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A TIME-OF-FLIGHT MASS SPECTROMETER FOR STUDIES OF IONS PRODUCED BY SIMULATED MICROMETEOROID IMPACT

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A TIME-OF-FLIGHT MASS SPECTROMETER FOR STUDIES OF IONS PRODUCED BY SIMULATED MICROMETEOROID IMPACTS

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SUMMARY

A time-of-flight mass spectrometer has been developed to study the ions produced by the impact of hypervelocity microparticles on solid targets. Flight time measurement is performed by using the pulse induced on the target by the charged microparticle. As the accelerating potential on the target is increased from 250 V to 1000 V, the ion transmission efficiency in the main tube of the spectrometer varies from 7 to 13 percent and the efficiency in the side arm of the spectrometer varies from 4 to 7 percent. It is possible to detect 100 ions/pulse at the electron multiplier with a resolution of 10 ns. Use of a different electronics system, adapted to automatic digital data handling, degrades the time resolution to 500 ns, but increases the sensitivity to 1 ion/pulse at the electron multiplier.

INTRODUCTION

Information on the chemical composition of micrometeoroids and interplanetary dust would add to our knowledge concerning the formation of the solar system. To date, this information has been obtained primarily from sounding rocket collection experiments and from observation of optical meteor spectra. The flight profile of the collection experiments inherently limits the sample size. In addition, contamination from terrestrial dust makes unique interpretation of the data difficult (ref. 1). To extract quantitative composition data from the observed meteor spectra, the excitation processes producing these spectra must be known in some detail (ref. 2). Although work has been done in this area, sufficient information is not yet available (ref. 3). An in-space observational technique has been proposed, which utilizes the impact light flash produced by meteoroid impact on a target (ref. 4). The resultant optical spectrum is quite complex and necessitates a preselection of observable elements. This basic limitation obviates the possibility of observing small amounts of unexpected materials in the meteoroid.

A more promising technique is mass spectroscopy of the ions produced by the hypervelocity impact of the meteoroid on a target. In addition to the composition and meteoroid flux information, the mass and velocity of the impacting particle could be determined

if the mechanisms of ion production were well understood. A mass spectrometer based on time-of-flight techniques has been proposed by TRW (ref. 5) and others (ref. 6). The time-of-flight mass spectrometer (TOF), described below, is an improved instrument that will extend knowledge of impact ionization phenomena using ground-based simulation of in-space impacts.

THEORY OF THE TIME-OF-FLIGHT MASS SPECTROMETER

When a particle traveling at high velocity (>1 km/s) impacts a target, part of the kinetic energy of the particle vaporizes a portion of the particle. In this cloud of vaporized material a portion of the particle constituents is ionized. The ratios of the observed ionic species are a function of the vaporization and ionization cross sections of elements constituting the projectile and the target and the impacting particle kinematics.

If the target is positively biased (Figure 1) with respect to a grid located a small distance (a few mm) in front of the target, the ions produced by impact will be accelerated in the direction whence the projectile came and the electrons would be collected by the target. After passing the grid, the ions drift in a field free region at constant velocity

$$v = \sqrt{\frac{2qV}{m}} \tag{1}$$

where q is the charge on the ion, m its mass, and V the biasing voltage on the target.

If an ion detector is placed a known distance (~ 1 m) from the grid, the velocity may be calculated from the measured flight time T between the grid and the ion detector by

$$v = d/T \tag{2}$$

where d is the grid-ion detector distance. In practice the timing signal is taken from the target rather than from the grid, but the error introduced by this procedure is calculated to be less than 1 percent. The charge-to-mass ratio can then be calculated as

$$\frac{q}{m} = \frac{(d/T)^2}{2V} \tag{3}$$

If the major constituent elements of the vapor appear as singly-ionized atoms, the charge is known and hence the mass

