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THE X-RAY DRIFT CHAMBER (XDC):
USE OF CONVENTIONAL MWPCs AS DRIFT CHAMBERS
FOR DETECTION WITH HIGH ENERGY RESOLUTION OF SOFT X-RAYS
WITH ENERGY DOWN TO 500 eV

U. Gastaldi

CERN, Geneva, Switzerland

ABSTRACT

A new way of using conventional MWPCs for detection with good energy resolution of low-energy X-rays is suggested. The method is based on the measurement of the drift-time of the primary electrons and on the strong energy dependence of the absorption cross-section of low-energy X-rays. While the low-energy detection threshold is, as usual, determined by the thickness of the chamber entrance window and can be set below 500 eV with thin windows, the energy resolution is no longer dictated by the number of primary electrons, but instead by the accuracy of the drift-time measurement. The method is illustrated in the 3-6 keV energy region, using $\bar{p}\text{He}$ data collected with the high-pressure cylindrical MWPC used by the "Protonium" Collaboration in Exp. S142 at CERN.

The use of this new detection technique in a 4π X-ray counter may allow substantial progress in the spectroscopy of low-Z exotic atoms.

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1. INTRODUCTION

The use of gas proportional counters for the detection of low-energy X-rays is indispensable when a large solid-angle coverage is required.

This situation is typical of the spectroscopy of low-Z exotic atoms formed by stopping negative charged particles (μ^- , π^- , $\bar{p}$, ...) in gaseous H_2 , D_2 , or He targets. Here a large solid-angle coverage is necessary, a) to compensate for the small number of exotic atoms formed by stopping the negative particles in gas (the stop in gas is mandatory to minimize the interactions of the exotic atom with the surrounding medium) and b) to collect in coincidence two or more X-rays produced subsequently in the same atomic cascade.

Owing to their basic simplicity, the low-Z exotic atoms are of great interest for the study of the perturbations induced by strong and electromagnetic interactions on their atomic levels, which have energies that are determined principally by the Coulomb interaction. However, most of the radiative transitions have energies below 2 keV (see Table 1), where the use of solid-state detectors is precluded because of the extremely low detection efficiency due to a) the small solid angle coverage and b) the X-ray attenuation of the protection window and of the front dead layer of the semiconductor. Only a few pilot experiments exist in this field¹⁻⁷⁾, owing to the difficulty of detecting the low-energy X-ray transitions and to the poor resolution obtainable for the detected lines with gas proportional counters [see Table 2^{6,8-11)}].

In selected cases the difficulty connected with the poor energy resolution has been overcome using differential counting techniques [filters³⁾, induced spectroscopy^{4,5)}, detection of two X-rays in coincidence⁷⁾], which do not rely principally on the resolution of the X-ray detector.

A substantial progress in this field can be achieved only with a detection system with high angular acceptance (to allow detection of many coincident X-rays) and with lower energy threshold and better energy resolution (to allow detection and identification of more lines).

In the case of the $\bar{p}p$ atom a method fully satisfying these requirements has been proposed^{12,13}): this method profits from the fact that antiprotons are stable particles and can therefore be stored in a storage ring, and exploits the Doppler magnification of the energy of the X-rays emitted in the forward direction by $\bar{p}p$ atoms formed in flight. This method cannot, of course, be applied to μ 's, π 's, and other unstable particles.

A new technique¹⁴), based on the detection with photomultipliers of the scintillation light produced by the primary electrons drifting in a weak electric field not causing multiplication, allows improvement of the energy resolution of conventional gas proportional counters by a factor of two^{14,10}). The main drawbacks of this new detection technique are that a) it seems very difficult to design a 4π detector of this type, b) the detection system is voluminous and hardly compatible with a strong magnetic field, owing to the presence of the photomultipliers, and c) the energy resolution is still dictated by the statistical fluctuations on the production of primary electrons and deteriorates rapidly for X-ray energies below 1 keV (the energy resolution $\Delta E/E$ has an energy dependence of the type $\Delta E/E \propto E^{-1/2}$).

