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Changes in the annihilation delay time distribution of stopped antiprotons in helium gas, due to contaminants. - II

THE OBELIX COLLABORATION
A. BERTIN [1], M. BRUSCHI [1], I. D'ANTONE [1], S. DE CASTRO [1], A. FERRETTI [1]
D. GALLI [1], B. GIACOBBE [1], U. MARCONI [1], M. PICCININI [1], N. SEMPRINI CESARI [1]
R. SPIGHI [1], S. VECCHI [1], A. VEZZANI [1], F. VIGOTTI [1], M. VILLA [1], A. VITALE [1]
A. ZOCCOLI [1], M. CORRADINI [2], A. DONZELLA [2], E. LODI RIZZINI [2]
L. VENTURELLI [2], A. ZENONI [3], C. CICALÓ [4], A. MASONI [4], G. PUDDU [4]
S. SERCI [4], P. TEMNIKOV [4], G. USAI [4], V. G. ABLEEV [5], O. YU. DENISOV [5]
O. E. GORCHAKOV [5], S. N. PRAKOV [5], A. M. ROZHDESTVENSKI [5]
M. G. SAPOZHNIKOV [5], V. I. TRETYAK [5], P. GIANOTTI [6], C. GUARALDO [6]
A. LANARO [6], V. LUCHERINI [6], F. NICHITIU [6], C. PETRASCU [6], A. ROSCA [6]
C. CAVION [7], U. GASTALDI [7], M. LOMBARDI [7], A. VORONIN [8], M. MORANDO [9]
R. A. RICCI [10], G. BENDISCIOLI [11], V. FILIPPINI [11], A. FONTANA [11]
P. MONTAGNA [11], A. ROTONDI [11], A. SAINO [11], P. SALVINI [11], M. AGNELLO [12]
F. IAZZI [12], B. MINETTI [12], F. BALESTRA [13], E. BOTTA [13], T. BRESSANI [13]
M. P. BUSSA [13], L. BUSSO [13], D. CALVO [13], P. CERELLO [13], S. COSTA [13]
F. D'ISEP [13], L. FAVA [13], A. FELICIELLO [13], L. FERRERO [13], A. FILIPPI [13]
R. GARFAGNINI [13], A. GRASSO [13], A. MAGGIORA [13], S. MARCELLO [13], D. PANZIERI [13]
D. PARENA [13], E. ROSSETTO [13], F. TOSELLO [13], G. V. MARGAGLIOTTI [14], G. PAULI [14]
C. RIZZO [14], S. TESSARO [14], E. ZAVATTINI [14], L. SANTI [15]

[1] *Dipartimento di Fisica, Università di Bologna - Bologna, Italy*
INFN, Sezione di Bologna - I-40100 Bologna, Italy
[2] *Dipartimento di Elettronica per l'Automazione, Università di Brescia - Brescia, Italy*
INFN, Sezione di Torino - Torino, Italy
[3] *Dipartimento di Elettronica per l'Automazione, Università di Brescia - Brescia, Italy*
INFN, Sezione di Pavia - Pavia, Italy
[4] *Dipartimento di Scienze Fisiche, Università di Cagliari - Cagliari, Italy*
INFN, Sezione di Cagliari, Cagliari, Italy
[5] *Joint Institute for Nuclear Research - Dubna, SU-101000 Moscow, Russia*
[6] *Laboratori Nazionali di Frascati dell'INFN - I-00044 Frascati, Italy*
[7] *Laboratori Nazionali di Legnaro dell'INFN - I-35020 Legnaro, Padova, Italy*
[8] *PN Lebedev Physics Institute - Moscow, Russia*
[9] *Dipartimento di Fisica, Università di Padova - Padova, Italy*
INFN, Sezione di Padova - I-10125 Padova, Italy
[10] *Dipartimento di Fisica, Università di Padova - Padova, Italy*
INFN, Sezione di Padova - I-10125 Padova, Italy
Laboratori Nazionali di Legnaro dell'INFN - I-35020 Legnaro, Padova, Italy
[11] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia - Pavia, Italy*
INFN, Sezione di Pavia - I-27100 Pavia, Italy
[12] *Politecnico di Torino - Torino, Italy*
INFN, Sezione di Torino - I-10125 Torino, Italy
[13] *Dipartimento di Fisica, Università di Torino - Torino, Italy*
INFN, Sezione di Torino - I-10125 Torino, Italy

