Rate of formation of symmetric $\mu He^+ (2s\frac{1}{2})$ He_4 and $\mu He^+ (2s\frac{1}{2})$ He_6 complexes in pure helium

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The hypothesis that symmetric complexes $\mu He^+ (2s\frac{1}{2})$ He_n form in an atmosphere of pure helium is discussed in connection with the study of the possibility of devising experiments to observe P-odd effects in the γ transitions of a muon, $2s\frac{1}{2} \to 1s\frac{1}{2}$, as a result of a weak neutral interaction between the muon and nucleus. The rate of the conversion transition $2s\frac{1}{2} \to 1s\frac{1}{2}$ of a muon in an electron shell of the complexes is estimated for $n = 4$ (a tetrahedron) and $n = 6$ (an octahedron) in the relativistic version of the $X\alpha$-PB method. The rate of this process is shown to be tens of times as large as the value reported by experimentalists for the total rate of the decay of $\mu He^+ (2s\frac{1}{2})$ in an atmosphere of pure hydrogen at pressures $P = 7$–50 atm. On the other hand, it agrees with the results of independent measurements at $P = 6$ atm.

§1. INTRODUCTION

1. The parity-breaking weak neutral interaction of the negative muon and a nucleus mixes the muonic-atom states $|2s\rangle$ and $|2p\rangle$, of opposite parity. This mixing is manifested in the appearance of an antisotropy α_γ of

$$w(\theta) = 1 + \alpha_\gamma \cos\theta, \tag{1}$$

which is the angular distribution of photons with an energy $\hbar\omega_0$ which are emitted in the muon transition $2s\frac{1}{2} \to 1s\frac{1}{2}$ (θ is the angle between the spin polarization vector of the initial $|2s\frac{1}{2}\rangle$ state of the muonic atom and the momentum of the photon), or it is manifested in the appearance of a circular polarization $\mathcal{P}_\gamma$, independent of the angle θ, for these photons. If α_γ or $\mathcal{P}_\gamma$, can be found experimentally, it becomes possible to determine the constants of the weak neutral muon-nucleon (μN) interaction (or some linear combination of these constants) and the parameter of the standard model of the electroweak interaction, $\sin^2\theta_W$ (θ_W is the Weinberg angle).[1)]

2. The quantities α_γ and $\mathcal{P}_\gamma$ were calculated in Refs. 1–6 for the case of an isolated μ^- atom completely devoid of an electron cloud. The P-odd correlations of α_γ and $\mathcal{P}_\gamma$ reach their maximum values in the lightest muonic atoms, with $2 \leqslant Z \leqslant 5$ (Z is the atomic number of the nucleus). In the muonic atom μHe, for example, we have $\alpha_\gamma \approx 1.3 \cdot 10^{-2}$, referred to a 100% spin polarization of the $|2s\frac{1}{2}\rangle$ initial state. With increasing atomic number of the nucleus, Z, the values of α_γ and $\mathcal{P}_\gamma$ decrease in proportion to Z^{-3}.

The accompanying background processes, which complicate measurements of α_γ and $\mathcal{P}_\gamma$ and their interpretation under actual experimental conditions, were analyzed in Refs. 7–11. It was found that these processes essentially rule out the use of muonic atoms with $3 \leqslant Z \leqslant 8$ for corresponding experiments. Apparently the most promising muonic atoms are μNe and μNa, but resolving the question of their use requires overcoming some serious difficulties, both experimental and theoretical.

3. In the present paper we examine the possibility of measuring α_γ and $\mathcal{P}_\gamma$ in the muonic ion $\mu He^+ (2s\frac{1}{2})$ formed in an atmosphere of pure helium. According to calculations in Refs. 7 and 12–14, the effect which would cause the most difficulties in the measurement of P-odd correlations of α_γ and $\mathcal{P}_\gamma$ in this case would be the radiative decay of $\mu He^+ (2s\frac{1}{2})$ due to Stark mixing of the muonic-atom states $|2s\frac{1}{2}\rangle$ and $|2pj\rangle$ ($j = \frac{1}{2}, 3/2$) in binary collisions of the muonic ion with helium atoms. In addition, at helium pressures $P > 1$ atm this process would basically determine the total lifetime $\tau_{2s}(P)$ of the muonic ion $\mu He^+ (2s\frac{1}{2})$.

