a rather high investment. Specially designed time-of-flight devices may be somewhat cheaper, but mostly do not offer the same versatility as multichannel analysers.

This paper describes a time-of-flight system, which has been realised by interfacing a CAMAC (Computer-aided Measurement and Control) system with a minicomputer. Although at a first glance the investment seems to be rather high, this method has been preferred for several reasons. Firstly, the system is modular and can be easily upgraded by adding standard off-the-shelf or home-made CAMAC modules. Secondly the system can also be used for other purposes, such as signal averaging of mass spectra with weak signals buried in noise or pulse height analysis by changing the software or introducing new CAMAC modules. Because of the wide variety of existing CAMAC modules from different manufacturers a great flexibility can be achieved. Although the system has been designed for a Hewlett–Packard 21MX minicomputer the principles can readily be applied to other types of computer.

2 Principles of operation

A detailed description of drift tubes themselves being beyond the scope of this article (excellent reviews are found in McDaniel and Mason 1973), we will restrict ourselves to a brief description of the drift tube, which we have been using with our CAMAC time-of-flight system.

Our drift tube is very similar to the instrument described by McFarland *et al* (1973) although we have used only very small gas flows. It consists of an electron impact ionisation source, followed by a thermalisation section, an ion gate and a drift tube. The thermalisation section, in which the ions and electrons are separated, consists of three guard rings of 6 cm internal diameter and has a total length of 4 cm. The electric field is kept constant in this region at approximately 5–6 V cm^{-1}. Between this section and the drift tube an ion shutter is mounted; this consists of three stainless steel grids, 0·1 cm apart. In the open mode the grids are set to different potentials, which are chosen to maintain field homogeneity in the drift and thermalisation regions. When operating in the pulsed mode the middle grid is biased +5 V with respect to the upstream grid, thus preventing positive ions from coming into the drift region. To open the ion gate a negative pulse of 5 V and 5–10 μs long is applied to the middle grid.

The drift section consists of nine guard rings of 11 cm internal diameter which maintain the uniform electric field over a drift length of 18·49 cm. The ions enter the drift section through a hole of 0·5 cm, thus limiting transverse diffusion to that fraction of the total tube diameter where the electric field is constant. The ions are sampled through a hole of 0·015 cm into the mass spectrometer, which is pumped by a 3000 l s^{-1} diffusion pump baffled by a liquid nitrogen trap. After filtering by a quadrupole mass spectrometer (Extra Nuclear 270–9) the ions are detected by a channeltron electron multiplier (Bendix model 4501), the pulses of which are counted by the electronic measuring system.

The quantity to be measured by this system is the time of arrival of an ion moving through the drift tube under the influence of a known electric field. Because of the transverse diffusion of the ions and the ion–molecule reactions, not every ion injected along the axis into the drift tube will leave it. Those ions which are able to survive the voyage through the gas will build up a time-of-arrival histogram or spectrum. To measure this spectrum a swarm of ions is periodically injected into the drift tube and all arrival times of the surviving ions along the axis of the instrument are registered.

From an electronic point of view this is realised in the following way. At the beginning of the measuring cycle, which is represented in figure 1, a 'shutter open' signal is made, at the rising edge of which the ion gate in the drift tube is opened for a fixed time interval. This interval is determined by a small circuit mounted close to the drift tube (ion gate opening module). The 'shutter open' signal also starts a delay down counter, the function of which is to provide for a fixed offset in time for the arrival spectrum. At the end of the delay time another counter is started which determines the number of time units in the spectrum; this is the window down counter. The arrival times of the ions detected during the window time are stored in successive

