Plasma excitations and polarization of ion-core electrons in transition metals

M. V. Zharnikov, V. D. Gorobchenko, and I. L. Serpuchenko

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The energy-loss spectra of fast (25-keV) electrons traversing V, Nb, Mo, Ta, and W thin films have been measured. This is the first use of this technique for all of these elements except V. The spectra observed for all of these metals are qualitatively similar. The structure observed in the low-energy part of a spectrum (< 30 eV) is due to the excitation of plasma oscillations by valence *s*- and *d*-electrons and also collective interband modes. The broad resonances in the energy interval 35–45 eV result from a dynamic polarization of electrons of the ion core (these resonances are split into two peaks for several of the elements). The binding energies of the *p*-levels of the core closest to the valence band are determined for these elements by a model calculation.

1. INTRODUCTION

A distinguishing feature of the electron subsystem of a metal is the ability of its electrons to execute plasma oscillations. These oscillations, which involve conduction electrons, are a consequence of the repulsive interelectrons Coulomb interaction and the inertia of the electrons. The most common method for studying plasma operations is to measure the spectra of inelastic electron scattering. These spectra are usually measured in one of two ways. The first, approach is to shoot fast electrons, with an energy of several tens of kiloelectron volts, through thin films of the material of interest. A second way is to reflect relatively low-energy electrons (50–500 eV) from the surface of a test sample. In either case, one measures the energy lost by the electrons upon scattering. These two methods have been used to study nearly all metals as well as several other elements and compounds in which plasma excitations are observed.

The resulting electron energy-loss spectra are interpreted on the basis of a theoretical understanding of the properties of the dielectric constant of a system of interacting particles. The situation is clearest in the case of simple metals, in which the properties of the electron subsystem are similar to those of a homogeneous electron gas, and the spectrum of the metal is dominated by a strong plasma resonance corresponding to the excitation of collective oscillations of the conduction electron density.[1]

Nevertheless, although a well-defined plasma excitation is observed in several simple metals, it is seen at a frequency quite different from $\omega_p = (4\pi ne^2/m)^{1/2}$, which is the value at which a plasma resonance of a free electron gas of density n would occur (see Ref. 2, which deals with Cd). This frequency renormalization is attributed to a polarization of the ion cores; it becomes important when the excitation energy of the core electrons is close to $\hbar\omega_p$.

Turning to the transition metals, we find that the corresponding experimental spectra have a rather complex structure, which in several cases has not been completely explained.[3] The polarization of the ion cores, which lie fairly close to the valence band along the energy scale in the elements of this class, is usually ignored in the analysis of the spectra.

The transition metals have been studied for the most part exclusively by the method of the reflection of low-energy electrons. The spectra obtained by this method, however, pose several difficulties in interpretation. The reason is that the electron which is being scattered interacts with both the volume and the surface of the substance under study. It can be shown that in the first Born approximation the energy-loss spectrum of electrons which are interacting with the volume of a solid is described by the so-called loss function $\mathscr{L}(\mathbf{q},\omega)$, which is related to the macroscopic dielectric constant $\varepsilon(\mathbf{q},\omega)$ of the given substance by

$$\mathscr{L}(\mathbf{q},\omega)=-\operatorname{Im}[\varepsilon(\mathbf{q},\omega)]^{-1},$$

where $\hbar\mathbf{q}$ is the momentum lost by the electron, and $\hbar\omega$ is the energy which it loses. The surface loss function $\mathscr{L}_s(\mathbf{q},\omega)$ is given by[4]

$$\mathscr{L}_s(\mathbf{q},\omega)=-\operatorname{Im}[\varepsilon(\mathbf{q},\omega)+1]^{-1}.$$

The volume and surface loss functions will appear in the experimental spectrum with different weights, depending on the experimental conditions. These functions differ in form for a given sample.[5] In transmission experiments, with a sample of appropriate thickness, the electrons interact with the volume for a significantly longer time than with the surface, and the contribution from the surface loss function is minimal. In the reflection geometry, on the other hand, the depth to which an electron penetrates into the sample is relatively small (although it can be varied, up to a certain limit, by varying the electron energy and the scattering angle), so that the surface contribution is quite large, often dominant. It is an exceedingly complicated matter—usually impossible—to separate the contributions from the interior and the surface under these conditions.