The lifetime $\tau_{2s}(P)$ was found experimentally in Refs. 15 and 16 at helium pressures P between 7 and 50 atm. The total decay rate $W_{2s}(P) = \tau_{2s}^{-1}(P)$ was found to be of order $(6–7) \cdot 10^5\ s^{-1}$, or one or two orders of magnitude lower than the theoretical estimates of Refs. 7 and 12–14. In this connection, it was hypothesized in Refs. 12 and 16 that at helium pressures $P = 7$–50 atm binary collisions of $\mu He^+ (2s\frac{1}{2})$ with helium atoms are suppressed [at least beginning at a time $\tau \lesssim 10^{-7}$ s after the formation of the $\mu He^+ (2s\frac{1}{2})$, and symmetric complexes of the type $\mu He^+ (2s\frac{1}{2}) He_n$ form. These complexes consist of n helium atoms and a muonic ion $\mu He^+ (2s\frac{1}{2})$, at the center of symmetry. In this case, the intramolecular electric field vanishes at the position of the $\mu He^+ (2s\frac{1}{2})$, and the Stark mixing of the muonic-atom states $|2s\frac{1}{2}\rangle$ and $|2pj\rangle$ is suppressed. In principle, therefore, this situation might be suitable for measuring P-odd correlations of α_γ and $\mathcal{P}_\gamma$. We note, however, that the measurements of $\tau_{2s}(P)$ carried out in Ref. 17 at a helium pressure $P = 6$ atm yield $\tau_{2s}(P) < 250$ ns; these values are at least sixty times lower than the value found in Ref. 16 at $P = 7$ atm: $\tau_{2s}(P) = 1.8 \pm 0.4\ \mu$s.

4. Our purpose in the present paper is to determine how well the hypothesis of a possible formation of symmetric complexes $\mu He^+ (2s\frac{1}{2}) He_n$ corresponds to the experimental values found for $\tau_{2s}(P)$ in Refs. 15 and 16. For this purpose we use a relativistic version of the $X\alpha$-PB method,[2)] in the program used in Ref. 19, to calculate the electronic structure

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and the rate of the $E0$ muon conversion transition $2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}}$ in an electron shell of possible complexes $\mu He^+(2s_{\frac{1}{2}})He_4$, and $\mu He^+(2s_{\frac{1}{2}})He_6$. These complexes take the form of respectively a tetrahedron (symmetry group T_d) and an octahedron (symmetry group O_h), with the muonic ion at the center of symmetry. In choosing the shapes of the complexes we were guided by the following considerations. The electric field fails to vanish exactly at the $\mu He^+(2s_{\frac{1}{2}})$ because of the vibrations of the nuclei making up the complex. For the linear system $\mu He^+(2s_{\frac{1}{2}})He_2$, this effect was evaluated in Ref. 20. It was found that the rate of the radiative decay of $\mu He^+(2s_{\frac{1}{2}})$, caused by the Stark mixing of the muonic-atom states $|2s_{\frac{1}{2}}\rangle$ and $|2pj\rangle$ due to the vibrations of the nuclei is an order of magnitude greater than the experimental value[15,16] of $W_{2s}(P)$. Accordingly, a linear molecule $\mu He^+(2s_{\frac{1}{2}})He_2$ could hardly form. Corresponding estimates have not yet been carried out for more complicated complexes. It seems to us, however, that the formation of a "plane" triangular molecule $\mu He^+(2s_{\frac{1}{2}})He_3$ (of symmetry group D_{3h}) would also fail to explain the anomalously large experimental values[15,16] of $\tau_{2s}(P)$. Specifically, in a collision of such a molecule with helium atoms these atoms could "approach" the muonic ion very closely (to a distance on the order of $a_0 = \hbar^2/m_e e^2 = 5.29 \cdot 10^{-9}$ cm; here m_e is the mass of the electron) in directions perpendicular to the plane of the molecule. This effect would apparently lead to a pronounced Stark mixing of the muonic-atom states $|2s_{\frac{1}{2}}\rangle$ and $|2pj\rangle$. We accordingly believe that the simplest symmetric systems in which would be substantially impeded by the muonic ion in passing it "closely" would be the complexes $\mu He^+(2s_{\frac{1}{2}})He_4$, and $\mu He^+(2s_{\frac{1}{2}})He_6$. The question of the Stark mixing of the muonic-atom states $|2s_{\frac{1}{2}}\rangle$ and $|2pj\rangle$ in a collision of a complex with a helium atom of course requires a separate study.

