Observation of low-lying resonance states of He^- at the $2\,^1S$ and $2\,^3S$ He thresholds

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We measured the cusp electron production associated with target ionization at the impact of a 400-keV pure $2\,^3S$ He beam and a mixed beam containing all three long-lived He states, i.e., $1\,^1S$, $2\,^1S$, and $2\,^3S$. Using the results of an earlier experiment [Kuzel *et al.*, Phys. Rev. A **48**, R1745 (1993)], we estimated the cross section for both metastable states of He. We found that the cusp for the $2\,^1S$ state is much larger and sharper than for the $2\,^3S$ state. The peaks are manifestations of excitation of low-lying virtual or weakly bound states of the He^- ion at the $2\,^1S$ and $2\,^3S$ thresholds. [S1050-2947(97)50401-X]

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Virtual resonance states in low-energy scattering of particles play an important role in nuclear and particle physics. They are, however, less known in atomic physics, probably because of the greater experimental difficulties in carrying out measurements with such low-energy electrons. These resonances are expected to occur at the excitation threshold of certain metastable atomic states. For instance, a virtual resonance of the $He(2\,^1S)+e^-$ system was predicted by several theoretical works [1,2], and it was observed in the excitation function of He [3]. Due to this resonance, an enhancement of the elastic scattering cross section close to zero energy is expected. This effect has not been demonstrated in low-energy electron scattering measurements. However, employing a *translational electron spectroscopy* method, which takes full advantage of the kinematic transformation of the velocities from the projectile to the laboratory frame, allows us to enhance this small energy scale, making it accessible to experiment.

Measuring the electron spectrum in ion-atom collisions in the forward direction, a cusp-shaped structure is observed at the energy where the velocity of the electron matches that of the projectile. This singularity can be attributed to the final-state interaction between the projectile and the electron. In the case of target ionization, this process is called *electron capture to the continuum* (ECC). The ECC effect was first observed at the impact of charged projectiles [4]. In the case of charged outgoing projectiles, the ECC cusp can be explained adequately in the framework of different continuum-distorted-wave and impulse theories [5] by means of a factorization of the double differential cross section (DDCS) $d^2\sigma/dEd\Omega=F(v')d^2\tilde{\sigma}/dEd\Omega$. Here $d^2\tilde{\sigma}/dEd\Omega$ is a reduced DDCS, which does not include the electron-projectile final-state interaction. The *enhancement factor* $F(v')$ reads $F(v')=(2\pi Z_p/v')/[1-\exp(-2\pi Z_p/v')]$, where v' is the velocity of the electron in the projectile system and Z_p is the charge of the projectile [6]. It has an $1/v'$ behavior close to the cusp maximum, and tends to unity at large v'.

Calculations made in the above picture predicted a small and broad peak for the shielded Coulomb potential [7]. Surprisingly, Sarkadi *et al.* reported a narrow and pronounced cusp in a coincidence measurement using He^0 projectiles [8]. To explain the ECC cusp production by neutral atoms, several models have been constructed [7,9–11]. The most promising among them is Barrachina's concept that a weakly bound or low-lying virtual state of the e^-+ projectile system can be responsible for this effect [11]. Using a previous theory of Garibotti and Barrachina [12], the enhancement factor of the final-state interaction can be expressed as $F(v')=1/|f_0(v')|^2$, where $f_0(v')$ is the s-wave Jost function of the low-energy electron-projectile system. In the vicinity of the cusp, this Jost function behaves as $f_0(v')\propto(1+iav')/a$, leading to $F(v')\propto a^2/(1+a^2v'^2)$. Here a is the s-wave scattering length. As discussed above, a low-lying virtual state, characterized by a large scattering length of about $a\approx-330$ a.u. [2], can be found at the $e^-+He(2\,^1S)$ system. With this value, the enhancement factor $F(v')$ turns out to be in good agreement with the cusp shape measured by Sarkadi *et al.* [8]. In usual experimental conditions where the neutral He beam is produced from He^+ by electron capture, the He^0 beam (henceforth the "effective beam") contains not only ground-state but, e.g., $(24\pm4)\%$ metastable $2\,^1S$ and $2\,^3S$ He as in Ref [13]. According to Barrachina, the cusp electron production can be attributed mainly to the $2\,^1S$ fraction of the beam [11]. In an experiment by Kuzel *et al.* the metastable fraction of the beam was changed systematically from 0 to approximately 24% by collisional quenching in a gas cell [13], and the cusp electron yield was measured as a function of the metastable fraction [14]. It was found that the DDCS was about an order of magnitude larger for metastable He atom projectiles than for

