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CORRELATED TWO ELECTRON EFFECTS IN COLLISIONS OF MULTIPLY CHARGED Au IONS WITH He

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Abstract

We have studied the fate of electrons released in collisions between highly charged Au^{q+} ions (20 MeV) and He atoms and find that the large transfer ionization (TI) cross section observed can be accounted for by transfer of two electrons to a highly correlated state on the Au projectile followed by the loss of one electron to the continuum. Autoionization lines are also observed, but they are attributable to electron transfer accompanied by core excitation (TE).

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At first sight, the study of collisions of highly charged 20-MeV gold ions with helium atoms would hardly seem an appropriate test-bed for fundamental interactions of correlated two-electron systems. The apparent complexity of this system is considerably mitigated when viewed from the proper perspective. First, 20-MeV Au ions are moving at velocities comparable to the orbital velocity of the 1s electrons in He. Second, if the ionic charge is large enough, charge transfer from the target will take place to high n states. For large enough n, the core configuration becomes relatively unimportant and the charge transfer cross section to a given $n\ell$ state depends only on ion charge, i.e. the behavior of Au^{14+} will be quite close to Si^{14+} or U^{14+} at the same velocity. Finally, the He target atom contains only two electrons which may act either as independent particles or together as a correlated pair.

The effect of the two electron interaction is easily seen in the large values of the transfer ionization cross section reported for this system [1]. In Fig. 1, the cross sections for various charge-changing cross processes in the system 20-MeV Au^{8+} + He are shown as a function of q (q=5-21). The superscripts refer to the initial, and final charge of the He and subscripts to the initial and final Au charge states. As one would expect, simple charge transfer $\sigma^{01}_{q,q-1}$ increases with increasing q. Most noteworthy is the increase in transfer ionization, $\sigma^{02}_{q,q-1}$, with q (note that the other cross sections for two electron loss from He, $\sigma^{02}_{q,q-2}$ and $\sigma^{02}_{q,q}$ are lower than σ^{02}_{q-1} by more than an order of magnitude for q > 15).

The TI cross section approaches half the value of simple charge transfer and reaches $\sim 10^{-15}$ cm^2 at $q = 16$!

To investigate the nature of the two electron correlation in these processes, we collided Au^{q+} at 20 MeV ~100 keV/a with He and measured the spectrum and yield of ejected electrons moving in the rest frame of the Au in coincidence with the charge state of the emergent Au ion [2]. The apparatus is pictured in Fig. 2. The Au-ion beam was provided by the Aarhus EN tandem accelerator. The desired charge state beam is magnetically selected and cleaned of impurities immediately before the target-gas cell by a 3° deflection. The target gas was contained in a 4-mm-long cell located at the focus of a 30° parallel-plate spectrometer which energy analyzed the electrons emitted in the forward direction. The spectrometer had an acceptance angle of 3.4° and an energy resolution of $\lesssim 1\%$ (full width at half maximum). The transmitted ion beam could be measured in a Faraday cup or be charge analyzed by a set of electrostatic plates and then detected in a ceramic channel-electron multiplier which was capable of counting up to 10^5 ions/sec.

Figure 3 shows electron spectra obtained with Au^{17+} ions. The singles spectrum at the top of the figure displays two features: a peak at 54 eV made up of electrons with velocities corresponding to zero velocity in the rest frame of the 20 MeV Au ions and a symmetric set of small peaks corresponding low energy autoionizing electrons leaving the Au core in the forward and backward laboratory directions.

From the coincidence spectra, it can be seen that the observed autoionizing electrons are all associated with Au^{15+} and hence with transfer plus excitation (TE), i.e.

$$Au^{q+} + He \rightarrow [Au^{(q-1)+}]^{**} + He^{+} \rightarrow Au^{q+} + He^{+} + e \,.$$

The positions of the autoionization lines vary with Au charge state [3], but they are independent of collision partner and thus characteristic of a single core configuration. This can be seen in Fig. 4 which shows coincidence 15→15 spectra for H_2, He, and Au targets.

