Absence of the cusp in the single-electron detachment spectrum of the He^- ion

L. Víkor* and L. Sarkadi
Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), P.O. Box 51, Debrecen, H-4001 Hungary
(Received 9 January 1997)

The energy spectrum of electrons emitted in the single-electron detachment process in collisions of 200-keV He^- ions with He was measured. Taking advantage of the method of the 0° electron spectroscopy carried out with good angular and energy resolution, the lines from the decay of the $(1s2p2p')$ $^4P^e$ shape resonance of He^- were resolved, and the absence of the characteristic cusp peak in the double-differential cross section was established. [S1050-2947(97)51104-8]

PACS number(s): 34.50.−s, 34.60.+z

The strong enhancement of the cross section for electron emission in the forward direction in ion-atom collisions due to final-state interaction between an electron and an outgoing charged projectile appears as a sharp, cusp-shaped peak in the energy spectrum. The process of target ionization that leads to the cusp is called *electron capture to the continuum* (ECC), and the corresponding process of the electron emission from the projectile is called *electron loss to the continuum* (ELC).

The cusp is centered at the electron energy that corresponds to a velocity which is equal to that of the projectile ion. The equality of the velocities in the laboratory frame of reference implies electron scattering on the projectile (ECC), or electron emission from the projectile ion (ELC) with infinitely small energy in the projectile-centered reference frame. The cross section in the forward direction is enhanced by the factor v_e/v_e' by the transformation to the laboratory frame, where v_e and v_e' are the electron velocity in the laboratory and the projectile frame, respectively. This transformation may result in a singularity of the cross section at $v_e=v_p$ (here v_p is the velocity of the projectile), which appears as the cusp peak (see, e.g., [1]). According to the Wigner threshold law [2], a nonzero cross section at the threshold occurs for electron emission in the presence of the long-range Coulomb potential of charged particles, whereas the cross section is zero for the short-range potential of neutral atoms. Liu and Starace showed that the dipolar potential of the collisionally excited H atom can also result in a finite cross section at the threshold [3]. However, the collision-induced dipole moment (see, e.g., Siegmann *et al.* [4] and references therein) is a unique feature of the hydrogen atom. Apart from this special case, a cusp is expected only when the projectile emerges from the collision as a positively charged particle.

However, the interpretation of the cusp by the long-range nature of the Coulomb force [5] had to be reexamined when Sarkadi *et al.* [6] observed a narrow ECC cusp associated with a neutral atom in the final state in a coincidence experiment made with He^0 projectiles, i.e., for a short-range potential. The observation was followed by several theoretical and experimental investigations [7–13]. Among the theoretical efforts to explain the unexpected finding, the model of Barrachina [8], in which the cusp electron production was related to the excitation of a virtual resonance state of He^- at the threshold of the He 2 ^1S state, was found to agree very well with the experimental observations. This result showed that excited states are likely the source of the cusp electrons associated with a neutral atom in the final state.

Besides ECC by neutral atom impact, collisional single-electron detachment (SED) from negative ions—as it terminates with a neutral particle in the final state—is another process suitable for the study of the cusp origin in the case of a short-range potential. Furthermore, this approach is very convenient from an experimental point of view because of the large cross section of the electron detachment. In the spectra of electrons collisionally detached from negative ions, a pronounced structure appears that consists of a cusp peak and two peaks on the wings of the cusp (see, for example, [1,14–16]). The latter two peaks result from the decay of a collisionally excited shape resonance of a negative ion to the corresponding parent state of a neutral atom. The doubling of the resonance peak in the laboratory frame is the consequence of forward and backward electron emission in the projectile frame of reference.

Most studies of this part of the spectrum were made with the H^- ion [1,14,15,17–19], and only in the last few years with He^- [20], Li^- [16,21], and B^- [16] ions. Mainly noncoincidence measurements were performed, i.e., the electrons were detected from both the single- and double-electron detachment. However, as was shown in a recent experiment [19], the contribution of the double-electron detachment is not negligible. Consequently, for a rigorous study of the electron emission at the threshold in the case of a neutral atom in the final state it is very important to eliminate the cusp arising from the double detachment process by coincidence measurement.