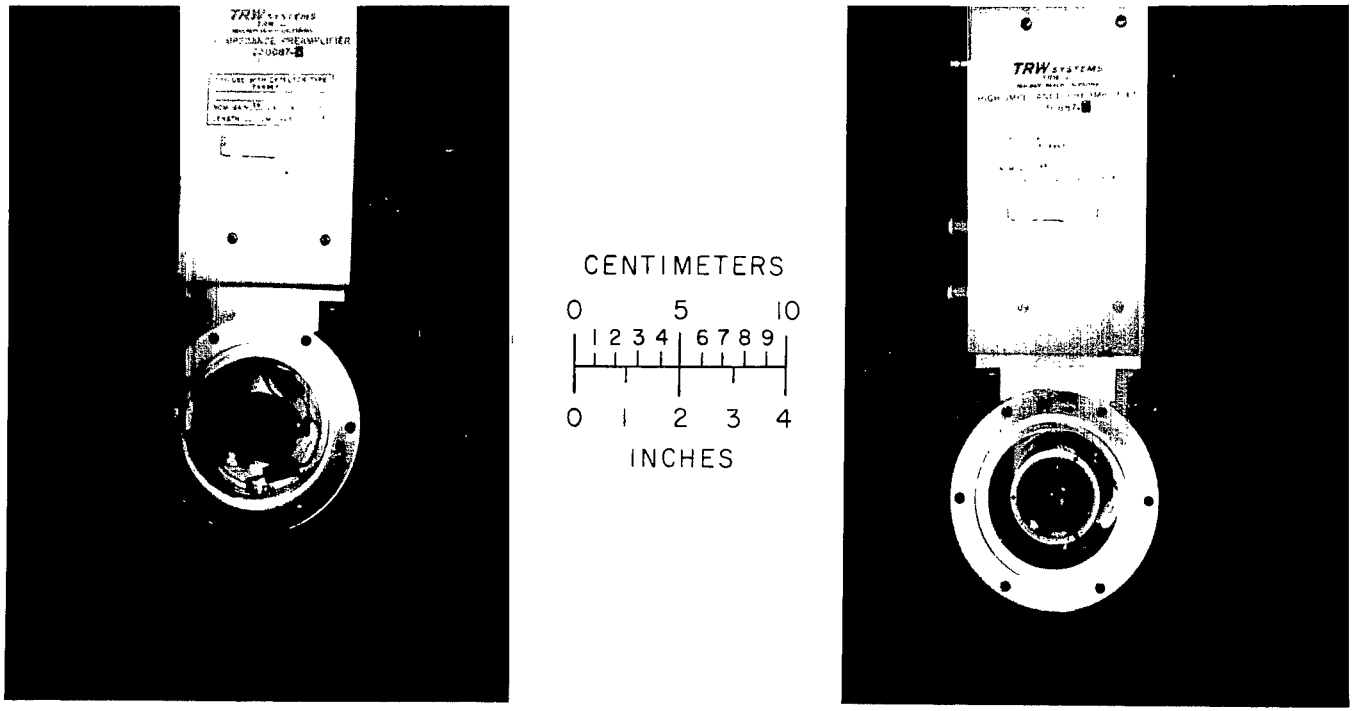

Figure 1.- Target holder and grid assembly

which identifies the ionic species. These measurements then yield the qualitative composition of the projectile.

The preceding explanation is a simplification of the observed situation. The initial thermal velocities of the ions, which cause a spread in flight time for each species, have been neglected. The time-resolved spectrum is further complicated by the formation of multiply-charged ions as well as of dimers, trimers (and other polymers), and ionized compound molecules. As mentioned above, the relative abundances of elements in the projectile (i.e. meteoroid) are not simply given by the ratios of the collected ionic species. The degree of ionization of the elements is a function of the impact particle kinematics and the nature of the target. All these phenomena are understood only qualitatively. In order to establish mass spectrometry on a quantitative basis for scientifically meaningful results, a detailed laboratory program was initiated to study the impact ionization phenomena. This step was recognized as an essential prerequisite to the development of a space-qualified instrument to determine meteoroid composition.

EXPERIMENTAL APPARATUS

Figure 2 is a block diagram of the TOF spectrometer developed for the laboratory study of impact ionization. Hypervelocity microparticles enter the TOF spectrometer from an electrostatic accelerator, pass through a 3/8-in. diameter central hole in the charge collector, and continue down the tube through a grounded grid, impacting upon a positively biased target. The positive ions produced are accelerated back up the tube by this positive bias, focused by an Einzel lens, and are intercepted by the 4-in. diameter charge collector. The central hole reduces the area of the charge collector by only about 1 percent. The distance between the charge collector and the target is approximately 1 m. An electron multiplier (EMI 9603B) is located in a side arm of the TOF spectrometer; ions may be directed into this tube by applying voltage to the deflection plates. The electron multiplier is electrically insulated from the rest of the TOF spectrometer, and the entire electron multiplier assembly can be operated at elevated potential. In this manner, the first dynode can be operated at potentials up to -13 kV, thereby causing the ions to impact with greater energy in order to increase the electron yield from the first dynode. A grounded grid is located in front of the electron multiplier to contain the electric fields. For calibration purposes the entire target assembly (including the grounded grid) can be removed and a thermal ion source assembly installed. The ion source is so constructed that the emitting surface lies in the impact-target plane.

