Absolute cross sections for binary-encounter electron ejection by 95-MeV/u $^{36}Ar^{18+}$ penetrating carbon foils

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Doubly differential electron velocity spectra induced by 95-MeV/u $^{36}Ar^{18+}$ from thin carbon foils were measured at GANIL (Caen, France) by means of the ARGOS multidetector and the time-of-flight technique. The spectra allow us to determine absolute singly differential cross sections as a function of the emission angle. Absolute doubly differential cross sections for binary encounter electron ejection from C targets are compared to a transport theory, which is based on the relativistic electron impact approximation for electron production and which accounts for angular deflection, energy loss, and also energy straggling of the transmitted electrons. For the thinnest targets, the measured peak width is in good agreement with experimental data obtained with a different detection technique. The theory underestimates the peak width but provides (within a factor of 2) the correct peak intensity. For the thickest target, even the peak shape is well reproduced by theory.

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Swift heavy ion induced effects in condensed matter (with important applications in, e.g., material science and radiation medicine) are closely related to energy loss by ionization of the target atoms leading to ejection of electrons. These primary electrons propagate through the solid and lose kinetic energy in secondary ionization events (inelastic collisions), or may be deflected in (quasi) elastic collisions. Thus, the measurement of doubly differential cross sections (DDCS) for electron ejection from thin solid foils is a useful tool to test basic atomic ionization and transport theories.

A basic process of electron ejection is the binary encounter (BE) between the incident ion and an atomic electron, which produces electrons with a maximum velocity of about twice the projectile velocity v_P [1]. Since electrons are bound to the target nucleus in different shells, the observed distribution of BE electrons at fixed angle reflects the initial momentum distribution of the bound electrons of the target (''Compton profile'').

Ejection of BE electrons from solids at high beam energies (above 10 MeV/u) was studied experimentally in the velocity range 13–400 MeV/u [2–9]. Earlier studies used magnetic momentum analysers and channeltrons or solid state detectors for particle counting. More recent studies performed with the ARGOS multidetector, based on time-of-flight techniques and scintillators, at LNS (Catania) and GANIL (Caen), allowed the measurements of absolute cross sections.

In ion-solid collisions, binary encounter electron emission results from two consecutive processes, single-collision electron production inside the target, followed by electron transport through the target. For the description of target ionization by fast, highly charged projectiles, the relativistic electron impact approximation (EIA) [10] is applied. Viewed in the projectile frame of reference, the target electron behaves quasifree and scatters elastically from the projectile, and the resulting cross section is folded with the electron momentum distribution (Compton profile) in its initial state. The carbon wave functions are obtained from a Hartree-Fock calculation. The second process, electron transport, involves multiple collisions with target atoms and is described with the help of an energy and angle-dependent distribution function. Energy loss by means of inelastic collisions with the target electrons is considered up to second order (including energy straggling), while angular deflection of the electrons in collision with the target cores is treated as an independent process. A detailed presentation of the transport theory can be found in Ref. [9]. In the following, BE electron emission from single collisions is denoted by EIA (electron impact approximation) while the theory that includes electron transport is termed *S*-EIA (straggling-EIA).

The experiments were performed at GANIL in Caen, France with ^{12}C targets of 100 and 1025 $\mu g/cm^2$ thickness. The pulsed 95-MeV/u $^{36}Ar^{18+}$ beam had a pulse width of about 500 ps. The multidetector ARGOS, consisting of about 100 scintillation detectors (so-called ''phoswiches''), was mounted inside the big scattering chamber NAUTILUS of GANIL for a complete detection and identification of electrons and nuclear reaction products [4,6]. Electrons were detected in a large angular range from 3° to 173°. Particles (in particular, electrons) were identified by shape discrimination of the photomultiplier signals (the ''fast'' and ''slow'' components of the detector), and their velocity was determined by measuring their times of flight as described in detail in Ref. [4].

An absolute velocity calibration was obtained from the prompt γ-ray peak due to nuclear reactions in the target, from elastically scattered projectiles, and from target X rays.

In previous studies, we observed a shift of the BE electron peak position with respect to theoretical calculations [4,6], a phenomenon also observed at lower projectile velocities (see, e.g., Refs. [11,12] and more references given in Refs. [1,2]). Although a small shift is also observed in the present experiment, its value falls within the error bars of the time-of-flight resolution.

