Fast electrons ejection by swift highly charged ions: absolute cross sections and evidence for "Fermi shuttle" acceleration

G. Lanzanò[a]*, E. De Filippo[a], D. Mahboub[b],
H. Rothard[c], C. Volant[d],
S. Aiello[a], A. Anzalone[b], N. Arena[a], S. Cavallaro[b],
E. Geraci[b], M. Geraci[a], F. Giustolisi[b], A. Pagano[a], G. Politi[a]

[a]*Istituto Naz. Fisica Nucleare and Dipartimento di Fisica*
Corso Italia 57, 95129 Catania, Italy
[b]*INFN-LNS and Dipartimento di Fisica,*
Via S. Sofia 44, 95123 Catania, Italy
[c]*CIRIL-Ganil (UMR 6637 CEA/CNRS/ISMRA),*
BP 5133, 14070 Caen Cedex 05, France
[d]*DAPNIA/SPhN, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France*

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Abstract

We shall report in this contribution on the results of recent experiments performed at the CS (Catania) and Ganil (Caen) cyclotron accelerators, with 45 A.MeV 19^+ and 28^+ ^{58}Ni and 95 A.MeV 18^+ ^{36}Ar pulsed beams respectively. Electron velocity spectra were measured in a large angular range with different conducting targets (C, Al, Ni, Ag, Au). Besides electrons with the beam velocity (convoy electrons, CE) and two times the beam velocity (binary encounter electrons, BE), in the case of Au target we observe also a high velocity tail, that can be explained by a Fermi-shuttle mechanism. We give also BE and CE absolute production cross-sections. In the Ganil experiment, as very preliminary result, the lack of the CE component at the most forward angles for the carbon target, is observed. For the other targets the CE component is increasing as a function of the target atomic number.

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*e-mail: lanzano@ct.infn.it

1 Introduction

Heavy ion beams at "intermediate energies" ($\approx$20A.MeV< E <200A.MeV) have extensively been used in nucleus-nucleus interaction studies. On the contrary, very little attention has been paid to the nucleus-electron interaction, a field being at the boundary between nuclear and atomic physics. The knowledge of fast electron ejection properties at these high projectile energies, like velocity spectra and production cross-section angular distributions, are important for testing basic atomic ionisation theories. In the forward beam direction, fast electrons are essentially due to two reaction mechanisms. A binary-encounter (BE) between the incident ion and an atomic electron produces electrons with a centroid velocity of almost twice the projectile velocity v_P. Since electrons are bound to the target nucleus in different shells, the observed distribution of BE electrons at fixed angle is a distribution which reflects the initial momentum distribution of the bound electrons of the target ("Compton profile"). Also, target electrons may be captured or projectile electrons may be lost into low lying projectile centred continuum states. These so-called convoy electrons travel with a velocity close to that of the projectile and lead to a cusp shaped peak in electron spectra.

Studies of BE electron emission at high beam energies above 10 A.MeV are quite scarce. We refer to our recent study [1] for a more complete bibliography on the subject.

2 Experimental lay-out and detection method

The experiments were performed at the CS Superconducting Cyclotron of LNS in Catania and at Ganil in Caen. In the CS experiment pulsed 45 A.MeV 19^+ and 28^+ ^{58}Ni beams with a pulse width (burst time resolution) of 1.2 ns were used. We used different targets: ^{12}C, ^{27}Al, ^{58}Ni and ^{64}Ni, ^{nat}Ag, ^{197}Au, of almost the same areal thickness, 300 μg/cm^2, in order to vary the target nuclear charge Z_T while keeping secondary effects connected to electron transport constant as discussed in [2]. Also, the possible dependence on the target thickness (electron transport) was investigated by using 7 different Carbon targets of 10, 20, 90, 300, 1000, 2000 and 8000 μg/cm^2 thickness. The multidetector ARGOS, consisting in about 100 scintillation phoswich detectors, was used inside the big scattering chamber CICLOPE of the LNS for a complete detection and identification of electrons and other nuclear products [1, 3]. Briefly, the in-plane electron detection was extended from 4° to 170° in coincidence with a nearly 0° geometry central wall. Some inclusive measurements at few selected angles were also carried out. Electrons were identified by shape discrimination of the photomultiplier output signals (the "fast" and "slow" components of the detector) and by measuring their time-of-flight as described in detail in [1]. For their absolute velocity calibration the prompt γ-ray peak centroid was measured.