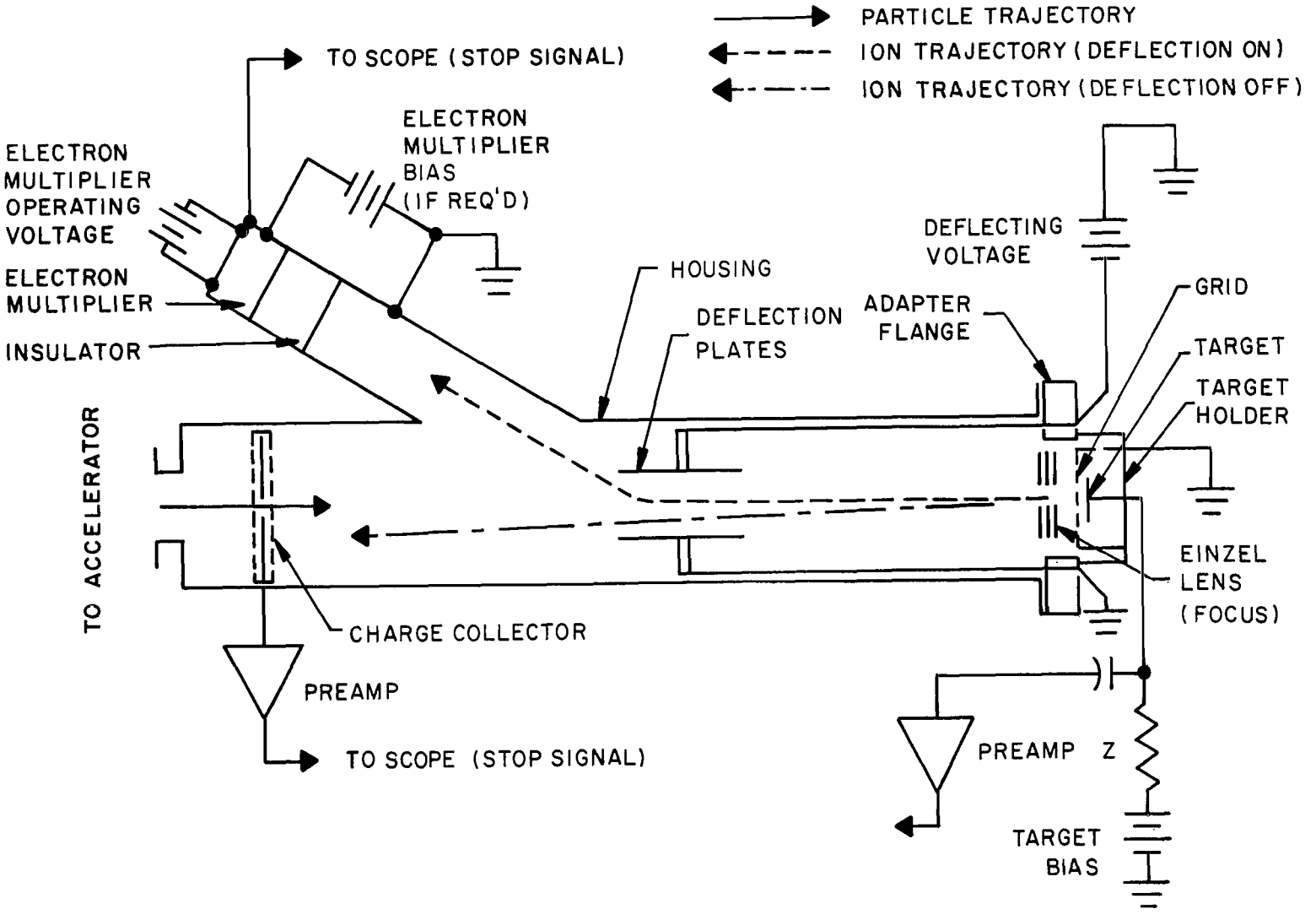

Figure 2.- Ion time-of-flight mass spectrometer

TIMING

"Start" Pulse Generation

The electronic process of measuring the flight time of the ions through the TOF spectrometer must be triggered by a "start" pulse. This pulse may be generated either by the collection of free electrons created by the impact ionization or by the charge induced on the target by the approaching charged microparticle. The latter method was used in the work reported here (see Figure 3).

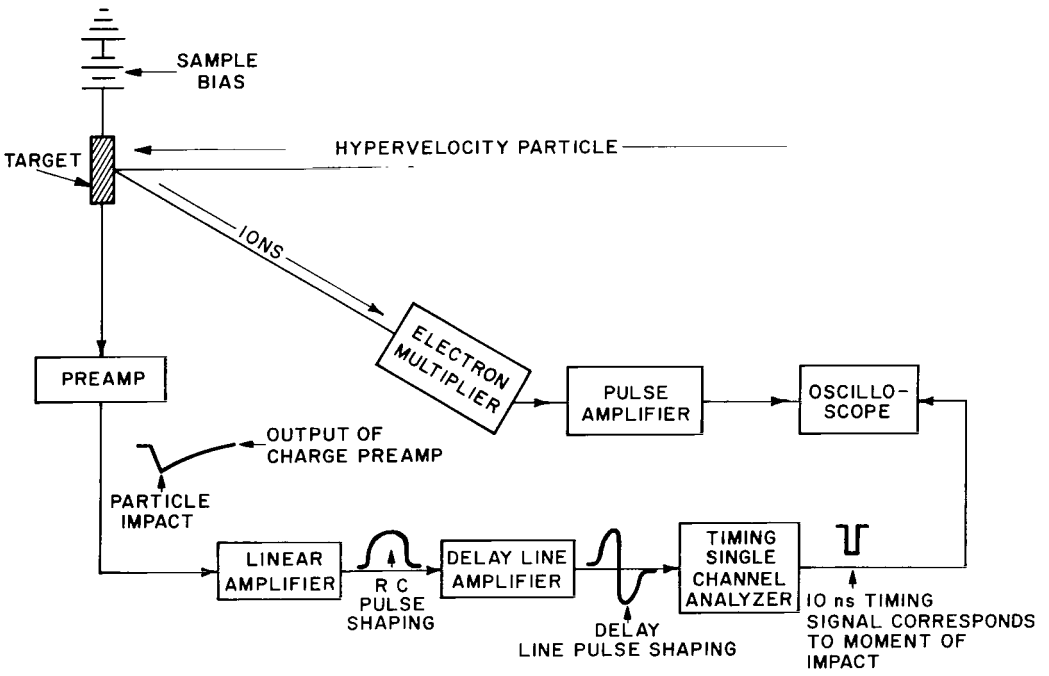

Figure 3.- Block diagram of flight timing system

The pulse induced on the target is positive and its peak occurs at the moment of particle impact. This pulse is amplified and shaped (2 μs integration time; 2 μs differentiation time) to produce a unipolar pulse whose peak corresponds to the impact time. This pulse is delay-line differentiated to produce a bipolar pulse whose zero-crossing corresponds to the impact time. This bipolar pulse serves as the input to a timing single-channel analyzer which generates a fast rise time, 10 ns-wide output pulse

at the time of the zero crossover. The leading edge of this "start" pulse is synchronized with the impact time with a "walk" of ±300 ns. The "start" pulse is used to trigger an oscilloscope sweep or to start a time-to-pulse height converter. Because of a lack of sensitivity of the charge-sensitive preamplifier pick-up, this method is usable only for particles with a charge greater than 10^{-15}C.

Alternatively, the pulse generated by collecting the free electrons caused by the impact ionization can be used in a similar manner for timing. Usually, due to the low energy of the impacting particles an insufficient number of free electrons are generated for this method to be workable.

Calibration

A thermal ion source (Figure 4) is used in place of the target assembly to obtain flight-time calibration. The thermal ion source consists of a porous tungsten cathode impregnated with one or more alkali hydroxides used to obtain singly ionized atoms, K^+, Na^+, Cs^+; the emitting surface is located in the impact target plane. Emission is obtained by heating the cathode with a tungsten resistance wire. The cathode is at a positive potential with respect to a grounded grid about 1 cm in front of the cathode. A control grid, located between the cathode and grounded grid, is maintained at 20 to 30 V above ground to prevent any ions from the thermal source from being accelerated into the tube until desired. In the calibration process a negative pulse is applied to the control grid, allowing a packet of ions to be accelerated down the tube, focused by an Einzel lens and detected after free flight by a charge collector in the main tube. Alternatively, the deflection plates can be used to shift the ions into the side arm where they will be detected by the electron multiplier. Figure 5 shows the calibration of flight time as a function of ionic mass for various accelerating potentials from 125 to 1000 V.

