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Author
Meyerhof, W.E.

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Lawrence Berkeley Laboratory
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Materials & Chemical
Sciences Division

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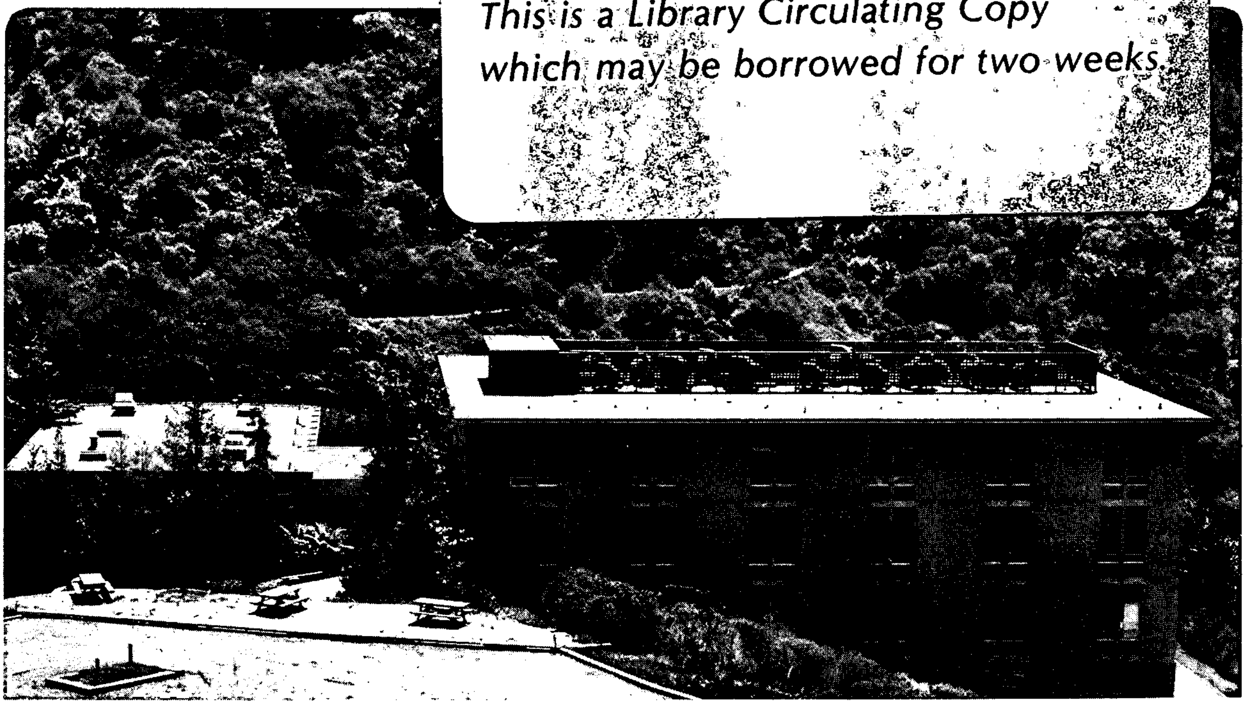

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DISCLAIMER

MULTIPLE IONIZATION AND CAPTURE IN RELATIVISTIC HEAVY-ION ATOM COLLISIONS

W.E. Meyerhof, R. Anholt, and Xiang-Yuan Xu[(a)]
Department of Physics, Stanford University, Stanford, CA 94305, USA

Harvey Gould
Materials and Molecular Research Division,
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720,
USA

B. Feinberg and R.J. McDonald
Accelerator and Fusion Research Division,
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720,
USA

H.E. Wegner and P. Thieberger
Department of Physics, Brookhaven National Laboratory, Upton, New York
11973, USA

We show that in relativistic heavy-ion collisions the independent electron model can be used to predict cross sections for multiple inner-shell ionization and capture in a single collision. Charge distributions of 82- to 200-MeV/amu Xe and 105- to 955-MeV/amu U ion beams emerging from thin solid targets were used to obtain single- and multiple-electron stripping and capture cross sections. The probabilities of stripping electrons from the K, L, or M shells were calculated using the semiclassical approximation and Dirac hydrogenic wavefunctions. For capture, a simplified model for electron capture was used. The data generally agree with theory.

1. Introduction

The transition from the two-body to the many-body system is one of the important areas of study physics. Since the two-body problem is largely solved in atomic physics, it is advantageous to investigate the atomic few-body problem, statically and dynamically. Theoretically, the simplest model to use is the independent particle model (IPM), which ignores interaction between the electrons and uses only single-particle wave functions.