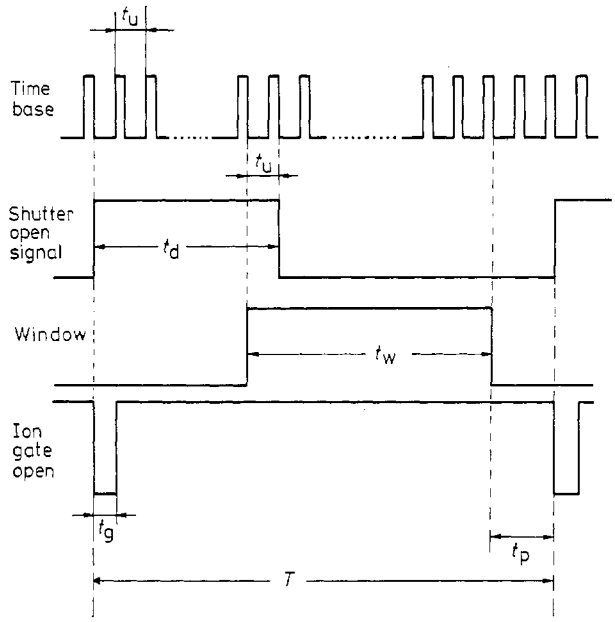

Figure 1 Timing of the measuring cycle.

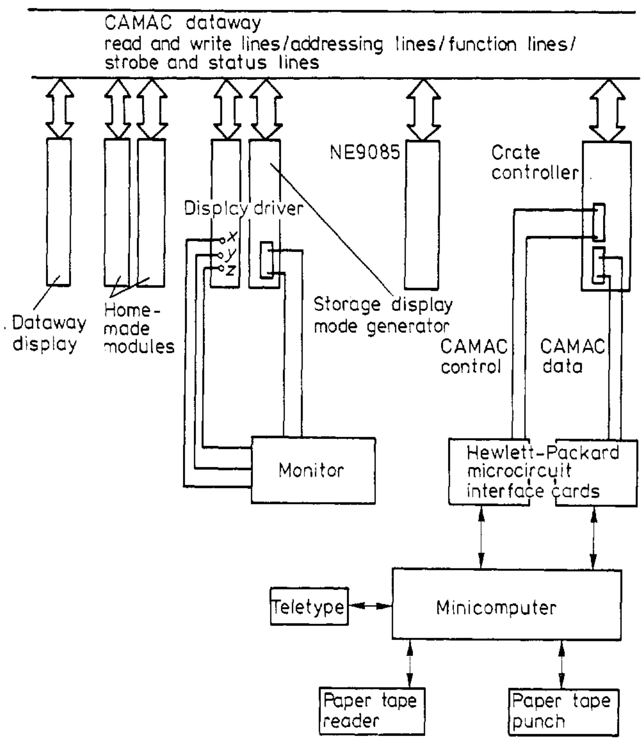

Figure 2 Actual electronic system configuration.

locations of a buffer memory. These times are transferred to the memory of the minicomputer through the CAMAC dataway at the end of the window period. This transfer takes a certain amount of time, which is called the processing time t_p. In the meantime the 'shutter open' signal becomes low, as can be seen in figure 1, and the cycle can be restarted.

3 Circuit description

For the reasons mentioned earlier a CAMAC system associated with a Hewlett-Packard 21MX minicomputer was chosen as the principal part of our apparatus. We recall that CAMAC is an instrumentation system that consists of various modules housed in a crate (Costrell 1973, Kirsten 1973). The modules communicate through a dataway, i.e. a back-plane bus system connecting up to 24 modules with each other and with a crate controller module occupying the extreme right slots of the crate. The crate controller is acting as an intermediary between the CAMAC modules and the computer, in our case the HP 21MX with an 8k memory. For our application a single crate controller (Borer model 1531 A) was selected, especially because of its compatibility with the minicomputer.

The CAMAC modules which are actually installed are (see figure 2):

(i) a dataway display module, type 1801 from Borer Electronics;

(ii) a display driver module and a storage display mode generator, types 7011 and 9028 from Nuclear Enterprises;

(iii) two home-made modules, which we will describe hereafter;

(iv) a multi-DAC module, type 9085 from Nuclear Enterprises; and

(v) the crate controller module.