In the recent (July 2000) Ganil experiment a pulsed 95 A.MeV 18^+ ^{36}Ar beam was used. An overall timing resolution (beam burst and detector) of 500 ps was obtained. The geometry of the ARGOS detectors was very similar to the one of the CS experiment. Due to the higher beam energy, threshold effects are here less important, so that convoy electron velocity spectra can be fully measured at the most forward angles.

3 Results

Fig. 1 shows typical inclusive time-of-flight spectra for electrons emitted at 5°, following the impact of 95 A.MeV 18^+ ^{36}Ar beam on different (C, Ni, Ag, Au) targets. The spectra are normalized to the integrated beam charge and to the number of target electrons per unit area. We observe two distinct components: fast binary encounter (BE) electrons and electrons with velocity close to the beam velocity (convoy electrons). Other less intense peaks are observed for much longer times of flight, mainly affected by electronic threshold (indicated by the shadowed area) effects. The integrated absolute values for the BE and CE components are shown in Figs. 2(a) and 2(b) respectively for the 45 A.MeV Ni beam (full circles) and the 95 A.MeV Ar beam (empty squares). As a function of the target atomic number Z_T the BE production cross section per target electron is almost constant within error bars. This means that the BE intensities are roughly proportional to the number of electrons "seen" by the projectile on its way through the target, i.e. to the number of electrons per unit area. Note, however, that forward BE production induced by 45 A.MeV 28^+ ^{58}Ni beam is larger by almost a factor 5 with respect to the case of a 95 A.MeV 18^+ ^{36}Ar beam. This is probably a pure kinematic effect. By using the simple Rutherford scattering formula, we get for the two cases a factor $(Z_{Ni}/Z_{Ar})^2 \times (A_{Ar}/A_{Ni})^2 \times (E_{Ar}/E_{Ni})^2 \approx 4.15$, in good agreement with the data. Increasing the detection angle θ, BE production increases as $\approx 1/\cos^3\theta$, while the centroid of the BE velocity spectrum decreases approximately as $2v_P\cos\theta$. Therefore, it seems that at these intermediate energies many of the observed BEE properties are well accounted for by treating the collision as a binary encounter between the incoming ion and a "free" electron.

Concerning the electron convoy component, their systematic study is made difficult because of important threshold effects. Consider for instance that in the forward direction convoy electrons of only $\approx$25 and 50 keV are produced with ^{58}Ni 45 A.MeV and ^{36}Ar 95 A.MeV beams respectively. For the ^{58}Ni beam experiment, more affected by threshold effects, some general considerations are possible, in connection either with the beam charge state and the different nature of targets. For a bare 28^+ ^{58}Ni projectile, convoy electrons are due essentially to a "pick-up" mechanism of electrons in the atomic medium, with subsequent re-emission. As expected [6], their production cross-section shows a dependence on the target atomic number (see Fig. 2), but more marked than in the case of BE electrons . For a 19^+ ^{58}Ni beam, a ^{58}Ni nucleus with a cloud of 9 electrons, the results are quite different [5]. The convoy electrons come essentially from the projectile, with a transfer mechanism to the continuum, being the pick-up component negligible. Their production cross-section is independent from the target atomic number. In this case, we observe a convoy component almost a factor ≈80 much higher than the BE component.

Looking now to Fig. 1 relative to the Ar beam experiment (95 A.MeV), we observe that the trend of the CE production cross section as a function of the target atomic number is very similar to the one obtained at lower energy (45 A.MeV). However, absolute values are much lower. Much more striking, in Fig. 1, is the lack of the convoy peak for the carbon target (either 100 or 1000 μg/cm^2 thick), at the most forward angles, up to ≈1.5°, specially if compared to the case of a gold target equally or less thick. Which is the reaction mechanism responsible for electron capture at these intermediate energies? Is there an evidence of a "threshold" effect in the case of the carbon target? Are the convoy electrons in the case of the gold target captured from inner shells, in order to "match" the high projectile velocity?

