Energy analyzer for spin polarized Auger electron spectroscopy

V. N. Petrov[a)] and A. S. Kamochkin

St. Petersburg Technical University, 29 Polytechnicheskaya Street, 195251, St. Petersburg, Russia

A double-pass cylindrical mirror energy analyzer for spin polarized Auger electron spectroscopy (SPAES) has been constructed and tested. The analyzer has high transmission, small electron emission angle (for the collection of electrons into an additional Mott detector), and large focal distance. The combination of this energy analyzer with a compact classical Mott detector provides a SPAES spectrometer with very high efficiency. © *2004 American Institute of Physics.*
[DOI: 10.1063/1.1711142]

I. INTRODUCTION

One of the most powerful methods for the analysis of local surface magnetic properties is spin polarized Auger electron spectroscopy (SPAES).[1–8] In terms of analyzing power this method is approaching the technique of x-ray magnetic circular dichroism. However, it does not require the application of synchrotron radiation and can be performed under laboratory conditions. A very impressive demonstration of this method was given by Landolt and Mauri,[1] Landolt,[2] Landolt, Allenspach, and Mauri,[3] and Allenspach *et al.*[4] SPAES is not widely used since suitable energy analyzers and electron polarization detectors were not available.

In this article, we describe design and performance of a high transmission cylindrical mirror analyzer coupled to a high efficient classical Mott detector. First, the relevant parameters for spin-resolved Auger electron spectroscopy are discussed. Then, the design of a analyzer is described. In the third part the performance of the system is demonstrated with measurements on $FeNi_3$.

At present there exist two surface analysis methods that successfully compete and complement each other, namely, photoelectron spectroscopy (PES) and Auger electron spectroscopy (AES). Thus it is useful to base our analysis on the comparison of PES and AES spectra. Despite the fact that the physical nature of PES and AES is in principle the same the spectra look different. While photoelectron spectra have characteristic peaks with amplitudes comparable to or greatly exceeding the background signal, the Auger peak's amplitude is usually considerably lower than the background. This results in a different approach to the registration and analysis of these spectra in conventional spectroscopy (without spin analysis). Photoelectron spectra are registered directly as a function of intensity against electron energy. An Auger electron spectrum is typically plotted as the derivative of the intensity as a function of the electron energy. Let us consider the peculiarities of these methods, which manifest themselves when a spin analysis is added.

An electron beam polarization measurement can be performed by means of Mott scattering.[9,10] A beam of relativistic electrons is scattered on a gold foil and the backscattered electrons are counted. For the determination of one component of the polarization vector two counters are needed in order to determine the number of electrons back scattered to the left (N_L) and to the right (N_R) with respect to the direction of the incoming beam.[9,10] The polarization of the incoming electron beam is then found to be

$$P = (N_L - N_R)/S(N_L + N_R), \qquad (1)$$

S is a parameter characterizing the Mott detector and is called effective Sherman function. The absolute statistical error ΔP of the polarization P is given by

$$\Delta P = 1/S \sqrt{N_L + N_R}, \qquad (2)$$

and the relative error δP by

$$\delta P = \Delta P/P = \sqrt{N_L + N_R}/(N_L - N_R). \qquad (3)$$

These equations are only valid for large values of N and for the case with $|N_L - N_R| \ll N_L, N_R$.

Note that the polarization is usually measured in percent and therefore also ΔP is given in percent. Since δP as well is expressed in percent one should be careful not to mix up ΔP and δP.

In the case of a photoelectron spectra where the peak amplitudes are higher than the background of the signal no problems arise during the analysis. Normally these spectra are presented as two independent curves (spin up and spin down).

In the case of Auger spectra the situation is different. Auger peaks are normally considerably smaller than the background. Typically the background exceeds the peak signal by one order of magnitude. Just plotting two polarization curves is not useful in this case. Also the plotting of the derivative of these curves would only obscure possible findings. Therefore often,[1–4,8] but not always,[5–7] a background is subtracted and the subsequently derived electron spin polarization is plotted as function of energy. But also this approach makes the interpretation of the experimental results complicated since the background subtraction might induce an artificial polarization at the edges of an Auger peak.