Furthermore, when the inelastic electron scattering spectrum is recorded in a reflection geometry, an averaging is carried out over scattering angle, while in transmission experiments the measurements are carried out at a fixed value of $\mathbf{q}$.

We have accordingly undertaken measurements of the energy-loss spectra of 25-keV electrons passing through V, Nb, Mo, Ta, and W thin films. All the experiments were carried out at a zero value of the wave vector $\mathbf{q}$. This is the first study by this technique for all of these elements except V. These elements span all three groups of transition metals, so that the experimental results furnish a basis for generalizations which apply to most of the elements of this class.

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There are several common features appearing in the electron energy-loss spectra of all the transition metals studied. These spectra are found to be qualitatively the same as the corresponding spectra found by the method of reflection of low-energy electrons, although there are certain differences in shape. We have accordingly been able to only refine the characteristics of the individual resonances observed in these spectra. Furthermore, we have attempted to construct a qualitative explanation for the appearance of these resonances in the experimental spectra. The spectra features at low and intermediate energies (0–30 eV), which are dominated by a strong resonance near the classical energy of plasma oscillations of all valence electrons, can now be regarded as understood, at least qualitatively.[6,7] At higher energies, a broad resonance is observed in the region 35–45 eV, often split into two peaks. The nature of this broad resonance has not been completely determined; it is interpreted in different ways in different studies. In the present study we accordingly attempted to find a qualitative explanation for the appearance of this resonance in the experimental spectra.

2. EXPERIMENTAL PROCEDURE, SAMPLES, AND RESULTS

The measurements are carried out in an electron spectrometer which can record the inelastic scattering spectra of fast electrons after they have traversed thin films of the substance of interest. The energy of the primary electron beam is 25 keV. The energy resolution of the spectrometer is 0.5 eV, while the resolution in terms of the momentum transfer is 0.2 Å^{-1}. The apparatus is described in more detail in Ref. 8.

The test samples are films 300–450 Å thick, which are deposited in fairly high vacuum on a substrate of rock salt. Two types of substrates are used: with an optically polished surface and with the surface formed by cleaving a NaCl crystal. The measurements show that the spectra of the characteristic energy loss in each specific metal do not depend on the type of substrate. The V, Nb, Mo, Ta, and W films are deposited in a high-vacuum apparatus by rf cathode sputtering. The films are removed from their substrate by "lowering them onto water", and then they are "fished out" on the fine copper mesh of the sample holder.

To monitor the quality of the resulting samples, we analyzed them by photomicrography, and we also recorded electron diffraction patterns. It was found that the average crystallite size in the resulting films is 200–300 Å. Analysis of the electron diffraction patterns also revealed that all the samples are polycrystalline and have a bcc structure, similar to the structure of the initial metals. The V, Nb, and Mo samples reveal a partial orientation of the microcrystallites. We determined the lattice constants of all the thin films. The differences between these lattice constants and those of bulk metal samples appear only in the third significant figure and can be explained completely in terms of errors in the calibration measurements and in the subsequent processing of the diffraction patterns.

We prepared several thin-film samples of each of the materials studied. The films differ insignificantly in quality, and the basic features in the energy-loss spectra are reproduced well from sample to sample for each specific metal.

Figure 1 shows some representative energy-loss spectra of beams of primary electrons as they pass through V, Nb, Mo, Ta, and W samples. These spectra were recorded at energy transfers up to 80 eV with zero momentum transfer. The origin for the energy scale is chosen in accordance with the positions of the peaks corresponding to elastically scattered electrons. Because of the significant difference in the intensities of the energy-loss spectra and the elastic peak, the latter is not shown completely.

