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Resonant Coherent Excitation of Mg^{11+}: Electronic Collisions of State Specified Short-lived Excited States in a Crystal Channel

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Abstract

Hydrogenic ions passing through axial and planar channels can be excited from $n = 1$ to $n = 2$ when the frequency of perturbation by the atoms in the crystal spaced a distance d apart comes into resonance with the spacing between eigenstates i and j,

$$\Delta E_{ij} = hK(v_i/d)$$

where K is a harmonic 1,2,3 ... of the (v_i/d) frequency. The degeneracy in the $n = 2$ levels is removed; first by the assymetry in the crystal field and second by Stark mixing of $2s$ with $2p_z$ (z being the direction of ionic motion) which is caused by the wake field. Thus, the resonant frequency, and hence velocity, for excitation to $2p_{x,y}$ is different than that for $2p_z$ and they can be excited selectively.

In the present work we used Mg^{11+}, where the $n = 2$ ionization cross section is small enough to permit escape of some of the excited ions from the crystal without being ionized by subsequent collisions and with the subsequent emission of radiation. Since we can excite different orientations (m states) of the ion selectively by varying the velocity we can measure the separate ionization cross sections for these states by determining the yields of totally stripped ions compared to those which emit a Ly α X-ray. A comparison of the two channels shows that the probability of escape from the crystal without ionization is greater for ions in the $2p_z$ state than those in the $2p_{x,y}$ state. These RCE data and are presented as proof of principal for experiments which measure electron bombardment ionization cross sections for short lived excited states with specific polarization.

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Hydrogenic ions passing through axial and planar channels can be excited from $n = 1$ to $n = 2$ when the frequency of perturbation by the atoms in the crystal spaced a distance d apart comes into resonance with the spacing between eigenstates i and j,

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In previous experiments on C, N, O and F hydrogenic ions [1-4] the effect was observed by measuring the enhancement of the ionization probability for the ion passing through a channel in a thin crystal, i.e. the probability of ionization from the $1s$ state by collision with electrons in the channel is sufficiently low for these ions that a large fraction pass through without ionizing. However, promotion to an $n = 2$ state raises the ionization cross section ($\sim$ a factor of ten) so that the probability of ionization in the target for low z ions approaches unity.

In the present work we used Mg^{11+}, where the $n = 2$ ionization cross section is small enough to permit escape of some of the excited ions from the crystal without being ionized by subsequent collisions and with the subsequent emission of radiation. Since we can excite different orientations (m states) of the ion selectively by varying the velocity we can measure the separate ionization cross sections for these states by determining the yields of totally stripped ions compared to those which emit a Ly α X-ray.

The Mg^{11+} ions with energies ranging from 135 to 167 MeV were obtained from the Holifield Heavy Ion Research Facility at Oak Ridge National Laboratory and were passed through an Au crystal 2000 Å thick in the $< 100 >$ axial direction. Observations were

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made of the Mg K X-ray yields using a Si(Li) detector placed at 45° to the beam and of the emergent charge state distributions. The emergent charge state distributions were measured using magnetic analysis and a position sensitive detector.

The beam leaving the crystal was collimated before entering the analysing magnet and measurements of the charge state distributions were made with two collimator slit settings. The first, with a slit setting allowing emergent angles of ±2 mr which sampled ions which passed close to the channel center is shown in Fig. 1. The second, with slits set to ±4.5 mr which allowed essentially all channeled ions into the detector, is shown in Fig. 2. The results of the X-ray measurements are shown in Fig. 3. Since no collimation was involved for the X-ray measurements the comparison with ionization is best made with Fig. 2.

Before discussing the resonance let us consider the secular trends in the ionization data and the information that can be obtained from the fraction of ionization concerning the electron density and hence impact parameter regions sampled by these ions. An ion passing through a channel can either be ionized directly or it may undergo collisional excitation and then be ionized in a second collision.

For direct ionization we can use the Lotz formula to estimate the cross section

$$\sigma_i = 4.5 \times 10^{-14} \frac{ln(E_e/I)}{(E_e I)} \text{ cm}^2$$

where E_e is the electron energy and I is the ionization potential, both in eV. At an Mg^{11+} ion energy of 160 MeV = 6.7 MeV/amu the equivalent electron bombardment energy is $\sim$ 3600 eV. Thus for ionization from $n = 1$ ($I_1 = 1960$ eV), $\sigma_i(n = 1) = 4 \times 10^{-21}$ cm^2 for $n = 2$ ($I_2 = 490$ eV), $\sigma_i(n = 2) = 5 \times 10^{-20}$ and for $n = 3$ ($I_3 = 218$ eV), $\sigma_i(n = 3) = 2 \times 10^{-19}$.