In the case of Auger spectroscopy we define the number of Auger electrons counted in the left and right detector as N_{LA} and N_{RA}. Both detectors do also count a considerable

a)Electronic mail: petrov@tuexph.stu.neva.ru

amount of background electrons. We call these N_{LB} and N_{RB}. The total number of electrons counted by the two detectors is then

$$N_L = N_{LA} + N_{LB}, \qquad (4)$$

$$N_R = N_{RA} + N_{RB}. \qquad (5)$$

If we put these expressions for N_L and N_R into Eq. (1) and if we set $N_{LB} \approx N_{RB} \approx N_B$ we obtain

$$P = (N_L - N_R)/S(N_L + N_R)$$

$$\approx (N_{LA} - N_{RA})/S(N_{LA} + N_{RA} + 2N_B). \qquad (6)$$

Note that the polarization of the background electrons does not have to be zero, but is normally small.[2] It is evident that the polarization P measured in the experiment will be smaller than the polarization of the Auger electrons. This difference can be as large as two orders of magnitude. Let us analyze what happens in this case to the statistical error. We make use of expression (3) and receive

$$\delta P = \sqrt{N_{LA} + N_{RA} + 2N_B}/(N_{LA} - N_{RA}). \qquad (7)$$

The relative error grows considerably in comparison with the ideal case (3). The only way to keep the relative error at the same low level is to increase the number of electrons by a factor κ by increasing the measuring time. Then δP becomes

$$\delta P = \sqrt{\kappa(N_{LA} + N_{RA} + 2N_B)}/\kappa(N_{LA} - N_{RA}). \qquad (8)$$

In order to reduce δP to the level it had with $N_B = 0$, κ has to solve the following equation:

$$\sqrt{\kappa(N_{LA} + N_{RA} + 2N_B)}/\kappa(N_{LA} - N_{RA})$$

$$= \sqrt{N_{LA} + N_{RA}}/(N_{LA} - N_{RA}). \qquad (9)$$

For κ we obtain

$$\kappa = 1 + 2N_B/(N_{LA} + N_{RA}). \qquad (10)$$

It is evident that in order to maintain the same relative error it is necessary to increase the number of electrons as many times as the background exceeds the signal.

It is useful to define D as

$$D = 1/\kappa = (N_{LA} + N_{RA})/(N_{LA} + N_{RA} + 2N_B). \qquad (11)$$

The final equation for the absolute error becomes then

$$\Delta P = 1/S \sqrt{D(N_L + N_R)}, \qquad (12)$$

where

$$D = N_{SIGNAL}/(N_{SIGNAL} + N_{BACKGROUND}). \qquad (13)$$

With this it is easy to calculate the time required for an analysis with predefined error. Suppose we would like to measure the Auger peak polarization with an absolute statistical error equal to $\Delta P = 0.01$ (1% polarization). The value of the Sherman function of a modern Mott detectors is between 0.1–0.3. We will take the worst case, i.e., $S = 0.1$. The value of D for low kinetic energy auger peaks will be taken as 0.1. By substituting these values into Eq. (12) we obtain N_L and N_R of the order of 5×10^6. Taking into consideration that the counting rate of a state-of-the-art Mott detector is $\approx 10^5$ cps,

the time required for the measurement of one spectrum point with absolute error $\Delta P = 0.01$ is 50 s. This is a quite reasonable time in terms of application of SPAES as a quick laboratory method for the analysis of local surface magnetism. Of course this is only practicable when the transmission of the energy analyzer is good enough to provide an electron counting rate of (10^5 cps) with an initial current of the electron gun not exceeding several microamperes.

The requirements for the components of a the SPAES spectrometer are therefore:

(1) The energy analyzer should have very high transmission.