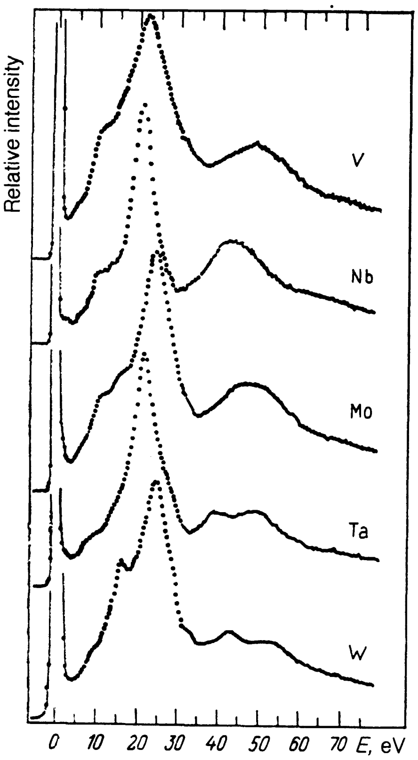

FIG. 1. Spectra of the energy loss of electrons traversing thin-film samples of V, Nb, Mo, Ta, and W.

In Fig. 1 we see that the spectra observed in all of these metals have several points in common. The basic feature in the spectrum is a strong resonance at 21–24 eV. This resonance is found to lie near the classical energy of plasma oscillations in the given metal, $\hbar\omega_p$ (Table I). This energy is found under the assumption that each atom of this metal contributes all of its valence electrons to the conduction band. In addition to this strong resonance there are some less intense lines at lower energies, and there is also a broad resonance at an energy above $\hbar\omega_p$. In the case of Ta and W, this broad resonance is split into two peaks.

In order to determine the energy positions of the individual lines into which the experimental spectrum can be decomposed, we calculated the second derivative with respect to the energy of these spectra, with smoothing. This procedure reveals resonances which appear only weakly in the experimental spectra. It also eliminates the quadratically growing background.

The energy positions of the lines in the experimental spectra which were distinguished by this procedure are shown in Table I. Shown for comparison are corresponding values taken from studies carried out to measure the inelastic-scattering spectra of electrons in the transmission geometry[9] and in the reflection geometry.[3,10] Also shown here are data from optical measurements (these results are marked

TABLE I.

Element	$\hbar\omega_p$	Reference	Procedure	Energy position of individual line, eV						
				1	2	3	4	5	6	7
V	22,15	This study		5,3	10,2		21,8	32,9	41.2	
		[10]		5,3	9.6	14.8	21.5	36.6	39.2	
		[9]		5,6	11,0		21,5		39	
		[11]	Opt.	5,2	11		18,4			
Nb	19,59	This study		4,2	10,0	13,9	21.2	28.0	42.9	
		[10]			9,6		20,8	30,3	37,9	
		[3]			9,5		19,6	32.4	42	
		[4]	Opt.	4,0; 5,1	9,0; 9,7	13.8	20,8	32.4		
Mo	23,04	This study		5,7	10,2	15,3	24.7	33.3	47.0	
		[10]			10,2		23.9	35.2	41.0	
		[3]			9.9		22.8		46.8	
		[11]	Opt.		9.5; 10,4		24.4	32,4; 34,6		
Ta	19,54	This study		7,3	8,1	14.9	21.6	28,0	38,7	49,1
		[10]		4,1; 8,2	12.5	18,0	20.5	26,7; 32,7	37,4	46.5
		[3]			9.4		19.6		38,7	48,8
		[12]	Opt.		8,6; 8,9	17,2	20,7	23,6; 26,0		
W	22,85	This study		6,1	8,8	16,0	24.8	33.5	42.6	54.1
		[3]			10,3		23.6		42,0	52.7

"opt." in the Procedure column). We turn now to a discussion of the results.

