Concerning a long-lived $(^2P^e)He^-$ state: Lifetime and energy-level measurements of He^-

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The question concerning the existence of a long-lived doublet $(^2P^e)He^-$ state has been addressed by measuring the lifetime and energies of autodetaching electrons from 20—120-keV He^--ion beams formed by charge exchange in Ca vapor—a vapor conducive with $(^2P^e)He^-$ formation. The measured lifetime and electron energy levels agree closely with accepted values for components of the $(^4P^o_J)He^-$ states. No other structures were detected in the electron energy spectrum encompassing the anticipated energy level of the autodetached electron from the $(^2P^e)He^-$ state.

I. INTRODUCTION

The negative—helium-ion state is a classical example of a core excited state which is bound within the detachment continuum of the neutral atom. It has, therefore, been the subject of many investigations directed toward elucidating its configuration identification,[1] lifetime against autodetachment,[2–5] energy levels,[1,6–11] fine-structure separations,[12,13] and destruction characteristics by electric field,[9,10,14] collisional,[15,16] and photoelectron-detachment processes.[17,18] Because of the nature of the forces involved in this weakly bound atomic system, it has served as a basis for development and testing of sophisticated wave functions and atomic Hamiltonians necessary for a proper description of the observed states of the system.

Theoretical studies of He^-, predating experimental detection of the ion, were made by Wu who used variational-type wave functions in investigating the stability of the $(1s2s^2)^2S$ He^- electronic configuration.[19] Evidence of a long-lived He^- state was first presented by Hiby who, while analyzing the negative-ion mass spectrum extracted from a helium plasma discharge, detected a weak signal in the mass-4 position.[20] This discovery subsequently gave impetus to a number of experimental and theoretical studies of the He^- ion.

The first plausible prediction of a He^- state with long-lived properties was made by Holøien and Midtdal who used multiterm variational-type wave functions to study the binding properties of various electronic configurations of the ion.[1] The $(1s\,2s\,2p)^4P^o_J$ He^- metastable states were found to be bound relative to the $(1s\,2s)^3S$ He atomic configuration by 0.075 eV and stable against direct Coulomb autodetachment as well as electric-dipole radiative-decay processes. The long lifetime characteristics of the state were explained according to the *LS*-coupling scheme by virtue of the fact that the respective $J=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ components could only decay through weak spin-dependent interactions. Furthermore, the respective fine-structure components were postulated to have significantly different lifetimes because of the possibility of coupling between the $^4P_{1/2,2/3}$ and $^2P_{1/2,3/2}$ states of the same configuration—the latter of which are allowed to decay promptly via the Coulomb interaction. Thus, the lifetimes of these states would be decreased relative to the pure $J=\frac{5}{2}$ component.

The theoretical calculations of Manson[12] indicate that the energies of the fine-structure levels of the $(^4P^o_J)He^-$ state increase with increasing J and have energy excesses of the $\frac{5}{2}$ level above the respective $\frac{3}{2}$ and $\frac{1}{2}$ levels of 8.43×10^{-6} and 3.89×10^{-5} eV. The experimental measurements of Mader and Novick[13] using magnetic-resonance techniques yielded values of 3.46×10^{-6} and 3.58×10^{-5} eV for the same energy excesses—which are in reasonable agreement with the theoretical estimates.

The advent of fast and larger computer facilities has enabled the use of more sophisticated wave functions for more accurate theoretical estimates of the binding energies and fine-structure separations of the $(^4P^o)He^-$-ion states. Table I summarizes the results of several theoretical estimates of the binding energy for the $(^4P^o)He^-$ states. The degree of progress in terms of accuracy is exemplified by the recent configuration-interaction calculations of Bunge and Bunge[8] in which a value of 0.077 eV was obtained for the binding energy of the $(^4P^o)He^-$ relative to the $(^3S)He$ state. The results agree closely with the experimental value of 0.076 eV obtained by Oparin *et al.*[10] using electric field detachment techniques and the 0.080-eV value determined by Brehm, Gusinow, and Hall[11] using laser photoelectron-detachment techniques.

The discovery and development of an efficient forma-

TABLE I. Summary of theoretically determined energy levels for $^4P^o_J$ states of He^-.