5. Since the size of a muonic ion,

$$a_\mu = (m_e/m_\mu) Z^{-1} a_0 \tag{2}$$

(m_μ is the mass of the muon), is smaller by a factor $m_e/m_\mu \approx 1/200 \ll 1$ than the typical size of the complex, a_0, the electronic structure of the complex $\mu He^+(2s_{\frac{1}{2}})He_n$ will be essentially the same as that of the molecular ion H^+He_n. According to SCF-LCAO-MO calculations[21] of the electronic structure of the complex H^+He_4, this system is unstable and can decay in accordance with

$$\begin{aligned} H^+He_4 &\rightarrow H^+He_3 + He + 0.23 \text{ eV} \\ &\downarrow \\ &H^+He_2 + He + 0.38 \text{ eV} . \end{aligned} \tag{3}$$

The linear system H^+He_2 which appears in the final state is stable. So far, no such calculations have been carried out for the complex H^+He_6. In principle, that complex may also prove unstable. Since we have no estimates of the lifetimes of these complexes at the moment, we will assume that these times are greater than the lifetime of $\mu He^+(2s_{\frac{1}{2}})$, and we will treat these complexes as stable systems.

§2. CERTAIN ASPECTS OF A CALCULATION OF THE ELECTRONIC STRUCTURE OF THE COMPLEXES AND OF THE RATE OF THE CONVERSION PROCESS

1. In the $X\alpha$-PB method,[18] the electronic structure of a complex is calculated for a fixed value of the quantity R, which is the distance between the proton H^+ [i.e., the muonic ion $\mu He^+(2s_{\frac{1}{2}})$ and the nuclei of the helium atoms. In order to determine the range over which R varies in the H^+He_4 and H^+He_6 systems, we have carried out some scaling estimates of the dependence of the potential energy of these complexes, U, on R. We made use of analytic approximations published in Refs. 12, 13, and 22–26 of the interaction potentials of two neutral helium atoms, U_{HeHe}, and of the interaction of a H^+ ion with a neutral helium atom, U_{H^+He}. For H^+He_4 we took

$$U(R) = 4U_{H^+He}(R) + 6U_{HeHe}(2\sqrt{2}R/\sqrt{3}), \tag{4}$$

and for H^+He_6 we took

$$U(R) = 6U_{H^+He}(R) + 12U_{HeHe}(R\sqrt{2}) + 3U_{HeHe}(2R). \tag{5}$$

The arguments of the potentials U_{H^+He} and U_{HeHe} are taken to be the distances between the corresponding nuclei here. We have also estimated the contribution to $U(R)$ from the interaction between those dipole moments of the helium atoms which are induced by the Coulomb field of the H^+ ion. Making use of the small parameter $\beta(a_0/R)^4 \lesssim \frac{1}{3}$ ($\beta = 1.39$ is the polarizability of the helium atom,[22] and $R/a_0 \gtrsim 1.5$–2.0), we estimated $\mathbf{d}_{ind}$, the induced dipole moments, from

$$\mathbf{d}_{ind} = \beta a_0^3 e\mathbf{R}/R^3; \tag{6}$$

i.e., we ignored the interaction of the dipole moments of the helium atoms. The combination of different forms of the potentials U_{HeHe} and U_{H^+He} leads to approximately the same estimates of the range over which R varies. Figure 1 shows some typical curves of $U(R)$ (with and without allowance for the interaction of the induced dipoles). In plotting these curves in the region $R \leqslant 3a_0$ we used analytic approximations of the potentials U_{HeHe} and U_{H^+He} from Refs. 13 and 24. For large values of R we used the asymptotic form of the potentials.[22,23] From the resulting curves of $U(R)$, we chose the following ranges for R: for H^+He_4,

$$1.5a_0 \leqslant R \leqslant 4.0a_0,$$

and for H^+He_6,

$$2.0a_0 \leqslant R \leqslant 4.5a_0. \tag{7}$$

The lower bound on R here corresponds to the point at which the potential-energy curve of the complex, $U(R)$, intersects the R axis. The value $R_e \approx 2.4a_0$ was found by the SCF-LCAO-MO method in Ref. 21 for the position of the minimum of R_e on the $U(R)$ curve of the H^+He_4 system. Similar calculations for the H^+He_6 system have yet to carried out; we estimated R_e from the curves found for $U(R)$: $R_e \approx 2.5a_0$ (Fig. 1).