(2) The electron polarization detector should have high efficiency and high maximum count rate.

(3) The time stability of the polarization detector should be very high for cases where the polarization is small and a long measuring time is required.

(4) The electron polarization measurement should be insensitive to movements and shape variations of the incoming beam since these effects might occur when the transmission energy of the energy analyzer is varied.

Any failure to meet one of these conditions gravely complicates the construction of an efficient SPAES spectrometer.

II. DESIGN

"Cylindrical mirror" energy analyzers are known to have a high transmission. Therefore they are suitable for SPAES spectroscopy and should in addition fulfill the following requirements:

1. The transmission should be extremely high, even at the cost of resolution. This is acceptable in our case because the width of an Auger peak itself is rather large. Our design goal is a relative resolution of $\Delta E/E < 0.7\%$.

2. The electron emission angle should be as small as possible. Conventional "cylindrical mirror" analyzers have an emission angle of about 43°. Such a large emission angle makes it difficult to recollect the electrons into a Mott detector.

3. The focal distance (the distance between the entrance of the analyzer and the sample) should be large enough. Limited space in front of the analyzer entrance complicates the work with magnetic samples and with coils needed to magnetize these samples.

The use of a small analysis angle requires the construction of a double-pass analyzer. A schematic drawing of the accordingly designed energy analyzer is given in Fig. 1. It consists of three cylindrical coaxial electrodes. The outer cylinder is always at earth potential and serves as support and protective screen. Ceramic rings hold the two inner cylinders in place. Energy analysis is performed by varying the potential of the inner cylinders. A hole in the inner cylinder at the location of the first focal point allows the electrons to cross the analyzer axis. A grid covers this hole in order to avoid singularities in the electric field.

Secondary electrons, which should be analyzed according to their energy and spin, have to pass through the entrance slit of the analyzer. The entrance slit accepts electrons
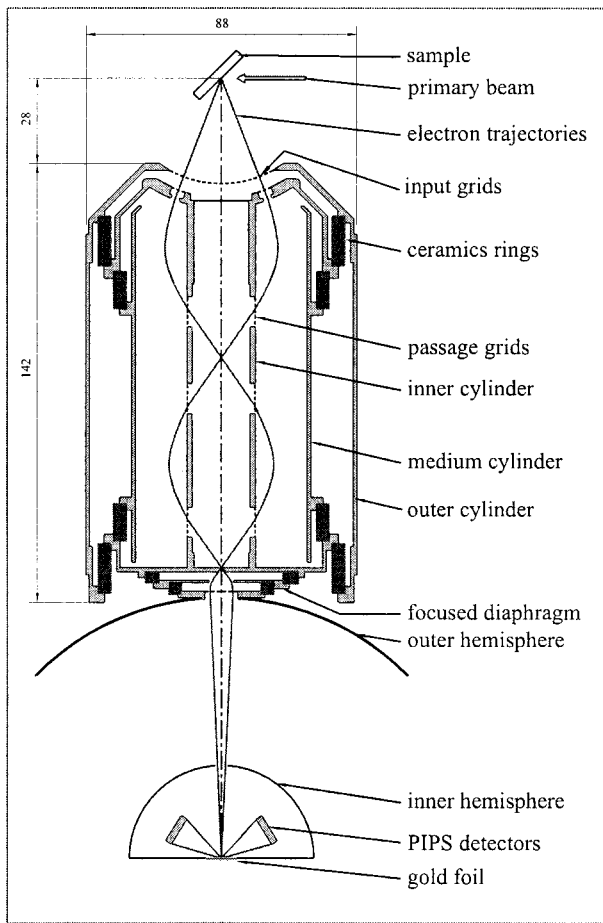
FIG. 1. Schematic of analyzer.

FIG. 2. Energy spectrum measured in one channel of the Mott detector. The energy and current of primary electron beam are 1500 eV and 0.4 μA, respectively.

on emission cones with opening angles between 18.5° and 21.5°.