Absolute cross sections can be calculated from the number of incoming projectiles (measured with a Faraday cup) and from the number of electrons detected in the scintillation detectors (their detection efficiency being equal to unity for high-energy electrons). Thus, the detector solid angle can be determined in a straightforward way from geometrical considerations only, i.e., from the detector area and the distance between target and detector (typically about 0.6 up to 5.3 m).

Let us now compare measured absolute doubly differential electron ejection cross sections (DDCS) for the thinnest carbon target (100 μg/cm^2 thick), to the calculated DDCS in Fig. 1. Since the measured spectra are obtained by means of a time-of-flight method, the DDCS are plotted as a function of the observed electron velocity. The experimental resolution is approximately $\Delta p/p = 0.08$, and the theory is averaged according to this experimental resolution. The DDCS for three different ejection angles, $\vartheta = 5°$ [close to the beam direction, Fig. 1(a)], $\vartheta = 15°$, and $\vartheta = 30°$ [Fig. 1(b)], are shown. The experimental results are represented by circles and the calculations are represented by a solid line (*S*-EIA) or a dotted line (EIA). The peak intensity is reasonably well described by theory, and the peak positions agree within resolution error bars. The experimental data are shifted by 0.7 cm/ns to lower velocities in order to provide the same peak position for theory and experiment, which facilitates the comparison of peak shapes.

Furthermore, we compare our results to the experimental data obtained by DePaola *et al.* [2] with comparable projectile energy and target thickness (93 MeV/u, 83 μg/cm^2, recorded at $\vartheta = 0°$) in Fig. 1(a). They used a different detection technique: magnetic analysis and channeltron electron counters, the experimental resolution being about $\Delta p/p = 0.03$. These relative data are normalized to the maximum of the theory. In Fig. 1(c), a further comparison of the two sets of the experimental data at larger emission angles $\vartheta = 40°$, 45°, and 50° is made. First, we emphasize the excellent agreement of the two data sets: note that for the thinnest targets of about 100 μg/cm^2, the measured peak width is equal for both sets of experimental data at small [Fig. 1(a)] and large [Fig. 1(c)] emission angles. Note that *S*-EIA calculations have not been performed for angles larger than $\vartheta = 30°$ because the approximations used are no more valid.

As can be seen from Figs. 1(a) and 1(b), according to the calculation, transport effects should be small for thin targets. The atomic EIA and the calculation including transport effects can hardly be distinguished. Only at the low-energy side a slight enhancement due to the electrons that were scattered and slowed down is visible, and the absolute height is very slightly diminished. A remarkable result is that the measured peak width is clearly underestimated even by transport theory for the thinnest targets as compared to the experimental data sets that are in good agreement. We emphasize again