([14]) *Dipartimento di Fisica, Università di Trieste - Trieste, Italy*
INFN, Sezione di Trieste - I-34127 Trieste, Italy
([15]) *Dipartimento di Fisica, Università di Udine - Udine, Italy*
INFN, Sezione di Trieste - I-34127 Trieste, Italy

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Summary. — A different type of analysis was performed to study the effect of contaminants on the temporal distribution of delayed annihilations of antiprotons stopped in helium gas, with respect to some first results published in ABLEEV *et. al.* (*Nuovo Cimento A*, **107** (1994) 1325). A more objective criterion was established to single out a *slow part* in the total delayed component, in order to deduce from this, for each case, the mean value of the product $(\overline{v\sigma})_{c,l}$ of the quenching cross-section and the mean velocity of contaminant molecules, and the fraction of the slow component $\eta_{c,l}$. The fraction $\eta_{c,l}$ was found to be amazingly stable for each impurity, independent of the concentration: around 79% of the total delayed component for all the atomic impurities (Ar, Ne, Xe) and 64% for the molecular ones (H_2, N_2).

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1. – Introduction

It is now well established [1-5] that by stopping antiprotons in helium one observes annihilation events, for which the temporal distribution is composed of:

A) A *prompt* component—corresponding to a fraction ε of about 97% of the stopped antiprotons—contained within a short temporal interval Δt (depending on the density of the helium target). Here, by *short temporal interval* one means an interval of time justifiable with the slowing-down time necessary for the antiproton stopping plus an interval of time caused by a fast atomic cascade (essentially made up of processes in which relatively slow radiative decays are negligible). For the case of antiprotons stopped in a target of helium at 3.0 atm and 20 °C—as in the case we are considering in this note—Δt is about 50 ns altogether.

B) A *delayed* component (containing the remaining $\eta = 1 - \varepsilon \cong 3\%$), visible of course after the *prompt peak* mentioned, with a temporal distribution for which the average $\langle t \rangle$ is around 3 ms, *i.e.* events for which before the annihilation, relatively slow radiative processes are dominant in the cascade.

Surprisingly this behaviour remains about the same for antiprotons stopped in helium, either at the density of liquid helium, or down to densities corresponding to a gaseous helium target at 5 mbar (RT) [2, 6]. It should be noted that below these pressures the slowing-down time for the antiprotons is comparable with or bigger than the radiative cascade time itself, making the above-mentioned distinction unclear.

Whether the helium antiprotonic systems, from which the delayed component originates, are atomic, molecular cluster, neutral or charged, and in which states the antiprotonic complex is initially formed has still not been clarified. It may in fact pass through different systems depending on the target density. However, as first emphasized in [7] there have to be systems for which Stark effects induced by neighbouring helium atom collisions are inefficient and Auger transitions are quite reduced.

In order to gain insight into this problem we experimentally studied the temporal distributions of delayed annihilations by stopping antiprotons in a pure helium target (3.0 atm RT) and then looking at changes in the annihilation temporal distributions caused by adding small quantities of different contaminants to pure helium. The measurements were carried out with the OBELIX apparatus in August 1992 and the raw experimental spectra were presented in [8], together with the results of the analysis.

In [8] we analysed each spectrum—the delayed components—in terms of an average time $\langle t \rangle_c$ (where c identifies the contaminant and its concentration) and the relation (which should be valid within the limit of very small contaminant concentrations):

(1) $$\frac{1}{\langle t \rangle_c} = \frac{1}{\langle t \rangle_{^4\mathrm{He}}} 1 + \lambda_c$$

with

(2) $$\langle t \rangle_c = \frac{\sum_i n_i (t_i - t_0)}{\sum_i n_i} ,$$

where $\langle t \rangle_{^4\mathrm{He}}$ is the value for pure helium, t_0 is the zero of the temporal scale, and

(3) $$\lambda_c = \varrho_c \overline{v}_c \overline{\sigma}_c ,$$

where $\overline{v}_c$ is the average relative velocity of the contaminant molecules with respect to the antiproton-helium systems, and the contaminant molecular concentration ϱ_c is defined as:

(4) $$\varrho_c = \frac{p_c}{kT}$$

(p_c is the partial pressure of the contaminant gas; k is the Boltzmann constant; T is the absolute temperature).