We suggest, in this paper, a new way of using conventional MWPCs for the detection of soft X-rays. This new detection technique is based on the measurement of the drift-time to the anode surface of the primary electrons produced in the X-ray absorption process and may allow good energy resolution even in the low-energy region below 1 keV, because the energy resolution is no longer dictated by the number of primary electrons, but instead by the accuracy of the drift-time measurement.

This new technique is discussed in close connection with the low-Z exotic atom spectroscopy, but can be likewise successfully applied in all cases when the X-rays incident on the detector can be tagged by a prompt signal providing the zero-time for the drift-time measurement.

In Section 1 we discuss the general features of the X-ray drift chamber (XDC), in Section 2 the method is illustrated using a subset of $\bar{p}\text{He}$ data¹⁵) collected with the apparatus¹⁶) used at CERN by the "Protonium" Collaboration in the energy

region 3-6 keV, where the absorption cross-section varies by an order of magnitude owing to the presence at 3.2 keV of the K absorption edge of the Ar counter gas. In the conclusions we discuss the progress that the XDC can allow in low-Z exotic atom spectroscopy and possible applications of technical interest.

2. THE X-RAY DRIFT CHAMBER

2.1 Principles of operation

The basic idea consists in using a standard MWPC¹⁷⁾ with a quite uniform electric field, obtained by adopting a big gap between the anode surface and the cathode surfaces and small spacing between the anode wires, and to measure the drift-time of the primary electrons generated by the X-ray absorption in the counter gas (Fig. 1). The zero time is given by the time at which the beam particle stops in the target gas, when studying the spectroscopy of exotic atoms. The absorption cross-section of low-energy X-rays in the counter gas depends very strongly on the X-ray energy [see Table 3, where the absorption cross-sections recommended in Veigele¹⁸⁾ have been used] and increases with decreasing energy of the X-ray roughly as $E^{-\alpha}$ with $2 < \alpha < 3$ away from the absorption edges: as a consequence, low-energy X-rays are stopped quite near the chamber entrance window, while more energetic ones produce a flatter stop distribution in the direction orthogonal to the anode surface. Lower energy X-rays are then qualitatively characterized by a long drift-time, giving a narrow peak at late time in the drift-time distribution. As the drift velocity in the direction orthogonal to the anode surface is very stable, owing to the constancy of the electric field up to quite near the anode wires, the X-ray stop distribution in slices parallel to the anode surface can be studied easily in terms of the drift-time distribution. In the case of normal incidence the absorption distribution $A(r)$ of X-rays of a given energy E in the direction r normal to the anode surface is, with the conventions of Fig. 1,

$$A(r) = \frac{IT}{\lambda} e^{-r/\lambda}, \quad (1)$$

where

$I = I(E)$ is the total number of X-rays incident on the chamber window,

$T = T(E)$ is the X-ray transmission of the window,

$\lambda = \lambda(E)$ is the X-ray mean free path in the chamber gas.

The corresponding drift-time distribution $D(t)$ is

$$D(t) = \frac{ITv}{\lambda} e^{-G/\lambda} (e^{-vt/\lambda} + e^{+vt/\lambda}), \quad (2)$$

where

v = drift velocity,

G = counter gap,

$0 \leq t \leq G/v$.

The energy of a monochromatic low-energy X-ray source can then be determined from the value of λ deduced from the drift-time distribution $D(t)$.

The energy resolution is, in principle, independent of the energy of the X-ray (which is proportional to the number of primary electrons produced when the X-ray is absorbed) as the drift-time is determined by the time of arrival of the first primary electrons in the amplification region and does not depend on the total number of primary electrons.

Changing the counter gas (e.g. Ne, Ar, or Xe), the thickness of the slice of proportional counter necessary to stop more than 63% of a given line (*stopping slice*) can be varied substantially at a given working pressure, if the pressure range in the target-gas region (see Fig. 1) is limited for physical reasons. Alternatively, if the target-gas pressure is not constrained *a priori* for physical reasons, the thickness of the stopping slice can be varied arbitrarily by changing simultaneously the target-gas and the counter-gas pressures. This possibility of varying the thickness of the stopping slice allows one to obtain an energy resolution which is also energy independent in practice.

When the counter is operated in the proportional régime the cut $(G - 2\lambda)/v < t < G/v$ in the drift-time distribution allows a reduction of the noise in the amplitude spectrum by a factor $4\lambda/G$.