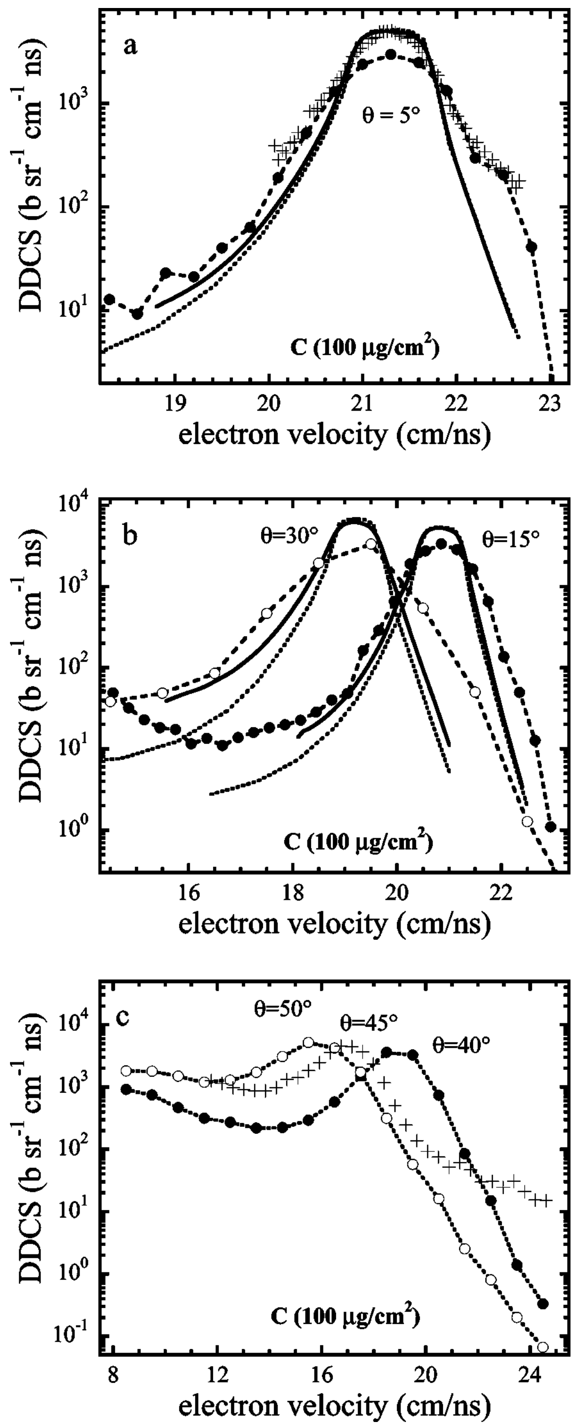

FIG. 1. (a) Absolute doubly differential electron ejection cross sections (DDCS) for the thinnest carbon target (100 μg/cm^2) for 95-MeV/u $^{36}Ar^{18+}$ impact at a laboratory angle of 5°. Solid line: *S*-EIA, dotted line: EIA, full circles: experiment (dashed lines are drawn to guide the eye). Comparison is also made with to experimental data obtained by DePaola *et al.* [2] at slightly different projectile energy and target thickness (93 MeV/u, 83 μg/cm^2, recorded at $\vartheta = 0°$)(denoted by +). (b) Same as (a), but for ejection angles of 15° and 30° (experimental results depicted by open circles in the latter case). (c) Same as (b), but only the experimental results (not the theory) for ejection angles of 40° (full circles) and 50° (open circles). Also shown are the experimental data obtained by DePaola *et al.* [2] at $\vartheta = 45°$ (denoted by +).

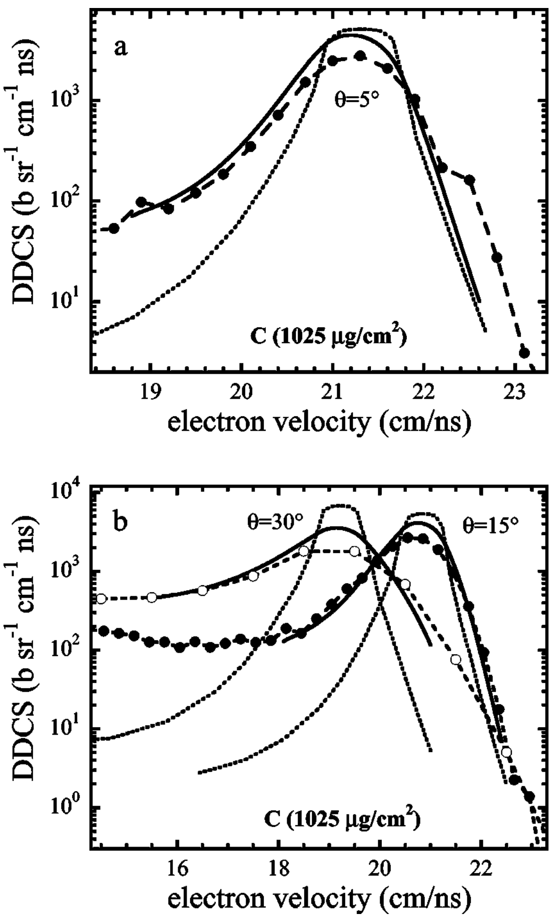

FIG. 2. (a) Same as Fig. 1(a), but for the thicker carbon target (1025 μg/cm^2, i.e., DDCS for 95-MeV/u $^{36}Ar^{18+}$ impact at a laboratory angle of 5°. (b) Same as (a), but for ejection angles of 15° and 30° (experimental results depicted by open circles in the latter case).

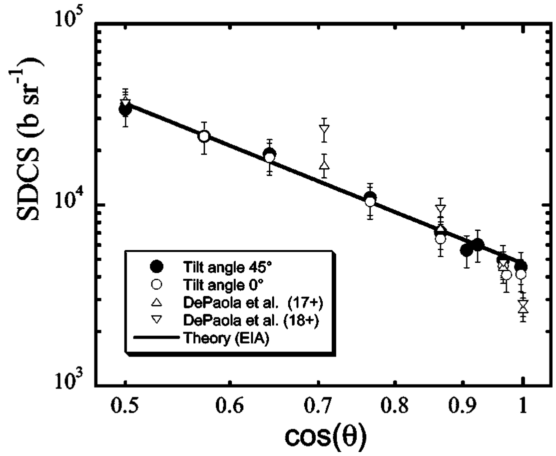

FIG. 3. Velocity-integrated absolute SDCS for BE electron emission as a function of the cosine of laboratory ejection angle ϑ for 95-MeV/u $^{36}Ar^{18+}$ penetrating a carbon target of 100 μg/cm^2 thickness. Open circles: perpendicular impact, full circles: target tilted at 45° with respect to the beam axis, solid line: EIA theory in absolute value. Relative data of DePaola *et al.* [2] are also shown: the SDCS of the two data sets for the charge states 17+ (open triangles) and 18+ (open inverted triangles) were reported in arbitrary, but internally consistent units, and were thus normalized to the theory at 60°.