The function of the dataway display module is to memorise and display the latest dataway signal pattern. This is a useful feature for trouble-shooting the CAMAC system software. The two single-width modules 7011 and 9028 provide facilities for the display of our time-of-arrival spectrum on a Tektronix storage monitor model 603. The display driver module contains two 10-bit DACs, which control X and Y deflections on the monitor, and also produces a bright-up pulse for the Z-axis input of the oscilloscope. The storage display mode generator programs the remote program connector of the Tektronix monitor. In our application it is used for erasing before a new spectrum is written on the screen.

The multi-DAC module has 12 analogue outputs, which are defined by digital data from the dataway. Three analogue outputs are used to control the X-axis, the Y-axis and pen displacements of a conventional X–Y paper recorder. In this way a hard copy of the spectrum display shown on the monitor can be made available.

The two home-made modules are a shutter control module and a time-of-arrival analyser. These modules have been developed in our laboratory because, at the time we started this project, no such CAMAC-compatible modules existed.

The task of the shutter control module is to produce the timing signals for the time-of-arrival analyser (TOAA) module. Figure 3 shows the schematics. In the first place a time base is generated by the combination of a register and a down counter. Each time the counter value becomes zero, it is reloaded with the register value N_1. In this way a clock with a programmable period (time unit t_u) of $N_1 \times 0{\cdot}2$ μs is derived from a 5 MHz clock oscillator.

This signal is used as the clock input both to a delay down counter and to a window down counter. The delay down counter is constantly loaded with the value N_2 of its associated register. When an execute (CAMAC) command arrives an 'open shutter' pulse is released and the delay down counter decreases at the time base rate. When the delay counter becomes zero (end of delay) the counter stops and again takes the value N_2. The window down counter then starts counting from its initial value N_3 until it reaches zero. During this part of the cycle of figure 1, a window pulse is generated, which determines the ion acceptance time in the time-of-arrival analyser. At the end of this pulse the module sets a 'look-at-me' (LAM) flag, which is a CAMAC feature to notify the crate controller that the module needs attention. The LAM flag provokes an interrupt in the minicomputer hardware.

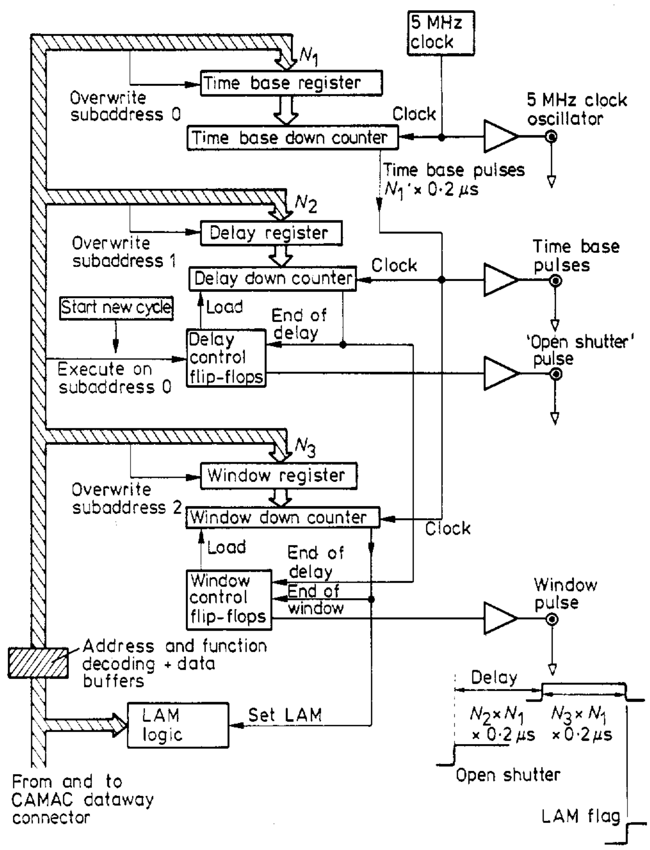

Figure 3 Schematic of shutter control module.