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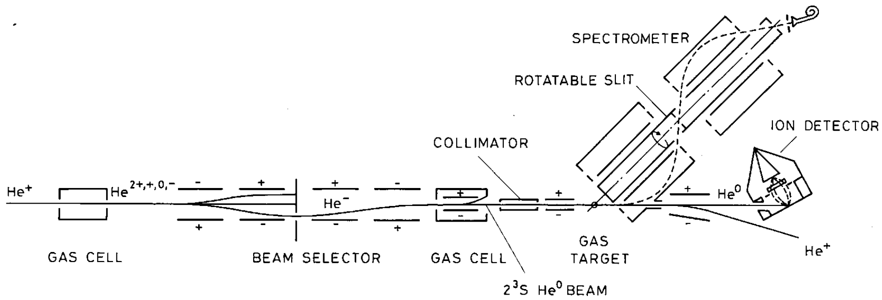

FIG. 1. Scheme of the experimental setup.

ground-state projectiles. Here, we report on a measurement in which the cusp electron production for the $2\,^1S$ and $2\,^3S$ He metastable states has been distinguished.

In order to achieve this separation of the cusp electron production for the two metastable states, we prepared the neutral He beam from He^- ions by collisional electron detachment in a gas cell. These He^- ions exist only in a ^4P state with all three spins parallel. Therefore, since magnetic interaction is negligible during the collision, the electron-detachment process must lead to a pure $2\,^3S$ He beam.

The experimental setup is shown in Fig. 1. The 400-keV He^+ ions were obtained by the 1-MV Van de Graaff generator of ATOMKI. The beam transverses a gas cell in which air has been introduced. In this cell a fraction of the beam is changed to He^- and sorted out by an electrostatic charge-state selector, which has a movable 2-mm slit. We applied an additional gas cell after the selector to detach electrons from He^- and produce $2\,^3S$ He^0. Any remaining charged components were deflected with an electrostatic field behind this cell. To reduce the He^+ contamination in the beam, which can be produced by collision with the residual gas atoms in the collimator region, we used a second deflector just in front of the target. The fraction of He^+ ions in the incoming beam was negligible (less than 1%). The beam was collimated with two 0.5-mm apertures separated at a distance of 200 mm. Our spectrometer was a double stage cylindrical mirror analyzer [15], which is combined with an electrostatic lens system [16] in order to improve the electron yield. The angular and relative energy resolution of the spectrometer was $\Theta = 2°$ (half angle) and 0.6%, respectively. The outgoing particles were charge-state analyzed after the collision and detected by a particle detector described in Ref. [17]. The cusp belonging to target ionization was identified, measuring the electrons in coincidence with the outgoing neutral He atoms.

The effective beam was produced by selecting the He^0 fraction of the beam with the beam selector, while all the other conditions remained the same. As a target, we used Ar gas that effused through a thin needle. We performed the measurements at three different target densities. The corresponding values of the overall chamber pressure (which was found to be proportional to the target density in our previous investigations) were 3.2, 6.8, and 12×10^{-6} mbar. We found that the electron yield was a linear function of the target density, and, therefore, we simply took the average of the spectra, which were normalized to the target thickness. The base pressure in the target chamber was 6×10^{-7} mbar.

The measured DDCS for the $2\,^3S$ beam and for the effective beam is shown in Fig. 2. The absolute scale was determined normalizing the electron yield in the cusp region of the present measurements to the data of Ref. [14]. In addition to the statistical error of our data, the absolute scale contains an uncertainty of 25%, which is not indicated in our figures. The shapes of the two cusps are very different: The cusp for the effective beam is much narrower and sharper than that for the He triplet beam.

The ratio of the two DDCSs integrated in the range between $0.8E_{\rm cusp}$ and $1.2E_{\rm cusp}$ is

$$\sigma_{2\,^3S}/\sigma_{\rm eff} = 0.99 \pm 0.03. \quad (1)$$

Assuming that the metastable fraction of the beam is 24% [13], we can approximate $\sigma_{\rm eff}$ in the form

$$\sigma_{\rm eff} \approx 0.24[r\sigma_{2\,^1S} + (1-r)\sigma_{2\,^3S}]0.76\sigma_{1\,^1S} \quad (2)$$

where r is the fraction of $2\,^1S$ states in the metastable part of the effective He beam. This equation is also valid for the doubly differential cross sections. In Ref. [14] it was found that

$$\sigma_{\rm eff}/\sigma_{1\,^1S} \approx 3.2. \quad (3)$$

Therefore

$$\sigma_{2\,^1S} \approx [3.17\sigma_{\rm eff} - (1-r)\sigma_{2\,^3S}]/r. \quad (4)$$