$E[(1s2s)^3S]-E[(1s2s2p)^4P]$ (eV)	$E[(1s2s2p)^4P]$ (eV)	Reference
≥ 0.075	19.744	1 (Theor.)
≥ 0.033	19.786	6 (Theor.)
0.067	19.752	7 (Theor.)
0.0774	19.7417	8 (Theor.)

tion technique for producing relatively intense ion beams in the long-lived He^- state through charge-exchange interactions between keV He^+ ions and gaseous or vaporous materials has greatly aided experimental investigation of the properties of the ion as well as enabled its use in high-energy—accelerator applications.[21,22] The technique is especially efficient whenever low—ionization-potential exchange vapors are utilized. The dominant process for $(^4P^o_J)He^-$ formation with Group-IA exchange vapors, as demonstrated experimentally,[21] is through sequential exchange collisions between energetic He ions and atoms of the exchange medium. The process proceeds according to the following spin-conserving reactions:

$$(1s\,^2S)He^+ + (^2S)X \rightarrow (1s2s\,^3S)He + (^1S)X^+ ,$$

$$(1s\,2s\,^3S)He + (^2S)X \rightarrow (1s2s2p\,^4P^o)He^- + (^1S)X^+ ,$$

where X represents the exchange atom. The latter interaction occurs with high probability due to the close proximity of the potential-energy curves for the entrance $[(^3S)He]$ and exit $[(^4P)He^-]$ channels.

According to theoretical prediction, the $J=\frac{1}{2}$ and $\frac{3}{2}$ levels of the $(^4P^o)He^-$ state are expected to decay at significantly faster rates than that of the $J=\frac{5}{2}$ level due to their coupling to the corresponding $(^2P^o)He^-$ levels of the same configuration.[1] The necessity of including coupling to such states considerably complicates theoretical calculations of the lifetimes for the $J=\frac{1}{2}$ and $\frac{3}{2}$ components. On the other hand, there are no states of the same configuration with which the $J=\frac{5}{2}$ level can couple and, therefore, the interaction Hamiltonian is explicitly known—making estimates of the lifetime of this metastable state considerably less difficult. Several theoretical estimates of the lifetime of the $J=\frac{5}{2}$ level have been made.[12,23–25] Of such calculations, the 455-μsec value determined by Labahn and Estberg[25] is considered the most accurate and is in reasonable agreement with experiment.

The admixture of several states with differential metastabilities also complicates experimental measurement of the lifetimes of the respective components. The difficulties of such determinations are exemplified by attempts to measure the lifetimes of the respective components of the $(^4P^o_J)He^-$ state.[3,5] The results of several measurements of the bound metastable states of He^- formed in a variety of exchange media are summarized in Table II.

In the presence of a uniform magnetic field, substates with the same M_J, the quantum number of the component of J which lies along the magnetic field direction, can be mixed (Zeeman effect). This effect will be more pronounced for states which lie close to each other and, hence, mixing between the $J=\frac{5}{2}$ and $\frac{3}{2}$ levels of the $(^4P_J)He^-$ states can occur at relatively low magnetic field strengths resulting in a decrease in population of the $J=\frac{5}{2}$ level and an increase in that of the $J=\frac{3}{2}$ level. Under such conditions, the average lifetime of the He^- ion will be decreased. Of the values shown in Table II, magnetic-momentum analyses were utilized in the experiments of Nicholas *et al.*[2] and Simpson *et al.*,[4] and, thus, one might expect an increase in the population of the lower-lying levels at the expense of the $J=\frac{5}{2}$ level in these experiments. This effect will be significant even at low magnetic field strengths.[5] The magnetic field mixing effect was utilized by Blau, Novick, and Weinflash,[3] and Novick and Weinflash[5] to separate the various fine-structure states, thus permitting estimations of their individual lifetimes.

TABLE II. Summary of experimental results of previous measurements of the lifetimes of metastably bound $^4P_{1/2,3/2,5/2}$ states of He^-.

Source of He^-	Lifetime (μsec)	Reference
$He^+ + He$	18.2	2
$He^+ + K$	11.5±5, 345±90	3
$He^+ + N_2$	9^{+5}_{-3}	4
$He^+ + K$	10±2, 16±4, 500±200	5

In spite of the large number of investigations that have taken place concerning the long-lived He^- state, questions still exist regarding the exact identity of the observed state or states. More specifically, plausible arguments have been made by three experimental groups[26–28] that a long-lived $(1s\,2p^2)^2P^e$ He^- may exist in addition to the well-established $(1s\,2s\,2p)^4P^o$ He^- state which was generally assumed to be the only long-lived negative-ion state of helium. The state, if bound, would be metastable against Coulomb autodetachment and direct electric-dipole radiative-decay processes.