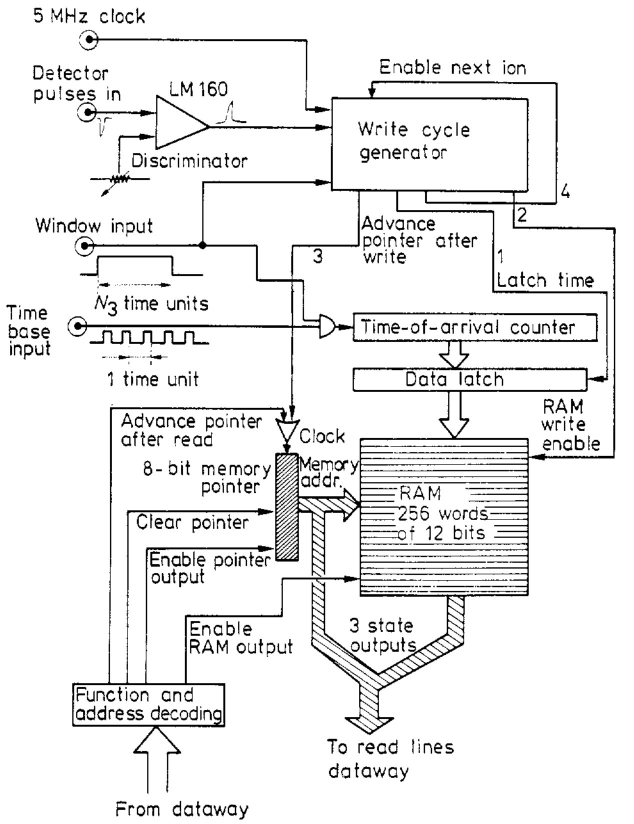

Figure 4 Schematic of time-of-arrival analyser.

As a consequence a jump is made to special software, which will be described in a later section. We should also add that each down counter and register is 12 bits long. This provides the possibility of choosing a time base (equal to 1 time unit) ranging from 0·2 to 819 μs, to shift the beginning of a spectrum up to 4095 time units with respect to the opening of the shutter, and to collect arrival times in a time span from 1 to 4095 time units. This makes a wide range of acceptable drift times possible, resulting in an instrument with a great adaptive power.

The TOAA module accepts electron multiplier output pulses in the range from 0 to −1 V. A comparator (LM 160, National Semiconductor) acting as a pulse height discriminator transforms the signals into TTL-compatible pulses. Each ion arrival (while the window is high) triggers the 'write' cycle generator. This circuit performs the following sequence in less than 1 μs: (i) the arrival time counter is latched, (ii) the latched arrival time is stored in a buffer memory, (iii) the memory address is incremented, (iv) the write cycle generator is prepared for the next ion arrival. Consequently the analyser has a very short dead time.

The buffer memory consists of three RAM circuits (random access memories of Advanced Micro Devices, type AM 9101 DDC) each containing 256 words of 4 bits. These 256 locations are addressed by an 8-bit counter, the memory pointer, which is advanced after each ion arrival. Thus, up to 256 ion arrivals can be stored during each acceptance window. Provisions are made to transfer the contents of the RAM memories and the number of arrivals to the minicomputer by using the appropriate CAMAC commands. During this processing time the memory pointer is read and cleared. Its value gives the number of arrivals. Then each RAM location of interest is read and the pointer is subsequently advanced. The schematic of the time-of-flight analyser module is shown in figure 4.

4 Software support

Parallel to the hardware construction effort a software development program was started (see flow chart of figures 5(*a*) and (*b*)).

Firstly, an assembler utility routine, CAMIO, was written, performing the CAMAC commands for read, write, block and dataless instructions. In this way the programmer was freed from remembering the specific instructions for control of the crate controller module (Borer 1531 A). CAMIO can be called by all other program segments through the entry points: WRITI, READY, INSTR and BLOKI. The calling routine prevents CAMIO from being interrupted while sending data or control words to the crate controller, thus avoiding confusion in the latter.