Transfer ionization is defined as the loss of a larger number of electrons from the target than are transfered to the projectile. In the case a helium target

$$Au^{q+} + He \rightarrow Au^{(q-1)+} + He^{++} + e$$

the occurrence of a free electron in coincidence with a bound state capture implies the formation of He^{++}. The spectrum of these electrons is shown in the bottom portion of Fig. 3 for q = 17. It remains to determine what fraction of all TI events can be accounted for by elecrons contained in this cusp and to see what information may be gained from the spectral shape.

To convert the yield of cusp electrons to a cross section, we adapted the procedure formerly used by Vane et al. [4]. We used lower charge state ion Au^{7+}(20 MeV) and measured its electron loss cross section in collision with He; $\sigma_{7,8} = 7.8 \times 10^{-17}$. Using the same Au^{7+} ion, we then measured the cusp yield in coincidence with charge 8+. Since this is an ionization event, i.e. an electron loss to the continuum (ELC), all the released electrons should be contained in the cusp distribution. Using this normalization procedure, we found a cross section for the cusp electrons in e.g. the 15+ → 14+ TI spectrum to be 6 x 10^{-16} cm^2. This, when compared with 7 x 10^{-16} cm^2, the measured $\sigma^{02}_{q,q-1}$ for Au^{15+} can account for approximately the entire TI cross section.

We can now consider the spectral shape of the TE associated cusp. The absence of any discernable line structure precludes contributions from transfer of two electrons into well defined (independent electron) states followed by autoionization. We are left with a simple cusp structure but considerable information can be obtained from cusp shapes [5]. Two generic cusp shapes exist. Electron capture to the continuum (ECC) gives rise to an asymmetric peak with an enhanced yield on the low energy side of the cusp. Electron loss to the continuum (ELC), on the other hand, gives a symmetric peak as was obtained, e.g. in our 7+ → 8+ coincidence spectrum. Remarkably, our 15+ → 14+ TI cusp has the ELC shape. This is better illustrated in Fig. 5 where we have transformed coordinates to the rest frame of the moving ion.

The TI process, in our case, involves two electrons which are transfered to the moving ion followed by the loss on one electron to the continuum. A number of models have been proposed to explain this phenomenon. The classical trajectory Monte-Carlo method in which no correlation effects are taken into account gives cross sections which are much too low for $q > 10$ [3]. In the "potential barrier model" (PBM) of McDowell and Janev [6] transfer ionization ic accounted for in terms of transfer of two electron to a doubley excited state which then autoionizes. The predicted PBM cross sections are close to experiment (~ a factor of 2 too large) for q = 16 → 21 and, if one could account for the continuum nature of the electron emission, might explain two results. A variant of this approach stipulates that the two electrons enter a projectile state which is highly correlated: the size of the two electron wavepacket is close to that of the He atom which is much smaller than that for two corresponding, but uncorrelated electrons. The specially correlated state autoionizes, and as a result of the short lifetime, the electrons are emitted with a continuous energy spectrum.

In an alternative explanation, we take into account the flatness of the electron energy distribution over the measured region (Fig. 6) which suggests a similarity to the process of ionization near threshold ((e,2e) wherein two electrons share the total available energy in a so-called Wannier state. The electrons dispose themselves on opposite sides of the nucleus and move apart along a line. In our case, we use a two-dimensional model to obtain an insight into the four-body Coulomb problem, i.e. two electrons in the field of two nuclei. To illustrate, we consider the potential surface for two electrons confined to the line of joining nuclei of charges 2+ and 16+ separated by a distance 10 a_0. In Fig. 6 we plotted a contour map of this surface in the plane generated by the coordinates of the two electrons relative to the helium nucleus; this represents a natural generalization of the hyperspherical plane used in discussions of threshold phenomena.

The quadrant IV contains the saddle point X associated with single-electron capture, but two-electron capture would more likely proceed via the ridge R or the pass P in quadrant I. In the latter case, the electrons would plausibly end up on the ridge W (quadrant II) which is the Wannier ridge associated with an almost isolated Au nucleus. On these grounds, we can conjecture that the energy distribution of cusp electrons should be predicted by Wannier theory which should apply whether both electrons are free or bound. It should be emphasized that this model, as yet, contains no dynamics, i.e. quasiadiabatic motion on the potential surface is assumed. The feasibility of numerical solutions to the model is being assessed.

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Figure Captions

Fig. 1. Partial cross sections for 20 MeV Au^{q+} (q=5-21) colliding with He.