Owing to the strong dependence of λ on E [for example, in Ar, λ decreases by a factor of 250 going from 3 keV to 300 eV (see Fig. 2)], a cut in the drift-time

spectrum operates a selection between X-rays of different energies and can be used to distinguish them independently of and in addition to the amplitude of the anode signal.

In the case of exotic atoms the energies of the X-rays emitted in the last transitions of the cascade between circular orbits are very different $[E \propto (2n + 1)/n^2(n + 1)^2, n = \text{principal quantum number of the final level}]$, so that the drift-time information alone can easily single out the higher transitions, while the lower and more energetic transitions can be recognized by looking at the amplitude spectrum. This way, if the low-energy background is well depressed by a good trigger, the energy resolution in the low-energy region is no longer controlled by the number of primary electrons formed by the absorbed X-rays, but instead by a) the accuracy of the drift-time measurements, b) the difference of the absorption cross-sections for X-rays of subsequent transitions in the exotic atom, and c) the working pressure of the chamber.

To give an example, we plot in Fig. 3 the absorption distribution and the corresponding drift-time distributions for K_{α} and L_{β} transitions of the μ^-p atom for a 1 cm gap chamber filled with Ar at NTP. All curves are drawn for $I = T = 1$; $I = 1$ is a good approximation as the X-ray absorption in the target gas (H_2 , D_2 , or He) is negligible.

By comparing the areas below the drift-time curves in a given drift-time interval and weighting them according to the respective T factor, one can easily calculate the contamination of a given line from X-rays of higher and lower energy transitions present in the same drift-time interval. One can, of course, minimize the contamination by varying the drift-time cuts. The contamination C of a line of energy E_1 and X-ray mean free path λ_1 in the drift-time window $(G - \lambda_1)/v \leq t \leq G/v$, where 63% of X-rays with energy E_1 are detected, is

$$C \leq 3.2 \frac{\lambda_1 T_2 I_2}{\lambda_2 T_1 I_1} \quad (3)$$

by a line with energy $E_2 > E_1$, and

$$C \leq 1.6 \frac{T_3 I_3}{T_1 I_1} \quad (4)$$

by a line with energy $E_3 < E_1$. In general, the higher energy contamination can be reduced considerably by looking at the pulse amplitude, while the lower energy one is damped by the transmission factor T (unless the lower energy line is below an absorption edge in the window material).

In order to fix some orders of magnitude one may consider that a cylindrical XDC as shown in Fig. 1, with a 2 μm thick mylar entrance window, could detect the 0.474 keV L_β transition of μ^-p with 6% total efficiency for normal incidence, with a contamination of less than 10^{-2} from M transitions and of less than 1.4 from K transitions in the stopping slice contiguous to the window (where more than 63% of the L X-rays are absorbed).

The low-energy detection threshold is essentially determined by the transmission T of the XDC entrance window owing to a) the absence of any dead regions in the XDC entrance region, b) the independence of the energy resolution of the X-ray energy, and c) the low noise level (< 100 eV) of standard MWPC electronics.

The transmission T depends strongly on the chemical composition and on the thickness of the window of the chamber and, for a given window, on the X-ray energy. In Fig. 4, T is plotted versus the X-ray energy for normal incidence on beryllium and mylar windows of various thicknesses.

The use of Be windows is tempting because of the lower absorption when compared with a mylar foil of equal thickness; but the handling of thin Be foils is not easy, while the technique for building a big thin cylindrical mylar window for a 4π detector is well established¹⁹).

Combining a thin window with Xe counter gas one can obtain a high total detection efficiency in a wide energy range up to 40 keV without the need for too high pressures.

2.2 X-ray coincidences

The cross contamination of lines of different energies can be still further reduced when working with a 4π detector by analysing the coincidences of X-rays in various sectors of the counter. As an example, if an L line is detected in one sector in coincidence with a K line in another sector of the counter, on one hand the L line is not a misinterpreted K line and on the other hand the K line is

necessarily a K_{α} transition. In this way, the coincidence technique allows the separation of the α transitions from the other lines of the same series independently of the energy resolution of the counter.