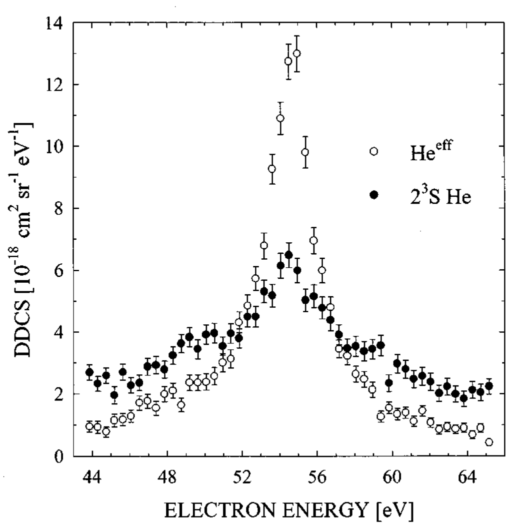

FIG. 2. Double differential cross section at the impact of a 400-keV $2\,^3S$ He beam and a mixed He beam (see the text) on an Ar target.

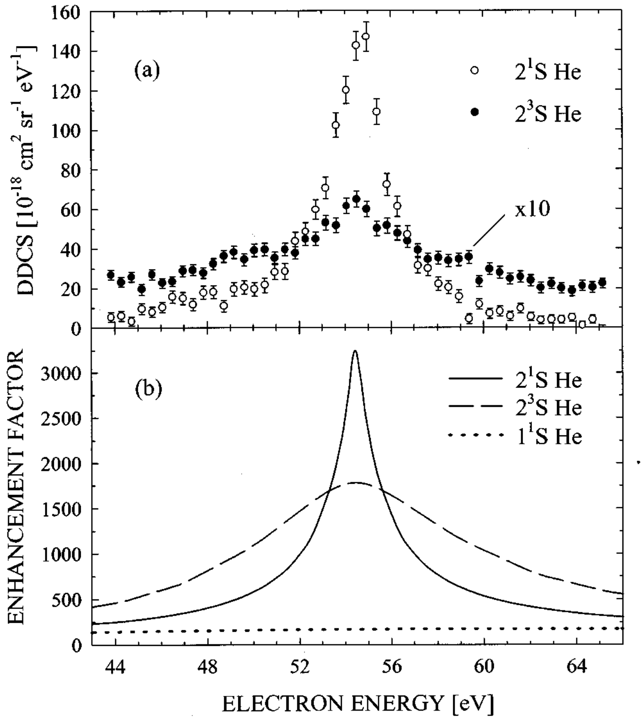

FIG. 3. (a) Double differential cross section at the impact of 400-keV 2 ^1S and 2 ^3S He on Ar. The 2 ^1S spectrum was obtained using Eq. (4). (b) Enhancement factors for the 1 ^1S, 2 ^1S, and 2 ^3S He states, integrated for the angular and energy resolution of the electron spectrometer.

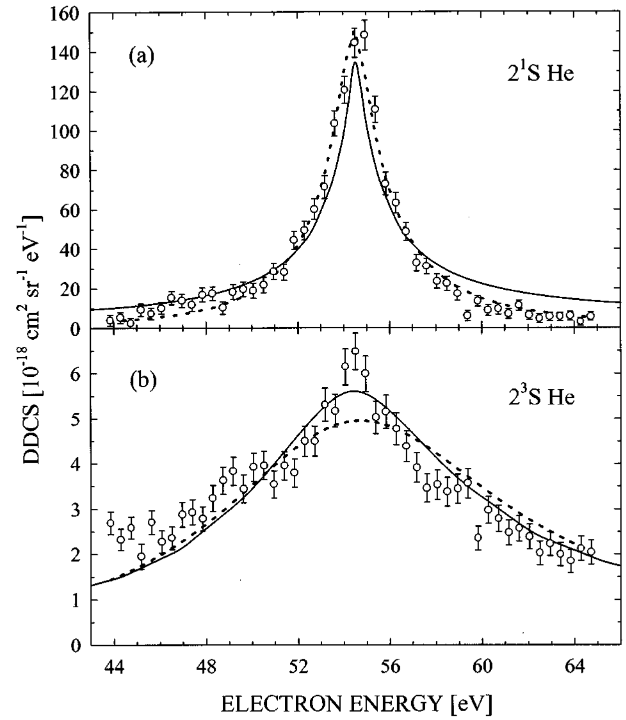

FIG. 4. Measured DDCSs at the impact of (a) $2\,^1S$ and (b) 2 ^3S He beams on Ar, compared with the calculated enhancement factors. The notation of the curves: full line, exact treatment of the e^-+He scattering; dotted line, result of fitting with Lorentzian $F(v')$ function.

