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MUPPATS -- A MULTIPARTICLE 3D IMAGING DETECTOR SYSTEM

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ABSTRACT

It has long been recognized that the foil-induced dissociation of fast molecular ions is a potentially powerful method to determine the stereochemical structures of the molecular projectiles. We have recently developed a detector system specifically designed for such experiments. The MUPPATS detector is a large-area multistep low-pressure gas counter. The requirements of multiparticle detection with good position and time resolutions leads to a rather complex data-readout and reduction scheme. The system relies on several state-of-the-art techniques, developed in high-energy physics during recent years, to dramatically reduce the cost of the MUPPATS detector. Preliminary results for several polyatomic molecular ions have already been obtained. Some new avenues of research opened up by this detector are also described.

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1. INTRODUCTION

As fast molecular ions (0.1-1.0 Mev/amu) pass through a thin foil, their valence electrons are stripped away initiating a rapid molecular dissociation process which has been termed a Coulomb explosion [1]. Since the stripping of outer-shell electrons takes place within a short time (10^{-17} sec) compared to vibrational and rotational motions, measuring the relative momenta of the Coulomb explosion fragment ions provides a "snap-shot" of the positions of the nuclei in the incident molecular ion [2]. This process has been successfully used by several groups to investigate simple molecular ions [2-6]. Different approaches have been used to perform these investigations. Complete, high-resolution measurements of some of the dissociation fragments gives valuable information for diatomic and, in special cases, triatomic molecular ions, but cannot be used to explore correlated variations in bond lengths and angles. On the other hand, two-dimensional imaging techniques allow the simultaneous measurement of the transverse velocity components of all of the fragments. This provides direct information about certain aspects of the stereochemistry of the molecule (e.g. linear or triangular shapes for triatomics) but fails in general to give an accurate determination of the structure for polyatomic molecules. Furthermore, such techniques cannot determine geometries of individual molecules but only ensemble averages.

Ideally, one hopes to measure, with high resolution, the relative momenta of all dissociation fragments. Due to recent developments in detector technology, both techniques can now be combined permitting the accurate determination of both the longitudinal and transverse momenta of all fragments as well as mass and charge states, thereby yielding complete information on the molecular ion structure, even for a single ion. In order to exploit the new technology, we have, over the past year, developed a new large-area, low-pressure, multiwire proportional detector which is capable of imaging in three dimensions all dissociation products resulting from the fragmentation of molecular ions.

2. THE MUPPATS DETECTOR

The MultiParticle Position- And Time-Sensitive detector is a large-area (34 cm in diameter), Breskin-like gas counter [7], with a wide dynamical range. A detailed description of the MUPPATS detector can be found elsewhere [8]. Among its more unique features, in comparison to more conventional gas detectors, is the ability to determine the ion positions and times for up to ~10 particles simultaneously striking the detector, independent of where the ions actually impinge.

Our detector consists of 5 hexagonal wire planes, rotated by 60 degrees with respect to one another (see Fig. 1). The central anode (at +350 volts) is sandwiched between two ca-

thodes (each 5 mm from the anode) which are both maintained at a potential of -350 volts. Interspersed between these cathodes and the anode plane are two "pick-up" cathodes, each 2 mm from the anode. All ~3000 wires are gold-plated rhenium-doped tungsten, 20 microns in diameter. The detector volume is filled with isobutane at 2.2 Torr pressure. This low pressure allows the use of a sufficiently thin containment window (stretched polypropylene ~100 $\mu\text{g}/\text{cm}^2$) to detect the very slow light ions (e.g. 100 keV protons) required by these experiments.

When charged particles penetrate the detector volume, electron avalanches develop towards the anode. Because of the low pressure, the large mean free path of the resulting electrons leads to high drift velocities and consequently short signal rise times (~4-5 nsec). As a result of this short rise time, extremely good time resolution can be obtained, of the order of a few hundred picoseconds. The electron cloud around the anode also induces signals on the nearest pick-up cathodes. In our detector, these electrodes serve to limit the radial spread of the field lines caused by the avalanche. Furthermore, the effects of space charge due to the slowly-moving gas ions are reduced by these cathodes and a field stabilization is obtained allowing higher gains and consequently the large dynamical range of signals necessary to detect ions of vastly different rates of ionization.

In order to keep the costs manageable, the electronic readout of the signals utilizes the latest generation of FASTBUS data acquisition modules developed for forthcoming experiments in high-energy physics and now becoming commercially available [9]. Compared to the use of conventional NIM and CAMAC electronics modules (e.g. constant fraction discriminators, time-to-digital converters, etc.), FASTBUS has enabled us to reduce the total cost for electronics by nearly a factor of 10. Furthermore, because of the high density of these modules, the resulting system is quite compact. All of the readout electronics, which are not connected directly to the detector, are housed in a single crate.

At the present time, all three planes are read out via tapped delay lines. Signals from different individual wires are pipelined along the delay lines with delays of 5 nsec between neighbors. Therefore, within a single event, several pulses appear at each end of a delay line necessitating careful pulse shaping at the junction of each wire to the delay line. To reduce signal damping, the delay lines are segmented into four sub-units (of 72 wires each) for each wire plane. The signals propagating to each delay line end are amplified and analyzed by four leading edge discriminators operating at different thresholds. The relative times of the leading and trailing edges of each train of logic signals (for each threshold) are recorded by a single

96-channel pipelined time-to-digital converter (TDC). The common stop used for these 96 channels is a simple trigger decision requiring that at least one pulse is seen in each wire plane.