The analyzer has two modes of operation: One where the relative resolution ($\Delta E/E$) is kept constant and one where the absolute resolution (ΔE) is kept constant. The different modes are realized by applying suitable potentials to the concentric cylinders of the analyzer.

In the $\Delta E/E$ = const mode all input grids do have the same ground potential. The inner cylinder is on ground potential as well. Scanning of the negative potential supplied to the medium cylinder provides the energy analysis. A potential of approximately ($0,7E/\mathbf{e}$) allows the transmission of electrons with a kinetic energy of E ($\mathbf{e}$ is the charge of one electron).

Electrons leave the analyzer at approximately 35°. This angle enables us to collect and direct the electrons into the Mott detector. On leaving the analyzer the electrons are directed into the Mott detector with the help of one focusing electrode. A voltage between 50 and 300 V (positive with regard to the inner cylinder potential) is supplied to this electrode. A fixed potential of 2 kV is supplied to the outer hemispherical electrode of the Mott detector.

Three grids at the entrance of the analyzer are used in the ΔE = const mode (these grids can be removed if the analyzer is operated exclusively in the $\Delta E/E$ = const mode). In this mode the outer cylinder is also held at ground potentia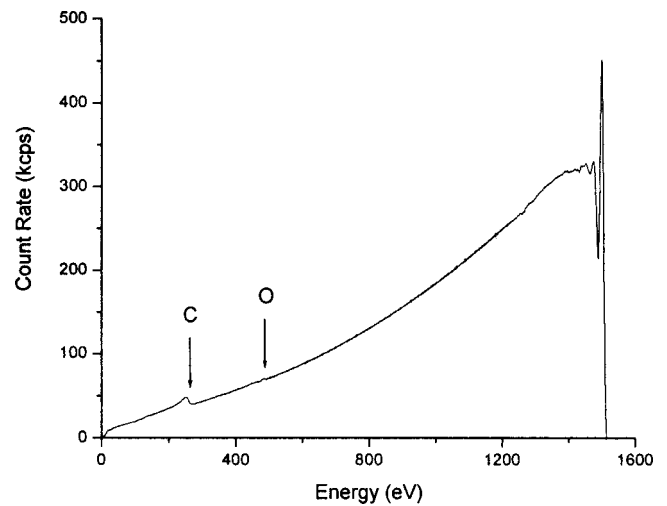l. The potential difference between the inner and the medium cylinders is kept constant. Energy analysis is performed by scanning the absolute potentials applied to these two electrodes. The energy resolution is the result of a retardation of the electrons between the first and the second grid.

All tests described in this article have been done in the $\Delta E/E$ = const mode.

The main dimensions of the analyzer are shown in Fig. 1. The energy analyzer can also be operated without subsequent spin analysis. In this case a channeltron is installed on the exit flange (size CF100). If the analyzer will be operated only in the $\Delta E/E$ = const mode, it can be installed without outer cylinder on a CF63 flange.

At the design stage the functioning of the analyzer was simulated by a homemade software using analytical methods for the solution of the electron-optical problem. Final design testing was carried out with the help of the SIMION software.[11]

Our Mott detector is characterized by high sensitivity and stability and is described in Ref. 12. It is equipped with an updated detector electronics similar to the one used in our compact Mott detector.[13] The detector efficiency is ~5,6 $\times 10^{-4}$ and the maximum count rate is 500 kcps. The overall spectrometer dimensions are 25×55 cm. The energy analyzer described above is equally compatible with the Mott detector.[13] This combination results in an even smaller system with outer dimensions of 15×40 cm.