The importance of constructing detectors of large angular acceptance Ω stems from the obvious fact that the efficiency of the coincidence technique is proportional to $(\Omega/4\pi)^n$, where n is the number of coincident X-rays that can be detected.

2.3 Rejection of signals from charged particles

If the X-ray detector completely envelops the target-gas region as has been realized in the counter described in Refs. 9 and 19, in order to have an $\sim 4\pi$ angular acceptance, the counter is exposed to a high flux of charged particles and pulse-shape discrimination is, in general, mandatory to separate pulses due to the X-rays from pulses due to charged particles. In the XDC case the discrimination can best be done by again exploiting the drift-time information. Charged particles stopping in the proportional counter leave a huge quantity of energy and cannot be misinterpreted as X-rays. Particles traversing the chamber cross the anode plane and thus generate some primary ionization electrons quite near to the wires. By skipping the first drift-time channels one then rejects the charged particles with good efficiency and just loses, in the detection of the higher energy X-rays, a fraction of the active volume of the chamber of the order of the ratio $d/2G$, where d is the spacing between the anode wires.

2.4 Further possible improvements

All that has been said up to now is valid even if one groups many anode wires in parallel to reduce the number of electronic channels and sends the signals to a common amplifier.

The energy resolution worsens in the general case of non-normal incidence. However, the angle of incidence can be determined and taken into account off line, event per event in the drift-time analysis, if the complete kinematics of every event (beam particle stop position, direction of emission of X-rays and of capture/annihilation prongs) is known. The complete kinematics of every event can indeed be determined¹⁹⁾ without the need for optical techniques because:

- i) applying charge-division techniques²⁰⁾ to the signals of the anode wires of a 4π XDC, one can get for every event a) a complete three-dimensional picture of the X-ray stop distribution in the chamber, and b) the intercepts with the anode surface of the tracks of charged prongs of the capture or annihilation processes,
- ii) the stopping point of the beam particle can be reconstructed rather accurately (the dE/dx is maximum there) by installing a projection chamber²¹⁾ inside the target gas region with the electric field parallel to the beam axis and the sensitive region at the downstream end of the target.

2.5 Testing facilities

It is essential in this method to have a good zero time for the drift-time measurements. This is not a problem in the case of exotic atoms, as the beam particle stop-time is defined usually to better than 10 nsec and the whole atomic cascade develops typically within less than 10 nsec until a stable or metastable level is reached and/or capture or annihilation occur.

For testing purposes a ^{54}Mn source is quite convenient as it emits 5.5 keV X-rays with an absolute yield of 25% and 835 keV γ -rays with a 100% yield, and an 835 keV γ -ray easily fires a scintillator supporting the source, thus providing a prompt trigger and the zero-time. For lower energy it is usual to use X-rays produced by fluorescence of various materials induced by electron bombardment²²⁾. This technique can be adapted in our case by pulsing the HV of an electron gun to shoot electrons with energy above the chosen fluorescence edge during short time intervals and using the time of the HV pulse as zero time for the drift-time measurement. Generators providing up to 2 kV pulses with 0.5 nsec rise-time and length adjustable between 2 and 20 nsec are commercially available²³⁾.

3. EXPERIMENTAL MEASUREMENTS

For a qualitative illustration of the method proposed in this paper, we discuss drift-time spectra of X-rays collected during $\bar{p}\text{He}$ runs by the "Protonium" Collaboration at CERN.