In their measurements with H^- ions, Penent *et al.* [18] eliminated the contribution from double detachment, detecting the electrons in coincidence with the Lyman-α photons emitted from the decay of $H(2p)$ formed in the collisions. They observed a cusp peak in the electron spectrum, and interpreted it by assuming a long-range dipole interaction between the H^0 atom and the electron, on the basis of the theoretical work of Liu and Starace [3]. In a direct measurement of SED, Víkor *et al.* [19] confirmed the result of Penent *et al.* [18]. Detecting the electrons in coincidence with the

*On leave from the Institute of Physics, P.O. Box 57, Belgrade, Yugoslavia.

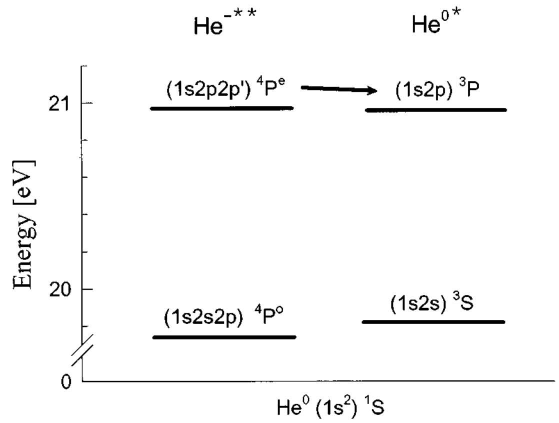

FIG. 1. Energy-level diagram for the metastable He$^-$ ion and the He^0 atom. The arrow shows the resonant detachment.

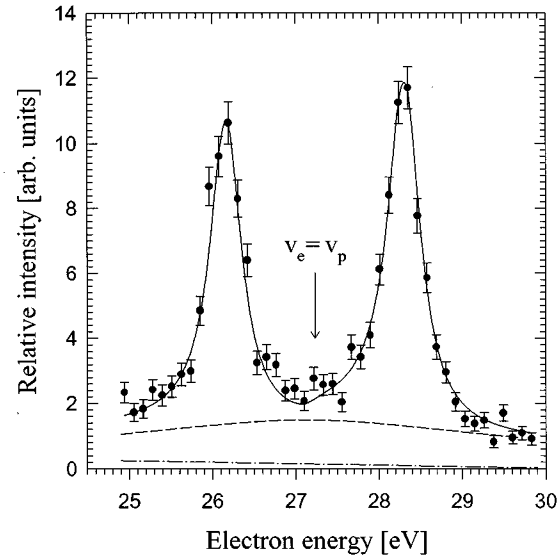

FIG. 2. The electron spectrum for SED obtained for 200-keV He$^-$ on He collisions. The solid curve through the data is the result of the fit. The dashed and dashed-dotted curves show separately the two background components discussed in the text.

outgoing hydrogen atoms, they also observed a distinct cusp peak in the electron spectrum.

The first electron-detachment measurement at 0° for impact of an He$^-$ ion was made by Závodszky *et al.* [20]. The SED process was identified by detecting the electrons in coincidence with the outgoing He^0 atoms. In the obtained electron spectrum the two lines from the $^4P^e$ shape resonance (see the energy-level diagram in Fig. 1) were not separated sufficiently, and from the spectrum shape the authors concluded that a cusp with a considerable intensity (29% contribution to the total yield) was present between the lines. This finding, however, cannot be supported by any theory. For SED from He$^-$, neither a direct nor a resonant process can lead to a cusp. *Direct* cusp formation can be excluded due to the lack of a long-range interaction (Coulombic or dipolar). Unlike for H$^-$, for impact of He$^-$a permanent electric dipole moment cannot be induced in the outgoing He^0. (A permanent dipole moment can be induced only in hydrogen due to the near degeneracy of the l states belonging to the same principal quantum number.) Regarding the *resonant* cusp formation, we can say that, according to Liu and Starace [3], the shape resonance does not give rise to a cusp since it has a zero cross section at the threshold, and because it is characterized by a repulsive radial hyperspherical potential at large distances. We also note that, after electron detachment, the He atom remains in the 2 ^3S metastable state (see Fig. 1), which excludes the formation of a cusp-shaped peak via the excitation of a virtual resonance, a mechanism known to exist for the 2 ^1S state [22,23].