III. TESTS

A. Transmission test

The experimental investigation of the transmission of an analyzer is not an ordinary task, because it is necessary to place a source of electrons with known intensity and variable energy at the focal point of the analyzer. Here we use a strongly contaminated FeNi3 crystal (not cleaned after baking), which is irradiated by an electron beam from an electron gun placed at a 90° angle with respect to the detector axis. The electron beam hits the sample surface at an angle of 30° with respect to the surface normal. Figure 2 shows the
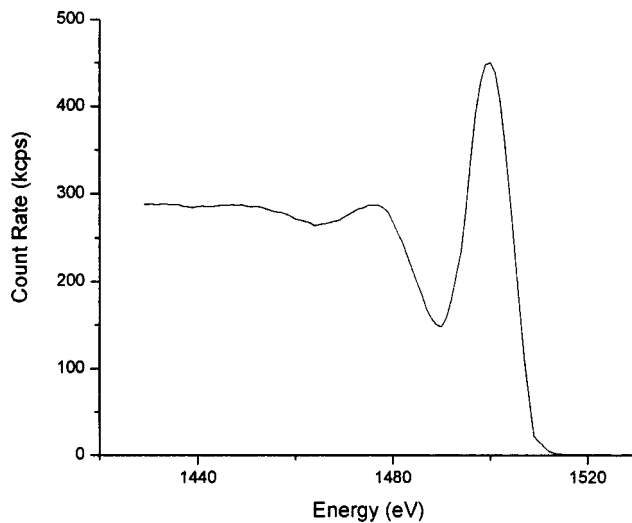
FIG. 3. Energy spectrum of elastically reflected electrons measured in one channel of the Mott detector.

energy spectrum of such a scattering measured in one channel of the Mott detector. The current of the primary electron beam was 0.4 μA. The analysis of the measured count rate reveals that the transmission coefficient is determined by a geometrical factor being equal to the ratio of the solid angle established by entrance slits to 2π. For the analysis we use the coefficient of secondary electron emission of carbon equal $\sim$0.5.[14]

Practically any point of the spectrum can be studied with a count rate of 500 kcps in the $\Delta E/E = $ const mode by using a primary electron beam current between 0.4 and 10 μA. Most metallic surfaces are not damaged or influenced by such a primary beam intensity.

The main difference between the present setup and the spectrometer built by Landolt and Mauri,[1] Landolt,[2] Landolt, Allenspach, and Mauri,[3] and Allenspach[4] is the efficiency of the energy analyzer. A simple comparison based on comparing the different geometries reveals that our device has a 19 times higher efficiency. This means that the registration of identical spectra can be done 19 times faster.

B. Resolution test

For the estimation of the energy resolution we zoom into a part of the spectra shown in Fig. 2 (see Fig. 3). $\Delta E/E$ is measured for the peak of the elastically reflected electrons and is found to be equal to 0.7%.

C. Spin resolved tests

As a test sample we use a $FeNi_3(110)$ crystal, which is particularly suitable because its concentration and magnetization parameters are well-known. The crystal was cut in the shape of a frame, with its sides coinciding with the easy magnetization axes {111}. The sample was magnetized by a coil of seven loops wound onto one of the frame sides. The crystal surface was cleaned by means of ion bombardment and high temperature annealing in ultrahigh vacuum. The crystal was irradiated by an unpolarized electron beam from an electron gun placed at a 90° angle with respect to the detector axis. The electron beam hit the sample surface at an angle of 30°.

All principal Fe and Ni peaks were registered during the experiment, but we will only present the low kinetic energy results since they are most interesting due to the following facts: (i) they are close in energy and therefore easy to compare and (ii) they exhibit a high signal to background ratio (high D value).

The number of electrons in the left N_L and right N_R counter of the Mott detector was measured as a function of the kinetic energy. These spectra corrected to $S = 1$, are shown in Fig. 4(a).

The upper curve is proportional to the number of electrons with spin up (M_L), while the lower curve is proportional to the number of spin down electrons (M_R):

$$M_L = N(1+P), \tag{14}$$

$$M_R = N(1-P), \tag{15}$$

where

$$N = (N_L + N_R)/2. \tag{16}$$

The absolute statistical error of ΔM was determined according to

$$\Delta M \sim \Delta M_L \sim \Delta M_R \sim (1/S)\sqrt{N}, \tag{17}$$

and is smaller than the points of the graph.