Given these assumptions we defined a kind of average *quenching cross-section* $\overline{\sigma}_c$ of the delayed component, in the antiprotonic system present in the 3 atm helium gas target, caused by collisions with the atoms of the contaminant.

We observed that the temporal distributions in experimental spectra are not exhaustively described by the single parameter $\langle t \rangle_c$. In fact, looking at the temporal distributions of annihilation events close to the prompt peaks, one clearly observes a region where faster components of delayed annihilations are present [6].

This fact prompts us to look for a different mathematical procedure for handling the data, in order to get an idea of its impact, particularly on the *long time components*.

In this paper we wish to present the results of a different type of analysis of the data published in [8]. In this paper, we have tried to establish a more objective criterion to single out the *slower part* in the total fraction ε of delayed annihilations, for each

TABLE I.

Target	Pressure (mbar)	Contaminant	Partial pressure (mbar)
^{4}He	3039	H_2	2.5 2.5/3 2.5/9
		Xe	5.0 5.0/3 5.0/9
		Ar	5.0 5.0/3 5.0/9
		Ne	5.0 5.0/3
		N_2	2.5
Pure ^{4}He	3039	—	—

(N.B. 5 mbar corresponds to about 1650 ppm, and 5/9 mbar corresponds to about 180 ppm).

contaminant and its concentration values. As a supplementary result we also obtained some interesting information about the *faster part* (later on we name it the *residual part*) of delayed annihilations.

In order to do this, for each case we deduce the relative fraction $\eta_{c,l}$, to look for possible regularities, and we also directly infer the values of the product $(\overline{v\sigma})_{c,l}$ (from now on the subscript l indicates the *slower part* of delayed annihilations).

In table I the different conditions of data acquisition considered in this analysis are reported.

Before describing the different steps followed in this analysis, we briefly restate that the nuclear capture time of the antiprotons was measured by detecting the annihilation charged products by means of plastic scintillation telescopes surrounding the target (two or more charged particles were requested by the trigger). The cylindrical target was put in a region were an axial magnetic field (5000 G) was present in order to focalize the antiproton beam toward the central region of the target [9]. The zero time was given by the entrance plastic scintillator monitor. The initial antiproton momentum was 200 MeV/c.

Prompt as well as delayed annihilations were recorded in a temporal interval 40 ms wide, with a temporal resolution of 19.53 ns per channel.

2. – The method

For each temporal distribution the analysis proceeds through several steps.

A) Data were fitted after 20 μs (we assume that this region is entirely of accidental origin) with an exponential, in order to find the slope and the fraction of the accidental events. In the analysis presented in [8], the slope was fixed for all the runs to