In this paper we present the results of our experimental study of SED for the He$^-$ ion. To distinguish SED, the electrons were detected in coincidence with He^0. To the best of our knowledge, this is the first experiment in which, with good energy and angular resolution, the lines from the shape resonance were completely separated, and the absence of the cusp was established.

The main components of the experimental setup and the measuring procedure have been described by Kövér *et al.* [24], and modifications for studies of the electron detachment from negative ions can be found in [19]. Briefly, the 200-keV He$^+$ ions from the 1.5-MV Van de Graaff accelerator of ATOMKI were momentum analyzed and passed through a gas cell where a part of the He$^+$ ions was transformed into He$^-$ ions. The He$^-$ ions were selected with a four-stage electrostatic charge-state selector, and then crossed with a He gas jet target. The forward-emitted electrons were measured with a distorted-field double-stage cylindrical mirror electrostatic electron spectrometer [26]. The relative energy resolution of the spectrometer was 0.3%.

To resolve the peaks corresponding to forward and backward electron emission from the shape resonance, the electrons have to be detected within an acceptance angle smaller than some ''critical'' value (see, e.g., [1]). This was achieved by the use of an electrostatic lens, made specially for 0° electron spectroscopy [25]. With the lens, mounted in front of the spectrometer, we attained an acceptance (half) angle 0.4°, preserving at the same time the good detection efficiency.

The outgoing projectiles were charge-state analyzed by an electrostatic deflector, and detected with a fast particle detector [27]. The electrons were detected in coincidence with the outgoing He^0 particles. The measured electron spectra were corrected for the contribution of the random coincidence events.

The obtained SED spectrum is shown in Fig. 2. It can be seen that the lines from the shape resonance are completely resolved, and that no sign of the cusp peak can be observed between them. Although the absence of the cusp is in accord with the general threshold law of the electron emission, our observation is still surprising: Due to the small electron affinity of He$^-$ (77 meV), a small perturbation by the target during the collision leads to SED, resulting in very-low-energy electrons in the projectile frame of reference. In a simple view of the collision, one would expect a strong cusp due to these electrons. Instead, we obtained that the detachment proceeds almost completely resonantly.

For the fitting of the measured spectra we used the method proposed by Závodszky *et al.* [20]. Their mathematical model starts with the parametrization of the cross section in the projectile frame, related to nonresonant and resonant electron emission [28]. Using this parametrization method the double-differential cross section (DDCS) in the projectile frame can be expressed as

$$\left(\frac{d^2\sigma}{dE_e' d\Omega_e'}\right)_p = \left(\frac{d^2\sigma}{dE' d\Omega_e'}\right)_p^{\mathrm{NR}} + \frac{\alpha(\mathbf{k}_e')\varepsilon + \beta(\mathbf{k}_e')}{1+\varepsilon^2}, \quad (1)$$

where $(d^2\sigma/dE_e' d\Omega_e')_p^{\mathrm{NR}}$ is the cross section of the nonresonant (direct) electron detachment, Ω_e' is the solid angle of the electron emission, $\varepsilon = 2(E_e' - E_r)\Gamma^{-1}$ is the reduced energy variable, E_e' and $\mathbf{k}_e'$ are the energy and momentum of the ejected electron in the projectile reference frame, and E_r and Γ are the energy and the width of the resonance. $\alpha(\mathbf{k}_e')$ and $\beta(\mathbf{k}_e')$ are the so-called Shore parameters [28] that describe the shape of the resonance, including the *interference* between the direct and resonant ionization amplitudes.