We show that in relativistic heavy-ion collisions the IPM can be used to predict cross sections for multiple ionization of an ion in a single collision with good accuracy, although some systematic deviations are found at low target Z, which may point to electron correlation effects [1,2]. In general, one would expect the latter effects to show up mainly in two-electron systems and in low-Z atoms [1,2].

We also show that a special version of the IPM, which we call the infinite-sink--infinite source (ISIS) model, reproduces features of the multiple-capture cross sections for relativistic heavy-ion collisions. Multiple capture is much more complicated than multiple ionization, because in the present regime capture of an electron occurs with comparable probabilities from all filled shells of the target to many empty states of the projectile. In multiple ionization of the projectile, the active electrons can also originate from many shells, but the dominant ionization occurs in the outermost shell.

2. Multiple ionization

According to the IPM, multiple ionization and multiple excitation should follow a binomial distribution. This distribution has been observed in satellite K x-ray spectra (simultaneous K- and L-vacancy production) [3], hypersatellite spectra (simultaneous double K-vacancy production) [4], in multiple-ionization and multiple capture [5,7], and in recoil ion measurements [8,9]. To date, detailed comparisons between calculated and measured multiple-ionization or excitation cross sections have been hampered by various side effects. In K-L satellite experiments, the interpretation of the measurements is sensitive to uncertainties in the fluorescence yields for each multiple-hole configuration. In many charge changing experiments, where outer-shell ionization is dominant, one cannot use hydrogenic wave functions to describe the initial and final electron states. Also, at ion velocities generally used, wave-function distortion effects such as binding and polarization are present [10]. These effects, themselves the subject of much investigation [11], tend to obscure possible electron correlation effects in multiple ionization. Recoil ion measurements have been analyzed by a statistical approach [12].

At relativistic energies, charge changing collisions can be well described by relatively simple theories, such as the plane-wave Born approximation (PWBA) for single-electron ionization [13] and the eikonal approximation for single-electron capture [14,15]. Wave function distortion, target-electron screening, and relativistic effects on ionization are present, but can be calculated accurately [11]. For high-Z ions, Dirac hydrogenic wave functions can be used. Hence, one should be able to compute relativistic multiple-ionization cross sections with a high degree of accuracy.

A recent upgrade of the Lawrence Berkeley Laboratory BEVALAC provides uranium ions with any desired charge state up to 1000 MeV/amu [16]. The method we used to determine single- and multiple-stripping cross sections is described in Ref. [17]. Uranium ions with selected incident charge states, such as 91^+, 90^+, 89^+, 83^+, and 68^+ (1, 2, 3, 9, and 24 electrons), were accelerated to energies between 105 and 955 MeV/amu. The ions were passed through thin Be, C, mylar (My), Al, Cu, Ag, and Au foils and charge distributions were determined as a function of target thickness. The stripping and capture cross sections were determined by least squares fits of the integrated rate equations to the data [6]. Only the near linear part of the charge state population dependence on target thickness [18] was used in order to avoid excited-state effects [19].

Figures 1 and 2 show single- and multiple-electron stripping cross sections divided by Z_t^2. For 955-MeV/amu U^{68+} ions (not shown), up to sixfold ionization in a single collisions could be observed. The U^{90+} and U^{91+} single-ionization cross sections agree with measurements of Gould et al [20] made at 437 and 962 MeV/amu.

The solid curves in Figs. 1 and 2 were calculated using the IPM. If $p_s(b)$ is the one-electron ionization probability in shell s at an impact-parameter b, the probability of ionizing n electrons out of a total of N electrons in the shell is given by the binomial distribution [7]

$$P_s(n,N) = \frac{N!}{n!(N-n)!}\, p_s{}^n\, (1-p_s)^{N-n}. \qquad (1)$$

If electrons can be ejected from more than one shell, e.g. from three shells, the cross section for stripping m electrons is given by [1,2]

$$\sigma_m = \sum_{n_1+n_2+n_3=m} \int_0^\infty P_1(n_1,N_1)\, P_2(n_2,N_1)\, P_3(n_3,N_3)\, 2\pi b db \qquad (2)$$

where the subscripts 1, 2, and 3 refer to the three shells considered.