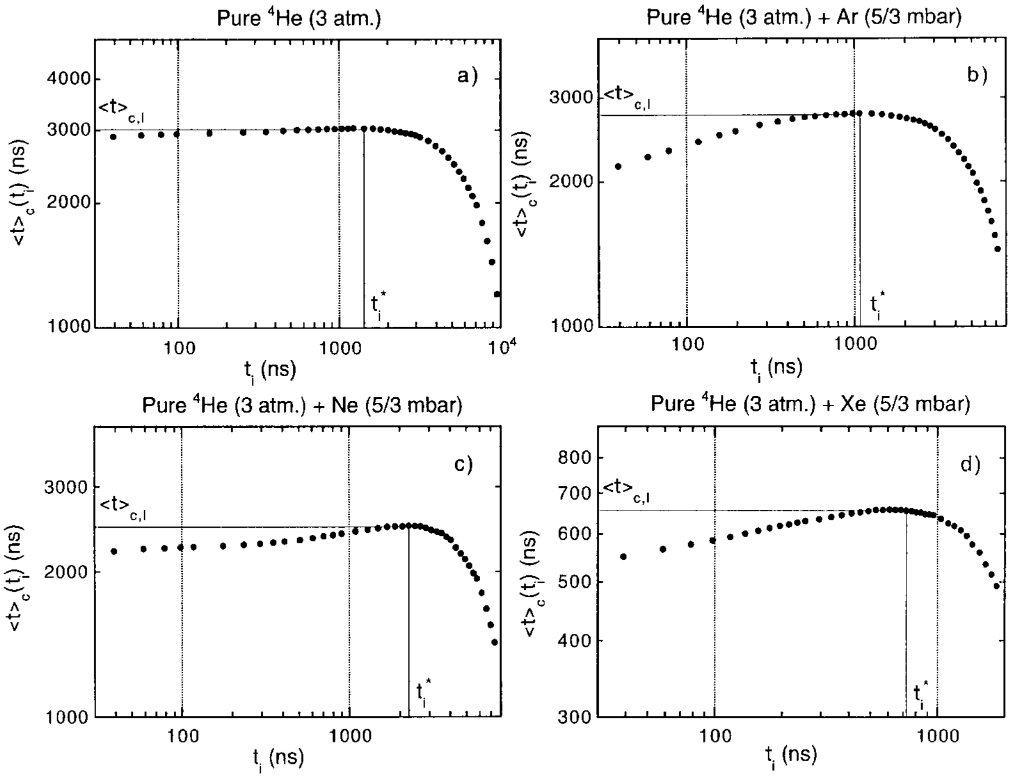

Fig. 1. – Typical distributions of $\langle t \rangle_c(t_i)$ values *vs.* (t_i). For each distribution we chose, for $\langle t \rangle_{c,\,l}$, the maximum value assumed by $\langle t \rangle_c(t_i)$.

the value obtained in just one dedicated run extremely rich in accidental events.

In the present detailed analysis, the inverse slopes of accidental events of each temporal spectrum were all found to be at least 100 μs.

The data to be analysed were therefore obtained, for each run, after subtraction of the estimated accidental events from the experimental spectra.

B) We defined an average time $\langle t \rangle_c(t_i)$ in the temporal interval $(t_i;\, 20\ \mu\text{s})$ (remember that the *zero* time value corresponds to the temporal position of the peak of prompt annihilations) as a function of the time (t_i):

$$\langle t \rangle_c(t_i) = \frac{\sum_{t_i}^{20} (t_k - t_i)\, n_c(t_k)}{\sum_{t_i}^{20} n_c(t_k)} = \frac{\sum_{t_i}^{20} (t_k - t_i)\, n_c(t_k)}{N_c(t_i)}\,, \tag{5}$$

where $N_c(t_i)$ represents the total number of events from t_i onwards, $n_c(t_k)$ is the number of events falling in the k-th bin (corresponding to the time t_k) of each spectrum after subtraction of accidental events, and all times are with respect to the time position $t_0 = 0$ of the prompt annihilation peak.

TABLE II.

Target		$\langle t \rangle_0$ ns	$\langle t \rangle_l$(ns)	$\langle t \rangle_{res}$(ns)	η_{tot} %	η_l / η_{tot}	η_{res} / η_{tot}
Pure ^{4}He 3.0 atm		2898 ± 133	3038 ± 127	1549 ± 2300	3.08 ± 0.02	0.95 ± 0.02	0.05 ± 0.02
Contam.	Partial press. (mbar)	$\langle t \rangle_{c,0}$(ns)	$\langle t \rangle_{c,l}$(ns)	$\langle t \rangle_{c,res}$(ns)	$\eta_{c,tot}$ %	$\eta_{c,l} / h_{c,tot}$	$\eta_{c,res} / \eta_{c,tot}$
Xe	5.0	234 ± 4	271 ± 4	147 ± 37	2.85 ± 0.02	0.81 ± 0.02	0.19 ± 0.02
	5.0/3	551 ± 18	658 ± 20	334 ± 102	2.99 ± 0.02	0.80 ± 0.02	0.20 ± 0.02
	5.0/9	1114 ± 43	1299 ± 43	656 ± 251	3.04 ± 0.02	0.83 ± 0.02	0.17 ± 0.02
Ar	5.0	1829 ± 109	2378 ± 97	1080 ± 297	2.65 ± 0.02	0.75 ± 0.02	0.25 ± 0.02
	5.0/3	2157 ± 122	2781 ± 104	1262 ± 346	2.90 ± 0.02	0.76 ± 0.02	0.24 ± 0.02
	5.0/9	2418 ± 127	2962 ± 110	1394 ± 471	2.93 ± 0.02	0.80 ± 0.02	0.20 ± 0.02
Ne	5.0	1358 ± 62	1736 ± 61	901 ± 201	3.03 ± 0.02	0.70 ± 0.02	0.30 ± 0.02
	5.0/3	2208 ± 125	2490 ± 120	1302 ± 773	3.09 ± 0.02	0.86 ± 0.02	0.14 ± 0.02
H_2	2.5	163 ± 9	211 ± 9	115 ± 25	2.93 ± 0.03	0.65 ± 0.02	0.35 ± 0.02
	2.5/3	425 ± 15	585 ± 17	290 ± 49	3.00 ± 0.02	0.63 ± 0.02	0.37 ± 0.02
	2.5/9	923 ± 30	1220 ± 31	608 ± 105	3.02 ± 0.02	0.68 ± 0.02	0.32 ± 0.02
N_2	2.5	1418 ± 85	2212 ± 65	922 ± 157	2.87 ± 0.02	0.60 ± 0.02	0.40 ± 0.02