CHARGE MEASUREMENTS

Instrumentation

The charge collector in the main tube is a plate (4 in. in diameter with a 3/8-in. diameter central hole) connected to a charge-sensitive amplifier (rise time ~ 100 ns; decay time 50 μs). The output signal of the amplifier has the form of a step function (Figure 6) where each step represents the arrival of a different ionic species. The ion groups can be separated by different techniques and ratios. Since the conversion factor of the amplifier is known, the number of ions in each group can be calculated.

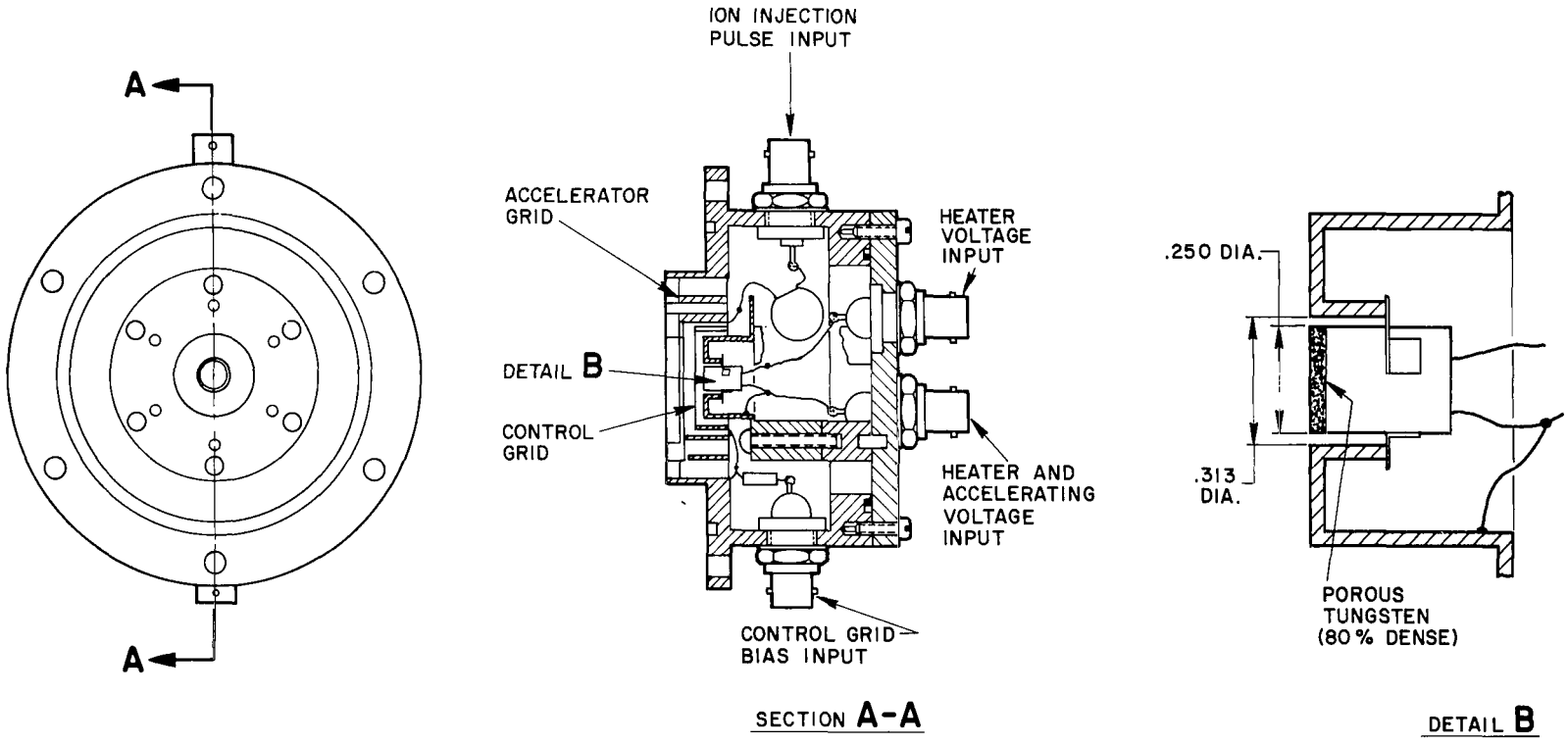

Figure 4.- Thermal ion source

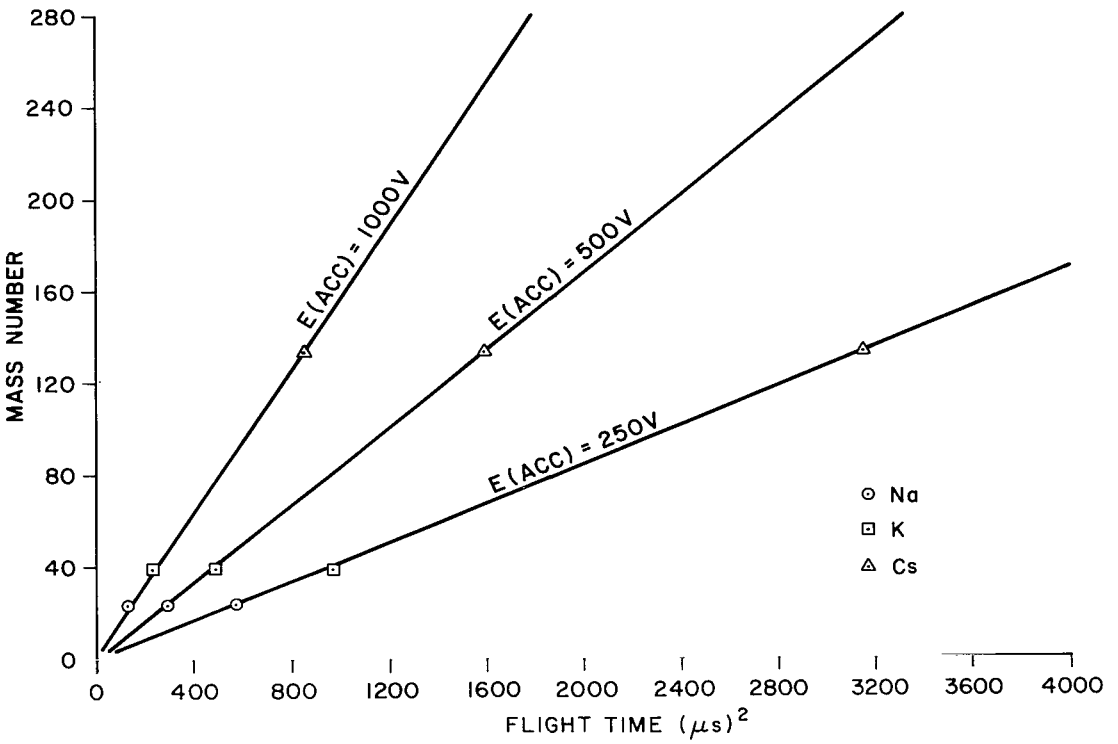

Figure 5.- Ion flight time calibration

The electron multiplier, located in the sidearm of the TOF spectrometer, has a 15-stage venetian-blind Be Cu O dynode system with a nominal gain of 10^6 at 3500 V. Two techniques are employed for the detection of the ions.

1. Time-resolution optimization (frequency response). The anode of the electron multiplier is dc-coupled to a 3-ns rise time, 150-MHz bandwidth pulse amplifier (Keithley 107). To minimize the RC decay time of the signal from the electron multiplier the 50-Ω input impedance of the amplifier was used as the load resistor; stray capacitance is kept as low as possible by use of short cables. The amplifier consists of 3 cascadable stages, each with a gain of X10, and can drive a 50-Ω load to 1.4 V peak-to-peak. The total time resolution of the system is 10 ns. If it were not for transmission and multiplication losses, it would be theoretically possible to detect each ion produced; however, in practice, these losses and system noise limit detection to about 100 ions/pulse.

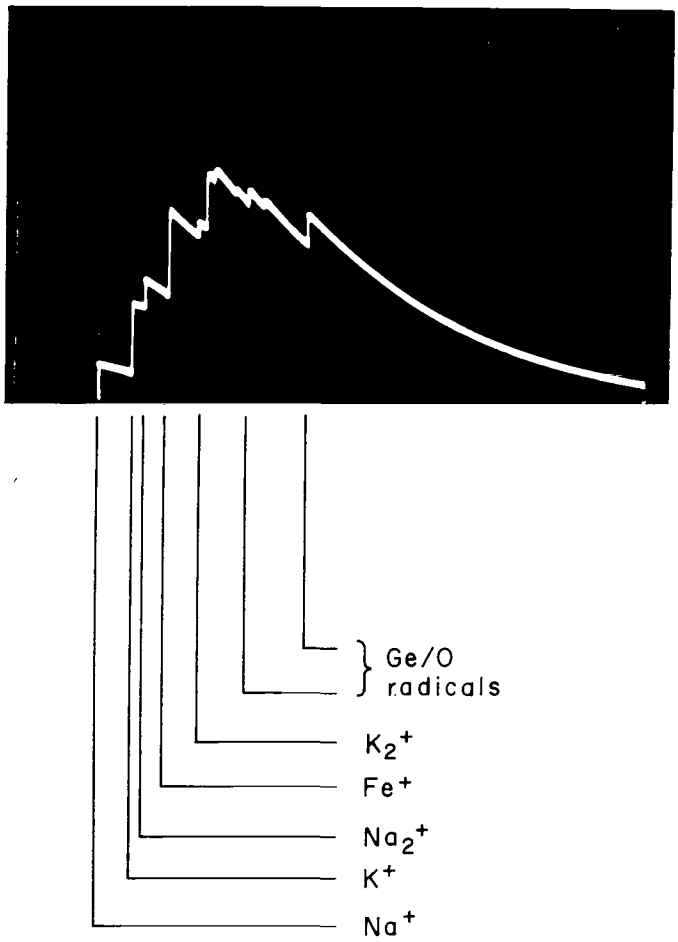

Figure 6.- Step function output of charge collector (carbonyl iron on germanium)