To eliminate the instrumental asymmetry and the asymmetry caused by the spin orbit interaction during the scattering process the magnetization of the target was periodically reversed by means of short field pulses. The counts in the left (right) channel were determined as the sum of counts in the left (right) channel with "positive" direction of the magnetization and in the right (left) channel with "negative" magnetization direction. All spectra were taken in remanence. The primary beam had an energy of $E_P = 1500$ eV. Multiple scanning of the energy was performed during the measurement. The whole spectrum was measured within 35 min.

Further processing of the spectra was performed in the following way. Each curve was treated independently. A portion before and after the Auger peaks was selected (in our case the ranges 20–30 and 65–80 eV) and fitted by a polynomial function (having the same order for both curves). This background curve was subtracted from the measured spectra. The result of this processing is shown in Fig. 4(b). The peaks are clearly resolved. However the peak ratio is not 1/3. This is probably caused both by the very crude background subtraction procedure. Figure 4(c) shows the derivative taken from the spin integrated curves in order to give a more familiar representation. Here the ratio of the peak heights is 1/3 as expected.

Figure 4(b) shows that the Ni atoms are weakly magnetized while the magnetic moment of the Fe atoms is fairly high. This agrees with our knowledge about the magnetic properties of $FeNi_3$. It is obvious that a certain technique should be developed for the full and correct analysis of such experimental curves. Here we propose two independent approaches for the analysis of SPAES spectra.
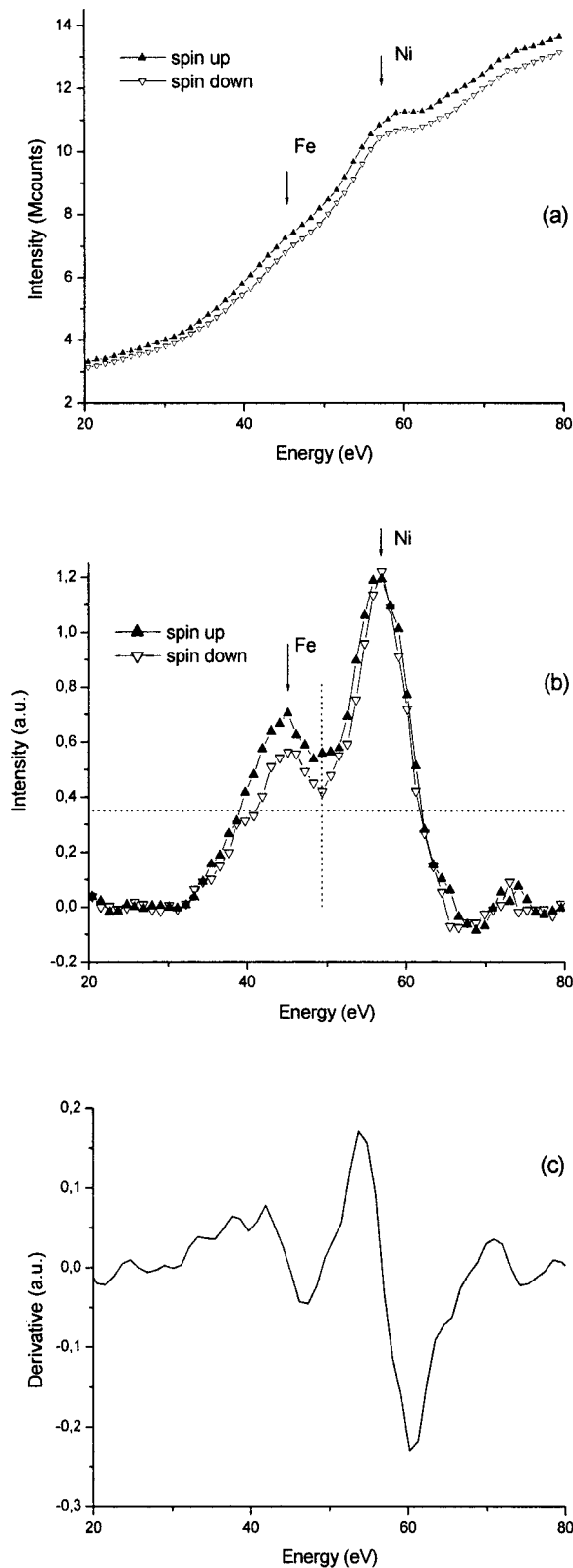
FIG. 4. (a) Number of electrons in the left (spin up) and right (spin down) channels of the Mott detector vs kinetic energy. These spectra corrected for the case $S=1$. (b) Background subtracted spectra. (c) Derivative from the spin integral curve.