In addition to the distance R, the following quantities are used as parameters in our calculations by the $X\alpha$-PB method (see Refs. 18 and 19 for a description of the parameters): r_{He}, the radius of the spheres of the helium atoms, which we chose to have the maximum possible value for the given value of R, corresponding to the case in which the spheres of the helium atoms touch each other; r_H

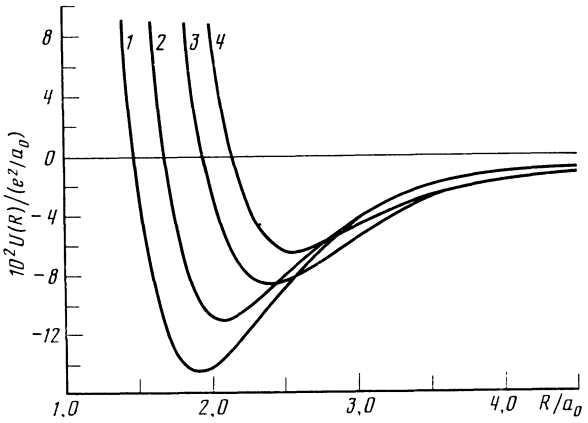

FIG. 1. Potential energy of the complexes, U, versus R, the distance between the proton H^+ and the nuclei of the helium atoms (§2, Subsection 1). 1—H^+He_4 system without an interaction between the induced dipole moments [see (6)]; 2—with this interaction; 3,4—respective curves for H^+He_6.

$= R - r_{He}$, which is the radius of an H^+ sphere, $r_0 = R + r_{He}$, the radius of a Watson sphere; the maximum orbital angular momentum in the helium-atoms spheres ($L_{max} = 1$ in the Watson and H^+ spheres, $L_{max} = 2$ for H^+He_4, and $L_{max} = 3$ for H^+He_6); and α, the coefficient of the exchange term ($\alpha = 0.773$ in the helium spheres; $\alpha = 0.978$ in the H^+ sphere,[18] and $\alpha = 0.8$ in the Watson sphere and in the region of constant potential). The results calculated for the energies of the filled one-electron orbitals and the distribution of the charges in the spheres with respect to partial waves are shown in Tables I and II. We take R to be equal to R_e ($2.4a_0$ for H^+He_4 and $2.5a_0$ for H^+He_6).

2. The rate of the conversion transition $2s_{\frac{1}{2}} \to 1s_{\frac{1}{2}}$ of a muon in an electron shell of the complexes was calculated in the model of "transition currents and charges."[28] As the wave functions of the coupled one-electron orbitals we used the functions found in the $X\alpha$-PB method. Since the wavelength of the electron in the final state of the continuous spectrum, $\lambda\!\!\!^{-}_p = \hbar^2/(2m_eE_p)^{1/2}$ ($E_p \approx \frac{3}{8}(Z^2m_\mu e^4/\hbar^2)$ is the kinetic energy of the electron], is a factor $(m_e/m_\mu)^{1/2} \approx 1/14 \ll 1$ smaller than the typical size of the complex a_0, we used as the one-electron wave function of the final state the solution of the Dirac equation for an electron moving with a kinetic energy E_p in a spherically symmetric field of the muonic ion $\mu He^+(2s_{\frac{1}{2}})$, i.e., essentially in the field of the H^+ ion.[28]

In constructing the one-electron wave functions of the discrete and continuous spectra, we approximated the Coulomb field of the helium nuclei by the field of a uniformly charged sphere of radius $R_N = 1.2A^{1/3}$ fm ($A = 4$ is the atomic weight of the ^{4}He nucleus). We ignored the fact that the muon charge distribution is nonzero over a volume with a radius on the order of a_μ, given by (2).

The $E0$ and $M1$ multipoles contribute to the amplitude of the muon transition $2s_{\frac{1}{2}} \to 1s_{\frac{1}{2}}$. As was shown in Refs. 29 and 30, the most likely process for isolated muonic atoms is conversion in (Ns) electron orbitals ($N = 1,2,...$). At small Z, the transition amplitude is dominated by the $E0$ multipole. We accordingly calculated only the rate of the $E0$ conversion for the $[16]^2$ electron orbital of $\mu He^+(2s_{\frac{1}{2}})He_4$ and the $[11]^2$ electron orbital of $\mu He^+(2s_{\frac{1}{2}})He_6$, for which the partial density of s waves at the center of the $\mu He^+(2s_{\frac{1}{2}})$ sphere, i.e., of the H^+ sphere, is nonzero (Tables I and II). Since the typical radius of the muonic-atom orbitals for $\mu He^+(2s_{\frac{1}{2}})$ ($Z = 2$) is $a_\mu \approx 128$ fm [see (2)], and much larger than the rms radius of the ^{4}He nucleus,[31] $^4He\langle r_{He}^2\rangle^{1/2} \approx 1.7$ fm, we used nonrelativistic Coulomb wave functions of the muonic-ion $|1s_{\frac{1}{2}}\rangle$ and $|2_{\frac{1}{2}}\rangle$ orbitals in the field of a point

TABLE I. Binding energies and partial distributions of the electron density for filled one-electron orbitals of the H^+He_4 system (of symmetry group T_d). The distance between the H^+ ion and the helium atoms is $R = 2.4a_0$.