2. Signal-to-noise ratio optimization. A charge sensitive preamplifier (rise time 100 ns; decay time 55 μs) with a conversion gain of 10^{12} V/C is connected to the anode of the electron multiplier. The preamplifier output signal rises in a staircase fashion with each ion group arriving during the decay of the preceding group(s). By post-amplification integration and differentiation a time resolution of 0.5 μs can be achieved, which is considerably longer than the 10-ns time resolution of the first method. However, a preamplifier input of

1.6×10^{-13}C (produced by one ion incident on the first dynode) results in an output voltage pulse of 160 mV which is easily observable above the measured noise level of 20 mV. The output pulses produced by this second method are better suited for digital data handling than those produced by the first method.

System Gain and Ion Transmission Efficiency Calibration

To perform quantitative measurements with the TOF spectrometer the absolute gain calibration of the electron multiplier and the transmission efficiency of the instrument (i.e., ions detected/ions produced) must be known.

Gain of the electron multiplier.- A calibrated charge-sensitive amplifier was connected to a screen, of known geometric transmission (81 percent), placed directly before the multiplier. The ion current collected on this screen was produced by operating the thermal ion source in a pulsed mode; square-wave pulses of known duration were used. Since the charge on the screen is measured by the preamplifier and its duration known, the current is easily calculated; knowing the transmission of the screen the amount of current arriving at the first dynode of the multiplier is known.

Calculations from the output pulses of the screen and the electron multiplier gave a gain of 10^3 at 4 kV, much below the manufacturer's specification of 10^6. It was found that long term baking of the electron multiplier at temperatures to 450°C increased the gain to 10^5. Periodic baking was necessary to maintain high gain levels. However, even with baking, it was observed, over a period of 6 months, that the gain was decreasing. It was possible to restore the gain by causing an oxygen discharge between the dynodes at 10 Torr O_2 with a 1-MHz, 150-V signal.

