Brief Reports

Brief Reports are short papers which report on completed research which, while meeting the usual **Physical Review** *standards of scientific quality, does not warrant a regular article. (Addenda to papers previously published in the* **Physical Review** *by the same authors are included in Brief Reports.) A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Electrons trapped in the wake of a negative muon

A. Rivacoba and P. M. Echenique
Fisika Saila, Kimika Fakultatea, Euskal Herriko Unibersitatea, Apartado 1072, 20080 San Sebastian, Spain and Cavendish Laboratory, Cambridge CB3 DHE, England
(Received 16 October 1986; revised manuscript received 18 February 1987)

Electron binding energies in the wake of a swift negative ion such as a muon or an antiproton have been evaluated. The velocity distributions of electrons emerging from the solid at the ionic velocities are also estimated. These calculations could be of guidance to the experimental project of Yamazaki and co-workers directed to elucidate the nature of convoy electrons emerging from solids after the passage of swift ions.

Since the pioneering works of Neufeld and Ritchie[1] and Ritchie[2] on the interaction of fast ions with an electron gas, a great deal of theoretical[3] and experimental work has been concerned with the distribution in space and time of perturbations of electron motion in solids caused by passage of swift, charged particles. Specifically, the influence of the wake of an ion on nearby ions in molecular clusters has been studied.[3] Several authors have evaluated the wake potential and induced electron fluctuations using an increasing degree of sophistication for the electron-gas dielectric-response function.[4-10]

When swift ions penetrate gaseous or solid targets, they emerge with accompanying free electrons traveling with nearly the same velocity as the ion. These are the so-called convoy electrons.[9] For gaseous targets, this phenomenon was first observed by Crooks and Rudd[10] and explained by Macek[11] in terms of charge transfer to continuum states associated with the attractive Coulomb potential of ions moving in vacuum. In condensed matter, however, a different mechanism might be also present; Neelavathi, Ritchie, and Brandt[4] pointed out that in solids the oscillatory wake of electron density fluctuations trailing a fast ion may give rise to wake-bound electron states that will emerge from the solid also with a velocity distribution centered at the ion velocity.[12] Some investigators[13,14] have observed two components in the measured energy distribution, and it has been suggested[12] that some of the convoy electrons from solids might originate from wake-bound electrons trailing the swift ion in the solid. Capture and loss cross sections for capture have been evaluated for the case of swift protons.[15] However, the experimental evidence for positive ions does not allow one to conclusively decide on this possibility.[16,17]

Very recently a new experiment that could, in principle, conclusively decide on the existence of wake-bound states has been suggested by Yamazaki.[18,19] The experiment, which uses negative muons or antiprotons as probes, is currently being carried out by Yamazaki.[18,19]

The direct interaction with the electrons is now repulsive and therefore does not lead to direct capture as in the case of a positive ion. The possibility of wake trapping, associated with regions of depletion of electrons in the induced-charge-density fluctuations, remains a valid one; such trapping, however, now occurs closer to the ion, since due to its negative charge the first depletion of electronic charge occurs in the region surrounding the ion (in the same region where there was a pile in the case of a positive ion). In this Brief Report we explore the possibility of the existence of such bound states in the wake of a swift negative ion, and conclude that, for an accessible range of velocities, binding exists and convoy electrons originating from wake-bound states may be experimentally detected. We hope that our results could be of guidance to experimentalists.

The wake potential [i.e., the scalar electric potential $\phi_w(b,\tilde{z})$] in a homogeneous, isotropic medium due to a swift point charge Z_1, with constant velocity v, is given by[8]

$$\phi_w(b,\tilde{z})=\frac{2Z_1}{\pi V}\int_0^\infty QJ_0(Qb)\,dQ\int_0^\infty \frac{\mathrm{Re}\{e^{i(\omega z/V)}[\epsilon^{-1}(k,\omega)-1]\}}{k^2}\,d\omega \ . \qquad (1)$$