Excitation cross sections may be obtained using the Seaton formula and for $\Delta n = 1$ transitions one obtains in units of cm^2

$$\sigma_e(n = 1 \rightarrow 2) \sim 7 \times 10^{-21} \text{ and } \sigma_e(n = 2 \rightarrow 3) \sim 1 \times 10^{-19}$$

and for $\Delta n > 1$ one obtains

$$\sigma_e(n = 1 \rightarrow n > 2) \sim 2 \times 10^{-21} \text{ and } \sigma_e(n = 2 \rightarrow n > 3) \sim 3 \times 10^{-20}.$$

Since cross sections for ionization for $n \geq 3$ are very large we can assume that such excitation is equivalent to ionization. Then the ionized fraction f_i after passing through a target of thickness ℓ and density ρ is given by

$$f_i \simeq (\frac{\ell\rho}{2})^2 \{\sigma_e(n = 1 \rightarrow 2)[\sigma_i(n = 2) + \sigma_e(n = 2 \rightarrow \geq 3)]\} + (\ell\rho)[\sigma_i(n = 1) + \sigma_e(n = 1 \rightarrow > 2)]$$

for the case of the narrow slits (±2 mr acceptance) $f_i \simeq 0.145$ which for $\ell = 2000$ Å gives a density of $\rho_e = 0.7/\text{Å}^3$, for the wide slits (±4.5mr) $f_i \simeq .24$ we obtain $\rho_e = 1.0/\text{Å}^3$. If we now refer to the tabulated density distributions in Au we find the corresponding distances from the Au nuclei are 1.05 and .95 Å respectively; both of which are well outside the first inner shell of Au. Ions passing at smaller impact

parameters with respect to the string should undergo rapid charge exchange and attain charge equilibrium which favors capture to Mg^{10+} and not ionization to Mg^{12+} in this energy region. If we now turn our attention to the X-ray yields (Fig. 3) we see that the secular trend varies as 1/E as would be expected for collisional excitation for $n = 1 \rightarrow 2$ well above threshold. But, without coincidence measurements made with ions traveling along the same trajectories, it is difficult to assign a meaning to absolute X-ray yields when compared to absolute yields of stripped ions.

In the X-ray data two peaks are clearly discernable at 159 and 161 MeV, respectively. the vacuum level for $n = 1 \rightarrow 2$ resonance excitation should appear at a velocity v_r corresponding to an ion energy of 163 MeV. The crystal field shifted levels give resonances here at $v/v_r = 0.988$ and 0.994, respectively. In accordance with our earlier work we associate the lower peak with excitation to the $2p_{x,y}$ state and the upper one with excitation to the $2p_z$ state. If we now compare the X-ray yield data with the charge state data of figs 1 and 2 we see that the upper $2p_z$ peak is almost entirely absent from the ionization data. One can infer from this comparison that ions excited into the $2p_z$ state are more likely to escape from the crystal without being ionized than those excited to the $2p_{x,y}$ state.

This effect may be ascribed to one or more of the following causes.

1. For a given electron flux, the ionization cross section for an electron in an orbital which is perpendicular to that flux is greater than for one which is parallel to it.

2. Since the $2p_{x,y}$ wave function extends out toward the atomic strings (i.e. higher electron density), the electron flux bombarding the excited electron may be larger than that experienced by an electron excited to $2p_z$ at the same transverse point in the channel.

3. Excitation to $2p_{x,y}$ states is more likely to take place at closer distances to the strings than $2p_z$ and hence $2p_{x,y}$ ions experience a higher electron flux.

To determine in detail how these factors contribute to the observed effects will require additional experimental work (coincidence measurements) and further theoretical development.

In summation, comparison of the two channels clearly shows that the probability of escape from the crystal without ionization is greater for ions in the $2p_z$ state than those in the $2p_{x,y}$ state. These RCE data are presented here as proof of principal for experiments which may be used to measure electron bombardment ionization cross sections for short lived excited states with specific polarization.

The authors gratefully acknowledge Dr. Elliot Kanter of Argonne National Laboratory, for his loan of the Au crystal used in these experiments.

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Figure captions

Fig. 1. Charge fraction of Mg^{12+} emerging from a Au < 100 > channel 2000 Å-thick as a function of entering Mg^{11+} ion energy. Entrance slits to charge state analyser set to accept ±2 mr.