Fig. 2. Schematic drawing of the apparatus; insert shows the target region and the spectrometer.

Fig. 3. Double-differential cross sections in the laboratory frame as a function of electron energy for 20-MeV Au^{17+} on He.

Fig. 4. Coincidence - electron-energy spectra of electrons emitted in the forward direction for 20-MeV Au (15+ → 15+) on H_2, Ar and He targets. Lines are drawn to guide the eye.

Fig. 5. Double-differential cross sections in the rest frame of the projectile as a function of electron energy. Shown are the experimental data for 11+ → 11+ (ECC) and 15+ → 14+ TI. (See Ref. 3 for explanation of fitted curves.)

Fig. 6. Potential energy contours at 0.3 a.u. (8.1 eV) intervals for two electrons in the field of charges 2+ and 16+ separated by 10 a_0. The coordinates z_1 and z_2 represent distances of the electrons from the 2+ nucleus. Thus, the points He' represents both electrons on the He nucleus and Au' both electrons on the Au nucleus. The quadrants correspond to the linear configurations: I(He-e-e-Au), II(He-e-Au-e), III(e-He-Au-e), and IV(e-He-e-Au).

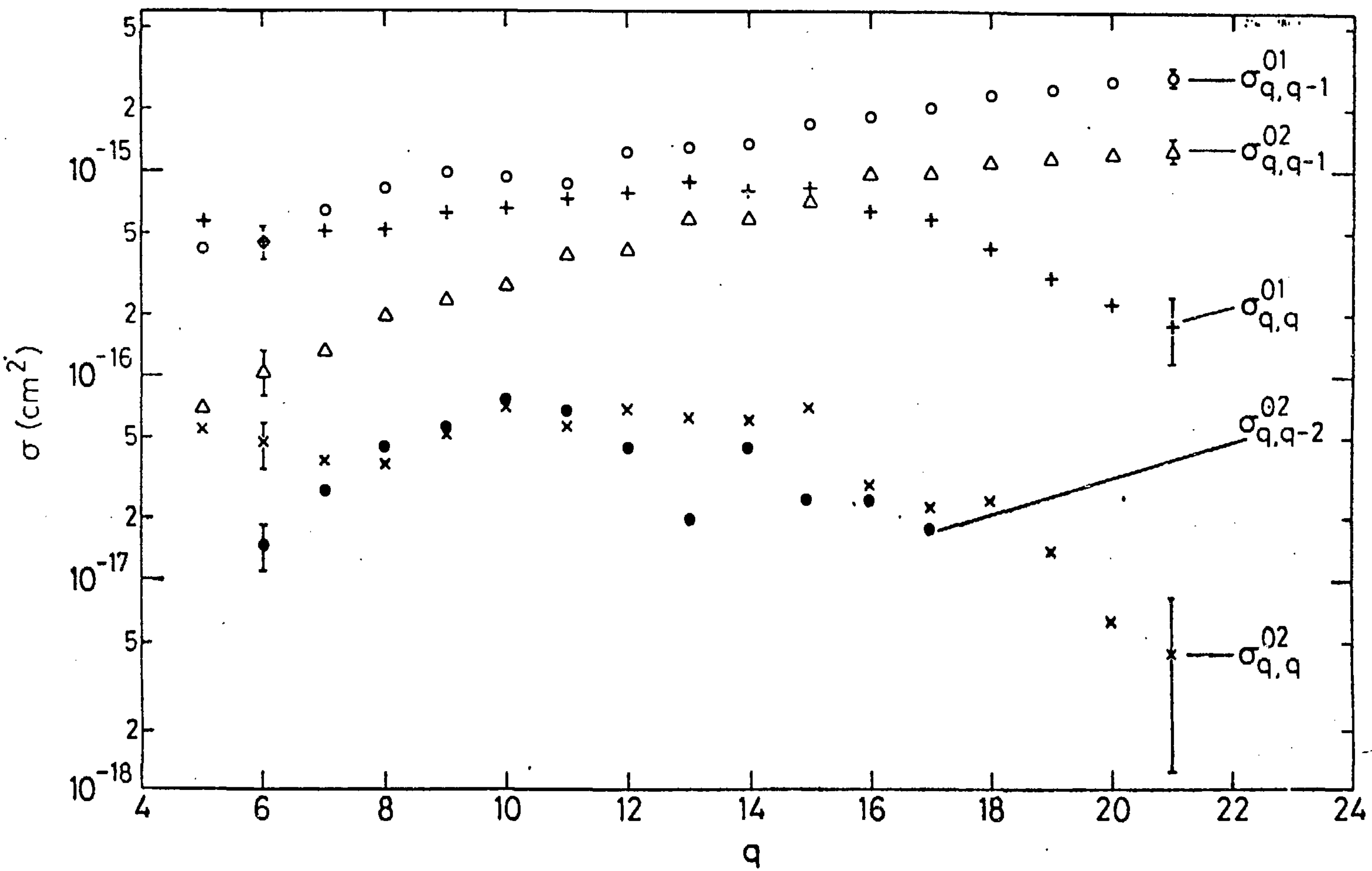