In the procedure proposed by Závodszky *et al.* [20], both terms in the cross section presented in Eq. (1) are series expanded. That is, the series expansion method of Meckbach, Nemiroksky, and Garibotti [29], introduced for the nonresonant cross section, is generalized for the Shore parameters. The advantage of the method is that one can characterize the cross section by a set of expansion parameters that are free of instrumental effects. However, this series expansion is too general, since it allows the resonant part to contribute to the cusp, which is in contradiction with the above-mentioned characteristics of the shape resonance. To exclude this contribution we applied a restriction for the Shore parameters introduced by Víkor *et al.* [19]. The expression to be compared directly with the experimental data is obtained by transforming the DDCS of Eq. (1) to the laboratory reference frame, integrating the transformed DDCS over the acceptance angle of the spectrometer and convoluting it with the spectrometer transmission function. The result contains the series expansion coefficients explicitly. The coefficients can be regarded as free parameters of the generated expression for the electron yield, which can be fit to experimental data.

To obtain a sufficiently good fit, we found it necessary to include two ''background'' components in the final expression. One component was a linear function. The other was a broad peak centered at $v_e = v_p$. The inclusion of this second component into the fit was motivated by the recent experimental finding of Báder *et al.* [22]. These authors observed a broad peak around $v_e = v_p$ in the spectrum of electrons associated with target ionization by impact of $2\,^3S$ He atoms. This structure was explained by the proximity of the ^2S Feschbach resonance of He^- to the $2\,^3S$ threshold of He. The corresponding theoretical calculations resulted in a spectrum shape that agreed well with the observed one. We may assume that the above resonance also plays a role in the single-electron detachment of He^-. To account for this effect in the fitting, we took the theoretical spectrum shape from the work of Báder *et al.* [22].

The solid curve through the data points in Fig. 2 represents the best fit obtained by using the function of the electron yield based on Eq. (1) and the above-discussed background components. Fitting the spectrum, we also considered the energy and width of the shape resonance as free parameters. As the main point of this work was to check whether the cusp is absent for SED from He^-, we made the fit retaining only the resonant part in Eq. (1). As is seen, a good fit ($\chi^2 = 2.1$) was obtained without a cusp. Our error analysis showed that the statistical accuracy of the data allows a maximal cusp contribution of about 7% to the integrated SED yield at the 95.4% confidence level. This value is quite small compared to the 30% cusp contribution in case of SED from H^- observed in the experiment of Víkor *et al.* [19].