The first of such reports was made by Baragiola and Salvattelli[26] who used a two-state approximation in analyzing He^--formation cross-section data obtained by interacting a 20—40-keV He beam with what was believed to be a known $(1^1S,2^3S)$ mixture with an atomic Mg target. The authors concluded that the cross sections obtained from ground-state He capture were consistent with the existence of a long-lived $(^2P^e)He^-$ state. Similar conclusions were also drawn by Pedersen *et al.*[27] who applied beam-attenuation techniques to measure metastable $(^3S)He$ fractions produced by both electric field and collisional detachment of He^-. The constant metastable fraction obtained from both experiments led the investigators to conclude that the ion beam was made up of both $(^2P^e)He^-$ ($\sim$29%) and $(^4P^o)He^-$ states ($\sim$71%). The formation of He^- ions by interactions between fast-moving He atoms in the (^1S) and (^3S) states and H_2 target has been investigated by Dunn *et al.*[28] who show that the cross section for He^- resulting from $(^1S)He$ electron capture is approximately one-half that of capture to the (^3S) state. In this experiment, the $(^1S)He$ state was prepared by collisions between doubly charged He^{2+} projectiles and H_2 exchange-gas molecules according to the following spin-conserving reaction:

$$He^{2+} + H_2 \rightarrow (^1S)He + (^2S)H^+ + (^2S)H^+ .$$

Negative He^- ions were then produced by allowing the $(^1S)He$ to again react with H_2. The process is assumed to proceed according to the reaction

$$(^1S)He + H_2 \rightarrow [(1s\,2p^2)^2P^e]He^- + H_2^+ .$$

Thus, if total electron spin is conserved, the latter reaction leads to a doublet rather than a quartet He^- state. How-

ever, in subsequent experiments, Pedersen finds that apparent metasable (^3S)He fractions derived by use of the beam-attenuation technique do not necessarily coincide with the true values—regardless of the attenuating gas used.[29] Thus, previously reached conclusions which were based on the use of the attenuating gas H_2, must be reevaluated.

According to the first-order perturbation calculations of Safronova and Senashenka,[30] the $(^2P^e)He^-$ state is bound with an eigenenergy of 19.91 eV above the ground state of He and can decay by forbidden autodetachment processes with lifetimes of the $J=\frac{1}{2}$ and $\frac{3}{2}$ levels of 92 and 5.5 μsec, respectively, and by radiative processes with a lifetime of 0.2 μsec. Thus, the state, although bound, would effectively have a short half-life. In addition, the state, if bound, is expected to lie above the $(1s2s2p)^2P^o$ He^- state to which it can decay radiatively. The latter state has been observed in energy-dependent differential electron scattering experiments.[31,32]

The $(^2P^o)He^-$ state appears as a resonance at $\sim$0.5 eV above the threshold for excitation of the $(1s2s)^3S$ level of He at an electron energy of 20.5 eV.[31] The energy-level value of this doublet state is in exact agreement with recent theoretical calculations of Chung[33] who finds the resonance to be of Feshbach character and the state to be bound to the $(1s2s)^1S$ He state by 83 and 124 meV for the $J=\frac{1}{2}$ and $\frac{3}{2}$ levels, respectively, which decay by autodetachment of a 20.495-eV electron. The $(1s2s2p)^2P^o$ He^- state is of particular relevance to the present study in that the conjectured $(1s2p^2)^2P^e$ He^- state can radiate to this level which, in turn, can decay promptly through Coulomb autodetachment. The 20.5-eV eigenenergy of the autoejected electrons associated with the decay of the subsequently formed $(^2P^o)He^-$ state would then serve as a signature of the existence of the $(^2P^e)He^-$ state.

In the present article, we address the question of the existence of a long-lived doublet state of He^- by measuring the lifetime and electron energy spectra from a He^--ion beam produced by charge exchange in calcium vapor—a vapor which can produce both $(^2P^e)He^-$ and $(^4P^o)He^-$ states. The $(^2P^e)He^-$-formation process proceeds according to the following spin-conserving reactions:

$$(^2S)He^+ + (^1S)Ca \rightarrow (^2P^e)He^- + (^1S)Ca^{2+} ,$$

in single collisions, while $(^4P^o)He^-$ formation proceeds according to the sequential collisional processes of

$$(^2S)He^+ + (^1S)Ca \rightarrow (^3S)He + (^2S)Ca^+ ,$$

$$(^3S)He + (^1S)Ca \rightarrow (^4P^o)He^- + (^2S)Ca^+ .$$

Thus, based on these spin-conserving reactions, the doublet-state $(^2P^e)$ population should increase linearly with exchange vapor pressure p, while the quartet-state $(^4P^o)$ population should increase as p^2. If we relax the Wigner spin-selection rule, $(^4P^o)He^-$ can be formed also in the former reaction and the $(^2P^e)He^-$ can be formed in the latter reaction as well.

