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Measurement of the Initial Population and Decay Rate of the $(\mu^4\mathrm{He})_{2S}{}^+$ System in a Helium Target at 50 atm

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We have measured the fraction and lifetime of the $(\mu^4\mathrm{He})_{2S}{}^+$ systems formed by stopping negative muons in gaseous helium at 50 atm. An estimate of the external Auger effect, which contributes to depopulate the $(\mu\mathrm{He})_{2S}{}^+$ level, is given. First experimental evidence of the two-photon decay of such a level is presented.

When negative muons are stopped in a helium target, they first get captured forming a highly excited $(\mu\mathrm{He})^*$ atom, which then decays to a stable or metastable state. This occurs in a time of the order of 10^{-10} sec through an electromagnetic cascade which eventually results in leaving a $(\mu\mathrm{He})^+$ ion in the $1S$ ground state or in the $2S$ metastable state. For any experimental study which is based on the existence of the $(\mu\mathrm{He})_{2S}{}^+$ systems, therefore, the two following points are of major interest: (a) to establish which fraction ϵ_{2S} of the stopped muons lands on the $2S$ level; and (b) since the $2S$ level can depopulate through the different channels summarized in Table I,[1-4] to know how much the lifetime τ_{2S} of the $(\mu\mathrm{He})_{2S}{}^+$ systems—formed in a given physical condition—differs from the zero-density value

$$\tau_{2S}(0\ \mathrm{atm}) = [\lambda_{2S,\mathrm{tot}}(0\ \mathrm{atm})]^{-1} = 1.78\ \mu\mathrm{sec}. \qquad (1)$$

These questions were partially answered by the experimental investigation by Placci *et al.*,[2] who stopped negative muons in a target of pure helium at 7 atm, and observed the time distribution of the delayed x rays coming from the two-photon deexcitation of the $(\mu\mathrm{He})_{2S}{}^+$ level. These authors obtained

$$\epsilon_{2S}(7\ \mathrm{atm}) = (3.4 \pm 0.7)\times 10^{-2}, \qquad (2)$$

$$\tau_{2S}(7\ \mathrm{atm}) = (1.8 \pm 0.4)\ \mu\mathrm{sec}, \qquad (3)$$

$$\lambda_{St}(7\ \mathrm{atm}) \leqslant 2\times 10^{-2}\lambda_{2X}. \qquad (4)$$

Later results by Carboni *et al.*[5] gave some evidence for a small Auger effect on the $(\mu\mathrm{He})_{2S}{}^+$ systems formed at helium pressures between 30 and 40 atm.

When higher-density conditions are taken into consideration, the two above points (a) and (b) need a more definitive investigation. Since we are presently interested in working with $(\mu\mathrm{He})_{2S}{}^+$ metastable ions at pressures around 50 atm,[6] we have performed a measurement of ϵ_{2S} and τ_{2S} for negative muons stopped in a target of pure helium at 50 atm and 293°K. The purpose of this Letter is to report on this measurement.

The experiment was carried out using part of an apparatus already described[6] (see Fig. 1), which has recently been used at CERN to determine the energy difference between the $2S_{1/2}$ and $2P_{3/2}$ levels of the $(\mu\mathrm{He})^+$ ion.[7] The method followed here essentially coincides with the one used by Placci *et al.*[2] The only relevant differ-

TABLE I. Disappearance channels for the $(\mu^4\mathrm{He})_{2S}{}^+$ system and corresponding rates.

Process, rate symbol	Rate (sec^{-1})
Muon decay, λ_0	4.54×10^5
Muon capture, λ_c	45 ± 5 [a]
Stark-mixing collision, $\lambda_{St}(P)$ [b,c]	$< 3\times 10^2$ [d]
External Auger effect, $\lambda_A(P)$ [c]	$(2.7\pm1.6)\times 10^3$ [e]
Spontaneous M_1 transition, λ_{M_1} [b]	0.53 [f]
Two-photon decay, λ_{2X} [g]	1.06×10^5 [h]
Total disappearance rate $\lambda_{2S,\mathrm{tot}}$:	
at zero density, $\lambda_{2S,\mathrm{tot}}(0\ \mathrm{atm}) \simeq \lambda_0 + \lambda_{2X}$	5.6×10^5
at pressure P, $\lambda_{2S,\mathrm{tot}}(P)$	$\lambda_{2S,\mathrm{tot}}(0\ \mathrm{atm}) + \lambda_{St}(P) + \lambda_A(P)$

[a] Experimental value (see Ref. 1) corrected for the case that the nuclear capture proceeds from the 2S state of the μHe atom.