To compute σ_m, for p_s we used the semiclassical approximation (SCA) formulation of Hansteen et al [21], taking the electron binding energies for highly charged ions computed by Carlson et al [22], and Slater screened projectile charges Z_s [23]. Instead of using the cross section scaling correction factor μ defined by Hansteen et al [21], we simply normalized the calculated SCA cross sections to the PWBA [13]. Although the tables of Hansteen et al [21], are computed for non-relativistic ions, we showed previously [13] that relativistic effects on the cross section are small in the present regime. Hence, we believe that the use of non-relativistic calculations for p(b) may be reasonably valid and that our normalization procedure takes care of small discrepancies which may occur.

As is well known, for large values of the perturbing target atomic number Z_t the SCA breaks down, giving values of p_s that can exceed unity. Although the probabilities at small impact parameters are very large (which results in large multiple-ionization cross sections), for relativistic U they never exceed unity, partly because Z_t/Z_s never exceeds unity. In the actual calculations, ionization from the 1s, 2s, 3s, 3p, and 3d shells are taken into account. Binding effects, screening effects, and relativistic effects are negligible here, as will be discussed in a forthcoming publication [24].

The data shown in Figs. 1 and 2 are overall in good agreement with the IPM for multiple ionization in the K and L shells. Major evidence for multiple-ionization effects in these collisions is found not only in the multiple-ionization cross sections themselves but also in the fall-off of the reduced single-electron ionization cross section $\sigma_1/Z_t{}^2$ with increasing Z_t. In the PWBA, $\sigma_1/Z_t{}^2$ should be a constant for a given degree of ionization [11, 13]. The fall-off in $\sigma_1/Z_t{}^2$ is mainly due to the role of the unionized electrons. Requiring that only one electron be ionized, e.g., in a nine-electron ion (U^{83+}), requires that 8 electrons not be ionized, so that one has terms such as $(1-p_K)^2\ (1-p_L)^6$ in Eq. (2) for the K and L electrons. Since p_L and p_K are close to unity at large Z_t, these factors become quite small. If more electrons are present initially, the terms $(1-p_s)$ are raised to even higher powers, so that the cross-section fall-off becomes even more significant, in agreement with the observed results: in 955-MeV/amu U^{89+} and U^{83+}, $\sigma_1/Z_t{}^2$ drops by factors ~ 1/1.3 and ~ 1/3, respectively, over the Z_t range investigated.

Disagreement with the IPM for multiple ionization is apparent in U^{68+} collisions at low Z_t where we have shown that the major discrepancy is due to L-shell ionization followed by LMM Auger transitions [24]. For U^{89+} and U^{93+} (Figs. 1a and 2a), Auger transitions can make no contribution. For U^{83+} collisions (Figs. 1b and 2b), the reduced K-shell cross section is only about 2 barns and the K-shell Auger yield is less than 5 percent, so the Auger contribution is below the scale of the figures. Nevertheless, systematic deviations from the calculations remain for $m = 2$ at low Z_t. These deviations may point to possible correlation effects [1,2].

3. MULTIPLE-ELECTRON CAPTURE

The calculation of multiple-electron capture cross sections from an exact theory is complicated by the many combinations of initial and final states which must be considered in nonradiative capture in the present regimes [17]. To compare the present measurements with theory, we assume that the theoretical capture probabilities $P_c(b)$ at impact parameter b obey an "infinite-source--infinite-sink" assumption: for any given electron configuration of the target (source) or vacancy configuration of the projectile (sink), so many transitions are possible that reducing the number of electrons in the target or reducing the number of *available* vacancies in the projectile will have little effect on P_c. This assumption is partly confirmed by the experimental results shown in Figs. 3 and 4 which indicate that the single-capture cross sections in the collisions under consideration depend relatively little on q. (The assumption works best in situations where capture into excited states is dominant; it cannot be used if K → K transitions dominate, i.e., at asymptotically high projectile velocities.) On the basis of this model, in multiple capture in a single collision, the capture probability per electron is independent of the other electrons or vacancies and the m-fold capture probability is given by

$$P_m = (P_c)^m. \tag{3}$$

All statistical and unionized-electron factors, such as those in Eq. (1) for multiple ionization, are absent in this model due to the infinite-source--infinite-sink approximation. The theoretical m-fold capture cross section is then given by

$$\sigma_m^{th} = \int_0^\infty 2\pi b \, db \, (P_c)^m. \tag{4}$$

In the present model, this cross section must be interpreted as the cross section for the capture of m electrons, independent of what happens to the other electrons on the target. Hence, σ_m^{th} also contains the possibility of (m+1, m+2, ...)-fold capture. But, the experimental m-fold capture cross section σ_m^{ex}, as determined by charge state analysis, excludes all higher-order capture. Consequently, experimental and theoretical cross sections in this model are related by