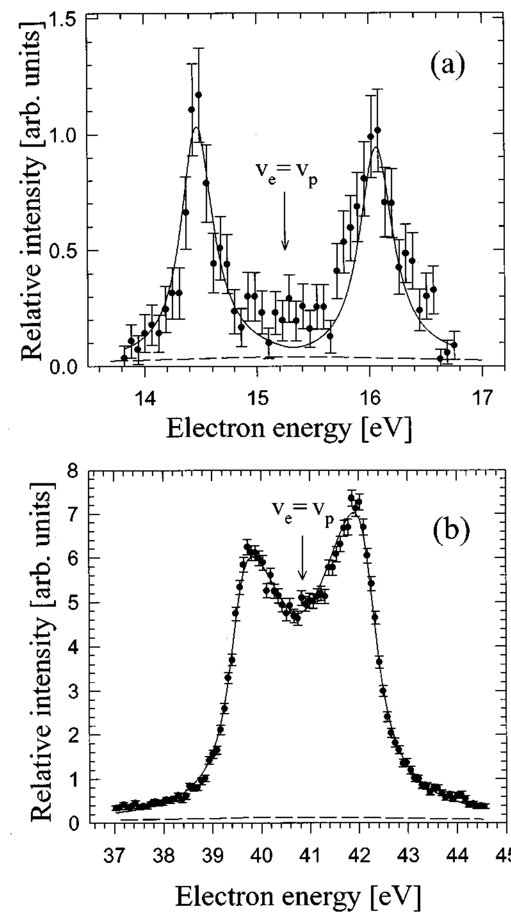

FIG. 3. SED electron spectrum (a) for 112-keV He^- on Ar collisions and (b) for 300-keV He^- on Ar collisions. For the latter spectrum the data are from Závodszky *et al.* [20]. In both spectra the curve through the data is the result of the fit without the inclusion of cusp.

For the present study of SED from He^-, we chose He as a target, since the theoretical interpretation in this case is easier than for a heavier target. At the same time, in our test measurements, made to improve the angular resolution for the electron analysis, we used an Ar target because of the larger electron yield. One of the spectra obtained in these latter measurements carried out at 112-keV impact energy is seen in Fig. 3(a). Although the statistical accuracy of the spectrum is low, one can also establish the absence of the cusp in this case, i.e., this feature of the SED spectrum of He^- is not specific for a He target. In Fig. 3(b) the spectrum for 300-keV He^- on Ar collisions is shown, obtained in the first measurement of this resonance by Závodszky *et al.* [20]. The curve through the data points of this spectrum is the result of a new fit made under the same conditions as for the spectra in Figs. 2 and 3(a), i.e., without inclusion of the cusp.

A good fit was achieved taking a somewhat larger angular acceptance, 1.2°, instead of the 0.8° used by Závodszky *et al.* [20].

Besides the importance of the obtained results for a deeper understanding of the threshold electron emission, we would like to emphasize the spectroscopical value of the present work. For the resonance parameters we obtained the following values: $E_r = 10.67 \pm 0.14$ meV and $\Gamma = 9.1 \pm 0.3$ meV. The following simple calculation demonstrates how the frame transformation amplifies the very small value of E_r to ~ 1 eV for the spectrum in Fig. 2. The two peaks observed in the laboratory frame correspond to forward and backward electron emission in the projectile frame; therefore their energies are given by $E^{\pm}_{\rm lab} = \frac{1}{2} m (v_p \pm v_r)^2$. Here $v_r = \sqrt{2E_r/m}$ is the velocity of the electron in the projectile frame emitted with the resonance energy E_r, and m is the electron mass. Using the value $E_r = 10.67$ meV, $v_r = 0.02800$ a.u. For 200-keV He^- impact, $v_p = 1.41477$ a.u., thus we have $E^{+}_{\rm lab} = 28.32$ eV and $E^{-}_{\rm lab} = 26.16$ eV.

Our E_r and Γ values are close to those obtained by Walter, Seifert, and Petersen [30] in photodetachment measurements, $E_r = 10.80 \pm 0.07$ meV and $\Gamma = 7.16 \pm 0.07$ meV. The reasonable agreement exemplifies that the 0° electron spectroscopy can be a supplement to the very precise photodetachment method in investigations of low-energy resonances. It can be particularly important for states that can be only collisionally excited. However, the disadvantage of the method is that the collisional excitation is nonselective, and simultaneously excited resonances belonging to different parent states may result in overlapping peaks that cannot be resolved. This can be a reason that the resonance width observed in the present work is larger than that obtained by Walter, Seifert, and Peterson [30].

In summary, we measured SED for a 200-keV He^- on He collision, and demonstrated the absence of a cusp peak in the electron energy spectrum in the forward direction. The present result indicates that the cusp with a neutral atom in the final state is an exception rather than a rule. To investigate the question of the existence of the cusp systematically, it would be desirable to carry out similar coincidence measurements with heavier negative-ion projectiles.

This work was supported by the Hungarian Scientific Research Foundation (OTKA, Grant Nos. 3011 and T016636). The authors wish to express their thanks to P. A. Závodszky for providing the computer program by which the fitting of the data was carried out.

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