Secondly, a drift tube data routine was developed. This assembler routine has three sections with entry points: DRIFT, SHOT and ENDWI. DRIFT is the name of an initiator section where CAMAC commands, used by other sections, are assembled and stored to shorten future time-consuming operations. Also in the DRIFT section, CAMAC commands are sent out (via calls to CAMIO) to overwrite the time base, delay and window registers in the shutter control module. A typical FORTRAN call to the assembler routine DRIFT looks like:

CALL DRIFT (NSHUT, NSPEC, IWDTH, IDELA, IWIND, IARRI, NACCU, ISTOP, MAXIM, IBUSY, ISTAT).

Here, NSHUT and NSPEC are the station numbers in the CAMAC crate where the shutter control module and the time-of-arrival analyser are located. IWDTH, IDELA and IWIND are the values N_1, N_2 and N_3 mentioned in figure 3 (time base, delay and window). IARRI is the histogram array with length equal to IWIND, and NACCU and MAXIM specify the desired total number of successful shots and the requested peak value of the histogram. Finally ISTOP, IBUSY and ISTAT are

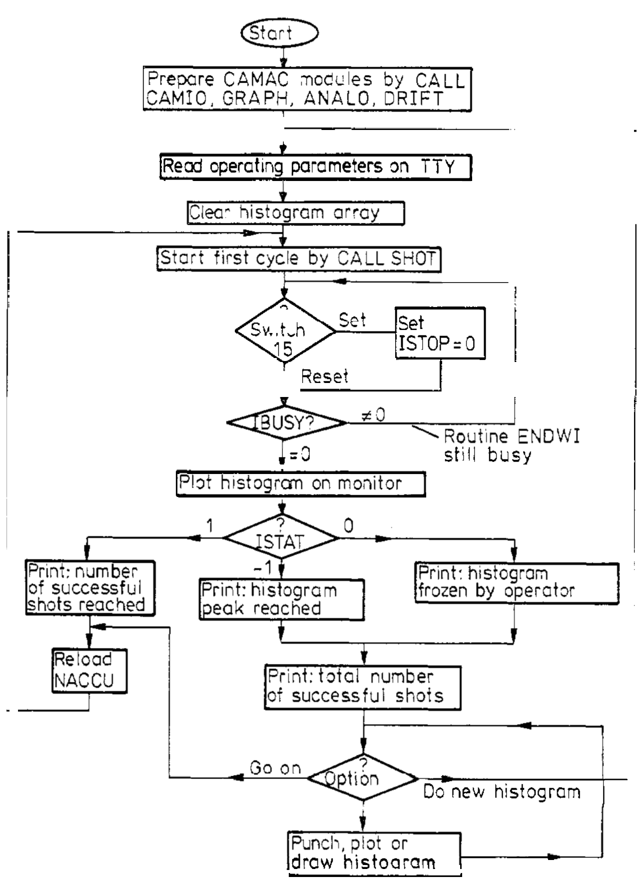

Figure 5(*a*) Flow diagram of main program DROPS.