[b] These processes yield the emission of an 8.2-keV x ray.

[c] P is the pressure of the helium target; the rates given here are then to be considered in units of sec^{-1}/atm.

[d] See Ref. 2.

[e] Result obtained in the present work.

[f] See Ref. 3.

[g] This process occurs through the emission of two x rays; the sum of their energies is 8.2 keV.

[h] See Ref. 4.

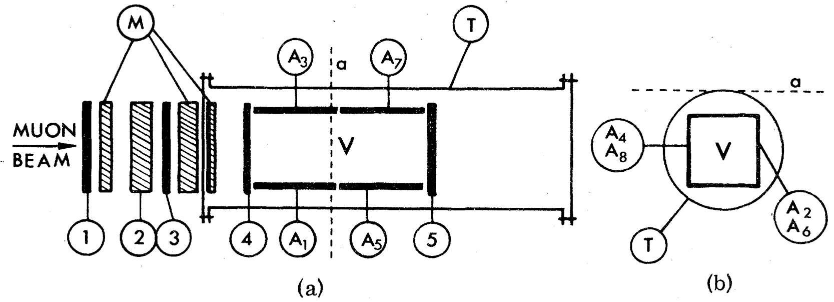
ence lies in the fact that, in the present case, the delayed x rays were detected by eight NaI(Tl) counters (A_1–A_8 in Fig. 1), which subtended a solid angle larger than 80%, whereas in the former work[2] a proportional counter was used. To reduce the accidentals, the A_i counters were also requested to detect the muon decay electrons in delayed coincidence.

The muons stopped within the useful volume V of gaseous helium (see Fig. 1) were defined by a coincidence-anticoincidence signal MUSTOP $=[1,3,4,-(2+5+\sum A_i)]$; here (–) means "not." An x-ray signal was defined by a coincidence between the MUSTOP signal and a pulse coming from any of the A_i detectors within a gate, 4 μsec long, opened by the MUSTOP pulse. A delayed muon-decay electron was recognized by a large-amplitude signal in one of the A_i counters, and accepted after the x-ray signal during a gate 2 μsec long. The x-ray coincidence started the recording of the following main information for each event: (i) the digitized amplitudes of the signals from the A_i detectors (one or more within 200 nsec) which had been triggering; (ii) the delay of the x-ray signal with respect to the MUSTOP time; (iii) the delay of the muon decay electron—if this was present—with respect to the MUSTOP time.

An effective calibration of the energy response of the A_i counters was obtained on-line, by recording continuously the K-line x rays coming from the deexcitation of the $(\mu\mathrm{He})^+$ system, of which 62%[2] are due to the $K\alpha$ line (8.2 keV).

The measurements were carried out for a total amount of about 10^6 MUSTOP pulses in the target filled with pure helium. These runs were alternated with measurements performed keeping the target under vacuum, which supplied information on the time and energy spectrum of the accidentals. The rate λ_n of accidental counts was found to be $\lambda_n = 5\times 10^4\ \mathrm{sec}^{-1}$.

For the measurements under pressure conditions, the decay rate $\lambda_{\mathrm{expt,tot}}$ of the differential time distribution for the detected x rays can be



(a) (b)

FIG. 1. Simplified scheme of the apparatus. (a) Side view; T = stainless steel tank; V = useful volume of helium for stopping muons ($40\times40\times140\ \mathrm{mm}^3$); $M=\mathrm{CH}_2$ moderators; 1, 3, 4, 5 = plastic scintillators; 2 = Plexiglas Cherenkov counter, used to anticoincide the electron contamination in the muon beam; A_1–A_8 = NaI(Tl) detectors. (b) Front view of the target.

