

Spin and energy analysis of electron beams: Coupling a polarimeter based on exchange scattering to a hemispherical analyzer

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We have coupled a high efficiency polarimeter based on exchange scattering from a magnetized target to a hemispherical analyzer. The target is a Fe(001)-*p*(1×1)O surface which gives rise to highly spin-dependent scattering in the 4–6 eV electron kinetic energy range. Due to the low scattering energy, the design of the transfer electron optics from the analyzer exit slit to the target is really crucial. We describe in detail the adopted solution along with the performances of the entire apparatus. For low values of the analyzer pass energy we have measured an overall efficiency of 7×10^{-4} with an analyzing power (Sherman function) of 0.2. As an example of application spin-resolved photoemission data from Fe(001) are reported. © 2002 American Institute of Physics. [DOI: 10.1063/1.1512342]

I. INTRODUCTION

Since the beginning of the electronic structure investigation by means of electron spectroscopies, the relevance of measuring the spin polarization of emitted electrons in addition to their energy distribution has been recognized. The first pioneering work on spin-polarized photoemission¹ dates back to 1969 but, even though much work has been done in the last 30 years, the efficiency of the spectrometers for spin-polarized experiments still remains very low if compared to that of similar apparatus for spin-integrated experiments. This is essentially due to the fact that it is impossible to use a macroscopic magnetic field to separate spin-up and spin-down electrons as in the classical Stern and Gerlach experiments for atoms, and scattering processes instead have to be exploited.^{2,3} The physical basis of a spin polarimeter, in fact, is the asymmetric spin-up spin-down scattering suffered by electrons interacting with matter: spin-orbit and exchange interaction are the driving forces for this asymmetry.² The determination of the spin polarization for an electron beam, defined as $P = (N_{\uparrow} - N_{\downarrow}) / (N_{\uparrow} + N_{\downarrow})$ where N_{\uparrow} (N_{\downarrow}) is the number of spin-up (spin-down) electrons, is based on the measurement of an experimental asymmetry A_m in the intensity of the electrons emerging from the scattering. Neglecting any instrumental asymmetry, the beam polarization results to be $P = A_m / S$, where S represents the analyzing power, known as the Sherman function in Mott polarimetry.⁴ This is a key parameter, as it determines the sensitivity of the instrument and the relative weight of spurious asymmetries, but also because it strongly influences the polarimeter efficiency, F_{pol} . This quantity, defined as $F_{\text{pol}} = S^2 \cdot (N/N_0)$ where N_0 (N) is the number of electrons per unit time in the incident (scattered) beam, represents the figure of merit of the device when uncertainty is dominated by counting statistics.² In such a case, in order to get the same relative precision in polarization measurements as in intensity measurements, the

total counts must be increased by a factor $(F_{\text{pol}})^{-1}$. Unfortunately typical values of F_{pol} for the presently used polarimeters do not exceed 2.5×10^{-4} , so that spin-resolved experiments still remain very inefficient.^{4,5}

According to the interaction occurring during the scattering, the existing polarimeters can be divided into two classes: the detectors based on spin-orbit interaction (Mott detectors,⁴ low energy diffuse scattering,⁶ spin-polarized low energy electron diffraction⁷), and those based on exchange interaction,^{8–10} which have attracted much attention due to the high achievable values of both analyzing power and efficiency. In particular, we have developed a novel polarimeter based on the scattering of low energy electrons (kinetic energy, E_k , between 4 and 6 eV) from a magnetized Fe(001)-*p*(1×1)O surface.¹⁰ It exploits the large spin dependence of the absorbed and reflected current in correspondence of the edge of a relative gap in the spin-resolved band structure of this surface. The main features are a very high value of the analyzing power ($S = 0.13$ and 0.48 in the absorption and reflection mode, respectively) and of the efficiency ($F_{\text{pol}} = 1 \times 10^{-2}$ and 6×10^{-3} in the absorption and reflection mode, respectively).¹¹ An important characteristic of this polarimeter is the high target stability, which preserves its features for more than 2 weeks in ultrahigh vacuum (UHV) conditions; after prolonged operation the initial performances can also be restored refreshing the surface by a simple annealing procedure in O_2 .¹⁰ Thus the target surface can be prepared in a dedicated UHV system, equipped with surface preparation and analysis facilities, and then transferred to the operating position, e.g., close to the exit slit of an electron energy analyzer in another UHV chamber. We have checked this procedure and found that the performance of the freshly prepared surface is achieved in the operating position as well: details of a prototype apparatus have been presented elsewhere.¹⁰ The present article is devoted to the description of a complete device for spin and energy analysis of electron beams, as obtained by coupling a spin detector to a commercial electron energy analyzer. In particular we put