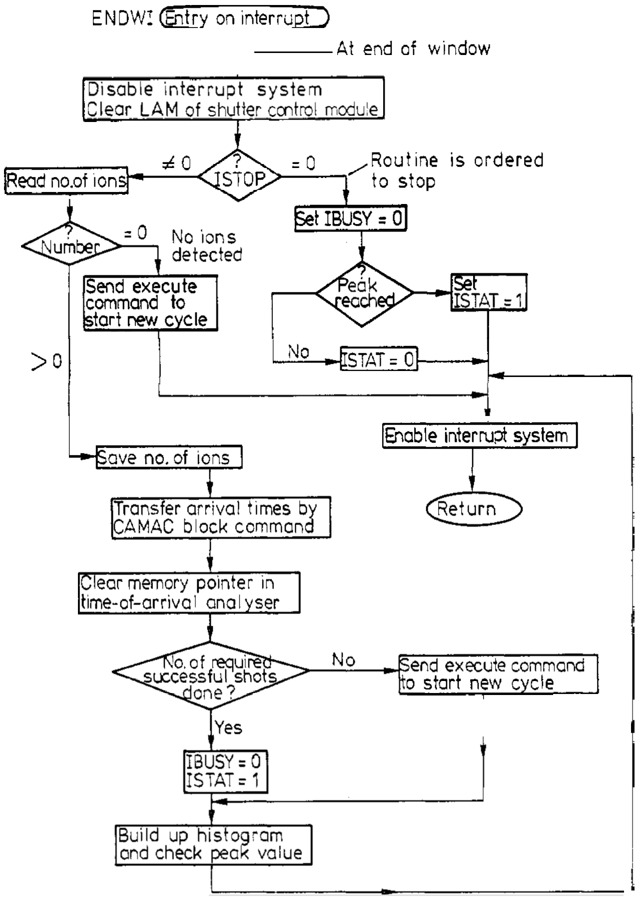

Figure 5(*b*) Flow chart of interrupt section of drift tube data routine.

status and control words, the functions of which will become clear in the discussion of the ENDWI section. The SHOT section is called by a FORTRAN statement: CALL SHOT. It is used to start the automatic shooting process of the drift tube. Firstly, the memory pointer is cleared in the time-of-arrival analyser and then ISTOP, IBUSY and ISTAT are reset to their original values. Finally a CAMAC 'execute' command is sent to the shutter control module in order to start a cycle as described in §3.

At the end of the acceptance window, the shutter control module causes an interrupt by setting its LAM flag. The computer program counter then jumps to the interrupt section ENDWI of the drift tube data routine. The subsequent operations are shown in the flow chart of figure 5(*b*).

In the first place the 21MX interrupt system is disabled and the LAM flag is cleared. Then a decision is made whether the routine should stop or continue, depending upon the value given to ISTOP either in the main program or in ENDWI itself. If ISTOP is not zero the number of arrivals at the detector is transferred from the memory pointer in the TOAA to the routine.

If no ions have arrived no further processing is required and immediately a new 'execute' command is sent to the shutter command module to trigger another cycle. If the number is not zero (successful shot) a CAMAC block transfer from the TOAA buffer memory to a temporary buffer in the computer is performed and the memory pointer in the TOAA is reset to memory location zero. The shutter control module and the time-of-arrival analyser are then ready for another cycle.

Then NACCU is decremented and checked. If the required number of successful shots is reached, IBUSY is cleared and the status word ISTAT becomes 1 to indicate to the main program that the shooting cycle in the drift tube stopped for this reason. If not, another shooting cycle is triggered, as for the case where no ions arrive.

While both CAMAC modules are busy gathering new ion arrival times, the routine ENDWI continues handling the previous assembled arrival times saved in the temporary buffer. These have values between 1 and IWIND and are used to compute the addresses of those histogram array elements which are to be incremented. At the same time as incrementing takes place, the array elements are compared with MAXIM, the specified histogram peak value. If overflow is detected an overflow flag is set and ISTOP is cleared. Both flags are checked at the next entry in the ENDWI section. Now the interrupt routine again enables the 21MX interrupt system. The main program resumes its activities and at the next end-of-window condition a new interrupt will make a call to ENDWI.

Besides the utility routine CAMIO and the drift tube data routine, two non-interrupting routines ANALO and GRAPH are written. GRAPH is intended for plotting the histogram, stored in IARRI, on the screen of the Tektronix storage monitor. This routine works in conjunction with the Nuclear Enterprises display modules mentioned earlier. The ANALO routine drives the Nuclear Enterprises multi-DAC module. Three DAC outputs are now being used for drawing the histogram on a conventional X–Y chart recorder. In the future other DAC outputs will be used to control the quadrupole mass spectrometer of the experiment and the electric field in the drift region.

With the previously described subroutines, which were separately tested, a FORTRAN IV main program, called DROPS (for drift tube operating system) was written. The flow chart of DROPS is shown in figure 5(*a*). The main program issues calls to CAMIO, GRAPH, ANALO and DRIFT in order to initiate the corresponding CAMAC modules. Then, parameters concerning the shutter control module and the TOAA are entered via the operator's teletype. The histogram contained in the array IARRI is cleared and the first swarm is released in the drift tube via a CALL SHOT. From now on building up of the histogram takes place automatically without the intervention of the main program. The remaining task for DROPS is watching the computer's switch register to see if the operator wants to 'freeze' the histogram and to check whether IBUSY becomes zero. If this happens, the monitor screen is erased and a histogram is plotted.

