CONF-881151--33

Comparison of the target-thickness dependence of the convoy electron yield and the Rydberg electron yield measured in coincidence with exit charge states in fast ion-solid collisions.

C.C. Gaither III, M. Breinig, J. Freyou and T.A. Underwood

University of Tennessee
and
Oak Ridge National Laboratory

CONF-881151--33

DE89 002267

Abstract

We have simultaneously measured the yield of convoy electrons and the yield of electrons in high Rydberg states of the projectile ($n \gtrsim 70$), produced by 2MeV/u C projectiles passing through C foils, whose thicknesses range from 4-10 ug/cm^2, for incident charge states q_i = 4-6 and exit charge states q_e = 4-6. We have found that these yields exhibit similar trends as a function of foil thickness, but that, nevertheless, the ratio of the number of convoy electrons detected in coincidence with ions of exit charge state q_e to the number of electrons detected in high Rydberg states of ions with the same exit charge state is a function of foil thickness. This may be due to a broadening of the convoy electron energy spectrum with increasing foil thickness.

Introduction

When fast heavy ions pass through thin solid targets they may exit the solid with electrons in Rydberg states, atomic bound states with high quantum number n, or they may be accompanied by convoy electrons, free electrons which have the same velocity $\bar{v}$ as the ions themselves. Convoy electrons and electrons in high Rydberg states produced in fast ion-solid and ion-gas collisions have been studied separately for many years. Convoy electrons have been investigated, for example, by Yamazaki et al. [1] and Schramm et al. [2], while the production of high Rydberg states of the projectile in fast ion-solid and ion-gas collisions has been studied by Betz et al. [3], Schiwietz et al. [4] and Dybdal et al. [5]. A close relationship between the production of high Rydberg states and the phenomenon of convoy electron production is often assumed, although the details of this relationship have not been investigated for sub-equilibrium thickness targets. Here we define equilibrium thickness as being achieved when the exit charge state fractions become constant and are no longer affected by increases in foil thickness. Burgdörfer developed a transport theory for convoy electrons and Rydberg electrons under the influence of both the strong Coulomb field of the projectile and stochastic scattering processes in the solid which reveals a close relationship between convoy electron production and the production of electrons in high Rydberg states [6].

A way to more closely investigate this relationship is to compare the yields of convoy electrons and the yields of electrons in high Rydberg states of the projectile as a function of foil thickness. If the production mechanisms are closely related, changes in the convoy yield will be mirrored by similar changes in the yield of high Rydberg states of the projectile.

The convoy electron yield as a function of foil thickness, incident charge state q_i, and exit charge state q_e has already been measured for 2 MeV/u C projectiles passing through C foils [1]. These measurements are consistent with Burgdörfer's theoretical results and indicate that convoy electron production is closely related to electron loss to the continuum (ELC) processes in the solid with the main contribution to the convoy electron yield coming from ionization of excited states of the projectile within a characteristic distance λ_c of the target.

Experiment

We have simultaneously measured the yield of convoy electrons and the yield of electrons in high Rydberg states of the projectile with n $\gtrsim$ 70 produced by 2MeV/u C ions with incident charge state q_i = 4-6 and exit charge state q_e = 4-6 striking C foils, with thicknesses ranging from 4-10 ug/cm^2. The yields are measured at the same time so that possible changes in foil thickness and structure with time will affect both measurements equally. The C^{q_i+} beam, supplied by the EN Tandem Van de Graaff accelerator facility at the Oak Ridge National Laboratory, is allowed to pass through C foils placed at the entrance focus of a 30^o parallel plate electron energy analyzer. The dimensions of the 30^o analyzer are chosen so that only electrons in extremely high Rydberg states, $n >> 70$, will be stripped by the electric field in the analyzer. The C beam is collimated to 0.75mm diameter. The 30^o analyzer deflects the convoy electrons into a channel electron multiplier (CEM), while the carbon beam exits through a hole in the back of the 30^o analyzer. It then enters a region of intense, inhomogenous electric field between two concentric spherical sectors of a spherical ionizer held at different potentials. The ion beam passes radially through the ionizer. In the ionizer, electrons in high Rydberg states are field stripped and then accelerated out of the ionizer where the C beam and field stripped electrons enter a 160^o spherical sector electrostatic energy analyzer. The Rydberg electrons are deflected into a second CEM while the carbon beam exits through a hole in the back of the analyzer and is subsequently electrostatically separated by charge state and detected with a multidynode electron multiplier. The entire apparatus from the foil targets to the 160^o analyzer is surrounded by magnetic shielding to prevent deflection of the convoy and field stripped Rydberg electrons by stray magnetic fields.