3. QUALITATIVE ANALYSIS OF THE RESULTS

Transition metals contain electrons which are localized to a significant extent near sites in the ion lattice. The electron subsystem of these metals thus cannot be described by the relatively simple homogeneous electron gas model used in analyzing the dielectric properties of simple metals. An analysis of the corresponding properties of transition metals requires consideration of their actual band structure, which is rather complicated. As a result, it is not a simple problem to calculate the dielectric constant for transition metals, and only recently has a solution to this problem become possible. In particular, calculations of this type were carried out in Refs. 13 and 14 for many transition metals. It was shown there that the large number of interband transitions which are taken into account in a microscopic calculation of the imaginary $[\varepsilon_2(\omega)]$ and real $[\varepsilon_1(\omega)]$ parts of the long-wave dielectric constant results makes the dependence of these quantities on ω complicated. In turn, the loss function calculated on the basis of these components of the dielectric constant has a rather complicated structure, whose constituent components are difficult to separate. Nevertheless, we can attempt to distinguish the primary mechanisms which are responsible for this structure. These mechanisms stem from features of the band structure which are common to all transition metals, and for this reason we find similar types of behavior in the electron energy-loss spectra in the various transition metals. This question was examined in detail in Refs. 6 and 7, where it was shown that in transition metals, in contrast with simple metals, there is not just one plasma oscillation mode; there are at least two, which are seen in different ways in the experimental spectrum. One of these modes corresponds to oscillation of all the valence electrons of the given transition metal and has an energy close to the classical value $\hbar\omega_p$. The second, additional plasma mode appears because of the existence of an intense group of interband transitions which are characteristic of transition metals. These transitions go from *d*-bands into bands with a strong *p-f* hybridization (*d-p* transitions) in the energy region 12–20 eV. The energy corresponding to this additional mode lies below this region. The peaks in columns 2 and 4 in Table I, which are observed in all of the experimental spectra, apparently correspond to precisely these plasma modes. The presence of such peaks in these spectra is further confirmation of the phenomenological theory of Ref. 7.

In the transition metals there are of course groups of interband transitions other than these *d-p* transitions. Among these other transitions we can distinguish transitions within the *d*-band, with typical energies of 5–10 eV, and from *d*-band to higher-lying unfilled states of the hybridized *p-f* band (*d-f* transitions), with energies of about 22–30 eV. The role played by these interband transitions was analyzed accurately in Refs. 13 and 14, where it was shown that the low-energy plasma resonance always lies in the region between *d-d* and *d-p* transitions. The fundamental plasma resonance near $\hbar\omega_p$ falls precisely in the region of the *d-d* and *d-f* transitions, so that this resonance has a significant width, and an additional fine structure appears on it. A structure of this sort apparently corresponds to the most intense interband transitions: the so-called collective interband modes,[6,7] which are also observed in our experimental spectra (peaks 3 and 5 in Table I). The first peak in this table is usually linked with surface effects (Ref. 11, for example).

It can be seen from Table I that these results agree quite well with data on electron reflection and with data from optical measurements. Nevertheless, there are some differences. In particular, in nearly all of these elements the measured value of the energy corresponding to the most intense plasma peak is greater than the corresponding values found in experiments on electron scattering in the reflection geometry. Furthermore, if we compare these spectra with those found from scattering in the reflection geometry, we find that in the latter case there is a pronounced renormalization of the relative intensities of the two plasma resonances. This renormalization tends to make the heights of these resonances more nearly equal. A renormalization of this sort can also be observed by comparing the electron inelastic-scattering spectra obtained in experiments on the transmission by thin V films in Ref. 9 with the corresponding spectra from Refs. 3 and 10, where the measurements were carried out in a reflection geometry. These circumstances can be explained by taking note of the study by Weaver *et al.*,[5] who reconstructed the bulk and surface loss functions for Nb from optical measurements. Analyzing the results of that study, we conclude that as we go from the bulk loss function to the surface loss function the intensities of the two plasma modes become more nearly equal in transition metals. In addition, the plasmon peaks shift down the energy scale; the shift of the low-energy plasmon is quite small, while that of the fundamental plasmon is a matter of several electron volts. Here we are seeing a manifestation of the difference between the electron energy-loss spectra found in the reflection geometry and those reported in the present paper. We thus find support for our assertion that the latter spectra correspond far better to the actual bulk loss function, so that the positions of the resonances in these spectra correspond more closely to the positions of the actual bulk excitations.