II. LIFETIME MEASUREMENTS

A. Experimental techniques

A negative-ion beam composed of bound metastable particles will spontaneously autodetach during free flight by electron emission and in the absence of a perfect vacuum lose additional electrons through collisions with the residual background gas. A beam of particles with initial intensity $I^-(0)$ will decrease exponentially to value $I^-(t)$ after having drifted for a time t and distance x according to the following relationship:

$$I^-(t)=I^-(0)\sum_{j=1}^{s} f_j \exp\left[-\frac{t}{\tau_j}\right]\exp\left[-\sum_{i=0}^{z}\sigma_{-1,i}nx\right] ,$$

where f_j is the fraction of the beam in state j with lifetime τ_j, s is the number of metastable components in the ion beam, z is the atomic number of the negative ion, and $\sigma_{-1,i}$ is the cross section for electron loss to the ith state of the projectile due to collisions with the residual gas atoms of density n. For simplicity the assumption is made that the residual gas is composed of one species only.

A schematic diagram of the apparatus utilized in measuring the average lifetime of the decaying states of He^- is shown in Fig. 1. A positive—He^+-ion beam formed in and extracted from a duoplasmatron ion source was focused through a charge-exchange cell containing chemically pure-grade Ca vapor. During all measurements, the charge-exchange cell was operated at intermediate power levels which were commensurate with the production of both $(^2P^e)He^-$ and $(^4P^o)He^-$. The power on the cell was typically maintained at values such that the total negative—He^--ion current was $\sim$10% of those normally achieved using Ca exchange vapor under equilibrium capture and loss conditions. (Total momentum-analyzed He^-—negative-ion currents of 0.2 μA were typically produced compared to $\sim$2 μA for equilibrium production and loss conditions.) The region of He^- production was situated $\sim$2.5 m from the experimental measurement apparatus.

The negative—He^--ion beam emerging from the cell was increased to the desired energy by a postacceleration stage, momentum analyzed, collimated, and finally passed into the experimental apparatus. The technique employed in measuring the lifetimes of autodetaching states of He^- differs from those previously reported in that it is differential in nature rather than integral. The device utilized consisted of a 26-cm-long parallel-plate charge-collection system composed of a grounded top plate and a biasable bottom plate separated by 2.86 cm. Autodetached and collisionally produced electrons were collected on the positively biased bottom plate of the system. Negatively biased apertures were placed at the entrance and exit ends of the parallel-plate arrangement to ensure that only those electrons emitted or collisionally produced during transit across the plates were collected. The ion beam was monitored in a biased and carefully shielded Faraday cup which could be externally positioned with respect to the ion beam to compensate for beam deflection whenever voltage was applied to the bottom plate. All ion and elec-

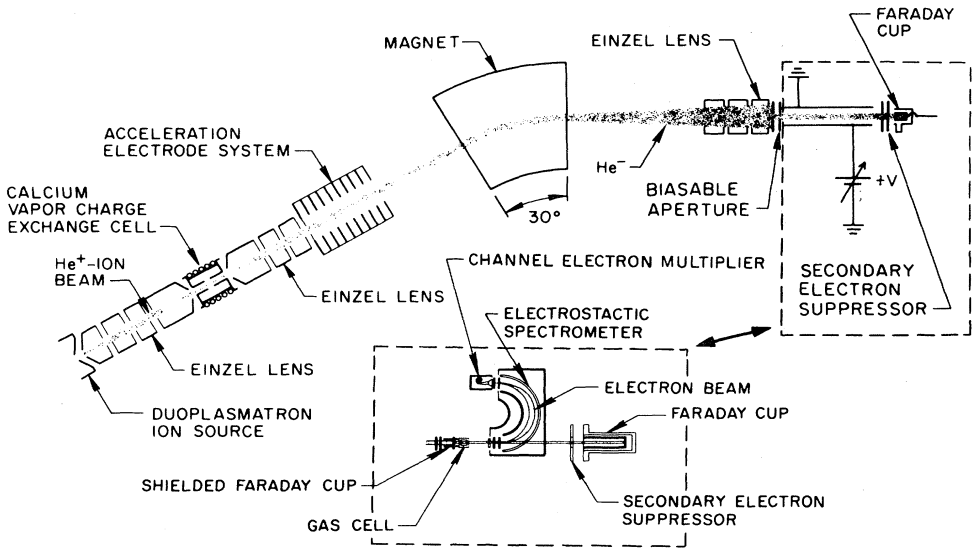

FIG. 1. Experimental arrangement for measuring the lifetimes and energy levels of metastably bound He^- formed in charge-exchange collisions with Ca vapor.