The convoy electron energy spectrum has a distinct cusp shaped peak centered at an electron energy corresponding to electrons moving with the beam velocity, which for our experiments is 1080 eV. The energy spectrum of field stripped Rydberg electrons shows a strong peak at an energy of 3080 eV in our experiment. This is the energy of electrons travelling with the beam velocity before being accelerated through a 2000 V potential difference. The electrons producing this strong peak are stripped as the beam enters the ionizer and then are accelerated through the stripping potential of 2000 V. All electrons in states with $n \gtrsim 70$ are stripped as the beam enters the ionizer. As the beam traverses the ionizer, the field strength increases and even lower n states are stripped. They are then accelerated through a potential difference of less than 2000 V. The Rydberg energy spectrum therefore has a small tail produced by these electrons on the low energy side of the strong peak. In our experiment the analyzer voltages are chosen such that only 1080

$\pm$ 11 eV convoy electrons are deflected into the 30° CEM and only field stripped electrons of energy 3080 $\pm$ 62 eV are deflected into the 160° CEM, which corresponds to counting only electrons in the convoy peak and Rydberg peak.

Data are collected by simultaneously counting coincidences between convoy electrons and ions of exit charge state q_e and coincidences between field stripped Rydberg electrons and ions of exit charge state q_e for all foil thicknesses, q_i and q_e.

Results and Conclusions

The exit charge state fractions for any q_i are not constant as a function of foil thickness thus insuring that the relatively thick 4 - 10 ug/cm^2 foils used in our experiment are still sub-equilibrium thickness foils. Figures 1 and 2 show the number of Rydberg and convoy electron coincidences with ions of exit charge state q_e normalized to the number ions of the same exit charge state q_e as a function of foil thickness for C^{6+} and C^{4+} incident ions, respectively. The error bars shown represent statistical errors only.

Consider the Rydberg electron and convoy electron yields for C^{6+} incident and C^{6+} exit ions shown in figure 1. Obviously capture of an electron from the target has to occur. Yamazaki et al. propose that capture into high n bound states of the projectile and subsequent ionization near the exit of the foil is the dominant convoy electron production mechanism. Rydberg states of the projectile are produced by a similar capture process but exit the foil prior to ionization and are only field stripped in the ionizer. The yields for q_i = 6, q_e = 6 vary slowly with foil thicknesses indicating that the characteristic time scale for these production processes is shorter than the transit time of the projectiles through the foil. We observe that trends in the convoy yield as a function of foil thickness are mirrored by similar trends in the Rydberg yield. This applies to all the measured yields suggesting that similar processes are responsible for convoy and Rydberg electron production regardless of incident or exit charge state. Of particular interest are the Rydberg and convoy electron yields for C^{4+} incident and C^{4+} exit ions as they show the strongest dependence on foil thickness. If the projectile carries electrons into the collision, convoy electrons may be produced via capture of target electrons into high n states of the projectile with the subsequent electron loss, as well as via ionization of a bound projectile electron accompanied by an additional bound state capture. Similarly Rydberg electrons may be produced by direct capture into high n states or by excitation of projectile electrons accompanied by a bound state capture. We expect the time scale for the first processes to be shorter than the time it takes the projectiles to traverse the foil. Our data suggest that the time scale for the second processes is on the order of this transit time and that the increase in the yields is due to these second processes. The Rydberg electron yield slightly lags the convoy electron yields as a function of foil thickness, as shown in figure 2, suggesting that excitation of bound electrons to high n states precedes ionization.