$[N\lambda]^K$	$E(N\lambda)$, eV	q	$P(qJL)$, %				
			$s^{1/2}$	$p^{1/2}$	$p^{3/2}$	$d^{3/2}$	$d^{5/2}$
		1	0.472	0.0	0.0	0.0	0,0
$[16]^2$	28,28	2	0.246	0.0	0.0	0.0	0,0
		3	92,017	0.262	0.524	–	–
		1	0.0	0.411	0.0	0.0	0,259
$[17]^2$	26,57	2	0,0	0.004	0.0	0,0	0,000
		3	95.674	0.222	0,001	–	–
		1	0,0	0.0	0.411	0,155	0,103
$[18]^4$	26,57	2	0.0	0.0	0.004	0.000	0.000
		3	95.674	0,000	0,222	–	–

1) *Note.* For the one-electron orbitals we use the notation $[N\lambda]^K$, where λ specifies the irreducible representation of the symmetry group,[27] N is the order number of the state with the given value of λ, K is the filling number, and $E(N,\lambda)$ is the binding energy of the $(N\lambda)$ orbital. The index q specifies the groups of spheres which convert into each other under the symmetry transformations. The value $q = 1$ corresponds to a Watson sphere, $q = 2$ to the H^+ sphere, and $q = 3$ to the spheres of atomic helium. For a separate $(N\lambda)$ orbital, $P(qJL)$ is the probability for finding an electron with orbital angular momentum L and total angular momentum J in region q. The notation 0,0 means that the given value of (JL) is not realized because of the group symmetry of the complex.

TABLE II. Binding energies and partial distributions of the electron density for filled one-electron orbitals of the H^+He_6 system (symmetry group O_h) at $R = 2.5a_0$.

$[N\lambda]^K$	$E(N\lambda)$, eV	q	$P(qJL)$, %						
			$s^{1/2}$	$p^{1/2}$	$p^{3/2}$	$d^{3/2}$	$d^{5/2}$	$f^{5/2}$	$f^{7/2}$
$[11]^2$	29.66	1	0.768	0.0	0.0	0.0	0.0	0.0	0.0
		2	1.849	0.0	0.0	0.0	0.0	0.0	0.0
		3	86.141	0.500	1.004	–	–	–	–
$[12]^2$	26.73	1	0.0	0.391	0.0	0.0	0.0	0.0	0.111
		2	0.0	0.027	0.0	0.0	0.0	0.0	0.000
		3	91.921	0.476	0.249	–	–	–	–
$[15]^4$	25.44	1	0.0	0.0	0.0	0.439	0.656	0.0	0.0
		2	0.0	0.0	0.0	0.003	0.004	0.0	0.0
		3	94.874	0.117	0.234	–	–	–	–
$[16]^4$	26.74	1	0.0	0.0	0.387	0.0	0.0	0.070	0.039
		2	0.0	0.0	0.027	0.0	0.0	0.000	0.000
		3	91.930	0.126	0.606	–	–	–	–

1) *Note.* The notation is the same as in Table I.

nucleus in the calculations. We took the energy of the muon transition $2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}}$ to be[32] 8.22 keV.