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our high efficiency polarimeter working in the reflection mode¹² in cascade with a 150 mm mean radius hemispherical energy analyzer (HEA).¹³ A similar task has already been accomplished by other groups.^{14,15} In both cases a spin-orbit based mini-Mott detector⁴ has been used. As outlined above, our approach is instead based on spin detection via exchange interaction: this is clearly a major challenge for improving the apparatus performance. Note, however, that in general the overall efficiency (F_{tot}) of an apparatus for energy and spin detection does not coincide with the polarimeter efficiency F_{pol} . In fact, as usual in particle beam optics, the electron-optical acceptance of the instrument has to be considered, i.e., one has to take into account that both the energy analyzer and spin analyzer accept a limited volume of the electron beam phase space.⁵ The polarimeter acceptance is given in terms of the phase space volume Φ_{pol} , defined as the product of the cross section A , the kinetic energy E_k , and the solid angle Ω of the beam accepted by the spin detector, $\Phi_{\text{pol}} = A \cdot E_k \cdot \Omega$. If this quantity is smaller than the electron beam phase space volume at the HEA exit slit (hereafter called the primary beam), the transfer electron-optics will select only a portion of the primary beam, to be used for polarization determination. This leads to an overall efficiency given by the polarimeter efficiency attenuated by the electron-optics transmittance. If, following the notation of Ref. 15, N_{00} is the number of electrons in the primary beam and N_0 the number of electrons entering the polarimeter, the efficiency of the entire apparatus results

$$F_{\text{tot}} = F_{\text{pol}}(N_0/N_{00}) = S^2 \cdot (N/N_{00}).$$

At variance with the cases quoted above which employ spin detectors working at relatively high energies,^{4,14,15} our polarimeter operates at very low energy ($E_k = 4-6$ eV). From the previous discussion it is then clear that this poses severe constraints on the device design and may strongly affect its overall efficiency. As it is shown in the following, this is particularly true for high values of the HEA pass energy (PE). Nevertheless, we get F_{tot} values comparable to the best reported ones at high PE values, while sizeable improvements are achieved at low PE values: we measured $F_{\text{tot}} = 7 \times 10^{-4}$ at PE = 4.4 eV, and even higher values are to be expected for smaller PE.

II. TRANSFER ELECTRON OPTICS

The maximum accessible electron-optical phase space is determined by the energy analyzer acceptance, which for our 150 mm radius HEA is approximately $\Phi_{\text{an}} = 4.5 \cdot \text{PE} \text{ mm}^2 \text{ sr eV}$.^{5,14} Typical PE values range from 4.4 to 44 eV (with a corresponding reduction of energy resolution), leading to Φ_{an} values in the 20–200 $\text{mm}^2 \text{ sr eV}$ range. These are the values to be considered for the primary beam at the HEA exit slit, which should possibly be accommodated by the spin detector. On the other hand, it is not easy to give an accurate value of the electron-optical acceptance of our polarimeter. In fact, the dependence of the analyzing power upon the angle between the incident electron beam and the Fe(001)- $p(1 \times 1)$ O target surface is poorly known. Actually, we do not know which is the allowed angular spread com-