Finally, let us comment on two other results obtained in the experiment with the 45 A.MeV ^{58}Ni beam. The first one concerns the presence of high energy electrons in the backward direction. For solid thick targets a consistent part of the initially forward focused electrons interact more or less strongly with the atomic medium, so that a fraction of them are deviated in the backward direction. We expect also that this effect should depend on the size of the scatter atomic center, and hence from the target atomic number. Absolute values obtained at -140° are shown in Fig. 2(c) as a function of the target atomic number. At the most backward angles the detected electrons are affected in a significant way by threshold effects. The experimental points have been obtained by integrating the electron velocity spectra starting from the threshold (≈7.5 cm/ns) up to the high velocity part of the spectrum, that extends up to two times the beam velocity. It is also noteworthy that the spectra are relative to targets of different atomic numbers but with the same areal thickness (300μg/cm^2), and hence roughly with the same total number of electrons. In other words, this should be regarded as an evidence of the importance of the target size scattering center in the production of fast electrons at backward angles.

The second result concerns the presence, in the case of a gold target, of an extended tail in the high energy part of the BE peak. It extends up to velocities as high as 24-25 cm/ns with an intensity of almost 1/1000 of the BE peak maximum intensity. This behaviour, peculiar of the gold target, is observed for all the forward angles up to 60°. This can only in part be due to the very complex Compton profile for the gold target. An additional possible mechanism involves multiple collision sequences of electrons between target and projectile nuclei. This is often referred to as “Fermi-shuttle” mechanism, already invoked to explain high energy cosmic rays [4]. A part of the BE electrons produced in the collision interacts with the target atoms along the ion trajectory. Possibly, they are scattered back with a certain velocity distribution, and a certain probability of colliding again with the same incident nucleus. We emphasize that the probability of such higher order processes may be sharply enhanced in ion- solid compared to ion-atom collisions, because of the high target nucleus density. We made simple Fermi-shuttle calculations, described in [3, 5] that accounts in a satisfactory way for the tails of the BE velocity spectra.

4 Conclusion

In conclusion, we have shown the complexity of the origin of fast electrons at intermediate energies. At the most forward angles they are due in great amount to two distinct direct mechanisms, wich give origin to electrons with beam velocity (convoy electrons) or two times the beam velocity (BE, binary encounter electrons). Their relative production depends on the beam charge state as well on the target atomic number. The convoy electron capture production cross section at most forward angles strongly depends on the target atomic number, as already observed [5, 6], and on the beam energy. In particular we observe a lack of convoy electron in the case of a Carbon target for a 95 A.MeV ^{36}Ar beam. Also (see Fig. 1), an increasing amount of electrons, with velocity intermediate between the beam velocity and two times the beam velocity, is apparent with the increasing atomic number of the target.

For heavy target, like Au, an enhancement of the high velocity tail in the BE peak is present, that can be explained with a simple “multiscattering” or “Fermi Shuttle” mechanism.

Finally we have shown that fast electrons are present also at most backward angles. Very probably they are due to transport effects in the atomic medium of the target. Their production is very sensitive to the size of the target atom.