It follows from this discussion that the complex structure which is observed at low energies in the experimental spectra has now been explained, at least at a qualitative level. In contrast, opinion is divided regarding the broad resonance which is observed in the experimental spectra at 35–45 eV and which splits into two peaks in several elements (column 6 and 7 in Table I). A microscopic calculation of the dielectric constant in this energy region could be of little help in the interpretation of these peaks, since at these energies the errors in the calculation of the required matrix elements for the interband transitions can reach 50–100%.

We would like to stress that since these resonances are observed in all of the transition metals which we studied, they should also have formation mechanisms which are basically similar. One could of course link the appearance of this resonance with the excitation of two high-energy plasmons by a single electron as it passes through the sample. The interpretation, however, would be at odds with the circumstance that the height of this peak does not increase as the energy of the primary electron peak decreases, as we would expect in the case of multiple scattering. It should also be noted that the energy corresponding to this resonance in nearly all of the elements studied differs from twice the energy of the high-energy plasmon. This interpretation is thus totally incapable of explaining the splitting of the broad resonance into two peaks, as is observed in the heavy elements Ta and W.

This splitting can be explained if we attribute the observed broad lines to the excitation of electrons of deep atomic shells. It is specifically in the heavy elements Ta and W in which the spin-orbit interaction is strong, and the $5p$ level nearest the conduction band splits. In the lighter elements V, Nb, and Mo, the splitting of the corresponding levels is slight. Although it has been suggested previously that these resonances are associated with the excitation of electrons of the ion cores, that suggestion could not explain the discrepancy between the binding energies of the corresponding levels and the maxima of the observed resonances (Tables I and II).

We have suggested that the broad high-energy resonance stems from a dynamic polarization of the inner electrons of the core p-levels closest to the conduction band of these metals. To describe this polarization we use a very simple model of a frequency-dependent dielectric constant:

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega(\omega+i\gamma_0)}+\Delta\varepsilon_d, \tag{1}$$

where

$$\Delta\varepsilon_d=-\sum_j\frac{f_j\omega_j^2}{\omega^2-\omega_j^2+i\gamma_j\omega}. \tag{2}$$

The first two terms in this formula yield the Drude function, which describes the dielectric properties of a gas of free electrons with a relaxation time $\tau=\gamma_0^{-1}$. For the metals which we have studied in this energy region, and apparently even near $\hbar\omega_p$, the interband transitions are seen much more weakly than in the energy interval 12–20 eV, and the dielectric constant of the valence electrons can be approximated in a similar way. Again in this region, of course, the given function is modified by interband transitions; this circumstance is taken into account to a certain extent by variation of the parameter γ_0.

The third term in (1) describes the dynamic polarization of the electrons of the p-levels closest to the valence band. This polarization can be taken into account by adding the following expression to the dielectric constant describing

TABLE II.

Element	Energy level	Binding energy, eV			Reference
		From result of fit by Eqs. (1)–(3)	From position of minimum in experimental spectrum	From photo-electron-spectroscopy data	
V	$3p_{1/2}3p_{3/2}$	38,7	37.4	37,2	[16]
Nb	$4p_{1/2}4p_{3/2}$	32,69	30.0	33.9	[17]
Mo	$4p_{1/2}4p_{3/2}$	37,4	35,2	35,1	[17]
Ta	$5p_{3/2}$	35,6	33.2	33.9	[17]
	$5p_{1/2}$	44	43.5	42,4	
W	$5p_{3/2}$	37,9	35.3	33	[17]
	$5p_{1/2}$	48.8	47,4	44	

the behavior of the valence electrons:

$$\Delta\varepsilon_d = 4\pi n_i \alpha(\omega), \tag{h}$$

where n_i is the ion density, and $\alpha(\omega)$ is the polarizability of the corresponding ion shell. For $\alpha(\omega)$ we can use the simple expression for the polarizability of a Lorentz oscillator:

$$\alpha(\omega) = f_j \omega_j^2 (\omega_j^2 - \omega^2 - i\omega\gamma_j)^{-1}, \tag{i}$$