For each contaminant and its concentration, the calculated value of $\langle t \rangle_c(t_i)$ is found to be constant within 5% over a relatively wide range of values of (t_i): we then chose as the average time of the slow delayed component, the maximum value of $\langle t \rangle_c(t_i)$ in that temporal range, corresponding to t_i^*, and we shall call it $\langle t \rangle_{c,l}$ (figs. 1a)-d)).

C) We defined the fraction $\eta_{c,l}$ for the slow delayed component, as

$$\eta_{c,l} = \frac{N(t_i) + M(t_i, \langle t \rangle_{c,l})}{N_{tot}}\,, \tag{6}$$

where $M(t_i, \langle t \rangle_{c,l})$ is obtained by extrapolating it from t_i back to $t_0 = 0$ (the position of the prompt annihilation peak), by means of an exponential of slope $\langle t \rangle_{c,l}$ normalized to $N(t_i)$.

N_{tot} is obviously the total number of all antiproton annihilations experimentally observed.

D) The delayed annihilations which contribute to the part of temporal spectra between t_0 and t_i^* (the time from which, for each spectrum, the values of $\langle t \rangle_{c,l}$ reported in table II are deduced) are called residuals. We calculate the values of

$$\frac{\eta_{c,res}}{\eta_{c,tot}} = \left(\frac{\eta_{c,tot} - \eta_{c,l}}{\eta_{c,tot}} \right) \tag{7}$$

and

$$\langle t \rangle_{c,\,\mathrm{res}} = \frac{\alpha_{c,\,\mathrm{res}} \langle t \rangle_{c,\,0} \langle t \rangle_{c,\,l}}{\langle t \rangle_{c,\,l} - \alpha_{c,\,l} \langle t \rangle_{c,\,0}} \tag{8}$$

as

$$\alpha_{c,\,\mathrm{res}} = \frac{\eta_{c,\,\mathrm{res}}}{\eta_{c,\,\mathrm{tot}}} \qquad \text{and} \qquad \alpha_{c,\,l} = \frac{\eta_{c,\,l}}{\eta_{c,\,\mathrm{tot}}} = (1 - \alpha_{c,\,\mathrm{res}}).$$

It should be noted that, in this case, the proximity of prompt peak contributes significantly, together with the lower statistical contents, to the growth of errors associated with the values obtained using (7) and (8).

Owing to our limited temporal resolution (19.53 ns per channel), we could not explore the zone close to the prompt peak in the range of a few tens of ns. Therefore we made the arbitrary statement that for each spectrum $\langle t \rangle_{c,\,0} = \langle t \rangle$ $(t_{i=1} = 39\ \mathrm{ns})$ represents the mean time of the complete distribution of delayed events, and $\eta_{c,\,\mathrm{tot}} = [N(t_1) + M(t_1, \langle t \rangle_{c,\,0})]/N_{\mathrm{tot}}$ represents the corresponding total fraction of delayed events. This choice implies, in our case, a systematic underestimation of the total fraction of delayed events, ranging from about 1.1% for pure ^{4}He to about 2.3%, for ^{4}He plus 2.5 mbar of H_2.