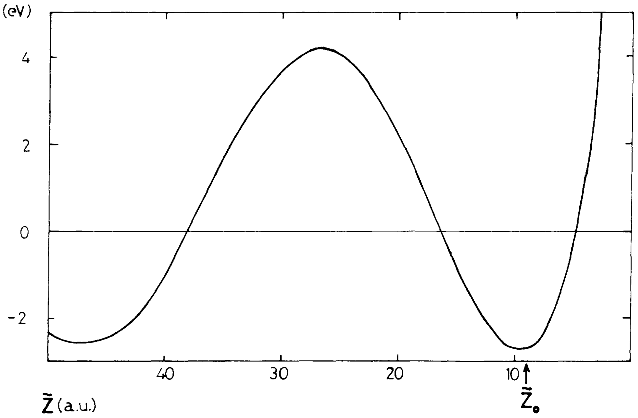

FIG. 1. Plot of the potential energy of an electron, in the wake of a negative muon ($v=4$, $b=0$, and $r_s=2$). The result is shown as a function of position along the track with $z=0$ and $b=0$ corresponding to the location of the muon. z_0 indicates the first minimum of the electron potential energy.

The cylindrical coordinates b and z refer to the direction of motion and are defined by $b=(x^2+y^2)^{1/2}$ and $\tilde{z}=z-vt$, relative to the position $(x,y,z)=(0,0,vt)$ of the moving charge Z_1. The wave number $k=(q^2+\omega^2/v^2)^{1/2}$ has component q in the b direction, J_0 is the Bessel function of order zero, $\epsilon(k,\omega)$ is the electron-dielectric-response function, and $\mathrm{Re}(x)$ stands for the real part of x. (We shall work in atomic units throughout.)

In the earlier calculations for positive ions,[4-8] numerical values of the total potential energy of the electron have been fitted in the neighborhood at $b=0, z=\tilde{z}_0$ by the expression

$$V(b,\tilde{z})=-\phi_w-\frac{Z_1}{(b^2+\tilde{z}^2)^{1/2}}$$
$$=-V_0+\alpha b^2+\beta(\tilde{z}-\tilde{z}_0)^2 . \quad (2)$$

The binding energies are then obtained from standard quantum mechanics. For the case of a negative muon, $Z_1=-1$, the direct Coulomb potential of the incoming muon is not negligible at z_0, as is usually the case for positive ions, because the localization occurs closer to the ion.

TABLE I. Binding energy and velocity distributions for electrons trapped in the wake of a negative muon or of a proton.

v (a.u.)	E_0 (eV)		Δv_b (a.u.)		Δv_z (a.u.)	
	μ^-	p	μ^-	p	μ^-	p
2	0.13	0.85	1.03	0.50	1.27	0.63
4	1.71	4.24	1.27	0.48	0.91	0.45
6	1.83	4.63	1.17	0.42	0.73	0.33

Numerical values of the potential energy of an electron in the wake of a negative muon are shown in Fig. 1 for $v=4$ and electron gas density parameter $r_s=2$. The wake potential of Eq. (1) has been evaluated using the full random-phase approximation[20] dielectric response function to represent the response of the medium. The binding energies we obtain are given in Table I for three different muon velocities.

To get an approximate expression for the velocity distribution when the ion emerges from the solid, we follow Brandt and Ritchie[12] and suppose that the wake created by the swift ion is not perturbed as the ion approaches and crosses the surface of the solid. Then, velocity distributions are Gaussian and their widths are given in Table I as Δv_z and Δv_b. We also include the values for the case of an electron trapped in the first trough of the wake of a proton.[8]

The results described in Table I do not include the effect of the self-wake of the trapped electron on its binding energy in the trough of the leading ion, but clearly show the existence of binding. In fact, once the electron is trapped, polaronlike nonlocal effects in the wake will tend to increase the binding further. This effect can be taken into account following the lines of the work of Enchenique, Brandt, and Ritchie[21] for the case of electrons localized in the wake of a swift proton.

One of the authors (P.M.E.) gratefully thanks Iberduero S.A. and the March Foundation for their help and support. The authors thank Gipuzkoako Foru Aldundia for support, Professor Volker Heine and the Theory of Condensed Matter group of the Cavendish Laboratory for their hospitality, and Dr. Y. Yamazaki for many stimulating discussions.