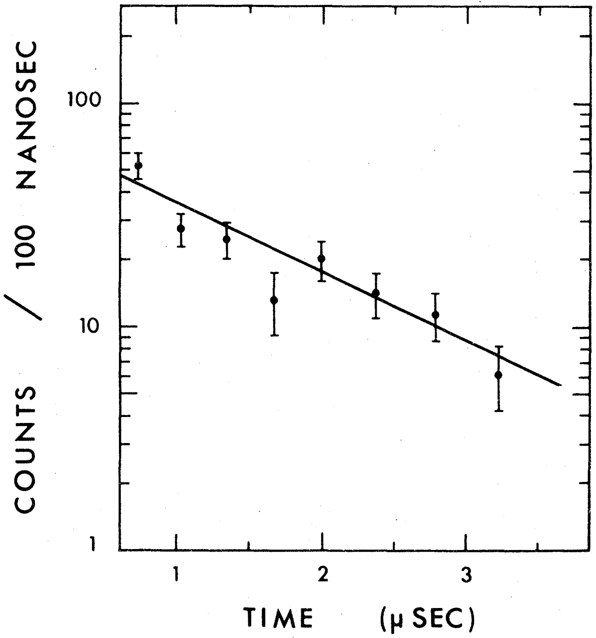


FIG. 2. Experimental time distribution $(dn_{X,e}/dt)$ of the delayed x rays observed in the present measurement after negative muons had been stopped in pure helium at 50 atm. The events are those for which the muon-decay electron had also been detected. The full line is a best fit ($\chi^2=9$) corresponding to a lifetime $\tau_{\text{expt,tot}}=(1.34\pm0.13)\ \mu\text{sec}=1/\lambda_{\text{expt,tot}}$.

written as (see Table I)

$$\lambda_{\text{expt, tot}}=\lambda_{2S,\,\text{tot}}+\lambda_n. \tag{5}$$

The experimental time distribution $dn_{X,e}/dt$ of the delayed x rays for which also the muon decay electrons had been observed is given in Fig. 2, after subtracting out the accidentals and with a low-energy cut at 3.2 keV. From these data, keeping in account Eq. (5), one gets

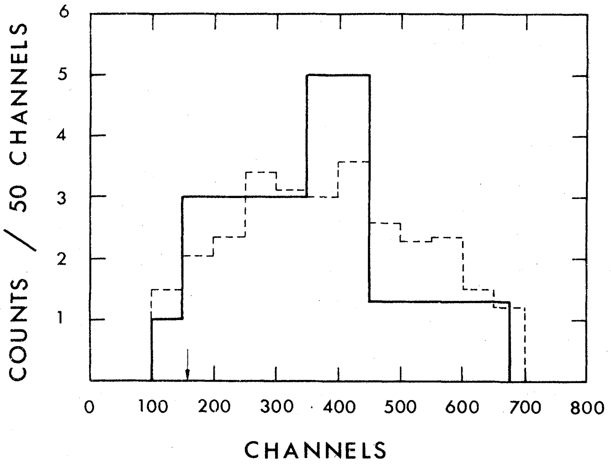


FIG. 3. The full line represents the energy spectrum of the summed amplitudes for each of the 29 "two-photon" events observed in the present measurement. (Abscissa: 1 keV = 50 channels.) The muon-decay electron had also been observed for the presented events. The arrow on the abscissa indicates the 3.2-keV low-energy cut which was operated for the analysis of the single-photon events. The dashed line represents the experimental energy spectrum—normalized to an equal area—of the prompt K-line x rays coming from the deexcitation of the $(\mu\text{He})^+$ system.

$$\lambda_{2S,\,\text{tot}}(50\text{ atm})=(7\pm0.75)\times10^5\ \text{sec}^{-1}, \tag{6}$$

i.e.,

$$\tau_{2S}(50\text{ atm})=(1.43\pm0.15)\ \mu\text{sec}. \tag{7}$$

Remembering the definition of $\lambda_{2S,\,\text{tot}}(P)$ given in Table I, one may derive from Eq. (6)

$$(\lambda_{St}+\lambda_A)_{50\text{ atm}}=(1.4\pm0.75)\times10^5\ \text{sec}^{-1}. \tag{8}$$

If we now assume (see Table I) $\lambda_{St}(50\text{ atm})\le 1.5\times10^4\ \text{sec}^{-1}$, one may extract from Eq. (8)

$$(1.25\pm0.75)\times10^5\ \text{sec}^{-1}\le\lambda_A(50\text{ atm})\le(1.4\pm0.75)\times10^5\ \text{sec}^{-1}. \tag{9}$$