In addition to comparing trends in convoy and Rydberg electron yields as a function of foil thickness we have also examined the ratios of convoy electron coincidences to Rydberg electron coincidences for any q_i and q_e. These ratios are shown in figure 3. If changes in the convoy electron yield are mirrored by similar changes in the Rydberg electron yield, these coincidence ratios are expected to be nearly constant for all foil thicknesses. With the exception of C^{4+} ions in and C^{4+} ions out, all the coincidence ratios as a function of foil thickness decrease. This decrease may be due to a broadening of the convoy electron energy spectrum for thicker foil targets. Such a broadening will decrease the number of convoy electrons within our energy window for detection and decrease the number of convoy electron coincidences observed, thus decreasing the coincidence ratios for thicker foils.

In the future, we plan to extend the measurements described in this paper and to measure the entire convoy electron energy spectrum as a function of foil thickness to determine if broadening indeed is responsible for the decrease in the coincidence ratios as a function of foil thickness. In addition, a wider range of sub-equilibrium thickness foils will be studied to better define trends in the convoy and Rydberg electron yields.

This research was supported in part by the National Science Foundation and by the U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

References

1. Y. Yamazaki, H.-P. Hulskötter, M. Breinig, R. DeSerio, J. Burgdörfer, T. Underwood, J. Gibbons, I. Sellin, Phy. Rev. A34 (1986) 4493.

2. R. Schramm, P. Koschar, H.-D. Betz, M. Burkhard, J. Kemmler, O. Heil, K. Groeneveld, J. Phys. B18 (1985) L508.

3. H.-D. Betz, D. Röschenthaler, J. Rothermel, Phys. Rev. Lett. 50 (1983) 34.

4. G. Schiwietz, D. Schneider, J. Tanis, Phys. Rev. Lett., 59 (1987) 1561.

5. K. Dybdal, J. Sørensen, P. Hvelplund, H. Knudsen, Nucl. Instr. and Meth. B13 (1986) 581.

6. J. Burgdörfer, "High Energy Ion-Atom Collisions", Proc. 3rd Workshop on High-Energy Ion-Atom Collision Processes, Debrecen, Hungary, August 3-5, 1987, eds. D. Berényi, G. Hock.

Figure 1

Rydberg and convoy electron yield measured in coincidence with projectile ions of exit charge state q_e normalized to the number of ions of exit charge state q_e as a function of foil thickness for C^{6+} incident ions.