$$\sigma_m^{th} = \sigma_m^{ex} + \sigma_{m+1}^{ex} + \sigma_{m+2}^{ex} \cdot \cdot \cdot \tag{5}$$

or

$$\sigma_m^{ex} = \sigma_m^{th} - \sigma_{m+1}^{th} . \tag{6}$$

To evaluate Eq. (6), we start with the OBK development of Lapicki and Losonski [25] who give theoretical expressions for K → K and L → L capture probabilities and on the relativistic treatment by Moiseiwitsch and Stockmann [26] who treat only the K → K case. As is well known, OBK cross sections for single capture differ up to an order of magnitude from experiment [14]. Probably, the OBK capture probability also has an incorrect impact parameter dependence, although this has not been tested in the present velocity and Z_p, Z_t regime. For these reasons, it is unavoidable that our model should contain an empirical fitting factor.

Following Ref. [25], we write for the theoretical differential single-capture cross section

$$d\sigma_1^{th} = P_c(b)\ 2\pi b\ db = \sigma_1^{th}\ W(x)\ x\ dx, \tag{7}$$

where

$$x = qb \tag{8}$$

and

$$\int_0^\infty W(x)\; x\; dx = 1. \tag{9}$$

Hence,

$$P_c(b) = \sigma_1^{th} q^2\, W(x)/2\pi. \tag{10}$$

The treatment of Ref. [26] and a rederivation by Eichler [27] of the results of Ref. [25] for the relativistic velocity regime show that a relativistically correct expression for q^2 can be written as

$$q^2 = p_-^{\,2} + U_t/I_0, \tag{11}$$

$$p_- = \frac{1}{2I_0}\,\frac{\alpha}{\beta}\left[\frac{mc^2-U_p}{\gamma} - (mc^2-U_t)\right], \tag{12}$$

where U_t and U_p are the electron binding energies in the target and projectile, respectively, $\beta = v/c$ (v = projectile velocity, $\gamma = (1-\beta^2)^{-1/2}$, I_0 is the lectron binding energy in H, and α is the fine structure constant.

From Eq. (4) it now follows that in the present model the theoretical cross section for m-fold capture can be expressed in terms of the single-capture cross section as

$$\sigma_m^{th} = \sigma_1^{th}(f\sigma_1^{th} q^2/2\pi)^{m-1} \int_0^\infty W^m\, x\, dx\;. \tag{13}$$

Because the OBK is not a correct theory, and because many transitions contribute to capture, we have introduced in the right side of Eq. (13) a factor f^{m-1} where f is assumed to be an empirical constant. Comparisons is now made with experiment using the relation, based on Eq. (6),

$$\sigma_m^{ex} = (\sigma_m^{th} - \sigma_{m+1}^{th})/(\sigma_1^{th} - \sigma_2^{th})\; \sigma_1^{ex} \tag{14}$$

and substituting for σ_1^{th} the expression given in Eq. (4) with $m = 1$.

In comparing Eq. (14) with our experimental results for 105- and 220-MeV/amu U projectiles and earlier unpublished results [17] for Xe (Figs. 3 and 4), we have found that satisfactory cfits can be obtained by assuming that transitions to the projectile L shell dominate in these capture processes as suggested by detailed eikonal calculations. We used experimental $L_{1,2}$ binding energies U_t for the target calculations of Carlson et al [22] for the L binding energies of partially stripped projectiles. For W we used W_{LL} from Eq. (A11) of Ref. [26] and found that a factor $f = 0.15$ gives the best overall fit to the experimental multiple-capture cross sections.

As one can see from Figs. 3 and 4, the proposed model reproduces the trends of the experimental cross sections satisfactorily. In particular, it explains the approximately exponential decrease of the cross sections with increasing multiplicity of the capture, and the steepening of the falloff with decreasing Z_t and with increasing projectile velocity.

4. CONCLUSIONS

Multiple-electron ionization and capture in relativistic heavy-ion collisions are amenable to calculations. Overall, the independent-electron approximation is in good agreement with the ionization data. This suggests that electron correlation effects must be small at least for high-Z targets, where larger cross sections make the data more accurate. For multiple-electron capture, which is a complex process, a simplified model explains the main trends of the cross section dependence on target atomic number and on projectile energy.

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(a) Permanent address: Department of Physics, Tsinghua University, Beijing, Peoples' Republic of China.