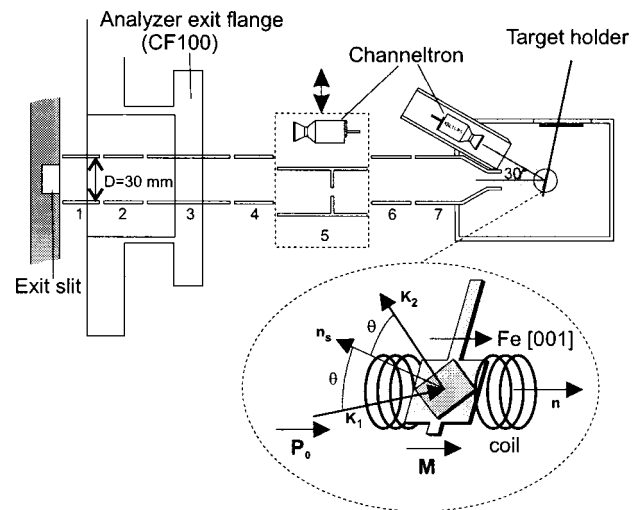


FIG. 1. Section view of the final part of the energy and spin analyzer. The inset shows a sketch of the scattering geometry: the incidence angle is 15° off normal and the specularly reflected beam is collected. At each beam energy the reflected current is measured for parallel and antiparallel orientation of the beam polarization and the target magnetization, which can be switched by a current pulse through the coil.

patible with a large spin-dependent scattering, and in turn with a high analyzing power, for instance, $S > 0.4$.¹⁰ A rough estimate can be done by looking at the results for the spin dependent absorbed current, whose angular dependence has been measured.¹⁰ On the basis of those results, we assumed a full angular acceptance of 30° for our polarimeter working in the reflection mode, too.¹² Concerning the beam cross section, the target spot size in our previous experiments¹⁰ was around 2 mm in diameter. Together with the operating energy $E_k = 4$ eV, this finally yields $\Phi_{\text{pol}} = 2.7 \text{ mm}^2 \text{ sr eV}$, i.e., one to two order of magnitude smaller than the primary beam phase space. The corresponding reduction of the overall efficiency with respect to F_{pol} represents, in our opinion, an unbearable drawback. In order to overcome this difficulty, we decided to increase the polarimeter acceptance by allowing for a larger target spot size. This trial was driven by experimental findings showing small variations of the spin dependence of the reflected current, i.e., of the analyzing power S , for small changes of the beam position on the target (at least within ± 2 mm, see Ref. 10). Thus we have designed an electron-optical system transferring electrons from the HEA exit slit to the polarimeter, aiming to produce at the Fe(001)- $p(1 \times 1)$ O target¹⁶ a beam spot of 8 mm diameter with 30° full divergence. In this way we get $\Phi_{\text{pol}} \sim 40 \text{ mm}^2 \text{ sr eV}$, which is significantly smaller than the acceptance of a Mott detector ($\Phi_{\text{pol}} \sim 10^4 \text{ mm}^2 \text{ sr eV}$), but comparable with that of the low energy diffuse scattering detector ($\Phi_{\text{pol}} \sim 10^2 \text{ mm}^2 \text{ sr eV}$), and considerably larger than that of the spin-polarized low energy electron diffraction detector ($\Phi_{\text{pol}} \sim 2 \text{ mm}^2 \text{ sr eV}$).⁵ This configuration permits the collection of some 40% of the primary beam current already at PE = 22 eV, with a presumably high overall efficiency for spin and energy analysis.

A section view of the final part of the energy and spin analyzer is schematically shown in Fig. 1. The adopted solution for the transfer electron optics consists of a seven ele-

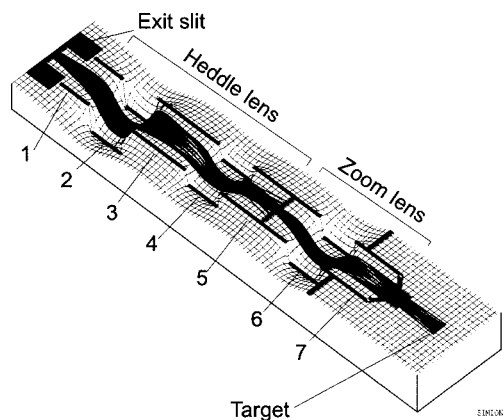


FIG. 2. Typical trajectories of the electrons emitted by the exit slit of the energy analyzer, set at a pass energy of 22 eV, as resulting from the SIMION 3D ray tracing simulation. As initial conditions we assumed electrons uniformly emitted from an area of 3 mm radius within a cone of $\pm 7^\circ$ aperture. The voltages (from the first electrode to the target) are set at 22, 61.6, 11.5, 32.2, 6, 35, and 4 eV, respectively. The last value defines the scattering energy (Ref. 19).