The "Protonium" group uses a cylindrical MWPC^{9,19)} surrounding a gas target from which it is separated by a thin aluminized mylar window. The configuration of the electric field (see Fig. 5) is similar to that of the " γ " detector used by Alberigi Quaranta et al.²⁴⁾ in μ -capture experiments in H_2 gas. It was chosen to have a good detection efficiency for 8 keV X-rays with a minimum number of independent anode wires and to have a good separation between contiguous cells of the counter. This chamber is indeed quite similar to a drift chamber of the type described in Walenta et al.²⁵⁾ and is more suited to measuring the azimuthal coordinate of the charged particles traversing it than the radial distribution of the X-rays absorbed in the chamber. However, owing to the fact that the drift-time to each anode wire is recorded independently for every wire together with the amplitude signal, the chamber is useful to illustrate the XDC technique when one compares the drift-time spectra of lines with very different absorption cross-sections. This situation occurs with the 3 keV X-rays of the fluorescence produced in the Ar counter gas^{*)} and the 3.9 keV X-rays emitted in $\bar{p}He$ 4-3 transitions (see Fig. 2). The 3 keV line is just below the Ar K edge and the absorption cross-section is relatively small, so that the X-ray absorption distribution is consequently rather flat along r , and in particular some X-rays stop near the anode wires and one then expects some signals at short drift-time. On the other hand, the 3.9 keV $\bar{p}He$ line is to the right of the Ar K edge and the absorption cross-section is one order of magnitude higher than that for the 3 keV line; at 4 abs. atm more than 95% of these X-rays are stopped in the first 5 mm of counter gas and, in particular, almost none are stopped near an anode wire: one then expects very few signals at short drift-times in the drift-time distribution. These qualitative predictions are confirmed by the experimental drift-time spectra shown in Fig. 7.

*) The fluorescence is induced by the charged particles crossing or stopping in the chamber; the 3 keV fluorescent X-rays originate in a cell of the chamber, traverse the He target, and are detected in a cell of the counter which is not contiguous to the one where they have been produced -- see Fig. 6.

The effect of drift-time cuts on amplitude spectra are shown in Fig. 8, which illustrates how powerful the XDC method we suggest can be also in a situation with a non-dedicated electric field configuration.

As a further illustration we show, in Fig. 9, 5.5 keV X-ray drift-time spectra taken at different pressures with the same gas gain. The stopping slice compresses towards the window of the chamber when increasing the pressure and the effect appears clearly in the experimental data where the peak of the drift-time distribution moves to longer drift-times and the signal at short drift-times reduces when going from low to higher pressures.

4. CONCLUSIONS

The measurement of the drift-time according to the scheme presented in this paper will allow, in general, an important noise reduction and a better separation between X-ray lines of different energies.

When dealing with a monochromatic tagged low-energy X-ray source, the X-ray energy can be deduced from the slope of the drift-time curve.

When the source -- as in the case of the exotic atoms -- emits a spectrum of discrete lines well spaced in energy, the drift-time technique can be used directly to separate the low-energy transitions.

In the special case of exotic atoms, when working in coincidence with a 4π counter, the detection of a lower energy line automatically allows a selection of the subsequent transition (e.g. an L X-ray in coincidence with a K X-ray implies that the K transition was a K_α , an M line in coincidence with a K transition implies that it was a K_β): this is equivalent to having a better energy resolution for the more energetic transition.

Inversely the measurement of the ratio between the number of X-rays populating a given level (higher transition with lower energy) and the number of the subsequent lower transitions (with higher energy) determines the level width in the case of hadronic atoms, and this is equivalent to having a much higher energy resolution for the lower energy line.

The use of the XDC technique should allow the detection of at least one more transition of lower energy in all low-Z exotic atoms. This would imply, in particular, the following possibilities:

- i) to fix the experimental conditions (see Ref. 6 and references quoted therein) for performing a precise measurement of the 2S-2P splitting in μ^-p [this experiment would provide a good test of QED²⁶⁾ on the one hand and a high precision determination of the proton electric form factor in the space-like region at low momentum transfer²⁷⁾ on the other hand, if one assumes the validity of the QED calculations];
- ii) to determine directly -- with the coincidence technique -- the strong interaction width of many excited levels of the low-Z hadronic atoms;
- iii) to monitor with the X-ray signature the quantum numbers of the state of a hadronic atom from which annihilation/capture occurs.

Moreover, a 4π XDC combined with a projection chamber defining the beam particle stopping point in the target gas would allow a substantial improvement in the precision of the measurement³⁾ of the πd scattering length. It would also allow the repetition of the first measurement of the proton form factor at the threshold of the time-like region²⁸⁾ when cooled $\bar{p}$ beams become available¹²⁾. The reaction $\bar{p}p \rightarrow e^+e^-$ could be studied in H_2 gas instead of in liquid H_2 and the total S-wave annihilation rate could be measured directly by measuring the width of the $\bar{p}p$ atomic S levels.