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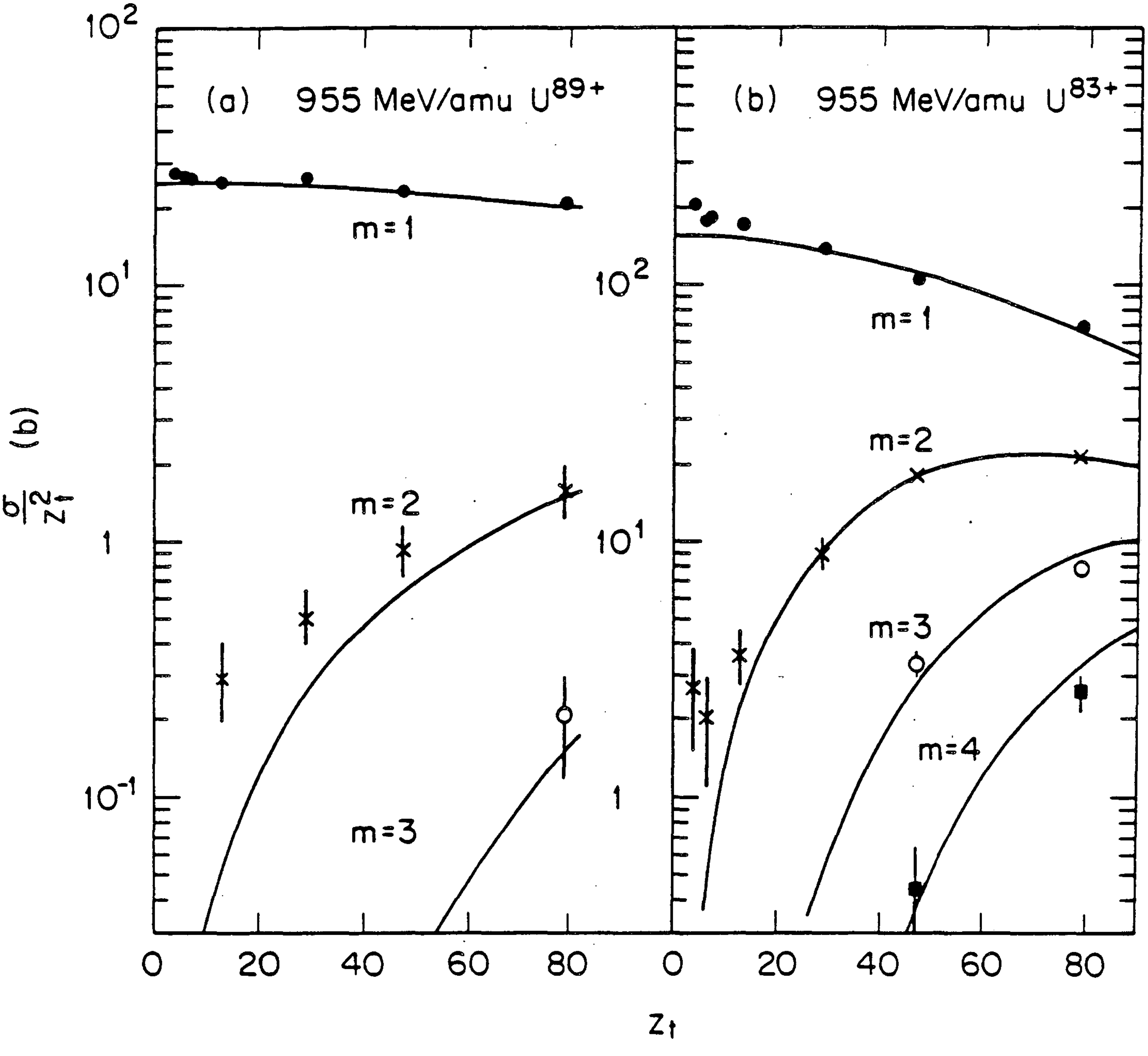
Figure Captions

Fig. 1. Single and multiple stripping cross sections for 955-MeV/amu U^{89+} (one L-shell electron) and U^{83+} (7 L-shell electrons) projectiles passing through various target foils as a function of the target atomic number (Z_t). The cross sections in barns have been divided by Z_t^2. On each curve, m indicates the multiplicity of the stripping process. The solid curves show the independent-electron approximation results.

Fig. 2. Same as Fig. 1, for 430-MeV/amu U^{90+} and U^{83+} projectiles.