ment decelerating column. The electrodes are cylindrical tubes made of a nonmagnetic alloy (Arcap AP4); the full system is shielded against spurious electric and magnetic fields to avoid perturbation of the electron path and the scattering geometry. The first five electrodes constitute a transfer afocal system, which sets the beam kinetic energy at $E_{\text{kin}} = 6$ eV and forms an image of the HEA exit slit in correspondence of the pupil present in the fifth electrode. In this configuration, originally studied by Heddle,¹⁷ the image position results independent from the kinetic energy of the electrons emerging from the HEA. The second part of the electron optics (electrodes 5, 6, and 7) is a three cylinder zoom lens: the last electrode determines the scattering energy, set at about 4 eV, while the sixth one allows one to change the overall transmission as well as the beam divergence and size at the target. Following the usual electron-optics convention, voltages are referred to the potential of a virtual source emitting electrons with vanishing kinetic energy. All the electrode potentials are to be clamped to the exit slit: the first column element, in particular, is set at the exit slit voltage, which in this convention corresponds the HEA pass energy. To this aim, an optimally designed control unit has been realized, interfaced to the one of the hemispherical analyzer and consisting of several floating power supplies referred to the exit slit potential. The behavior of the transfer electron optics has been analyzed in detail via ray-tracing simulations using the SIMION 3D program.¹⁸ As an example, Fig. 2 shows the ray tracing results for PE=22 eV, using 22, 61.6, 11.5, 32.2, and 6 V for the voltages of the first five electrodes, respectively. V_7 is set at 4 eV, corresponding to the scattering energy¹⁹ for which S has its maximum value for the reflection geometry.^{10,11} In this case the maximum transmission (32%) is obtained for $V_6 = 35$ V, with beam diameter and divergence at the target around 8 mm and $\pm 15^\circ$, respectively. As discussed above, the transmission smaller than one reflects the fact that the primary beam phase space cannot be completely accommodated by our low-energy polarimeter.

A sketch of the scattering geometry is shown as an inset

of Fig. 1. The electron beam is sent onto the target surface at 15° off normal and the reflected current is measured in the specular geometry by means of a channeltron, without any energy discrimination so that inelastically reflected electrons are not filtered out. The target is magnetized in plane along the [100] direction of the Fe lattice by means of a current pulse through a coil surrounding the sample (see inset of Fig. 1), and measurements are taken in magnetic remanence in order not to perturb the electron path. The apparatus is sensitive to the component of the electron beam polarization along the magnetization axis, which is measured by looking at the asymmetry of the reflected current for parallel and antiparallel orientation of the beam polarization and the target magnetization.¹⁰

Finally, when spin analysis is not required, the standard energy analysis functions are preserved via a retractile channeltron mounted on a linear motion feedthrough replacing the fifth electrode, as indicated in Fig. 1. Ray tracing simulations, successively confirmed by experimental tests, assure that this configuration causes no decrease of the HEA original efficiency for spin-integrated detection.

III. TEST AND CALIBRATION

A detailed calibration of the complete device for energy and spin analysis has been carried out in a multipurpose UHV system equipped with a GaAs spin-polarized electron source, whose polarization (25%) has been determined *in situ* by a mini-Mott detector mounted on the same apparatus.²⁰ The polarized electron beam, with energy fixed at 1200 eV, i.e., the optimal energy for our mini-Mott detector, is then electrostatically deflected into the HEA. The spin-integrated spectrum, measured with the first channeltron replacing the fifth electrode (see Fig. 1), presents a Gaussian energy distribution curve 160 meV wide (full width at half maximum), which represents the energy resolution of our gun.²⁰ The HEA is then set at the maximum of this curve (1200 eV) and the fifth electrode moved in the operating position for injecting the beam into the polarimeter. The electrons scattered by the target are detected by the second channeltron and an asymmetry is measured when reversing the incident beam polarization, while keeping the target magnetization unchanged. The polarimeter analyzing power S is obtained by normalizing this asymmetry to the known beam polarization. Such a method, which is feasible only when a fast and safe spin-polarization reversal is possible, eliminates the effects of any possible spurious instrumental asymmetry.^{4,5,10,15} The remaining ingredient of the overall efficiency is the N/N_{00} ratio. In our setup, the number of electrons in the primary beam N_{00} can be directly measured by the retractile channeltron replacing the fifth electrode, while the other channeltron (located after the target) gives N . Since the two multipliers are identical and present similar characteristics we can safely assume equal efficiencies for them, so that the N/N_{00} ratio is given by the ratio between the signals of the two channeltrons. The results for a scattering energy $E_{\text{kin}} = 4$ eV are collected in Table I. First of all, we note that the obtained analyzing power is considerably lower than the one envisaged on the basis of the data for the