Depending upon the value of the status word ISTAT, DROPS simply reloads NACCU with the specified value or tells the operator how to continue. In the latter case the operator has the choice between either punching, plotting or drawing the histogram and restarting DROPS to make a new histogram.

5 Performance of the system

A typical time-of-arrival spectrum as obtained with the previously described system is shown in figure 6. The mass spectrometer was tuned at mass 19 and the gas used in the drift tube was argon (99·99% purity, Air Liquide) at 0·185 Torr (24·6 Pa). With the electron impact source operating at 10 μA emission, the predominant ion mass peaks were: 19 (H_3O^+), 29 (N_2H^+) and 41 (ArH^+). All three ions are produced by ion–molecule reactions and consequently it may not be surprising if we find a non-symmetric form of the time-of-arrival spectrum. The spectrum of figure 6 was obtained by putting

IWIDTH = 10   IWIND = 1000
IDELA = 0   NACCU = 32 000.

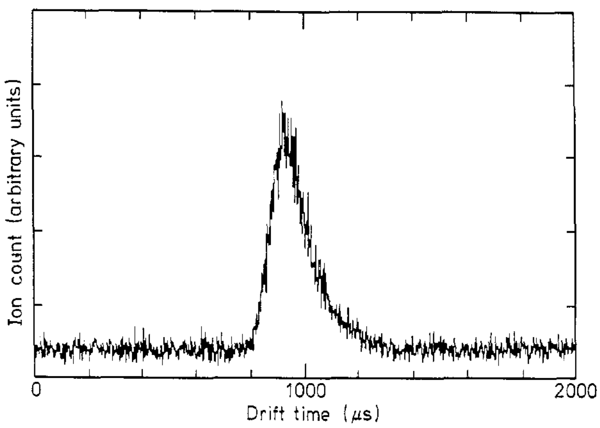

Figure 6 Typical time-of-arrival spectrum obtained with the system. H_3O^+ ions in argon, pressure 0·185 Torr (24·6 Pa), $E/N = 27{\cdot}5$ Td (1 Td $= 10^{-17}$ V cm^2).

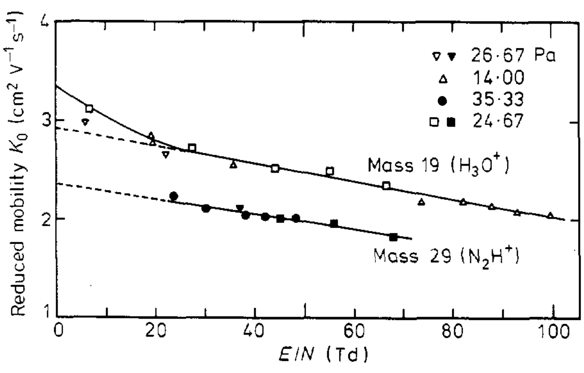

Figure 7 Reduced mobilities of H_3O^+ and N_2H^+ in argon. E, electrified intensity; N, gas number density.

Reduced mobilities of H_3O^+ and N_2H^+ have been measured at different gas pressures and electric field values. The results are shown in figure 7. The value which is found for H_3O^+ is in good agreement with the one found in the literature (Young *et al* 1970). Deviations at low E/P values may be due to space charge effects in the drift tube, but this can easily be overcome by using lower emission currents with the ion source.

The mobility of N_2H^+ in argon has as far as we know not been measured before. The good results obtained with the measuring system prove its reliability. The philosophy used in designing this time-of-arrival measuring system allows it to be easily upgraded. A future extension will be the installation of a movable ion source. The source position will then be determined by a stepping motor, which in turn can be controlled by the CAMAC system. This would be a straightforward action since stepping motor control CAMAC modules are now readily available. It is also possible to control the electric field in the drift tube by CAMAC or to measure the pressure or other experimental parameters using CAMAC input or output modules. All the extensions previously described can be constructed at moderate cost.

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