that two completely different methods of detection were used in the present experiment and in the experiment by DePaola *et al.* [2].

This result means that either the primary ionization peak shape is not only determined by the target Compton profile or that transport effects are important even at such small target thicknesses. Concerning the EIA theory, the neglect of the target potential in the intermediate and final electronic states in the EIA approach, which leads to the quasielastic scattering formulation, could be questioned. The scattering contributions of higher order in the target field might influence the shape of the primary BE electron peak. However, no big effects are expected from these assumptions at the high collision energies considered.

The second alternative would mean that the transport theory as described above does not correctly account for fast electron transport in very thin targets (and it is exactly in thin targets where one would expect it to work best). Are there further imaginable reasons? Or is there an unknown solid-state effect, such as an unexpected broadening of the Compton profile due to a different electronic structure in condensed matter compared to free atoms, involved? At present, we do not have an explanation for these findings.

In contrast, for a target ten times thicker (1025 μg/cm^2), the peak shape is well reproduced by theory. This can be seen from Fig. 2, where calculation and experiment are compared for the same ejection angles as in Figs. 1(a) and 1(b). For sufficiently large target thickness, transport effects dominate over primary ionization (where the peak width is mainly determined by the Compton profile). These results are in agreement with our previous results obtained with 45 MeV/u $^{58}Ni^{28+}$ [9]. The absolute value of the measured DDCS is slightly overpredicted by the theory. The overall agreement of the absolute values is, however, remarkable, and the peak shapes are well reproduced for thick targets.

Finally, we consider the BE energy-integrated singly differential emission cross sections (SDCS). They are shown in a log-log plot as a function of the cosine of the ejection angle ϑ in Fig. 3. Plotted in this way, they can be directly compared to Fig. 5 of DePaola *et al.* [2], to Fig. 4 of Azuma et al. [3], and to Fig. 4 of Rothard *et al.* [9]. The solid line indicates the theoretical absolute EIA prediction, the open circles indicate data obtained with the thinnest target of 100 μg/cm^2, and the full circles indicate data obtained with the same target tilted at 45° with respect to the beam axis. We also included the relative data of DePaola *et al.* in Fig. 3. The SDCS of the two data sets for the charge states 17+ (open triangles) and 18+ (open inverted triangles) were reported in arbitrary, but internally consistent units, and are thus normalized to theory at 60°.

As already discussed in Ref. [5], the angular dependence follows the $1/\cos^3\theta$ law, which one would expect from a simple two-body Rutherford scattering between a free target electron and the projectile nucleus including relativistic kinematics but a nonrelativistic Rutherford scattering formula [2]. The EIA calculation is in excellent agreement with our absolute experimental data. The relative data of DePaola *et al.* do not exactly follow the $1/\cos^3\vartheta$ curve. An interesting finding was the decrease in the SDCS at small emission angles observed by DePaola *et al.*, which could have been a hint for a relativistic effect. However, we do not observe such a decrease for emission angles as low as 5°, and thus conclude that all relativistic effects are well taken into account by the present theoretical EIA theory.

In summary, we have performed measurements of absolute doubly differential cross sections for binary encounter electron ejection from C targets and compared them with the predictions of a theory that includes the relativistic EIA for electron production and a transport of the transmitted electrons in matter. For the thinnest targets used, the measured peak width is in good agreement with the experimental data obtained by a different detection technique, but underestimated by the theory. For the thickest target, the peak shape is well reproduced by the theory. Further, the absolute measured cross sections are reasonably predicted by the theory. The present experimental results constitute an example for fruitful interdisciplinary collaboration and show the great interest in applying powerful detectors, developed initially for nuclear physics experiments, to atomic collision studies. Further measurements of absolute high-energy electron ejection cross sections, in a wider projectile energy range, and with both heavier and lighter ions as well as other targets, are in progress.

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