TABLE I. Key parameters, i.e., analyzing power (S), fraction of primary beam used for polarization determination (N/N_{00}), and overall efficiency (F_{tot}), for our spin and energy analyzer at different pass energies (PE).

| PE (eV) | $S \times 10^2$ | $N/N_{00} \times 10^3$ | $F_{\text{tot}} \times 10^4$ |
|---------|-----------------|------------------------|------------------------------|
| 44 | 15 | 2.9 | 0.65 |
| 22 | 20 | 3.9 | 1.6 |
| 9 | 20 | 12 | 4.8 |
| 4.4 | 20 | 18 | 7.2 |

spin detector alone (i.e., $S > 0.4$, see Ref. 10). This is likely a consequence of the need to increase the electron-optical acceptance of the polarimeter. In fact, we were required to use in the present design a large spot size and angular divergence for the scattering on the Fe(001)- $p(1 \times 1)$ O target, with values exceeding by far the limits exploited in our previous experiments.¹⁰ Surface inhomogeneity, zones with formation of multidomain structures, and edge effects are, for instance, very likely to occur over large sample areas (the spot size is 8 mm in diameter, while our samples physically consist of 10×10 mm² squares). The beam divergence, whose effects on the scattering spin dependence are poorly known, could constitute a further source of the S reduction. Note also that the total path length from the electron source to the spin detector in the present application is about 1.5 m,²⁰ i.e., ten times larger than what was experienced in our polarimeter-alone studies.¹⁰ One concern is therefore the possibility of spin precession due to stray magnetic fields along the path, leading to inaccuracies in the detected polarization. Though the magnetic shielding of the HEA and of the transfer optics should reduce these effects to a minimal value, any small beam perturbation would be emphasized by the lever effect. As a matter of fact, the analyzing power reduction is quite large (more than a factor of 2). We believe that it is inherent to the choice of using a spin detector based on exchange interaction, and in turn operating at low energy. Table I shows, for instance, that the lowest S value is obtained at PE=44 eV, which corresponds to the situation where the electron beam experiences the largest deceleration within the polarimeter optics. Finally, we note that operating with a different setup and electrode voltages we could modify the beam parameters and obtain a larger value of the analyzing power (up to $S = 0.35$), but this was achieved at the expense of the electron-optics transmission, yielding a situation of no practical use.

In spite of these findings concerning the analyzing power, the present device still displays interesting performance, as given by the measured efficiency. In a recent work describing the coupling of a large HEA to a state-of-the-art mini-Mott detector,¹⁵ the overall efficiency has been estimated to be $F_{\text{tot}} = 1.4 \times 10^{-4}$, which is the best value for energy and spin analyzers presently used, as far as we know. Table I shows that our device yields comparable results at PE=22 eV, while larger values are obtained for lower PE, i.e., when working with better energy resolution. In particular, at PE=4.4 eV using the present setup we measured an efficiency five times larger than the best reported value: in this case a sizable improvement for spin and energy analysis is achieved.

In considering the operation of a similar device, two further items have to be taken into account: the spurious asymmetries and the target surface stability. The latter is one of the main concerns when dealing with low-medium energy scattering. In our setup, the target is mounted on a sample holder with heating and magnetizing facilities (see inset of Fig. 1) and equipped with a valving system allowing for sample transfer without exposure to atmosphere. The sample holder is first mounted on a dedicated UHV chamber where the Fe(001)- $p(1 \times 1)$ O surface is prepared and characterized, as reported in detail elsewhere.¹⁰ It is then removed from the preparation chamber and mounted in the operating position (in another UHV chamber in cascade to the HEA). During such a transfer the target is kept under static vacuum conditions. Once UHV conditions are reestablished the target surface is refreshed by heating in O₂,¹⁰ and the system is ready to operate. In these conditions, we find stable polarimeter performances over several days. When degradation occurs, the surface refreshing procedure restores almost completely the initial performance. We could use the same surface for about 1 month; afterwards the small degradations summed up to an overall efficiency reduction of roughly a factor of 2, which we consider an unbearable situation requiring a complete new cycle starting from a new target surface preparation.¹⁶