Fig. 3. Multiple-capture cross sections of various charge states of 105- and 220-MeV/amu U ions passing through Al, Au, Ag and Au target foils, as a function of the multiplicity (m) of the capture. The theoretical curves are based on the "infinite-source--infinite-sink" model and are normalized to the experimental values at $m = 1$.

Fig. 4. Same as Fig. 3, but for 82-, 140-, and 200-MeV/amu Xe ions. No Al data is available in this case.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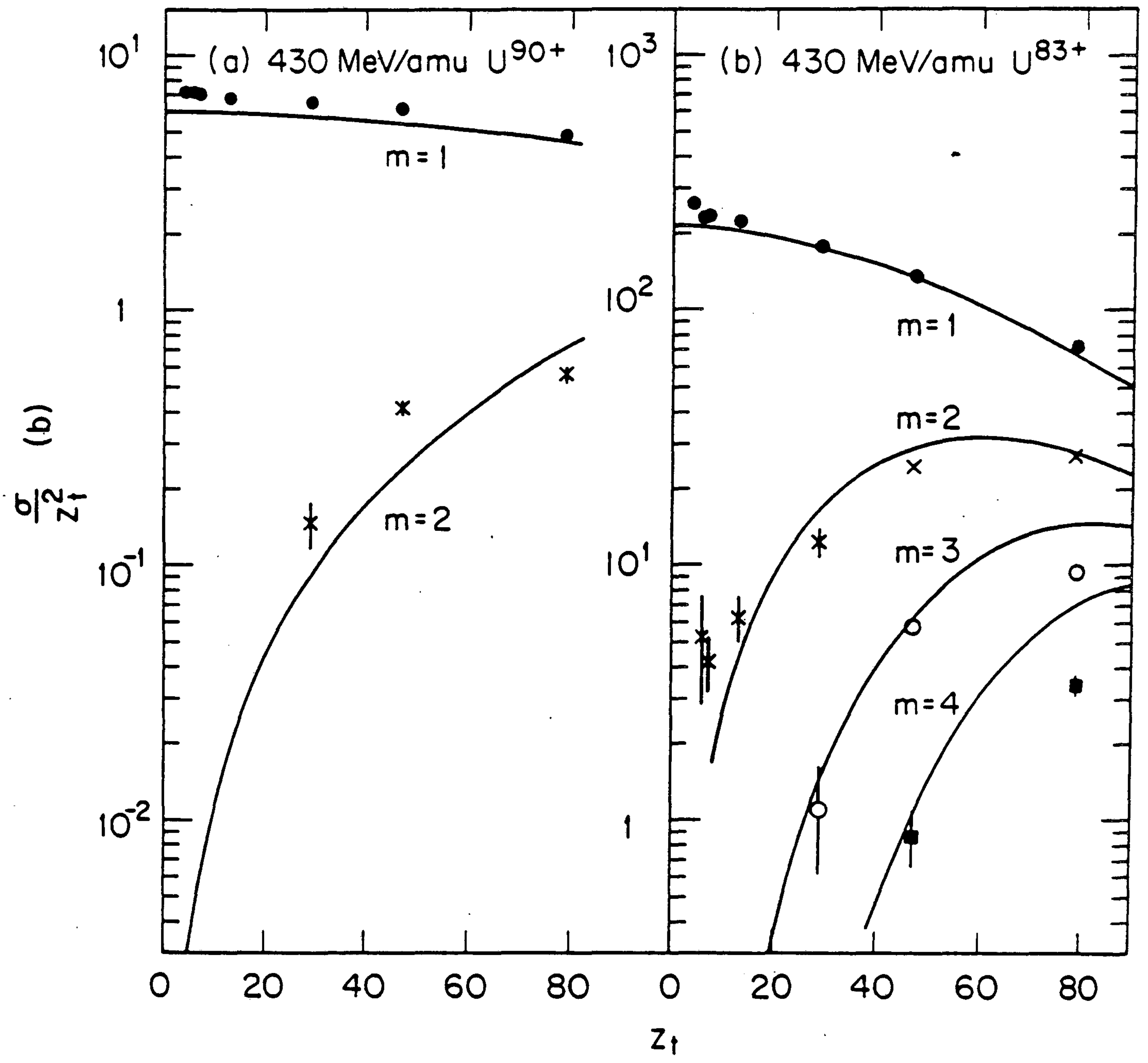
(b) 955 MeV/amu U^{83+}
10^2
10^1
1
10^{-1}
10^2
10^1
1
m=1
m=2
m=3
m=4
$\frac{\sigma}{Z_t^2}$ (b)
0
20
40
60
80
Z_t