In the following we report our data without taking into account this systematic underestimation.

3. – Summary of results

In table II the values of the average times $\langle t \rangle_l, \langle t \rangle_{\mathrm{res}}, \langle t \rangle_{c,\,l}$ and $\langle t \rangle_{c,\,\mathrm{res}}$, together with the relative fractions $\eta_l/\eta_{\mathrm{tot}}$, $\eta_{\mathrm{res}}/\eta_{\mathrm{tot}}$, $\eta_{c,\,l}/\eta_{c,\,\mathrm{tot}}$ and $\eta_{c,\,\mathrm{res}}/\eta_{c,\,\mathrm{tot}}$, are reported, with the values of $\langle t \rangle_0$, $\eta_{\mathrm{tot}}, \langle t \rangle_{c,\,0}$ and $\eta_{c,\,\mathrm{tot}}$. The errors reported for $\eta_{\mathrm{res}}/\eta_{\mathrm{tot}}$ and $\eta_{c,\,\mathrm{res}}/\eta_{c,\,\mathrm{tot}}$ values are obtained by propagating the errors from eq. (7).

In figs. 2 and 3, for each contaminant, the inverse values of the average times, $1/\langle t \rangle_l$, $1/\langle t \rangle_{c,\,l}$ and $1/\langle t \rangle_{\mathrm{res}}$ and $1/\langle t \rangle_{c,\,\mathrm{res}}$, are plotted as a function of the partial pressure p_c, showing, for each contaminant, amazingly good linear behaviour.

Moreover the remarkably large differences (see table II) between the numerical values of $\eta_l/\eta_{\mathrm{tot}}$, $\eta_{\mathrm{res}}/\eta_{\mathrm{tot}}$ and $\eta_{c,\,l}/\eta_{c,\,\mathrm{tot}}$ and $\eta_{c,\,\mathrm{res}}/\eta_{c,\,\mathrm{tot}}$, suggest that we should look only at the values of $1/\langle t \rangle_{c,\,l}$ and $1/\langle t \rangle_{c,\,\mathrm{res}}$ corresponding to the non-zero concentrations of contaminants.

The results of linear fits for the values of $1/\langle t \rangle_{c,\,l}$ and $1/\langle t \rangle_{c,\,\mathrm{res}}$, for the non-zero concentration of Xe, Ar, Ne and H_2, are also shown in figs. 2 and 3.

Extrapolating these fits to the point of zero concentration we found, for the slow delayed components, values significantly higher than for pure ^{4}He for Xe and H_2, whereas Ar and Ne, the less effective contaminants in reducing $\langle t \rangle_{c,\,l}$ and $\langle t \rangle_{c,\,\mathrm{res}}$ give values similar to that of pure ^{4}He.

In the case of residue components, for Xe and H_2 we found values higher than the central value of pure ^{4}He but within the errors, whereas Ar and Ne give values substantially in agreement with the central value of pure ^{4}He.

Because of these results and especially for the very probable dependence of the formation mechanism of metastable structure on the average velocity $\overline{v}_c$, we decided