We consider next the problem of spurious asymmetries. An ideal spin detector should allow the determination of the beam polarization without the need of reversing the polarization itself. For our device, this can in principle be obtained by measuring the reflected current asymmetry when switching the target magnetization. In practice, however, instrumental asymmetries, due, for instance, to imperfect geometry of the hardware or to the position of the beam on the scattering target, are always present.^{4,10,15,21} In our case the largest contribution arises from small deflections of the electron beam by stray magnetic fields originating from the magnetized target. If this instrumental asymmetry is not negligible with respect to the analyzing power, the measurement is affected by a significant systematic error, which becomes more and more relevant for smaller values of the polarization. By using an unpolarized electron beam, we have determined the spurious asymmetry for our setup, finding a value around 10%–15%, which is well within the range encountered in typical spin detectors.^{4–6,15} This instrumental effect, however, is larger than in our studies on the polarimeter alone,¹⁰ probably because of the mentioned lever effect. It cannot be neglected in any case, and has to be eliminated by acquiring a double set of data, as common in spin polarimetry.^{4–6,10,15,21} When studying ferromagnetic materials, this can be done by taking spectra for two opposite directions of the sample magnetization. Thus for each beam energy one can measure four different intensities, corresponding to the different combinations of sample and target sample magnetization ($\uparrow\uparrow, \uparrow\downarrow, \downarrow\uparrow, \downarrow\downarrow$). In analogy with Mott polarimetry, it is then possible to construct the quantity

$$X = \frac{I_{\uparrow\uparrow} \cdot I_{\downarrow\downarrow}}{I_{\uparrow\downarrow} \cdot I_{\downarrow\uparrow}} = \frac{1 + \text{PS}}{1 - \text{PS}},$$

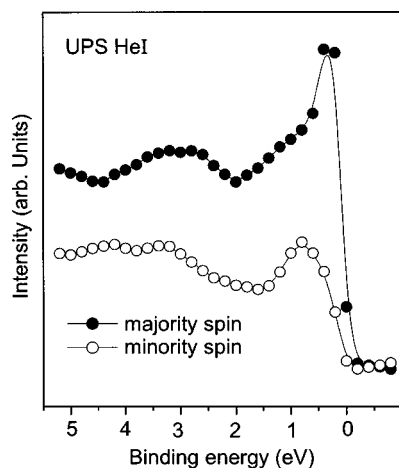


FIG. 3. Normal emission spin-resolved photoemission spectra from a clean Fe(001) surface: The sample has been magnetized in remanence along the [001] easy axis. Data have been taken at room temperature. Photon energy $h\nu=21.2$ eV. Total acquisition time 60 min.

which turns out to be independent on the instrumental asymmetry: since the analyzing power S is known, the polarization P can be determined.^{4,10,15,21}

As an application, we present in Fig. 3 spin-resolved valence band photoemission data from Fe(001). The spectra have been collected at normal emission with the HEA PE=9 eV, while exciting the sample with HeI radiation ($h\nu=21.2$ eV) from a commercial ultraviolet discharge lamp. The majority- and minority-spin spectra are obtained by a standard procedure combining the energy distribution curve (spin-integrated spectrum) with the measurement of the beam polarization as a function of the binding energy.²¹ The total acquisition time was about 60 min. The data are in very good agreement with the reported ones taken at the same photon energy,²¹ with dominant contribution of the majority-spin $3d$ band emission, as expected.

In conclusion we have realized a new apparatus for energy and spin analysis of electron beams. The device has been fully characterized: in particular it displays an analyzing power $S=0.2$ and overall efficiency F_{tot} up to 7×10^{-4} at PE=4.4 eV. This value indicates that our device represents a considerable improvement with respect to presently used similar apparatuses. The necessity of working at low energies and of dealing with well-characterized surfaces (though very stable, as discussed above) makes, however, its operation somehow more troublesome than for the setup based on a Mott detector. The last should be probably preferred in a context requiring user-friendly devices, as those needed at

synchrotron radiation beam lines.¹⁵ Our device, instead, is particularly well suited for on campus research, when high energy resolution is required together with spin analysis.

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