If N is the total number of events of Fig. 2, ϵ_{2S} can be estimated from the expression

$$N=\epsilon_{2S}F\lambda_{2X}\Omega_{2X}[1+(\Omega_{8\text{ keV}}/\Omega_{2X})(\lambda_{St}/\lambda_{2X})], \tag{10}$$

where $F=0.3$ is a constant defined by the time acceptance of the apparatus for the x rays and the muon decay electrons, Ω_{2X} ($\simeq0.37$) is the efficiency for detecting one of the x rays from the two-photon decay, and $\Omega_{8\text{ keV}}$ ($\simeq0.61$) is the efficiency for the 8-keV x rays emitted following a Stark-mixing collision of the $(\mu\text{He})_{2S}{}^+$ ion. Ω_{2X} and $\Omega_{8\text{ keV}}$ were evaluated by a Monte Carlo calculation. From these numbers, and setting in Eq. (10) the two limits $\lambda_{St}(50\text{ atm})=0$ or $1.5\times10^4\ \text{sec}^{-1}$, one gets for ϵ_{2S} the two extreme values

$$\epsilon_{2S}(50\text{ atm})_{\text{no Stark effect}}=(4.3\pm0.6)\times10^{-2}, \tag{11}$$

$$\epsilon_{2S}(50\text{ atm})_{\text{max Stark effect}}=(3.5\pm0.5)\times10^{-2}. \tag{12}$$

The quoted errors include the uncertainties on N, F, and the calculated parameters of Eq. (10).

During the measurements, 29 events were observed in which both the x rays coming from the two-photon decay of the $(\mu\text{He})_{2S}{}^+$ level had been detected by two separate A_i counters, and the delayed muon-decay electron had been observed. The number of these events is the number expected from the value of N and from the results of the Monte Carlo calculation. The energy spectrum of the summed amplitudes of the two-photons for each of these "double" events is given in Fig. 3. To our knowledge, this is the first direct experimental evidence of the two-photon decay of the $(\mu\mathrm{He})_{2S}^+$ system.

The following conclusions can now be drawn:

(i) The fraction ϵ_{2S} of $(\mu\mathrm{He})_{2S}^+$ systems formed by stopping negative muons in a target of pure helium does not vary in a sensitive way with the helium pressure going from 7 to 50 atm [see Eqs. (2), (11), and (12)].

(ii) The observed value of $\tau_{2S}(50\text{ atm})$ [see Eq. (7)] is large enough to make the $(\mu\mathrm{He})_{2S}^+$ systems available for observation for a time interval of the order of 1 μsec at least.

(iii) Pressure-dependent effects contribute to depopulate the $(\mu\mathrm{He})_{2S}^+$ state to an extent of 20% [see Eqs. (6) and (8)]. The allowed range of variation for $\lambda_A(50\text{ atm})$ is given by Eq. (9), which is in agreement with the findings by Carboni *et al.*[5]

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[7] The data are at present under analysis.

New Rotational Transition in the Hydrogen Molecule*

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Pressure-induced rotational-vibrational U transitions ($\Delta J = 4$) of hydrogen gas have been observed for the first time at 195 K for densities in the range 180–300 amagat. The spectrum is interpreted in terms of a hexadecapolar induction mechanism, and from the experimental integrated absorption coefficient of the $U(1)$ line, rough values are obtained for the hydrogen-molecule hexadecapolar moment and its derivative.

We report here the first spectroscopic observations of molecular $U(J)$ rotational transitions in H_2 corresponding to the selection rule $\Delta J = 4$. The $U(1)$ line ($J = 1 \rightarrow 5$) has been observed in the fundamental rotational-vibrational (near-infrared) band and the integrated absorption coefficient has been obtained. An analysis is given below in terms of hexadecapolar induction.

In Fig. 1 is shown the near-infrared spectrum in the region 5550–5900 cm^{-1} taken at a temperature of 195 K and a density of 300 amagat, together with the computed S-branch ($\Delta J = 2$) and Q-branch ($\Delta J = 0$) contributions following MacTaggart and Welsh.[1] The peak of the observed feature is shifted by about 50 cm^{-1} towards higher frequencies from the calculated position of the $U(1)$ line for the free molecule. From spectra such as that of Fig. 1 recorded over the density range 180–300 amagat, we have obtained the integrated absorption coefficient $\tilde{\alpha} = \int \tilde{A}(\nu)\,d\nu$ (as defined by Van Kranendonk[2]) as a function of the density ρ. In Fig. 2 where we have plotted the experimental $\tilde{\alpha}/\rho$ against ρ, it is apparent that a good fit is obtained for a straight line passing through the origin confirming that the line arises from a binary-collision mechanism.

The theory of the integrated absorption coefficient $\tilde{\alpha}$ has been developed in general by Van Kranendonk[2] and in detail for higher-multipolar induction by Gray.[3] For the hexadecapolar-induced $U(J)$ lines we find that the binary absorption coefficient $\tilde{\alpha}_1$, defined by the density expan-