3. RESULTS AND ANALYSIS

The MUPPATS detector has now been extensively tested with beams of H_2^+ , H_3^+ , N_2^+ , C_2^+ , HeH^+ , CH^+ , CH_2^+ , and H_2O^+ in the range of 2-4 MeV. Figure 2 shows the form of the raw data, as read from the pipelined TDC, for a typical multiparticle event observed following the foil-induced dissociation of 4.0-MeV CH_3^+ ions in a $2-\mu g/cm^2$ carbon foil. This figure shows all leading and trailing edges of all pulses observed for the four delay line subunits in each plane. The four discriminator thresholds are appropriately displaced for each subunit, allowing crude reconstruction of the pulse forms in each delay line. In cathode "A", the large pulse in delay line #1 (crossing all 4 thresholds) corresponds to a carbon ion, whereas the other three pulses in that plane were caused by the protons contained in the incident molecule. Note that delay line #4 in that plane contains pulses from two different protons. This figure shows the pulses at each end of the delay lines. Utilizing the crude pulse height information, we are able to determine the centroids of these pulses quite accurately. Pulses pro-

pagating rapidly to one end must arrive relatively late at the other end. The differences in propagation time to each end thereby yields the position information in each plane and the sums of these centroids gives the relative arrival time of each particle. Because of the relatively small difference in arrival times of the fragment ions (~ 10 -50 nsec) in comparison to the microsecond scale of the figure, the pulses are approximately symmetric with respect to the center of the figure. In tests with 2-MeV carbon ions, we have determined the position and time resolutions to be 260 microns (FWHM) and 1.0 nsec respectively when averaged over all three planes.

The position and time information provided by the detector is then converted into relative velocities of the constituent ions. A typical spectrum resulting from preliminary analysis by this process is shown in Figure 3. This histogram shows the distribution of the relative velocities of the protons and carbon ions produced by the foil-induced dissociation of 4.0-MeV CH_2^+ ions. The data in the figure include only those molecules in which the angle between the final velocities of the protons (in the projectile frame) is in the range 130-160 degrees. For this molecular ion, the angle between these velocity vectors is approximately equal to the bond angle in the incident molecule. The upper panel of Figure 4 shows the measured distribution of this angle for the same conditions, integrating over all

molecules contained in the beam. The lower panel of this figure shows a subset of that distribution, for molecules in which the mismatch in the two C-H bond lengths lies in the range of 10-20% of the average bond length. These asymmetric molecules exhibit a somewhat different distribution of bond angles than seen for the total distribution. As seen in the figure, there appear to be two peaks in this distribution. One peak is seen at approximately 140 degrees. This compares quite well with the best available theoretical calculations which predict an angle of 138.7 degrees for the ground electronic state [10]. In addition, these asymmetric molecules also seem to show a peak at of 105 degrees, although the bond lengths for these two groups are not measurably different. These data are now being processed further and it is hoped that these results will determine, for the first time, the geometrical structure of this fundamental molecular ion.

4. OTHER EXPERIMENTS

In addition to the results shown above, the MUPPATS detector has also been used to attack other problems as well. The unique property of this detector enabling the simultaneous detection of multiple particles, has permitted us to more fully exploit the use of molecular projectiles to study various atomic collision phenomena. A good example of this comes from a recent experiment aimed at studying the depen-

dence of electron emission probabilities for fast molecular-ion projectiles in solids [11]. Of fundamental concern in these experiments is the orientation of the molecule as it penetrates the target. The difficulty in designing such an experiment is that in order to determine the orientation of the molecule, one must detect the Coulomb explosion fragments, with high angular and energy resolution, together with the coincident electrons. Because the yield of energy-resolved electrons is small, traditional attempts to perform such measurements have been stymied by either terribly small coincidence efficiency, or low coincidence yields. With the MUPPATS detector we have been able to overcome these difficulties. Because this detector is able to detect all fragments striking its active area, such coincidence experiments can be performed without sacrificing solid angle (and hence efficiency) to determine the molecular orientation. Figure 5 shows the results of a typical measurement in which the yield of binary encounter electrons emerging along the beam direction (primary knock-ons) are shown as a function of the orientation of the N_2^+ projectile. Such experiments seem to be quite promising as a way of probing the electron density surround fast ions penetrating solids.

5. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

1. Arrangements of electrodes in the MUPPATS detector and the signal-readout and -processing schemes.
2. Computer reconstruction of the delay-line readout of the pick-up cathodes. The data shown represent a typical event observed following the foil-induced dissociation of 4.0-MeV CH_3^+ ions in a $2\text{-}\mu\text{g}/\text{cm}^2$ carbon foil. The left two panels are for pulses propagating to the "left" ends of each delay line subunit while the right panels show the pulses recorded at the "right" ends of each subunit. The full time scale for each panel is 1 microsecond.
3. A histogram showing the distribution of the C-H relative velocities for protons and C^{4+} ions observed following the foil-induced dissociation of 4.0-MeV CH_2^+ ions. The data shown are for molecules with a restricted range of bond angles as described in the text.
4. Distribution of the angles between the final C-H relative velocity vectors in the frame of reference moving with the beam velocity. The data are for the same case described in Figure 3. The upper panel is the distribution for all molecules observed, while the lower panel shows only those molecules in which the difference between the two C-H bonds lies in the range of 10-20% of the average bond length (1.08 Å).
5. The yield of binary encounter electrons as a function of the angle of the internuclear axis, with respect to the beam direction, for a beam of 4.5-MeV N_2^+ ions penetrating a $2\text{-}\mu\text{g}/\text{cm}^2$ carbon foil. Zero degrees corresponds to molecules aligned along the beam direction, while 90 degrees corresponds to those molecules with their internuclear vectors transverse to the beam velocity.

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