tron currents were measured with electrometers with stated accuracies of $\pm 5\%$.

In order to distinguish between autodetachment and collisional-detachment processes, both of which were present at the base pressures typically achieved ($\sim 2\times 10^{-7}$ Torr), electron-detachment data were accumulated as a function of N_2 chamber pressure for a given ion energy and a logarithmic plot of the corrected collection data versus pressure extrapolated to zero pressure. Such measurements were repeated for a range of ion energies lying between 20 and 120 keV. Corrections to the collected electron signal due to projectile ionization of the N_2 target gas were made by alternately reversing the plate polarity and measuring the collisionally produced positive-ion current. The total electron and ion currents collected during the polarity reversal cycle were then subtracted. Since the He^--ion current was measured on the exit side of the collection plate, corrections were made by adding the net electron current to the measured value.

The magnetic field flux densities required for momentum analysis of the He^--ion beams utilized in the experimental investigations ranged from 900 G at 20 keV to 2200 G at 120 keV. Thus, Zeeman mixing would be expected for closely lying levels such as those associated with the $^4P_J^o$ He^- states.

B. Results and discussions

Least-squares fits to the electron-signal collection data versus nitrogen density in the experimental chamber are shown in Fig. 2 for a number of ion energies. The consequent ordinate intercepts of these data are shown in Fig. 3 plotted against ion-beam transit time. The slope of a least-squares fit to the latter data yields the average life-

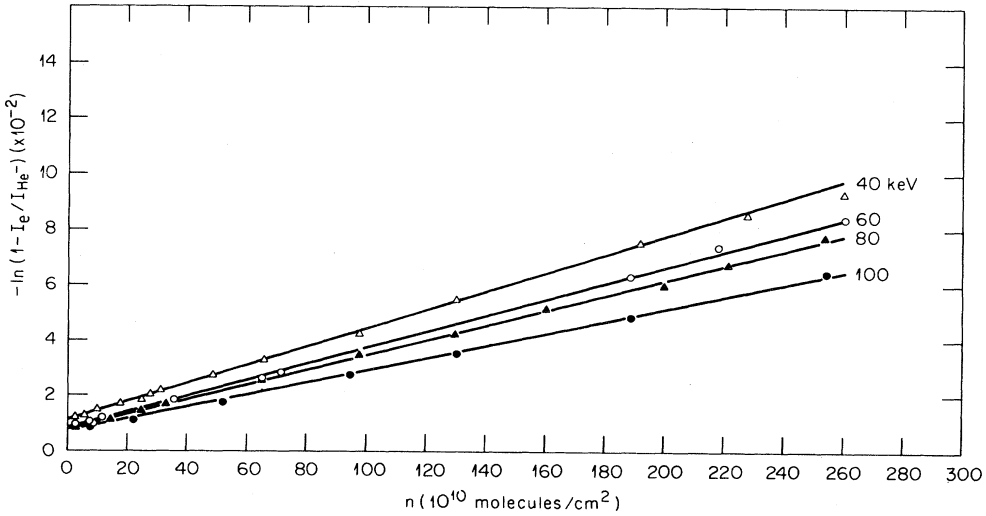

FIG. 2. Dependence of the collisionally induced and autodetaching electron signal vs N_2 molecular density for several ion energies.