The development of the XDC for detecting very soft X-rays could have interesting consequences from a technical point of view. Very low energy X-rays are used to study the ultimate precision obtainable in wire chambers²⁹⁾, since their energy deposition is more highly localized the softer the X-ray. The lowest energy line currently used in this research is the 1.56 keV X-ray from Al-fluorescence for which the linear dimension of the region around the absorption point, where the primary electrons form, is typically 20 μm at NTP. The use of still lower energy X-rays would reduce the size of this region thus providing a more sensitive probe in this kind of research. The results are of particular interest when considering that by application of the centre of gravity technique³⁰⁾ to ultra-thin cylindrical

4π detectors a miniaturization of the central detectors for $\bar{p}p$ and e^+e^- colliding rings could become possible¹⁹).

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Table 1

Energy of X-ray transitions between Coulomb levels of low-Z exotic atoms

Transition ($n_i \rightarrow n_f$)	Line	X-ray energy (eV)								
		μ^-p	π^-p	$\bar{p}p$	μ^-d	π^-d	$\bar{p}d$	$\mu^{-4}\text{He}^{++}$	$\pi^{-4}\text{He}^{++}$	$\bar{p}^{-4}\text{He}^{++}$
$\infty-1$	K_∞	2529	3235	12491	2663	3459	16652	10943	14328	79833
2-1	K_α	1896	2426	9368	1997	2594	12489	8207	10746	59875
$\infty-2$	L_∞	632	809	3123	666	865	4163	2736	3582	19958
3-2	L_α	351	449	1735	370	480	2313	1520	1990	11088
$\infty-3$	M_∞			1388			1850	1216	1592	8870
4-3	M_α			607			809	532	696	3881
$\infty-4$	N_∞			781			1041	684	895	4990
5-4	N_α			281			375	246	322	1796
$\infty-5$	O_∞									3193
6-5	O_α									976
$\infty-6$	P_∞									2218
7-6	P_α									588
Reduced mass (MeV)		94.97	121.50	469.14	100.02	129.90	625.42	102.75	134.53	749.59

Table 2

Characteristics of gas chambers used as detectors of soft X-rays from low-Z exotic atoms

Detector	Window thickness (μm mylar)	Area (cm^2)	$\Omega/4\pi$ (%)	Energy threshold (keV)	Energy resolution at 5.9 keV (FWHM eV)	Ref.	Footnote
Gas proportional counters	6-12	200	5-10	1	1000 (800 eV at 2 keV)	1-3, 8 6	
Gas proportional scintillation chamber	6	200	5-10	1	500 (340 eV at 2 keV)	14 10	a a
Cylindrical multicell proportional counter	6	10000	> 85	1	1500 (1050 eV at 3 keV)	9	b
Cylindrical XDC	2	10000	> 85	~ 0.5	1000 and XDC discrim.		c
Solid-state detector	50 < 1	1 0.1	< 0.1 < 0.01	3 < 0.3	200 (100 eV at 500 eV)	11 22	d a

- a) Lab. measurements.
b) In-beam calibration.
c) Design figures.
d) The characteristics of a solid-state detector used to detect X-rays from $\bar{\text{p}}\text{He}$ in liquid helium¹¹⁾ are given for comparison.

Table 3
X-ray total attenuation cross-sections of elements of relevance for the XDC

X-ray energy (keV)	Edge (keV)	σ_{tot} (cm ² g ⁻¹)									
		H	He	Be	Al	C	O	Ne	Ar	Xe	
0.1		12000	54000	8100 6400 160000	130000	27000	62000	120000	20000	18000	
	0.1103										
	0.1117										
0.15 0.2		3300 1300	19000 8600	85000 45000	88000 52000	11000 5600	26000 13000	54000 29000	13000 8000	5100 6200	
	0.2452										
	0.2500										
0.3 0.4 0.5											
	0.2831					2500			5600		
	0.2845					49000			78000		
0.3 0.4 0.5		360 140 68	2700 1100 570	16000 7800 4200	22000 11000 6700	42000 23000 13000	5000 2500 1400	11000 5300 3000	45000 29000 17000	7200 5800 4400	
	0.5313						1200				
	0.5327						19000				
0.6 0.7 0.8											
	0.6										
	0.7	37 23 14	320 190 130	2500 1700 1100	4300 2900 2100	8400 5700 4000	16000 11000 7900	1900 1200 880	11000 7800 5600	3400 23000 12000	
0.9 1.0 1.5											
	0.8662							710			
	0.8676							9000			
0.9 1.0 1.5		10 6.9 2.1	85 61 17	790 590 180	1500 1200 390	2900 2200 700	5900 4500 1600	9600 7700 2700	4100 3200 1100	9400 9400 4400	
	1.560				350						
	1.560				4500						

(cont.)