where ω_j, γ_j, and f_j are respectively the resonant frequency, the damping, and the strength of the given oscillator. Since we are dealing with a metal, the quantity ω_j, which corresponds to the energy of a virtual interband transition, varies continuously from the value E_0 (the energy of a transition from a core p-level to the Fermi level) to ∞. This fact is reflected by the summation over j in (2). In that expression, the expression for the polarizability of a Lorentz oscillator, which enters $\Delta\varepsilon_d$, is written in a slightly modified form. The dependence of the numerator on the resonant frequency of the oscillator is taken into account through the oscillator strengths f_j, which we have assumed to fall off continuously with increasing ω_j in accordance with $f_i \sim \omega_i^{-n}$, where n is an integer. The reason for this assumption is that the oscillator strengths of the virtual interband transitions should decrease as their energy increases. To simplify the discussion below, we also assume $\gamma_j = \text{const} = \gamma_1$. In order to carry out realistic calculations from (1) and (2) we need to switch from a summation over j to an integration over the energy, from E_0 to ∞, in function (2). In our calculations we varied n from 1 to 3. With $n = 3$ we find

$$\Delta\varepsilon_d(\omega) = f_1\omega_p^2 E_0^2 \int_{E_0}^{\infty} \frac{dE}{E^3(E^2-\omega^2-i\gamma_1\omega)}$$

$$= \frac{f_1\omega_p^2}{2\omega(\omega+i\gamma_1)}\left[\frac{E_0^2}{\omega(\omega+i\gamma_1)}\ln\left(\frac{E_0^2}{E_0^2-\omega^2-i\gamma_1\omega}\right)-1\right]. \tag{3}$$

To save space, we will not reproduce here the corresponding expressions for $n = 1$ and 2.

Figure 2 shows the imaginary and real parts of the dielectric constant $\varepsilon(\omega)$ for Nb according to calculations from (1)–(3), along with the corresponding loss function. The nature of these curves remains generally the same for other values of n. It can be seen from this figure, where the arrow marks E_0, that the polarization of the p-level electrons alters the functions $\varepsilon_2(\omega)$ and $\varepsilon_1(\omega)$ and gives rise to a broad peak in the loss function. The maximum of this peak is on the high-energy side of E_0. This is an extremely interesting point, which should not be overlooked. A second interesting feature is that effects stemming from the polarization of the electrons of the shells of the ion core, which are manifested extremely weakly in the spectra of other elements (except for certain simple metals; see the Introduction), are quite noticeable in the transition metals. They give rise to resonances in the experimental spectrum which are comparable in intensity to the plasma peaks. The presence of a polarization term of this sort in $\varepsilon(\omega)$ due to the finite value of γ_1 provides an additional damping mechanism and causes an even greater broadening of the plasma peaks in the experimental spectra. Furthermore, this polarization prevents the fundamental plasma peak from shifting up the energy scale, into the region 12–20 eV, under the influence of intense interband transitions.

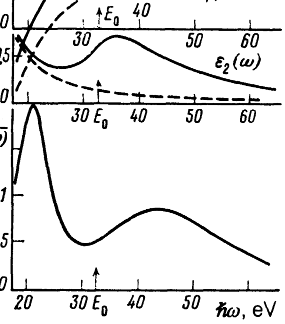

FIG. 2. Imaginary and real parts $\varepsilon_3(\omega)$ and $\varepsilon_1(\omega)$ of the dielectric function $\varepsilon(\omega)$ for Nb, calculated from Eqs. (1)–(3) with the following parameters: $\omega_p = 25.01$ eV, $\gamma_0 = 7.2$ eV, $E_0 = 32.69$ eV, $\gamma_1 = 4.1$ eV, $f_1 = 1.8$. The corresponding loss functions $-\mathrm{Im}[\varepsilon(\omega)]^{-1}$ are also shown. The arrow indicates the magnitude of the associated core binding energy E_0 calculated for the $4_{p1/2}$ $4_{p1/2}$ level of Nb. The part of the dielectric function given by the Drude term in (1) is indicated by the broken trace.