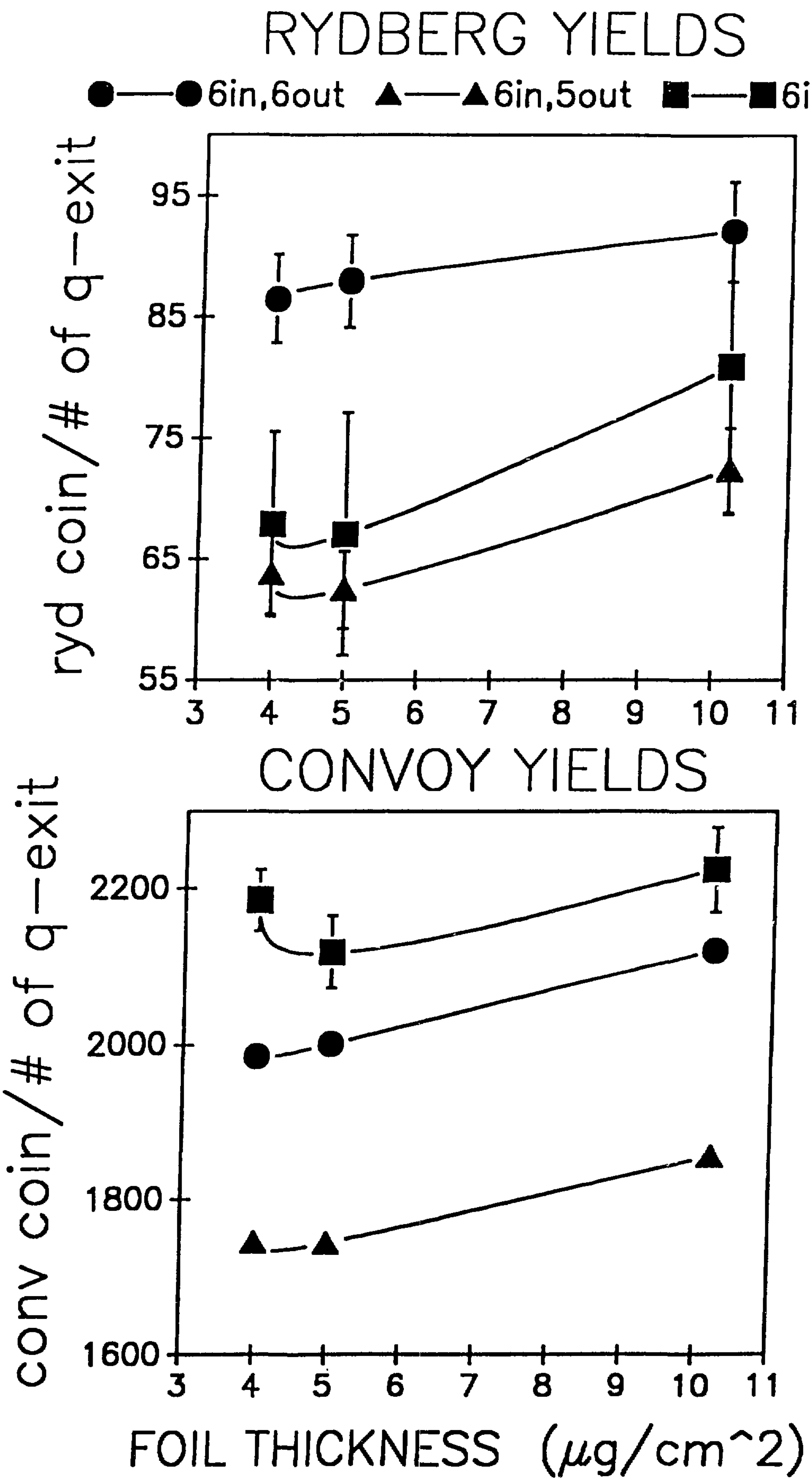
Figure 2

Rydberg and convoy electron yield measured in coincidence with projectile ions of exit charge state q_e normalized to the number of ions of exit charge state q_e as a function of foil thickness for C^{4+} incident ions.

Figure 3

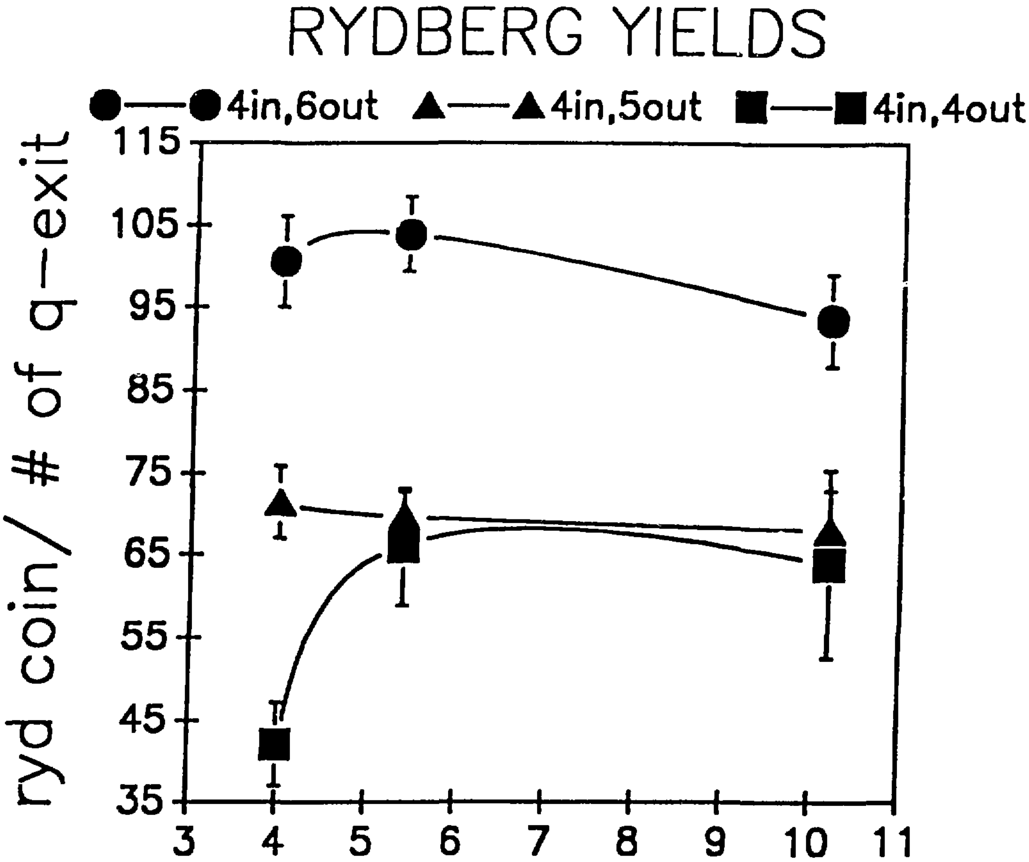
Ratio of the number of convoy electron coincidences to the number of Rydberg electron coincidences as a function of foil thickness for C^{4+} and C^{6+} incident ions.