Transmission efficiency.- Using the techniques developed for the gain measurements of the electron multiplier, the ion optics were varied for optimum system performance. The thermal ion source was operated in a continuous mode and the current impacting on a screen in front of the TRW charge collector in the main tube was monitored with an electrometer. The focus voltage on the Einzel lens was varied to maximize the current impacting on this screen. The transmission efficiency of the system was determined by measuring the beam current collected on the screen in front of the detector. It was found that the optimum efficiency varied from 7 to 13 percent as the accelerating potential was increased from 250 to 1000 V (Figure 7).

A similar procedure was followed for maximizing ion current to the electron multiplier. The focus voltage was initially set at the optimum value previously determined and the deflection voltage varied until the current measured at the screen in front of the electron multiplier was a maximum. The focus voltage was then varied; however, it was found that the best focus voltage was the same for both the direct beam to the charge collector and the deflected beam to the electron multiplier (for a fixed accelerating potential). Transmission efficiency at the electron multiplier varied from 4 to 7 percent depending upon the accelerating potential (Figure 8). These results are in agreement with similar measurements performed by TRW Systems which were communicated to us by J. Friichtenicht of TRW Systems. The increase in efficiency at higher accelerating potentials is due to the decreased effect of the transverse thermal velocities. The overall efficiency of the system can be improved considerably by removing the three 81-percent transmission screens from the system.

Data Handling

An oscilloscope is usually used to measure the flight time and total charge of ionic species — the position of the ion peak on the trace giving the flight time and the peak height giving the total charge in that particular ion packet. In order to reduce the data, it is necessary to photograph the oscilloscope trace for each event and measure the flight time and charge from the oscillogram.

A data handling system for automatic accumulation of flight time and total charge of the ionic species has been designed to eliminate the time-consuming manual process and to ensure greater accuracy of measurements (see Figure 9). In addition, the flight time and total charge of a large number of events can be accumulated to improve statistical accuracy; the flight time range can be set to cover all events of interest.

Flight time.- The pulse induced on the target is processed as described above and used to start a time-to-pulse height converter (TPHC). The signals produced by a particle ionic species on the detector are processed and fed into the "stop" input of the TPHC. For each "stop" event a pulse is produced at the TPHC output whose amplitude is proportional to the elapsed time between the "start" pulse and that particular "stop" event. This process continues until the end of a preset time (usually 50 μs), at which time the TPHC resets itself and awaits another "start" event. The TPHC output pulses, each being a function of elapsed flight time, serve as the x-input to a multiparameter pulse height analyzer (MPPHA).

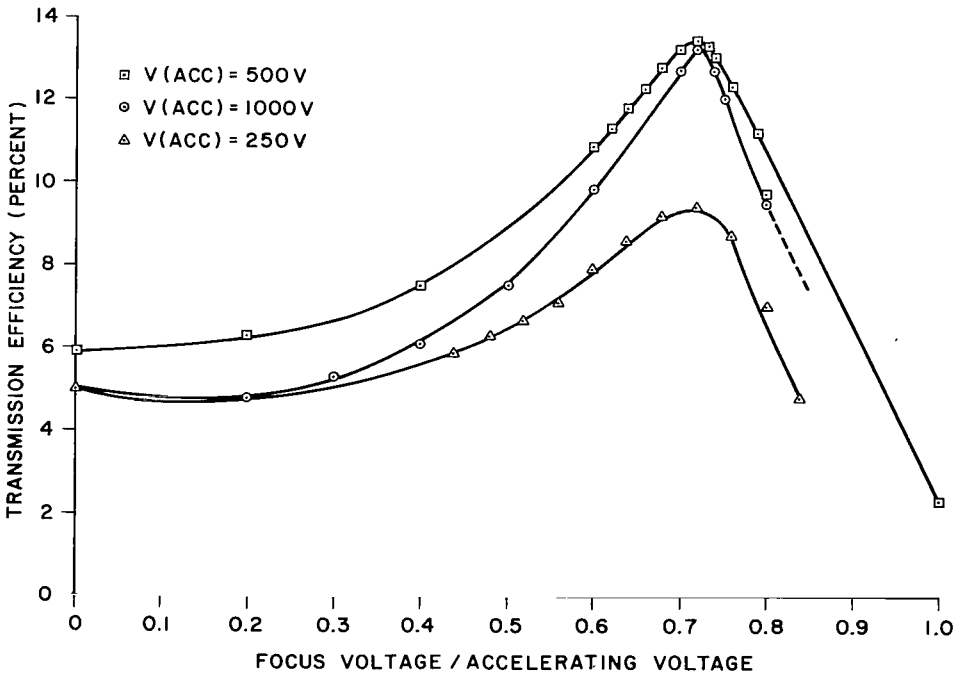

Figure 7.- Transmission efficiency: target to charge collector.