Fig. 1

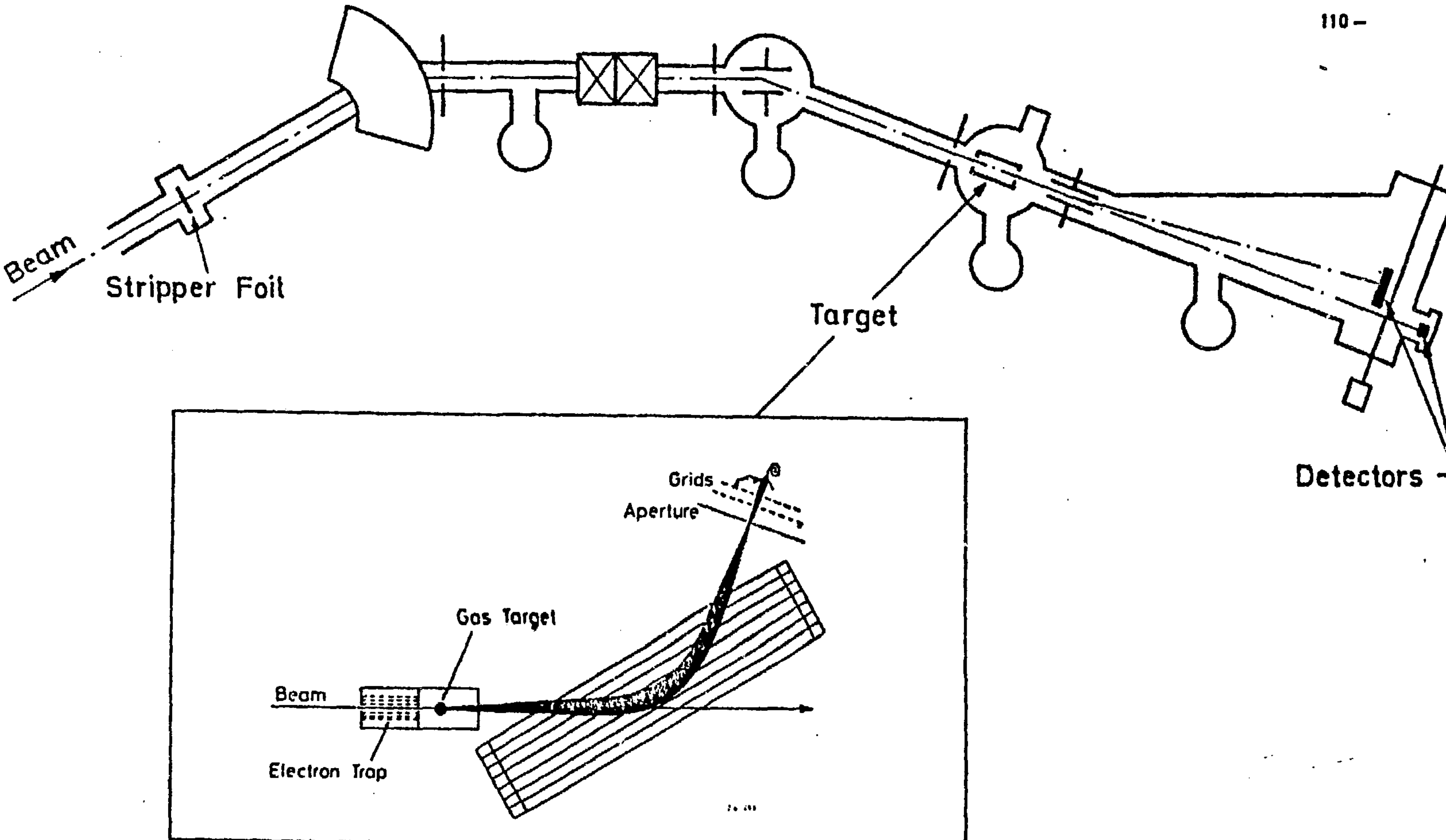

Beam
Stripper Foil
Target
Detectors
Grids
Aperture
Gas Target
Beam
Electron Trap

Fig. 2

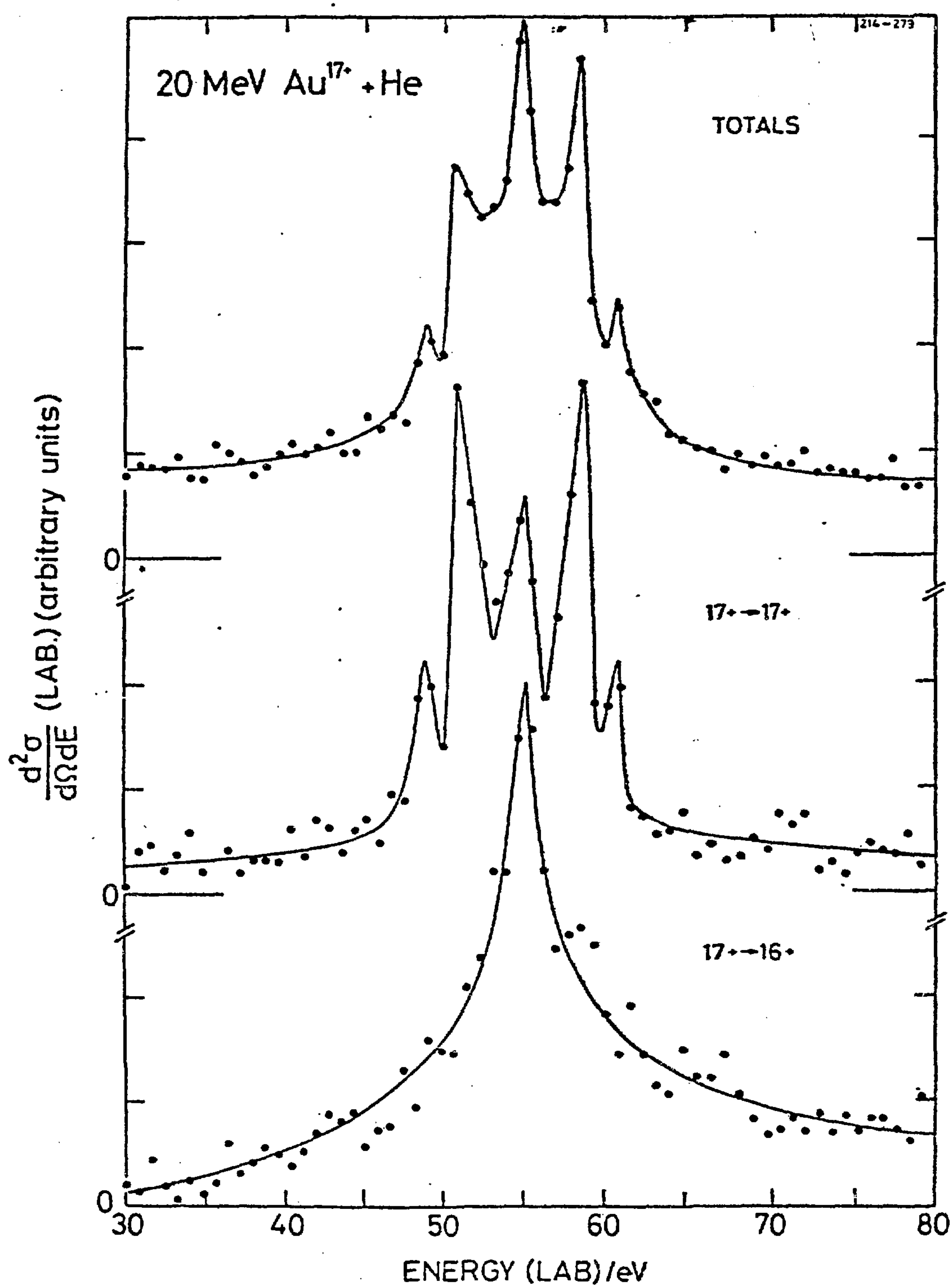
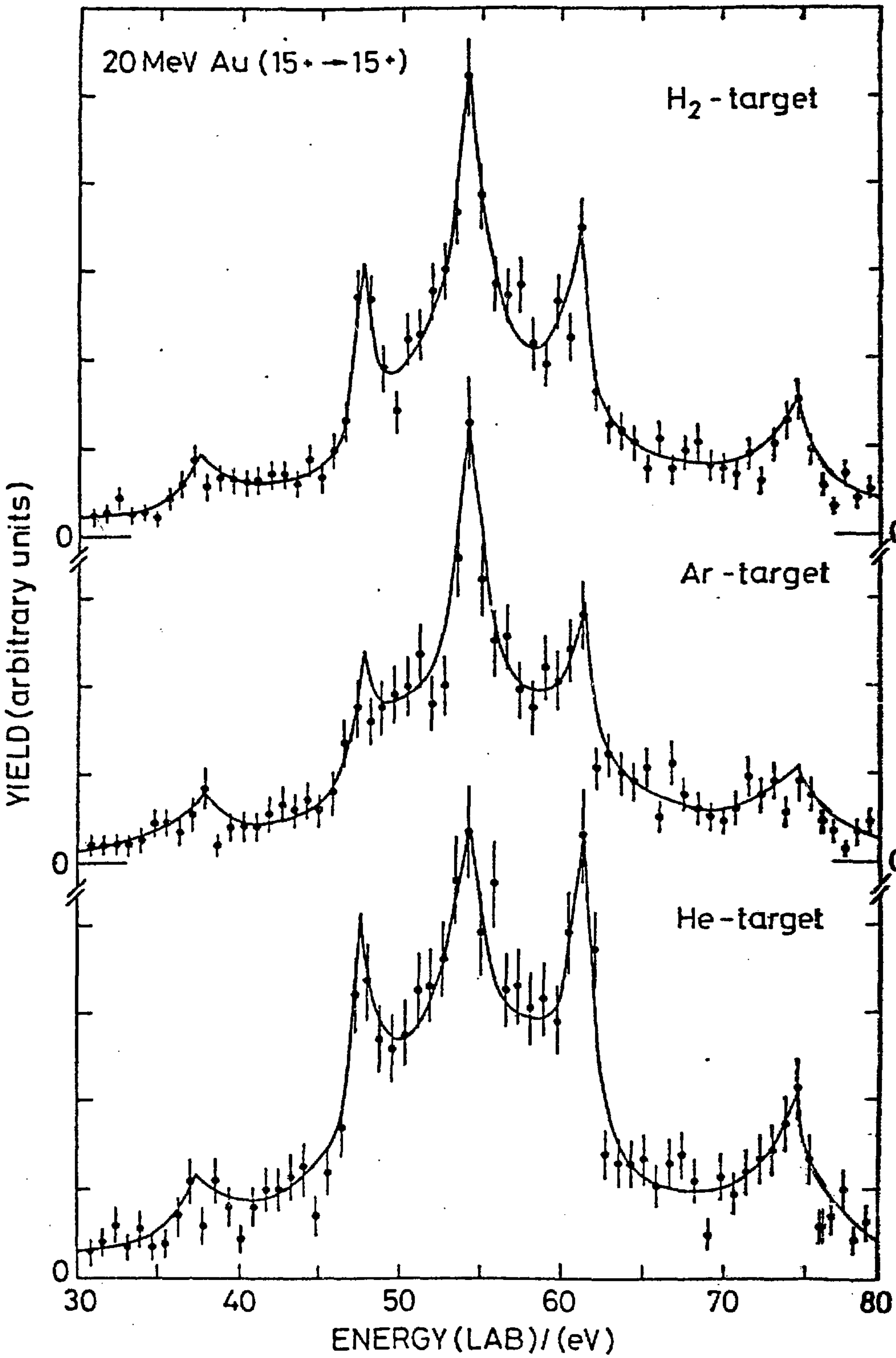
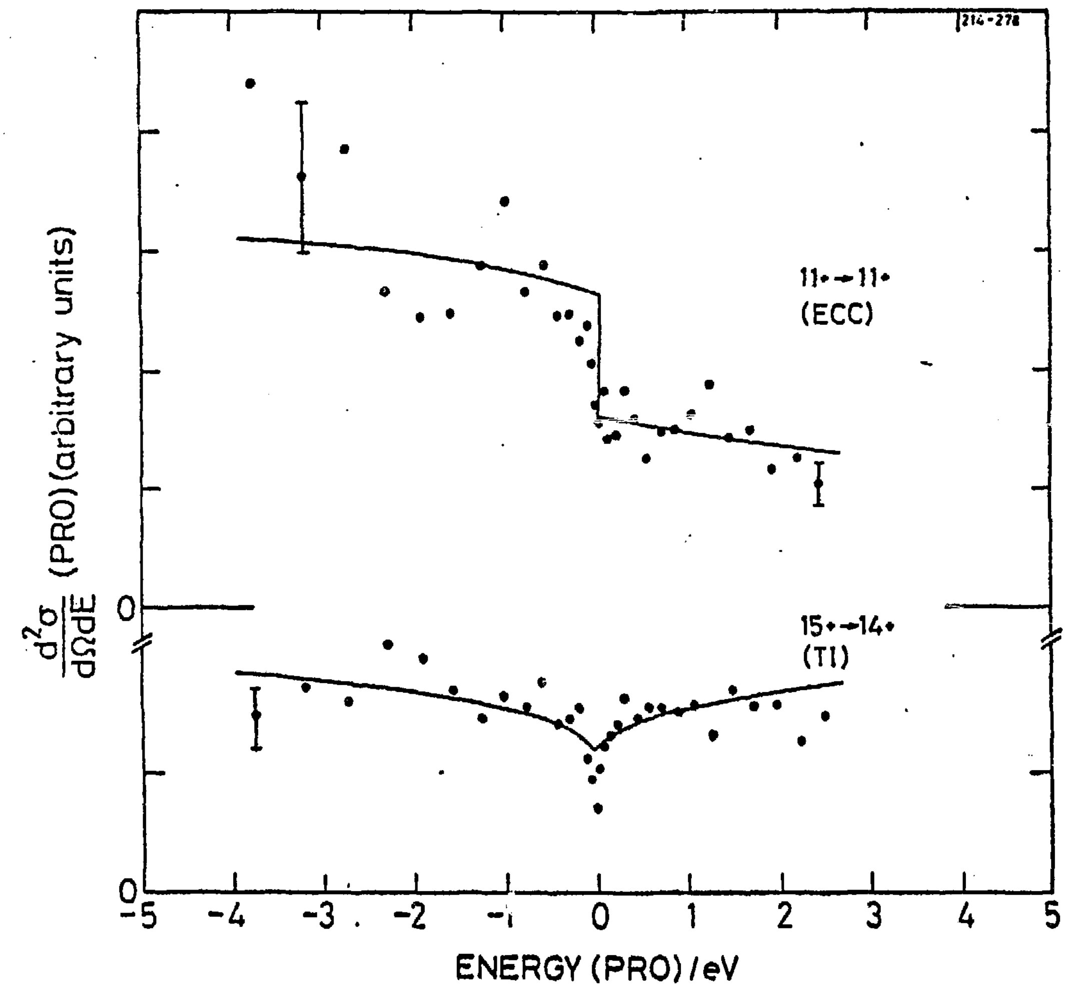