figure 1



RYDBERG YIELDS
6in,6out
6in,5out
6in,4out
ryd coin/# of q-exit
95
85
75
65
55
3
4
5
6
7
8
9
10
11
CONVOY YIELDS
conv coin/# of q-exit
2200
2000
1800
1600
3
4
5
6
7
8
9
10
11
FOIL THICKNESS (μg/cm^2)

Figure 2


RYDBERG YIELDS
4in,6out
4in,5out
4in,4out
ryd coin/ # of q-exit
115
105
95
85
75
65
55
45
35
3
4
5
6
7
8
9
10
11

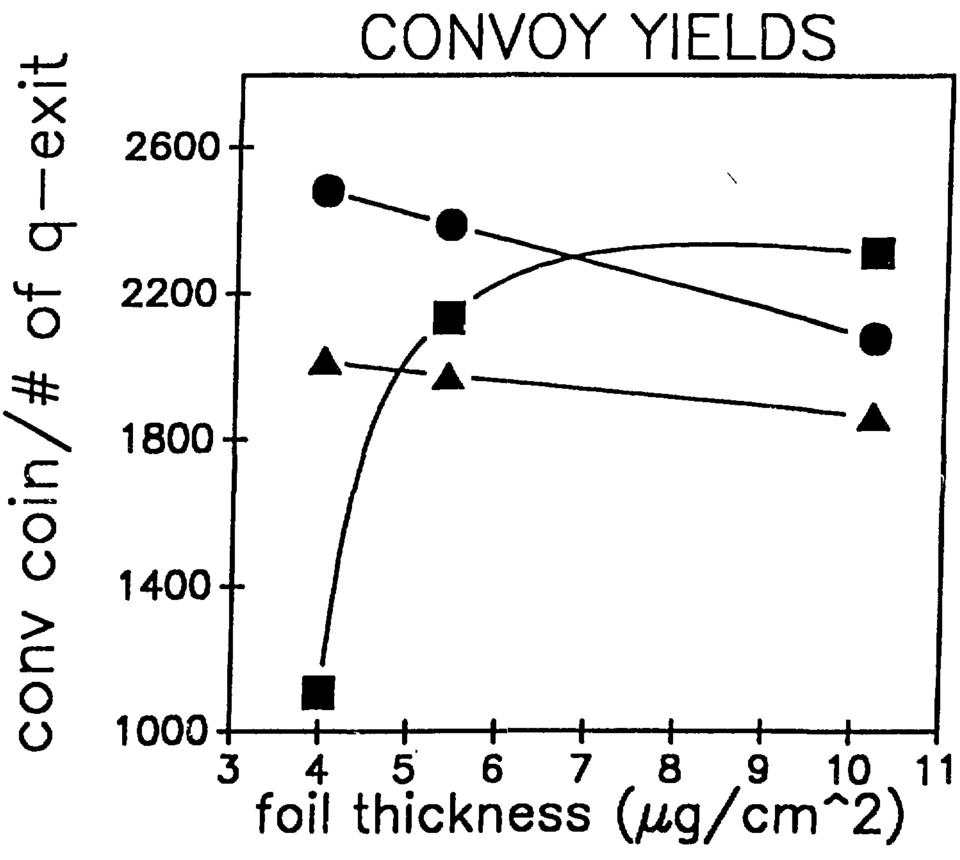