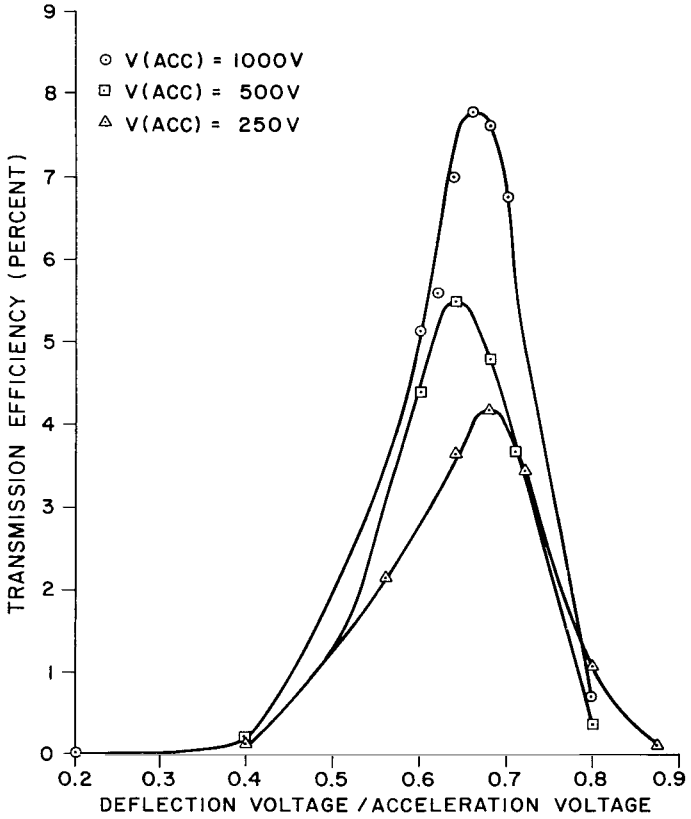

Figure 8.- Transmission efficiency: target to electron multiplier.

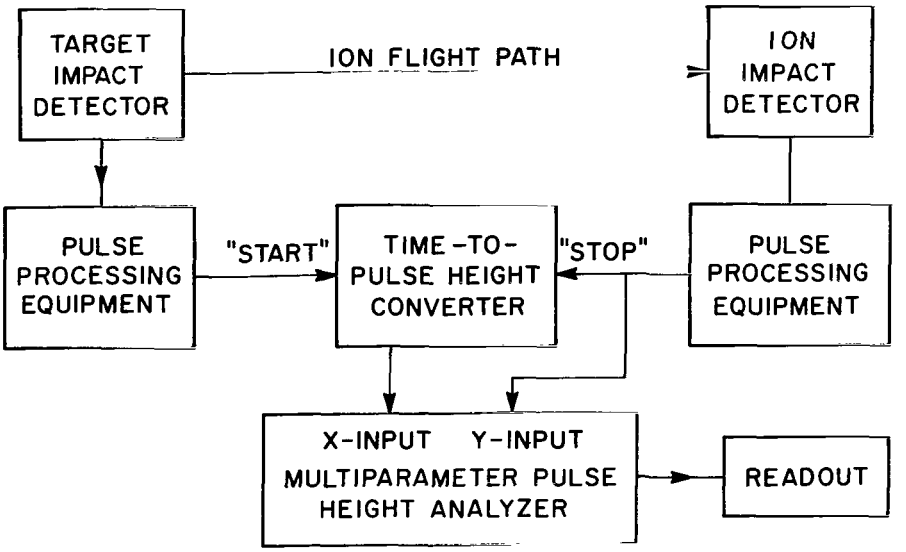

Figure 9.- Block diagram of data handling system

Charge.- The output of the detector, in addition to being used as a "stop" input to the TPHC, is fed to the y-input of the MPPHA. The pulse height of the y-input is a measure of the total charge in the ion packet.

The MPPHA has 4096 channels that can be used in the x- or y-single parameter mode or as a 64 x 64 matrix in the multiparameter mode. In the multiparameter mode of operation, time-coincident requirements are imposed upon the x- and y-inputs to assure that the arriving signals originate from the same event. After analog-to-digital conversion in the MPPHA the flight time and total charge are stored in discrete channels depending upon their pulse amplitudes. Ion flight times (species) and/or the total charge can be read out of the MPPHA on an oscilloscope, typewriter, or computer-compatible magnetic tape. Figure 10 is an oscillogram of the x-parameter (ion flight time) readout. The peak is Cs^{131} from a thermal ion source; the scaling is 250 ns/channel. Figure 11 is a readout of the x-parameter (ion flight time) for carbonyl iron impacting on lead. The ionic species are identified. The vertical axis is the number of counts in that channel. Using the mass-velocity selector system developed for the accelerator (ref. 7) to select the kinematics of the impacting particle it would be possible to accumulate rapidly and conveniently the results of many impacts at a fixed velocity or mass (or both, i.e. energy) for statistical analysis.