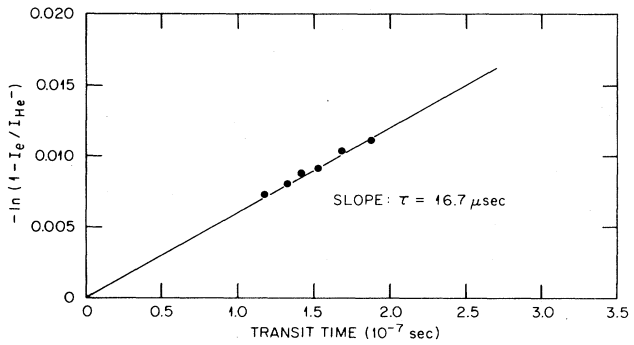

FIG. 3. Dependence of the autodetachment electron signal vs ion-beam transit time.

time of the He$^-$ states present in the ion beam. The lifetime agrees reasonably well with the weighted averages of the short-lived components of the ($^4P^o$)He$^-$ state obtained by Novick and Weinflash[5] when consideration is given to the quoted limits of errors associated with the respective lifetime values. However, the experimental arrangement and ion energies utilized in the present investigations discriminate against long-lived components relative to short-lived components. For example, if we assume the state to be that of the ($^4P^o_J$)He$^-$, in the absence of magnetic fields, the $J=\frac{5}{2}$ components would contribute less than 5% of the collected autodetachment signal at an ion energy of 20 keV—the lowest ion energy utilized in the experiment. As noted, the uncertainties associated with a least-squares fit to the semilogarithmic signal versus ion-beam transit-time data shown in Fig. 3 are small. However, we expect determinant (systematic) errors to dominate and estimate them to be approximately $\pm 15\%$, which leads to an uncertainty in τ of ± 2.5 μsec. The data were collected during two sets of experimental measurements separated by a time interval of a few months.

III. ELECTRON ENERGY MEASUREMENTS

A. Experimental techniques

As a more definitive test of the presence of long-lived ($^2P^e$)He$^-$ states, the energies of autodetaching electrons from the He$^-$-ion beam produced in the Ca charge-exchange medium were measured by replacing the parallel-plate arrangement with a high-resolution double-focusing 180° spherical-sector electrostatic energy analyzer with typical resolution between 0.2% and 0.5% (see the inset of Fig. 1). Although electrostatic energy analysis has been utilized for a number of years in fundamental research, it has not been used previously for measuring autodetachment electron energies from He$^-$ or other long-lived metastable-state negative ions. For reasons previously discussed, the Ca cell again was operated at power levels $\sim 10\%$ of those required for equilibrium production and loss He$^-$ formation. The momentum-analyzed He$^-$ beam was monitored in a biased and shielded Faraday cup located in the measurement chamber with a small hole located in the base of the cup which served as a collimating aperture preceding a 1.5-cm-long gas cell. The purpose of the cell was to provide a high-pressure region for collisionally stripping electrons from the He$^-$ beam when a small amount of gas was introduced in the cell. Electrons, moving collinearly with the ion beam which were stripped from the ion beam due to collisions in the gas cell or ejected in the forward direction by autodetachment in the 5-cm-long drift space following the cell were measured with the analysis system previously described. The beam collimation system used in the measurements permitted angular acceptances α of $\pm 1.5°$ with respect to the beam axis. The ion beam, after transit through the entrance aperture of the analyzer, was allowed to pass through a high-transmission gridded aperture located in the rear of the analyzer and into a shielded and biased Faraday cup where it was monitored. The electron spectrometer was operated in a fixed pass energy mode thus requiring the acceleration of electrons moving at energies less than and deceleration of those moving greater than the pass energy of the analyzer. This was accomplished by linearly varying the voltage across a single-gap electrode system at the entrance of the analyzer.

The experimental chamber was equipped with three sets of mutually perpendicular Helmholtz coils which were used to nullify the earth and stray magnetic fields in the vicinity of the electron spectrometer which could, otherwise, distort the energy spectrum. Electron spectra were taken with a standard x-y recorder with abscissa and ordinate directions, respectively, driven by signals from a precision ramp voltage generator and a conventional channel electron-multiplier circuit. A typical count rate at the peak of the autodetachment signal was $\sim 10^4$ electrons/sec.

The energies of autodetaching electrons were determined by measuring the energy difference between the auto-detachment and collisional-detachment electron peaks—the latter of which could be enhanced by introducing a small amount of gas in the cell preceding the analysis system. However, this procedure was not required because of the presence of a strong pressure-independent electron peak which appeared at a position corresponding to the velocity of the He$^-$-ion beam. The origin of this low-energy peak is, in part, attributable to electron photodetachment of He$^-$ by ambient blackbody radiation and is currently the subject of independent investigations.