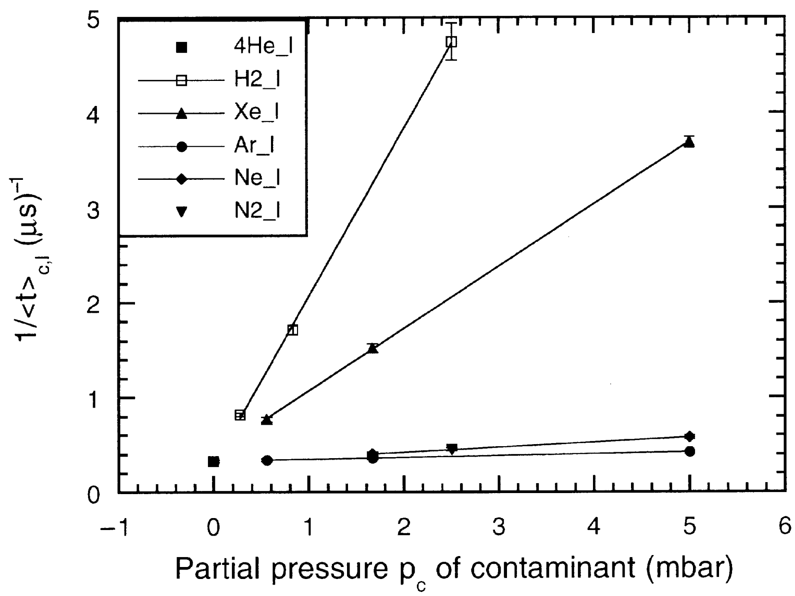

Fig. 2. – Values of $1/\langle t\rangle_{c,\,l}$ *vs.* the partial pressure p_c of contaminant gas.

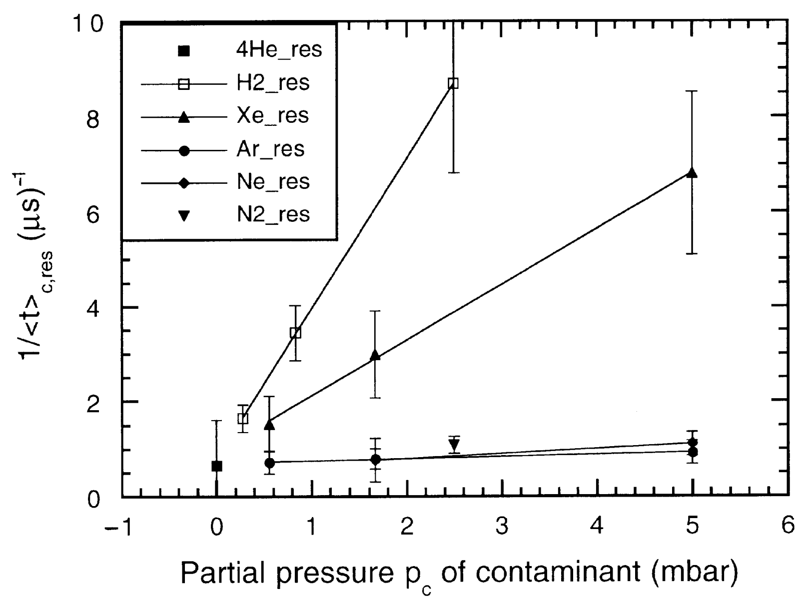

Fig. 3. – Values of $1/\langle t\rangle_{c,\,\mathrm{res}}$ *vs.* the partial pressure p_c of contaminant gas.

not to restrict our results to any particular hypothesis about the type and formation mechanism of the metastable structure itself.

To fit the values of $1/\langle t\rangle_{c,\,l}$ and $1/\langle t\rangle_{c,\,\mathrm{res}}$ with their associated errors, we therefore

TABLE III.

Contam.	Partial press (mbar)	$\varrho_c \left(\frac{\text{contam. at.}}{10^{17}\,\text{cm}^3}\right)$	$\left(\frac{\eta_{c,l}}{\eta_{c,\text{tot}}}\right)_{\text{av}}$	$(\overline{v\sigma})_{c,l}$ $(10^{-18}\,\text{cm}^3/\text{s})$	$\left(\frac{\eta_{c,\text{res}}}{\eta_{c,\text{tot}}}\right)_{\text{av}}$	$(\overline{v\sigma})_{c,\text{res}}$ $(10^{-18}\,\text{cm}^3/\text{s})$
Xe	5.0 5.0/3 5.0/9	12.07452 4.024839 1.341613	0.81 ± 0.02	2.724 ± 0.060	0.19 ± 0.02	4.97 ± 1.63
Ar	5.0 5.0/3 5.0/9	12.07452 4.024839 1.341613	0.77 ± 0.02	0.077 ± 0.020	0.23 ± 0.02	0.19 ± 0.31
Ne	5.0 5.0/3	12.07452 4.024839	0.78 ± 0.02	0.217 ± 0.034	0.22 ± 0.02	0.43 ± 0.65
H_2	2.5 2.5/3 2.5/9	24.14904 8.049679 2.683226	0.65 ± 0.02	1.753 ± 0.068	0.35 ± 0.02	3.28 ± 0.16

considered the linear relations

$$\frac{1}{\langle t\rangle_{c,l}} = b_{c,l} + \varrho_c(\overline{v\sigma})_{c,l} \tag{9}$$

and

$$\frac{1}{\langle t\rangle_{c,\text{res}}} = b_{c,\text{res}} + \varrho_c(\overline{v\sigma})_{c,\text{res}}, \tag{10}$$

where $b_{c,l}$ and $b_{c,\text{res}}$ dimensions are $[t]^{-1}$, and ϱ_c dimensions are [contaminant atoms/cm^3].