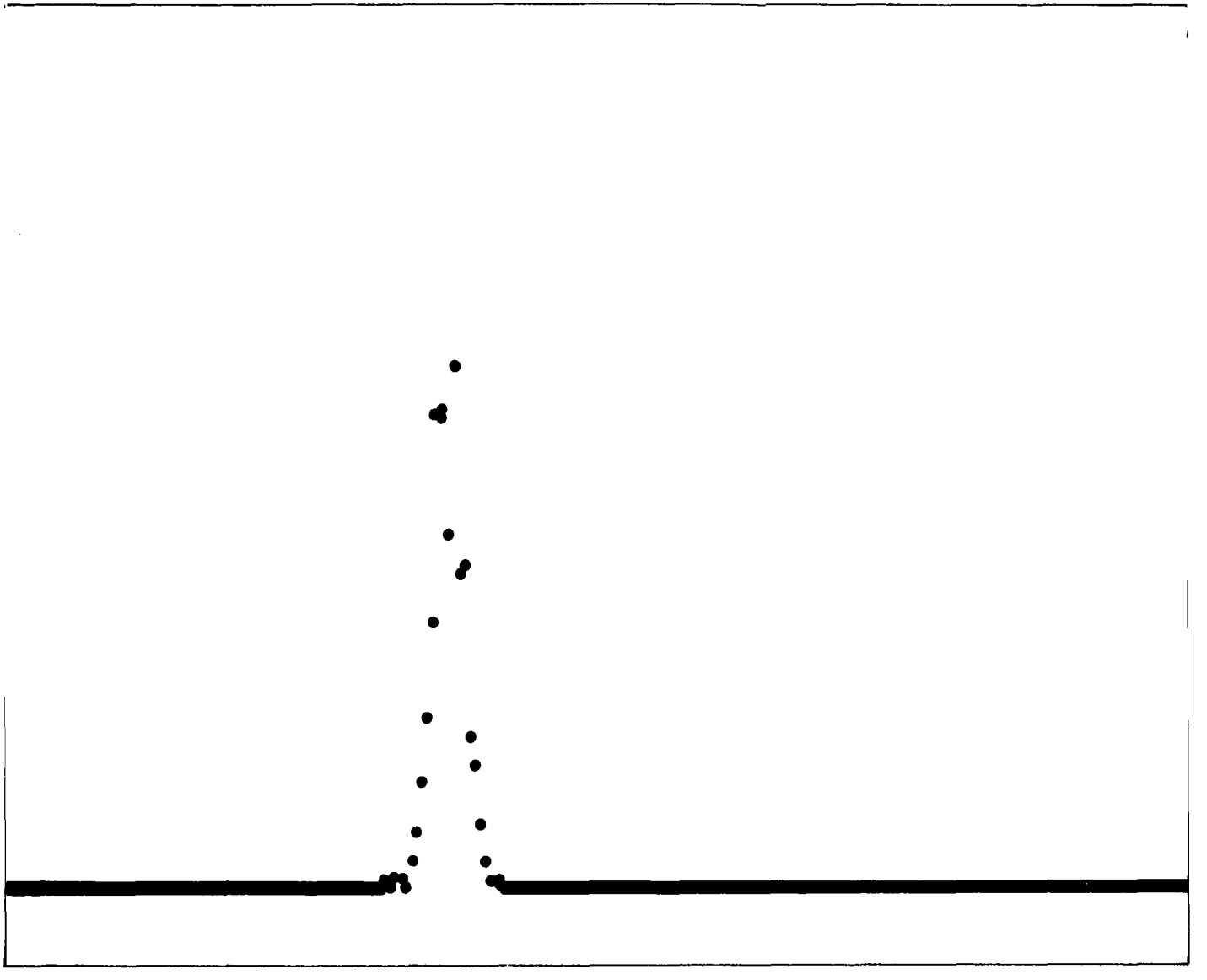

Figure 10.- Time resolved spectrum of thermal ion source (Cs^{131})

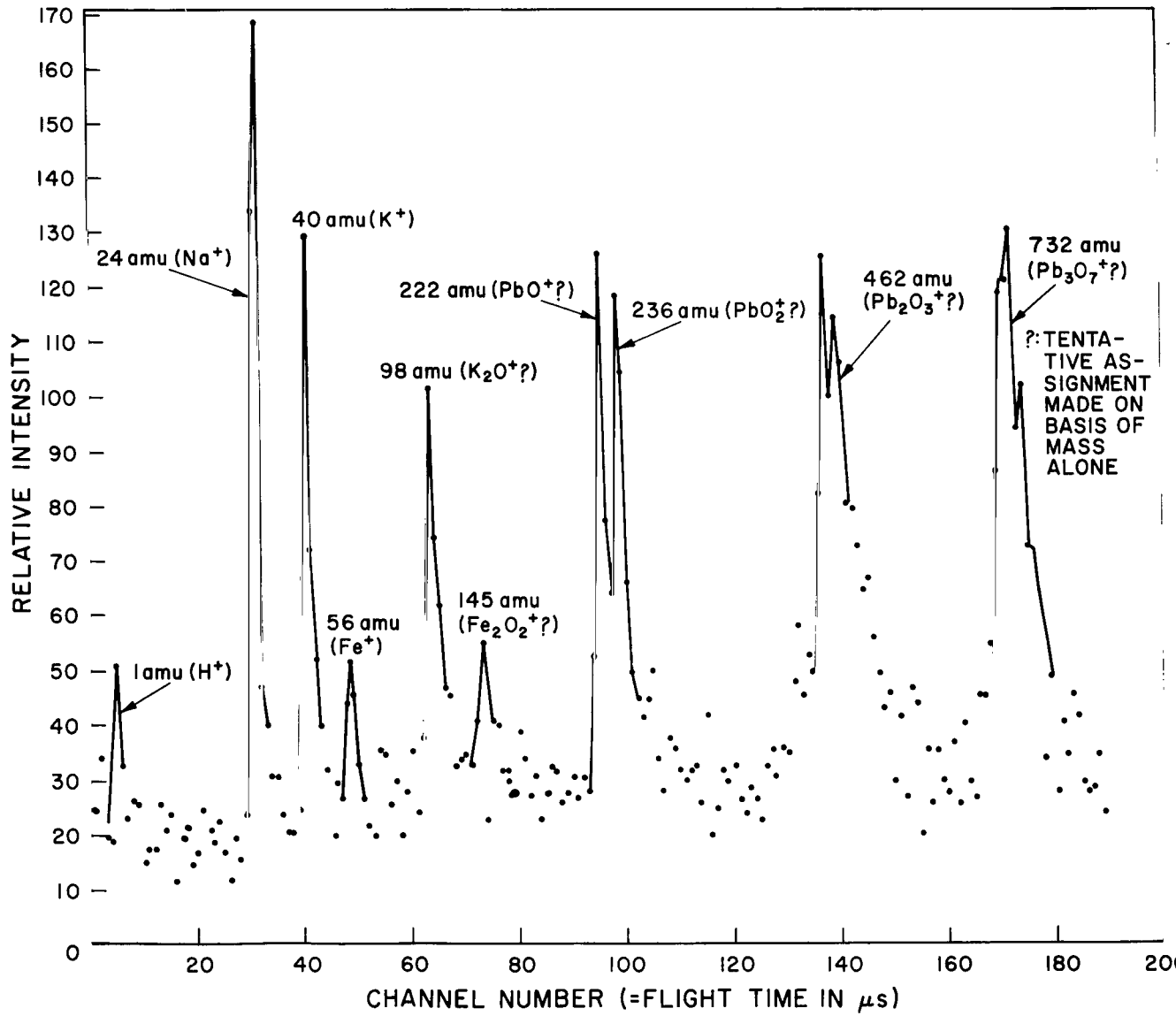

Figure 11.- Time resolved spectrum of carbonyl iron microparticle impacting on lead

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