The observed laboratory energy $E_{\rm lab}$ of an electron of energy E_e and mass m_e ejected collinearly with respect to a moving ion of energy E_i and mass M_i is given by the following small-angle kinematical approximation:

$$E_{\rm lab} \cong \frac{m_e}{M_i} E_i \pm 2 \left[\frac{m_e}{M_i} E_e E_i \right]^{1/2} + E_e \ , \qquad (1)$$

where the positive and negative signs refer, respectively, to ejection of electrons in the direction of or opposite to the motion of the beam. In the present experimental arrangement, only those electrons moving in the direction of the beam could be detected. The electrons ejected in the backward direction were embedded in a high background due

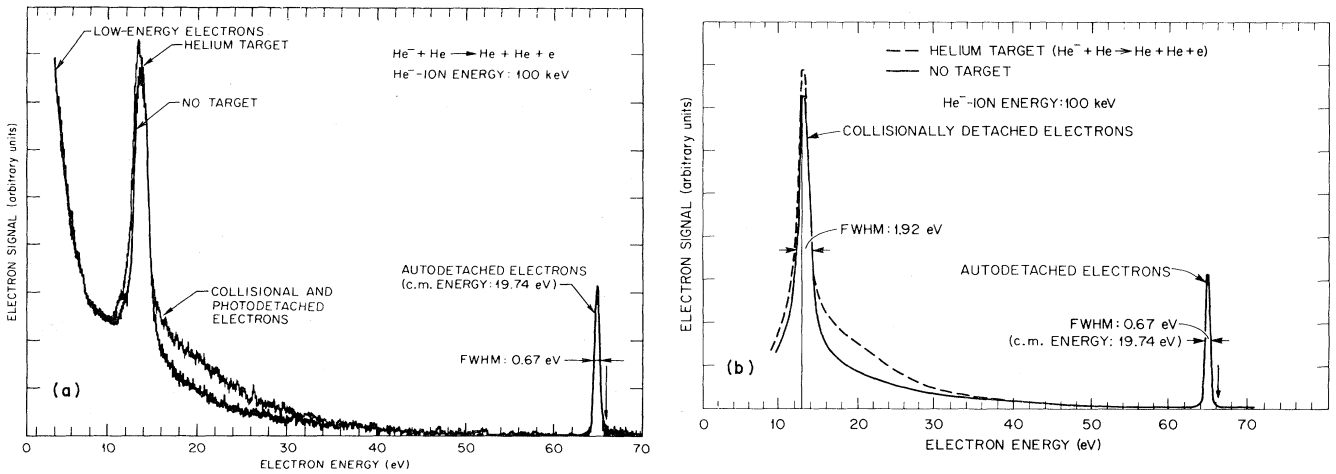

FIG. 4. Collisional and autodetaching electron spectrum from 100-keV He^- ions with and without N_2 stripper gas. Arrow indicates the position in energy where the 20.5-eV autodetaching electron peak from $(^2P^o_j)He^-$ would occur if present: (a) prior to background subtraction and (b) after background subtraction.

to low-energy electrons and, therefore, could not be resolved.

The center-of-mass energy E_e of autodetachment electrons ejected in the forward direction from a moving ion beam of energy E_i can be determined relative to the electrons which move at or near the projectile velocity by use of expression (1). The resulting relation for E_e is given by

$$E_e = \left[\left(\frac{m_e}{M_i} E_i + eX_i - eX_e \right)^{1/2} - \left(\frac{m_e}{M_i} E_i \right)^{1/2} \right]^2 , \quad (2)$$

where X_i and X_e are, respectively, the potentials through which the electrons moving at or near the velocity of the ion beam and the autodetaching electrons are accelerated or decelerated upon entrance into the analyzer, and e is the electronic charge. By using this procedure, based on differences, errors due to contact and surface potentials are minimized and the need for precise knowledge of the spectrometer constant and energy-scale calibration is avoided.

B. Results and discussions

Electron energy spectra were determined for a range of ion energies E_i between 20 and 120 keV. Examples of spectra taken at $E_i = 80$ and 100 keV are displayed in Figs. 4 and 5 which are illustrative of more than 20 determinations made over the previously indicated range of ion energies. The data of Fig. 4(a) shown in Fig. 4(b) have been corrected for background. The origin of the low-energy electrons with peak centered at $E_i = 0$ is attributed to secondary electrons generated during collisions of a portion of the He^--ion beam with apertures at the entrance to the analyzer. Figure 5 displays the region surrounding and including the autodetachment electron spectrum taken on a sensitive channel electron-multiplier scale. Among the factors which contribute to the observed widths of the electron energy spectra indicated in Figs. 4 and 5 are the physical processes involved in their formation, the spectrometer resolution function, and the kinematical broadening factor. The resolution function is dependent on spectrometer aperture sizes and the accepted electron-beam angular divergence. In turn, the resultant angular divergence is affected in an energy-dependent way by the lensing action introduced by the acceleration or deceleration of electric fields at the entrance to the analyzer.