[1] J. Neufeld and R. H. Ritchie, Phys. Rev. **98**, 1632 (1955); **99**, 1125 (1955).

[2] R. H. Ritchie, Ph.D. thesis, University of Tennessee, 1959 (unpublished).

[3] W. Brandt, A. Ratkowski, and R. H. Ritchie, Phys. Rev. Lett. **33**, 1325 (1974); **35**, 130(E) (1975); D. S. Gemmell, J. Remillieux, M. J. Gailliard, R. H. Holland, and F. Vager, *ibid.* **34**, 1920 (1975).

[4] V. N. Neelavathi and R. H. Ritchie, in *Atomic Collisions in Solids,* edited by S. Datz, B. R. Appleton, and C. D. Mosk (Plenum, New York, 1981); V. N. Neelavathi, R. H. Ritchie, and W. Brandt, Phys. Rev. Lett. **33**, 302 (1974); **33**, 670(E) (1974); **34**, 560(E) (1975).

[5] M. H. Day, Phys. Rev. B **12**, 514 (1975).

[6] R. H. Ritchie, W. Brandt, and P. M. Echenique, Phys. Rev. B **14**, 4808 (1976); P. M. Echenique, Ph.D. thesis, University of Barcelona, 1977 (unpublished).

[7] M. H. Day and M. Ebel, Phys. Rev. B **17**, 3434 (1979).

[8] Z. Vager and D. S. Gemmell, Phys. Rev. Lett. **37**, 1352 (1976); P. M. Echenique, R. H. Ritchie, and W. Brandt, Phys. Rev. B **20**, 2569 (1979); P. M. Echenique and R. H. Ritchie, Elhuyar **17**, 1 (1979); Phys. Rev. B **21**, 5854 (1980); A. Mazarro, P. M. Echenique, and R. H. Ritchie, *ibid.* **27**, 4117 (1983); J. C. Asley and P. M. Echenique, *ibid.* **31**, 4655 (1985).

[9] R. Laubert, I. A. Sellin, C. R. Vane, M. Sufer, S. B. Elston, G. D. Alton, and R. S. Thoe, Phys. Rev. Lett. **41**, 712 (1978).

[10]G. B. Crooks and M. E. Rudd, Phys. Rev. Lett. **25**, 1599 (1970).
[11]J. Macek, Phys. Rev. A **1**, 235 (1970).
[12]W. Brandt and R. H. Ritchie, Phys. Lett. **62A**, 374 (1977).
[13]A. Gladieux and A. Chateau-Thierry, Phys. Rev. Lett. **47**, 786 (1981).
[14]R. Latz, G. Astner, H. J. Frichkorn, P. Koschar, J. Pfenning, J. Schrader, and K. O. Groeneveld, Nucl. Instrum. Methods **194**, 315 (1982).
[15]Y. Yamazaki and N. Oda, Nucl. Instrum. Methods **194**, 415 (1982); P. M. Echenique and R. H. Ritchie, Phys. Lett. **111A**, 310 (1985).
[16]N. Oda, Y. Yamazaki, and Y. Yamaguchi, J. Phys. Soc. Jpn. **53**, 3250 (1984).
[17]Y. Yamazaki and N. Oda, Nucl. Instrum. Methods Phys. Res. Sect. B **10/11**, 161 (1985).
[18]Y. Yamazaki, in Proceedings of the U.S.A.-Japan Seminar on Charge States and Dynamic Screening of Swift Ions in Solids, Honolulu, Hawaii, December 1985 (unpublished).
[19]Y. Yamazaki, in Proceedings of the 10th W. Brandt Workshop, 1987, Alicante, Spain (unpublished); and (private communication).
[20]J. Lindhard, K. Dans. Vidensk. Selsk. Mat. Fys. Medd. **28**, 8 (1954).
[21]P. M. Echenique, W. Brandt, and R. H. Ritchie, Phys. Rev. B **33**, 43 (1986).