We then obtained the values of $(\overline{v\sigma})_{c,l}$ and $(\overline{v\sigma})_{c,\text{res}}$ reported in table III.

To significantly reduce the rather high errors on $\langle t\rangle_{c,\text{res}}$—and consequently on $(\overline{v\sigma})_{c,\text{res}}$—reported in table III, it is necessary to reduce the errors on $\langle t\rangle_{c,0}$ and $\langle t\rangle_{c,l}$, and this can be obtained only with much greater statistical content of temporal spectra.

4. – Conclusions

Our data and results concern $\bar{\text{p}}$ impinging on a ^{4}He target at 3.0 atm (RT), in which we introduce very small quantities of atomic (Ar, Ne, Xe) and molecular (H_2, N_2) contaminants.

From the behaviour of our results we can deduce that contaminants do not interfere with the primary stage of the formation mechanism of metastable structures. The absolute value of the total fraction of delayed events $\eta_{c,\text{tot}}$ is in fact amazingly constant and close to 3.08% the value for pure ^{4}He, for each contaminant and concentration.

On the contrary, looking at the values of $\eta_{c,l}/\eta_{c,\text{tot}}$ and $\eta_{c,\text{res}}/\eta_{c,\text{tot}}$, we can confirm that contaminants contribute to define the relative populations of the two different metastable groups: the *long living* and the *shorter living* (*residuals*). In particular, molecular contaminants (H_2, N_2) populate the *shorter-living* group more than monoatomic contaminants (Ar, Ne,Xr). If we look now at the values of the fraction $\eta_{c,l}$ for each selected *long-living* component, we see, except for Ne, an amazing stability independent of the impurity and its concentration (see $\eta_{c,l}/\eta_{c,\mathrm{tot}}$ in table II and ($\eta_{c,l}/\eta_{c,\mathrm{tot}}$) in table III): for the monoatomic impurities (Ar, Xe), $\eta_{c,l}$ is about the same for all of them, around 79% of the total delayed component; for the molecular impurities (H_2, N_2), $\eta_{c,l}$ is about 64% of the total delayed component, but in any case it is significantly lower than 95%, the value of pure ^{4}He.

This suggests to us that contaminants do not mix *long-living* and *shorter-living* groups, but only contribute to their initial formation.

For the *long-living* components we also see that the *linear* behaviour of the disappearance rate $1/\langle t\rangle_{c,l}$ as a function of the impurity concentrations (fig. 2) is clearly shown for a wide range of impurity concentrations, at least for Xe and H_2. Moreover the behaviours for Ne and Ar are clearly shown, indicating that Ne is a more effective quenching element than Ar. We also observed similar behaviour for the *residuals* (fig. 3), and the values so obtained for $(\overline{v\sigma})_{c,l}$ and $(\overline{v\sigma})_{c,\mathrm{res}}$ are reported in table III.

Looking now at the unsuccessful correspondence between the extrapolation at zero concentration of fits for $1/\langle t\rangle_{c,l}$ values, for Xe and H_2 we can suppose a saturation effect fulfilled before the linear behaviour evidenced out by our experimental values, that is for very small values of contaminant concentrations (lower than 180 ppm of contaminant molecules).

Remembering the low rate of the $\overline{\mathrm{p}}$ beam (between 10 and 20 kHz), we see that each $\overline{\mathrm{p}}$ impinging on the target falls to a prompt or delayed annihilation almost before the following $\overline{\mathrm{p}}$ enters the target.

With this statement, our results indicate, in the explored range of contaminant pressure, a direct dependence of the quenching effect on the absolute number of contaminant molecules.

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