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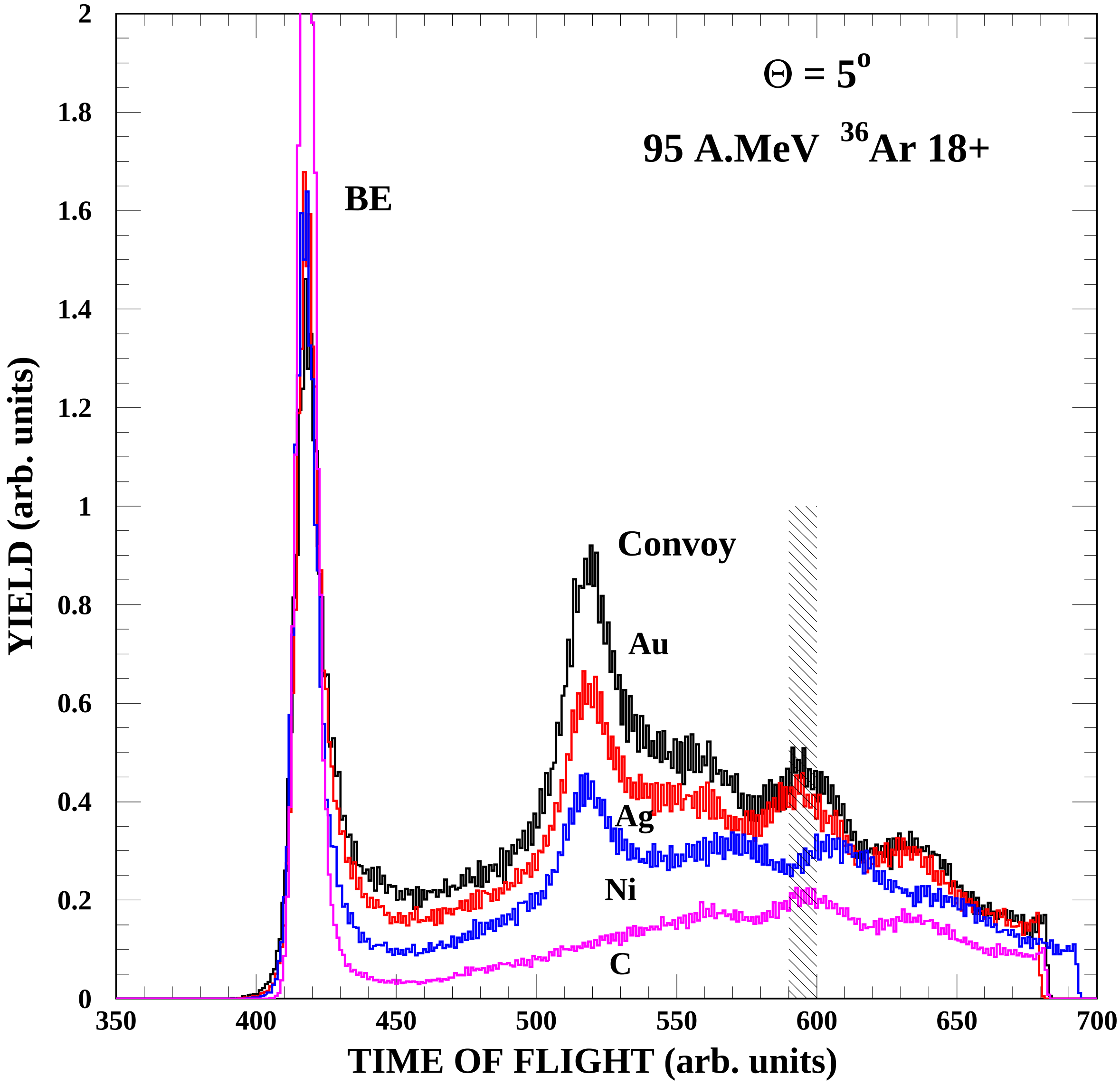
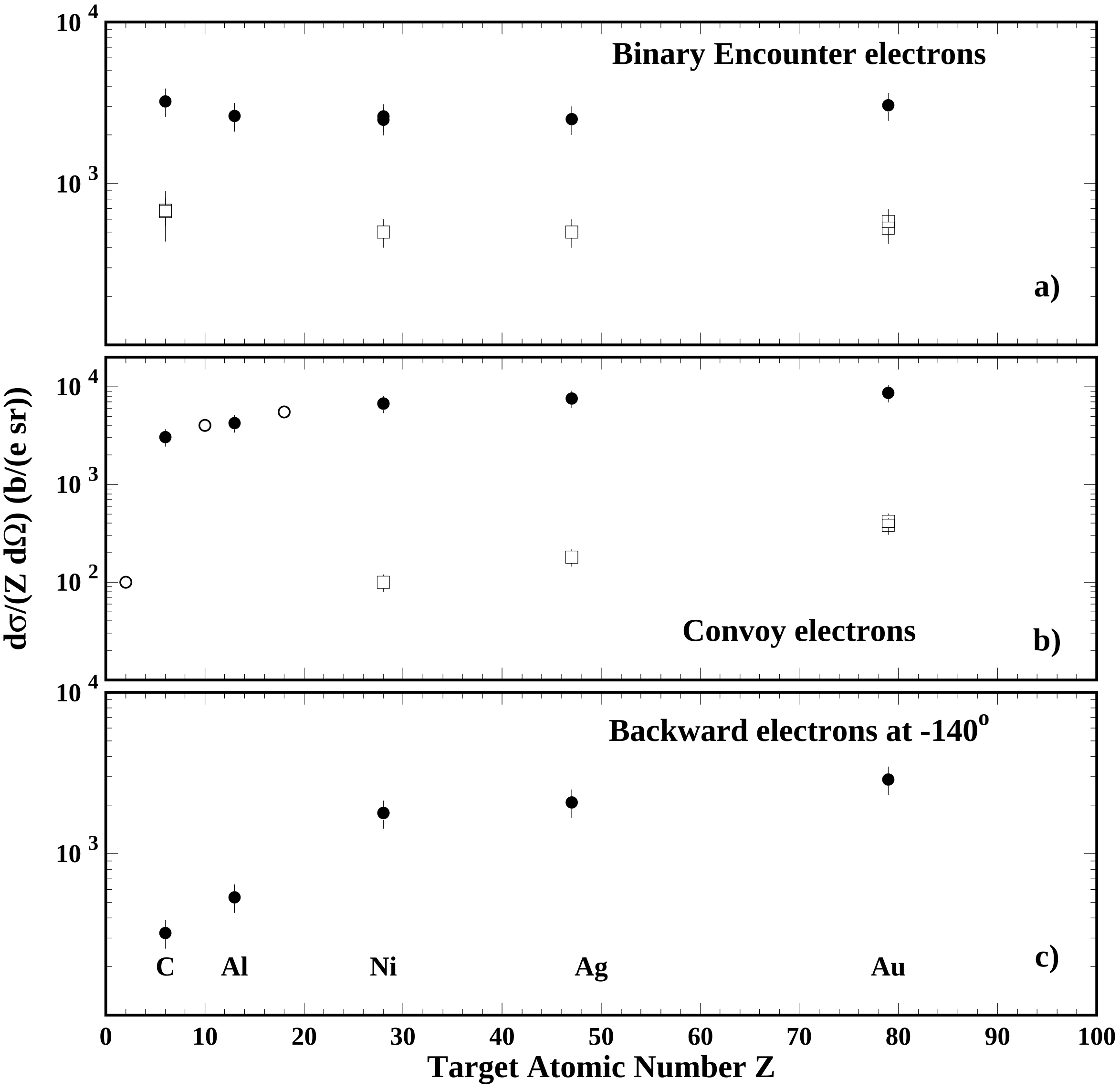
Figure caption