(1) A sufficient amount of spin resolved data from various magnetic elements and their alloys should be measured under identical conditions and should serve as a reference. Our group plans to carry out this work in the nearest future

since the described spectrometer enables us to do this quite efficiently.

(2) A theoretical model that allows calculating the absolute magnetic moment of atoms from spin resolved spectra should be developed.

Nevertheless we can do a preliminary analysis of our present results. The magnetization can be determined in the following way:[15]

$$I = \mu_B(N^\uparrow - N^\downarrow), \tag{18}$$

where $N^\uparrow$ and $N^\downarrow$ are spin up and spin down electrons in the valence band, μ_B is the Bohr magnetron.

We multiply and divide expression (18) by $(N^\uparrow + N^\downarrow) = N$, where N is the number of valence electrons:

$$I = (\mu_B N)(N^\uparrow - N^\downarrow)/(N^\uparrow + N^\downarrow). \tag{19}$$

Substituting the expression $(N^\uparrow - N^\downarrow)/(N^\uparrow + N^\downarrow)$ by $(S^\uparrow - S^\downarrow)/(S^\uparrow + S^\downarrow)$, where $S^\uparrow$ and $S^\downarrow$ are the areas under the Auger peaks [Fig. 2(b)], we obtain

$$I = (\mu_B N)(S^\uparrow - S^\downarrow)/(S^\uparrow + S^\downarrow). \tag{20}$$

The substitution of $(N^\uparrow - N^\downarrow)/(N^\uparrow + N^\downarrow)$ by $(S^\uparrow - S^\downarrow)/(S^\uparrow + S^\downarrow)$ might not be fully justified but gives a first estimate for the size of the magnetic moments. Background selection is also a delicate problem. Let us refer to Fig. 4(b) and keep in mind that the peak ratio should be 1/3. We can determine an artificial background corresponding to this peak ratio. It is indicated by the horizontal dotted line in Fig. 4(b). The Fe and Ni peaks are separated by the vertical dotted line.

Measuring the areas under the two peaks in Fig. 4(b) and substituting the result into Eq. (10) yields the following magnetic moments: $I_{Fe} = 2.9\mu_B$; $I_{Ni} = 0.7\mu_B$. The number of valence electrons in Fe and Ni was assumed to be 8 and 10, respectively. This result is in good agreement with neutron scattering experiments on bulk Fe and Ni atoms in $FeNi_3$. Fe and Ni magnetic moments of $I_{Fe} = 2.8\mu_B$; $I_{Ni} = 0.6\mu_B$ were reported.[16]

Our first analysis might be rather crude. However one should keep in mind that the results were obtained in a simple, home-built setup. We would also like to mention that no filtering of the experimental curves was performed. Even slight filtering would increase the signal to noise level and a shorter measuring time would become possible. In conventional Auger electron spectroscopy filtering is usually done via time averaging. With the experimental setup described above it becomes possible to collect a spin resolved Auger spectra as fast as a conventional retarding field spectrometer can collect a pure Auger electron spectra.

ACKNOWLEDGMENTS

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