Table 3 (cont.)

X-ray energy (keV)	Edge (keV)	$\sigma_{\text{tot}} \text{ (cm}^2 \text{ g}^{-1}\text{)}$								
		H	He	Be	Al	C	O	Ne	Ar	Xe
2.0 3.0	3.203 3.203	1.0 0.6	6.7 2.1	74 21	2400 810	300 88	700 220	1300 400	510 180	2100 780
4.0		0.5	0.9	8.5	370	37	93	180	820	390
5.0 6.0 8.0 10.0 15.0 20.0 30.0	4.782 4.782	0.4	0.6 0.4 0.3 0.2	4.3 2.5 1.1 0.6 0.3 0.2	200 120 50 26 8 3.4 1.1	19 11 4.5 2.3 0.8 0.4 0.3	48 28 12 6 1.8 0.9 0.4	92 54 23 12 3.6 1.6 0.6	450 270 120 63 20 8.4 2.6	650 670 310 170 57 27 9.3
40.0 50.0 60.0 80.0 100.0			0.3	0.15	0.13	0.17	0.15	0.15	0.16	1.2 0.7 0.5 0.3 0.2
ρ_{NTP} (g cm ⁻³)		8.381×10^{-5}	1.664×10^{-4}	1.845	2.694		1.331×10^{-3}	8.391×10^{-4}	1.660×10^{-3}	5.458×10^{-3}

Figure captions

- Fig. 1 : Cylindrical X-ray drift chamber (XDC).
- Fig. 2 : Mean free path of X-rays in Ar and Ne at NTP.
- Fig. 3 : a) Absorption distributions and b) associated drift-time distributions expected for K_{α} (1896 eV) and L_{β} (474 eV) X-rays from $\mu^{-}p$ atoms. (Normal incidence, Ar at NTP, $G = 1$ cm.)
- Fig. 4 : X-ray transmission of mylar and Be foils.
- Fig. 5 : Configuration of the electric field of the "Protonium" cylindrical multicell proportional chamber.
- Fig. 6 : a) Ar fluorescence and b) $\bar{p}He^{++}$ typical events.
- Fig. 7 : Drift-time distributions of a) 3 keV Ar fluorescence X-rays and b) 3.9 keV $\bar{p}He^{++}$ X-rays (4-3 transition). (Counter gas: 95% Ar + 5% C_3H_8 . Target gas: He, 4 abs. atm: 12 μm mylar. Zero time given by time of entrance of the antiproton into the target gas region.)
- Fig. 8 : Comparison of X-ray energy spectra collected with two different drift-time cuts and with two independent triggers: a) $\bar{p}$ stop trigger (a $\bar{p}$ stopped in the He target region), b) Ar fluorescence trigger (a $\bar{p}$ escaped from the He target and stopped in the Ar gas or traversed the proportional chamber). A prominent peak at 3.9 keV from 4-3 transitions in $\bar{p}He$ appears only in the late drift-time window, while the opposite occurs with the 3 keV peak from Ar fluorescence. (Same conditions as for Fig. 7.)
- Fig. 9 : Drift-time distributions of 5.5 keV X-rays from a ^{54}Mn source at various working pressures. Zero time given by the ^{54}Mn 835 keV γ . (Counter gas: 95% Ar + 5% C_3H_8 . Target gas: H_2 . 6 μm mylar. Same gas gain at all pressures.)

XDC (X-RAY DRIFT CHAMBER)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

DRIFT TIME SPECTRA

Fig. 7

Fig. 8

DRIFT TIME SPECTRA OF ^{54}Mn 5.5 keV X-RAYS

Fig. 9