Fig 1. For the reaction 18^{+} ^{36}Ar (95 A.MeV) + C, Ni, Ag, Au the electron inclusive time-of-flight spectra are shown. The binary encounter (BE) and convoy components of the spectra are indicated. The detector is placed at 282.1 cm from the target, at a laboratory angle of 5 °. The shadowed area indicates the electronic threshold. Note the lack of the convoy component in the case of the carbon target and the presence of several structures in the region of longer times of flight.

Fig 2. For the reaction induced by 28^{+} ^{58}Ni (45 A.MeV) (filled circles) and 18^{+} ^{36}Ar (95 A.MeV) (empty squares) on different targets, as below indicated, we show the absolute electron production cross section at 6° (circles) and 5° (squares) in (a) for the BE component, in (b) for the convoy component, in (c) for backward electrons at -140° ($v_e \geq 7.5$ cm/ns) respectively, as a function of the target atomic number (respectively C, Al, Ni, Ag, Au). Note that the absolute production cross-section scale is divided by the target atomic number Z. The empty circles in (b) are values taken from [6] and normalized to our data.


Θ = 5°
95 A.MeV ^{36}Ar 18+
BE
Convoy
Au
Ag
Ni
C
YIELD (arb. units)
TIME OF FLIGHT (arb. units)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
350
400
450
500
550
600
650
700


Binary Encounter electrons
a)
Convoy electrons
b)
Backward electrons at -140^o
c)
C
Al
Ni
Ag
Au
10 4
10 3
10 2
dσ/(Z dΩ) (b/(e sr))
0
10
20
30
40
50
60
70
80
90
100
Target Atomic Number Z