Assuming equal production rates of the $^2P^e$ and $^4P^o$ states in the source, the experimental arrangement for measuring autodetachment electron energy levels should

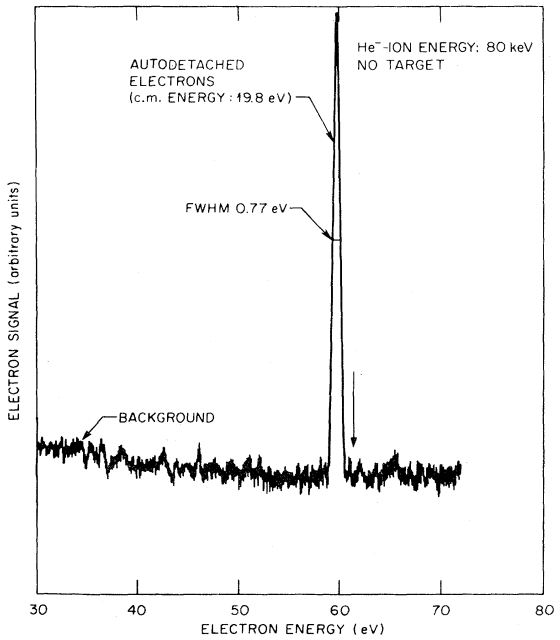

FIG. 5. Display of the region surrounding and including the autodetaching electron peak from 80-keV He^-. Arrow indicates the position in energy where the 20.5-eV autodetaching electron peak from $(^2P^o_j)He^-$ would occur if present.

have permitted detection of $^2P^e$-state populations with lifetimes as short as 0.5 μsec at the highest ion energy (120 keV) utilized in the measurements. No reproducible evidence of additional well-resolved peaks or distortion of the prominent autodetachment peak was observed which would suggest the presence of populations of other decaying states within a factor of ~ 50 in intensity of the principal peak. The positions of the arrows shown in all spectral-data figures indicate the energies at which the 20.5-eV autodetachment peak would have occurred. Again, the presence of the peak would act as a signature of the $(1s2p^2)^2P^e$ He^- state—assuming, of course, the existence of the state and that it lies above and radiatively decays to the promptly autodetaching $(1s\,2s\,2p)^2P^o$ He^- state.

The autodetaching electron energy level determined from more than 20 measurements is compared with other experimental and theoretical investigations of the $(^4P^o_J)$ states of He^- in Table III. The agreement between the present energy-level measurements and those obtained by others for the $(^4P^o_J)He^-$ state is taken as conclusive evidence that the predominate long-lived He^- state generated in Ca vapor is the $^4P^o_J$ even though the experimental conditions utilized were compatible with formation of $(^2P^e)He^-$ as well.

TABLE III. Comparison of previous and present energy levels for metastably bound He^-.

$E[(1s2s)^3S]-E[(1s\,2s\,2p)^4P]$ (eV)	$E[(1s2s2p)^4P]$ (eV)	Reference
≥ 0.075	19.744	1 (Theor.)
≥ 0.033	19.786	6 (Theor.)
0.067	19.752	7 (Theor.)
0.0774 ± 0.0003	19.7417	8 (Theor.)
0.080 ± 0.002	19.79	11 (Expt.)
0.076 ± 0.002	19.74	10 (Expt.)
0.056	19.76	Present

IV. CONCLUSIONS

Experimental investigations of the lifetime and energy levels of metastably bound He^- states formed in charge-exchange interactions with Ca vapor have been made under conditions compatible with the formation of $(^2P^e)He^-$—a state previously conjectured to exist based on the interpretation of experimental data[26–28] as well as the theoretical calculations of Safronova and Senashenka.[30] In contradistinction, the recent configuration-interaction calculations of Bunge and Bunge[8] show the state to be unbound. The present experimental results are supportive of the latter theoretical findings within the limitations imposed by the experimental arrangement on the lifetime of states which could be observed. Both lifetime and energy-level values determined in the present experiment agree closely with those measured or calculated previously for the $(^4P^o_J)He^-$ states. No other structures were observed over an energy range encompassing the anticipated autodetaching energy of the $(^2P^o_J)He^-$ state.

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