(a) 430 MeV/amu U^{90+}
(b) 430 MeV/amu U^{83+}
m = 1
m = 2
m = 3
m = 4
$\frac{\sigma}{Z_t^2}$ (b)
Z_t
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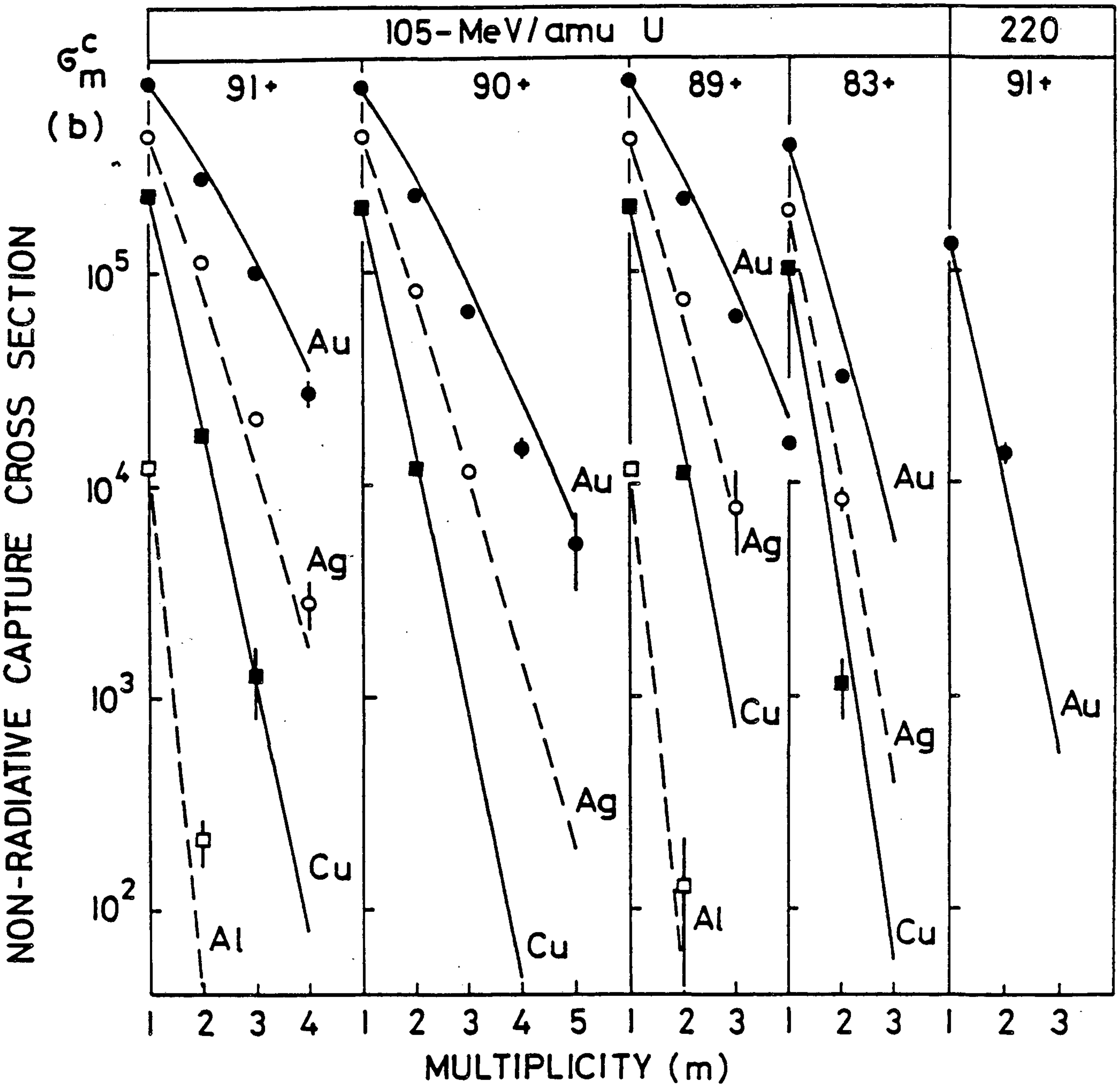
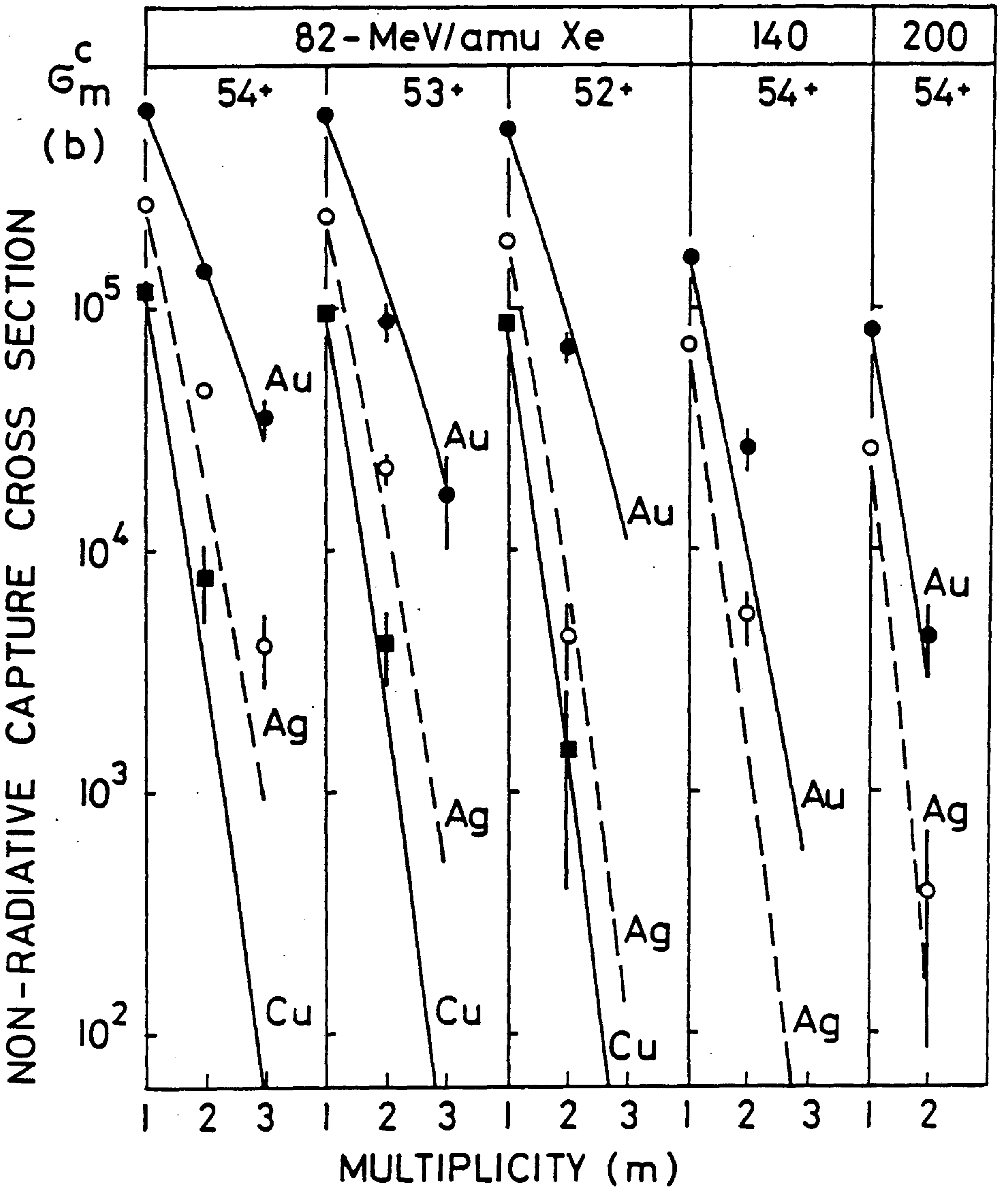
1
10^{-1}
10^{-2}
10^3
10^2
10^1
1
0
20
40
60
80


105-MeV/amu U
220
σ_m^c
(b)
91+
90+
89+
83+
91+
NON-RADIATIVE CAPTURE CROSS SECTION
10^5
10^4
10^3
10^2
Au
Ag
Cu
Al
1 2 3 4
1 2 3 4 5
1 2 3
1 2 3
1 2 3
MULTIPLICITY (m)


82-MeV/amu Xe
140
200
54+
53+
52+
54+
54+
G_m^c (b)
NON-RADIATIVE CAPTURE CROSS SECTION
10^5
10^4
10^3
10^2
Au
Ag
Cu
1
2
3
MULTIPLICITY (m)

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