20 MeV Au17+ + He
TOTALS
17+→17+
17+→16+
0
0
0
30
40
50
60
70
80
ENERGY (LAB)/eV
d²σ/dΩdE (LAB.) (arbitrary units)
214-273

Fig. 3



20 MeV Au (15+ → 15+)
H_2 - target
Ar - target
He - target
YIELD (arbitrary units)
0
0
0
0
0
30
40
50
60
70
80
ENERGY (LAB) / (eV)

Fig. 4



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11+→11+
(ECC)
15+→14+
(TI)
0
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
ENERGY (PRO) / eV
$\frac{d^2\sigma}{d\Omega dE}$ (PRO) (arbitrary units)

Fig. 5

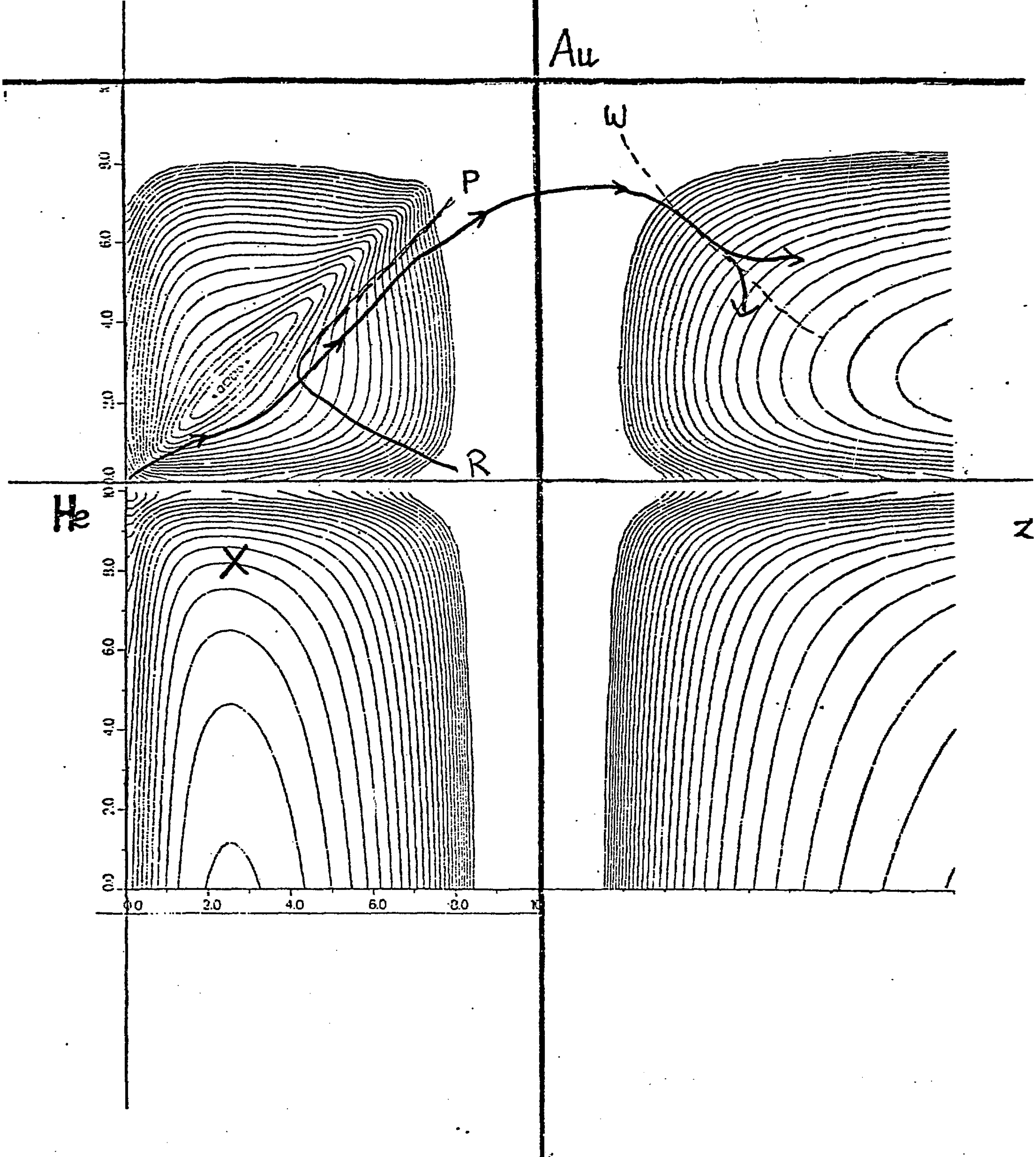

Fig. 6