Since the shape of the cusp in the case of the effective beam and that of the ground-state beam were found to be the same [14], Eq. (3) stands for the doubly differential cross sections, as well. Consequently, it is possible to calculate the DDCS for 2 ^1S He from the spectra belonging to the effective and the 2 ^3S He beam using Eq. (4) [see Fig. 3(a)]. Here, we have assumed a statistical $r=1/4$ relative population of the $2\,^1S$ states in the metastable part of the effective He beam. However, since the fraction r can differ considerably from this value due to cascades from other excited states [18], the DDCS in Fig. 3(a) might underestimate the spectrum for the $2\,^1S$ He beam by a large unknown factor. The enhancement factors $F(v')$ for the three different He states are shown in Fig. 3(b), integrated for the angular and energy resolution of our spectrometer. The $F(v')$ functions were calculated from the asymptotic behavior of the regular s-wave solution of a Schrödinger-type equation which describes the low-energy elastic scattering of an electron from a He target. Comparing Figs. 3(a) and 3(b) we conclude that, although the theory largely underestimates the $\sigma_{2\,^1S}/\sigma_{2\,^3S}$ ratio, there is a qualitative agreement between the theory and experiment. Figure 4 shows a comparison of the observed and the theoretical cusp shapes. The experimental data show a mild asymmetry towards lower energies, which the enhancement factors alone, without a complete calculation of the corresponding DDCSs, cannot reproduce. Except for this, the agreement between theory and experiment is reasonable for the 2 ^1S He and is very good for the 2 ^3S He. These findings strongly support the picture in which ECC induced by neutral He atoms is due to negative-ion resonance states [11]. In this picture, the large and narrow cusp at the impact of the 2 ^1S He beam is ascribed to a low-lying virtual state near the 2 ^1S threshold which has a scattering length of about $a\approx-330$ a.u. [2]. The much broader ECC peak observed for the 2 ^3S state is not due to a virtual state, but to the proximity of the ^2S resonance to the 2 ^3S excitation threshold [19]. Since in this case the ECC cusp maps, to a certain degree, the low-energy behavior of the elastic e^-+He(2 ^3S) cross section, it is similarly affected by the vicinity of an s-wave bound state [20], producing an enhancement at threshold. The corresponding scattering length is estimated to be of the order of $a\approx 5.5$ a.u. [2]. Finally, the ECC process by a ground-state He ejectile can only produce a very broad shoulder [7]. The fact that the cusp shape for a pure ground-state He beam is similar to that for the effective beam [14], where the cusp electron production by the 2 ^1S fraction is dominant, implies that a second-order process, in which the He projectile gets excited to the 2 ^1S final state during the collision, contributes to the ECC peak for the ground-state He incoming beam [11].

Concerning the relative cross sections for the different states, we estimate the following ratios from Eqs. (1), (3), and (4): $\sigma_{2\,^1S}/\sigma_{2\,^3S}=9.8\pm0.6$, $\sigma_{2\,^1S}/\sigma_{1\,^1S}=31\pm8$, and $\sigma_{2\,^3S}/\sigma_{1\,^1S}=3.2\pm0.8$. Most of the errors arise from the large uncertainties in the determination of the metastable fraction and the ratio r.

From Fig. 1(a) we note that there might be resonance peaks at both wings of the cusp for the 2 ^3S He beam at around 49 and 59 eV, which means a resonance energy of 150 meV in the projectile reference system. If such an effect is confirmed, it might represent a fingerprint of the resonance structure of the e^- + He(2 ^3S) system at low energies, as predicted by Szótér [9].

We conclude that the observation of an ECC peak at the impact of 2 ^3S He and a much larger and narrower cusp at the impact of 2 ^1S He supports Barrachina's model, namely that negative-ion resonances by low-lying virtual or weakly bound states are responsible for the ECC cusp induced by neutral atoms. In order to determine the scattering length of the resonance at the threshold of the 2 ^3S and 2 ^1S He states, we fitted the $F(v')\propto a^2/(1+a^2v'^2)$ function to the experimental data in the close vicinity of $v'=0$, with the modulus of the scattering length a as a fitting parameter. A quite good fit was obtained at $|a|=8$ $(+3,-2)$ a.u. for the 2 ^3S state and $|a|=120$ $(+80,-50)$ a.u. for the 2 ^1S state; see Fig. 4. These values are in good agreement with the theoretical estimates, in view of the theoretical uncertainty; which, for the case of the 2 ^1S state, amounts to as much as a factor of 2. We note that the error of the scattering lengths can be further decreased by improving the angular resolution of the electron spectrometer; however, this was not the main goal of the present work. The fact that we were able to determine the scattering lengths for the s-wave resonances at the thresholds of the 2 ^1S and 2 ^3S He states demonstrates that, measuring the ECC cusp at the impact of neutral atoms, one can get information about the scattering of extremely low-energy (even below 1 meV) electrons on those atoms. It would be very interesting to carry out similar investigations for atoms other than He, as well. It is hoped that the same method could be applied to determine the scattering length of low-energy virtual resonances in those cases where other methods only yield values with a large uncertainty.

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