The idea of a relationship between the broad resonances in the electron energy-loss spectra in transition metals and the polarization of electrons of ion-core levels was originally introduced by Hartley.[15] However, the description proposed in the present paper seems to be far more understandable from the physical standpoint, and it does not require the many model assumptions which were made by Hartley.

Using this model, we have attempted to determine the binding energy E_0 of the core p-levels closest to the valence band of these metals. To determine this energy, we use the method of least squares to fit the model function (1) and a "background," described by polynomial of second degree in the energy, to the real spectra. For this approximation we select a region beginning at the left-hand slope of the fundamental plasma resonance, near its crest. The best fit is achieved with $n = 3$. The calculated curves generated as a result of this fit reproduce essentially completely the shape of the spectra region studied. These curves are shown in Fig. 3, along with individual points from the experimental spectra, for comparison. The results calculated for E_0 are shown in Table II and marked by the arrows in Fig. 3. They are seen to reproduce within 10% the data from photoelectron spectroscopy. This agreement can be judged completely satisfactory in view of the simplicity of the approximation which we used.

An experimental quantity which correlates well with the data from photoelectron spectroscopy is the position of the minimum between the fundamental plasma peak and the resonance due to the polarization of the p-shells (see Table II, which also shows, for Ta and W, the energies corresponding to the minimum between the two peaks in the polarization resonance). The minimum appears because a resonance due to the polarization of the p-shells is superimposed on the right-hand descending slope of the fundamental peak in the electron inelastic-scattering spectra in these metals. The precise position of this minimum, although also determined by the particular position and shape of the plasma and polarization resonances, agrees approximately with the corresponding absorption edge; i.e., it is quite close to E_0.

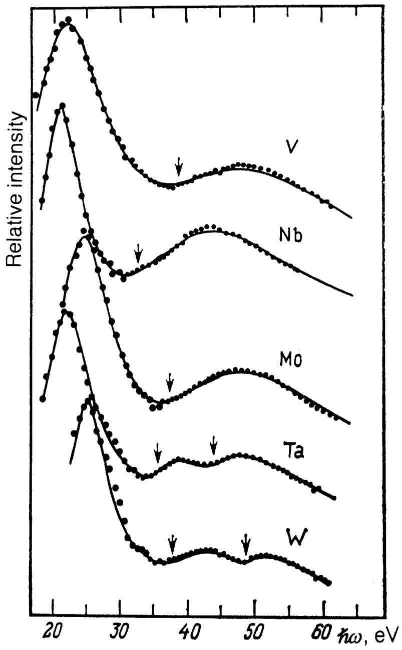

FIG. 3. Traces representing the result of approximating the different regions of actual spectra using the model function defined by Eq. (1)–(3) along with a background which is quadratic in energy. The arrows indicate the calculated values of E_0. The individual data points from the measurements are shown on the plots for comparison.

4. CONCLUSION

Our goals here have been to study the energy-loss spectra of fast electrons in transition metals and to classify the various excitations observed in these spectra. The classification proposed in Refs. 5 and 6, which we have examined and fleshed out in the present study, appears to be quite general, appropriate for not only the transition metals which we have studied (Tc was studied in Refs. 5 and 6) but also for most other elements of this class. This statement applies equally well to the polarization of the electrons of the core levels; we seem to be seeing a common feature here, which is inherent to some extent or other in all these elements. Actually, of course, this polarization is not described by the simple model function (1), (2); it depends on a large number of factors related to the actual band structure of each transition metal considered. Nevertheless, the basic features of how this polarization is manifested in the experimental spectrum can also be understood on the basis of the simple model proposed here. Despite its simplicity and the small number of adjustable parameters, this model reproduces the shape of the experimental spectrum well, and it predicts values of E_0 close to the values found from photoelectron spectroscopy.

In terms of the correlation between the experimental data of the present study and the experimental data obtained in the reflection geometry, we see a qualitative correspondence between the electron inelastic-scattering spectra in the two cases. We have managed to do no more than refine certain quantitative characteristics of the individual lines which can be distinguished in these spectra.

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