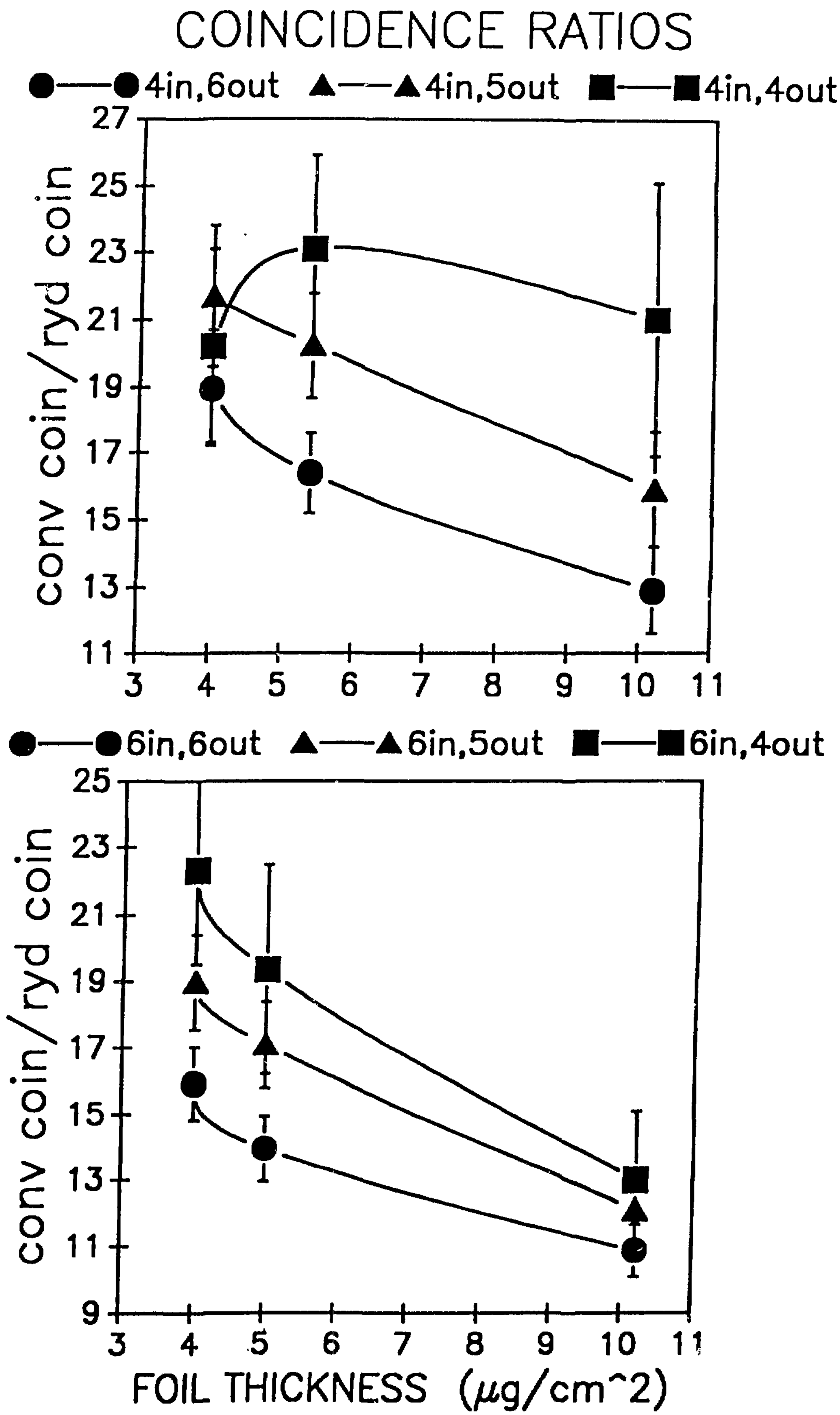

CONVOY YIELDS
conv coin/# of q-exit
2600
2200
1800
1400
1000
3
4
5
6
7
8
9
10
11
foil thickness (μg/cm^2)

Figure 3


COINCIDENCE RATIOS
4in,6out
4in,5out
4in,4out
27
25
23
21
19
17
15
13
11
conv coin/ryd coin
3
4
5
6
7
8
9
10
11
6in,6out
6in,5out
6in,4out
25
23
21
19
17
15
13
11
9
conv coin/ryd coin
3
4
5
6
7
8
9
10
11
FOIL THICKNESS (μg/cm^2)