§3. DISCUSSION OF RESULTS

Table III shows the results calculated for the rate of the $E0$ conversion as a function of R, the distance between the muonic ion $\mu He^+(2s_{\frac{1}{2}})$ and the nuclei of the helium atoms. We see that near the minimum of the potential-energy curves, $R = (2.4\text{–}2.5)a_0$, for these complexes the quantity $W(2s_{\frac{1}{2}} \rightarrow 1s^1;\ [N\lambda]^K)$ is greater by a factor of ~ 50 than the experimental value of the total decay rate of $\mu He^+(2s_{\frac{1}{2}})$ in pure helium, found in Ref. 16: $W_{2s}(P) \approx (6\text{–}7)10^5\ s^{-1}$. A reduction of the value of the parameter r_{He} (the radius of the spheres of helium atoms) in the calculations at a fixed value of R aggravates this discrepancy. These results suggest to us that if complexes $\mu He^+(2s_{\frac{1}{2}})He_4$, and $\mu He^+(2s_{\frac{1}{2}})He_6$ with a fairly long lifetime do indeed form in an atmosphere of pure helium, these systems should form in highly excited vibrational or rotational states. The wave functions of these states may be substantially nonzero only at large values of R ($R > 4a_0$), so that there will be an effective decrease in the rate of the $E0$ conversion. For example, the results in Table III show that for $R > 4a_0$ the values of $W(2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}};\ [N\lambda]^K)$ in fact become smaller than the experimental value[16] of $W_{2s}(P)$. A further study of this question will require estimates of the populations and lifetimes of these highly excited states. We of course cannot rule out the possibility that symmetric complexes more complicated than $\mu He^+(2s_{\frac{1}{2}})He_4$ and $\mu He^+(2s_{\frac{1}{2}})He_6$, also form.

We conclude by noting that the values which we found for the rate of the conversion process near the minimum of the potential-energy curves of the complexes agree in order of magnitude with the theoretical estimates in Refs. 7 and 12–14 of the rate of the radiative decay of $\mu He^+(2s_{\frac{1}{2}})$ in binary collisions with helium atoms at pressures $P \sim 10$ atm. They also agree with measurements of $W_{2s}(P)$ carried out in Ref. 17 at $P = 6$ atm: $W_{2s}(P) > 4.10^6\ s^{-1}$ [$\tau_{2s}(P) < 250$ ns]. Accordingly, to determine the mechanism for the decay of $\mu He^+(2s_{\frac{1}{2}})$ in an atmosphere of pure helium it will apparently be necessary to carry out measurements of $\tau_{2s}(P)$ more reliable than those in Refs. 15–17 or to carry out experiments to determine the rate of the conversion process. Note also that the $X\alpha$-PB method which we have used to calculate the electronic structure of the complexes and the rate of the $E0$ conversion can be used to study the behavior of halogen ions and atoms in atmospheres of inert gases.[21]

TABLE III. $W(2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}};\ [N\lambda]^K)$, the rate of the $E0$ conversion of the muon transition $2s_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}}$, in a one-electron $[N\lambda]^K$ orbital versus the distance (R) between the muonic ion $\mu He^+(2s_{\frac{1}{2}})$ and the He atom (for the case in which the spheres of the helium atoms touch each other).

R/a_0	$\mu He^+(2s^{1/2}) \times$ $\times He_6$; $W(2s^{1/2} \rightarrow 1s^{1/2};\ [16]^2)$, s^{-1}	$\mu He^+(2s^{1/2})He_6$; $W(2s^{1/2} \rightarrow 1s^{1/2};\ [11]^2)$, s^{-1}	R/a_0	$\mu He^+(2s^{1/2})He_4$; $W(2s^{1/2} \rightarrow 1s^{1/2};\ [16]^2)$, s^{-1}	$\mu He^+(2s^{1/2})He_4$; $W(2s^{1/2} \rightarrow 1s^{1/2};\ [11]^2)$, s^{-1}
1.5	$6.79 \cdot 10^7$	–	2.5	$9.94 \cdot 10^6$	$2.96 \cdot 10^7$
2.0	$2.59 \cdot 10^7$	$5.79 \cdot 10^7$	2.6	$8.13 \cdot 10^6$	$2.57 \cdot 10^7$
2.1	$2.14 \cdot 10^7$	$5.04 \cdot 10^7$	2.7	$6.64 \cdot 10^6$	$2.24 \cdot 10^7$
2.2	$1.77 \cdot 10^7$	$4.41 \cdot 10^7$	3.0	$3.64 \cdot 10^6$	$1.43 \cdot 10^7$
2.3	$1.47 \cdot 10^7$	$3.88 \cdot 10^7$	3.5	$1.28 \cdot 10^6$	$6.30 \cdot 10^6$
2.35	$1.33 \cdot 10^7$	–	4.0	$4.61 \cdot 10^5$	$2.45 \cdot 10^6$
2.4	$1.21 \cdot 10^7$	$3.40 \cdot 10^7$	4.5	–	$8.98 \cdot 10^5$

We wish to thank A. F. Mezentsev for calling our attention to the question of the possible formation of these complexes.

[1)] So far, no such experiments have been carried out in muonic atoms.
[2)] The $X\alpha$-PB method is described in detail in Slater's monograph.[18]

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