Fig. 2. Charge fraction of Mg^{12+} emerging from a Au < 100 > channel 2000 Å-thick as a function of entering Mg^{11+} ion energy. Entrance slits to charge state analyser set to accept ±4.5 mr.

Fig. 3. Yield of Mg^{11+} Ly α X-rays as from 2000 Å-thick Au < 100 > channeled Mg^{11+} ions as a function energy. The crosses and the rounded points represent two separate energy scans.

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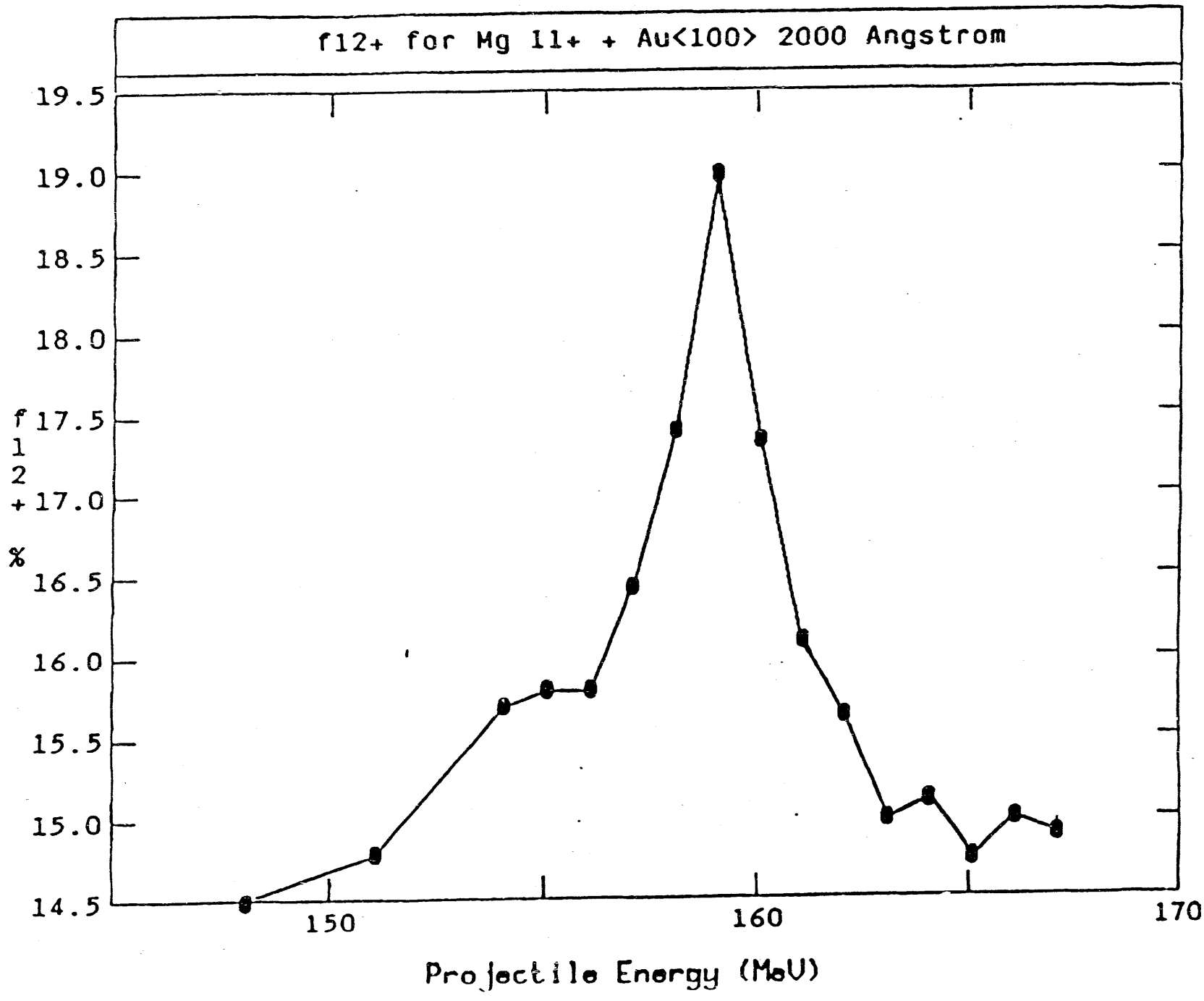
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19.5
19.0
18.5
18.0
17.5
17.0
16.5
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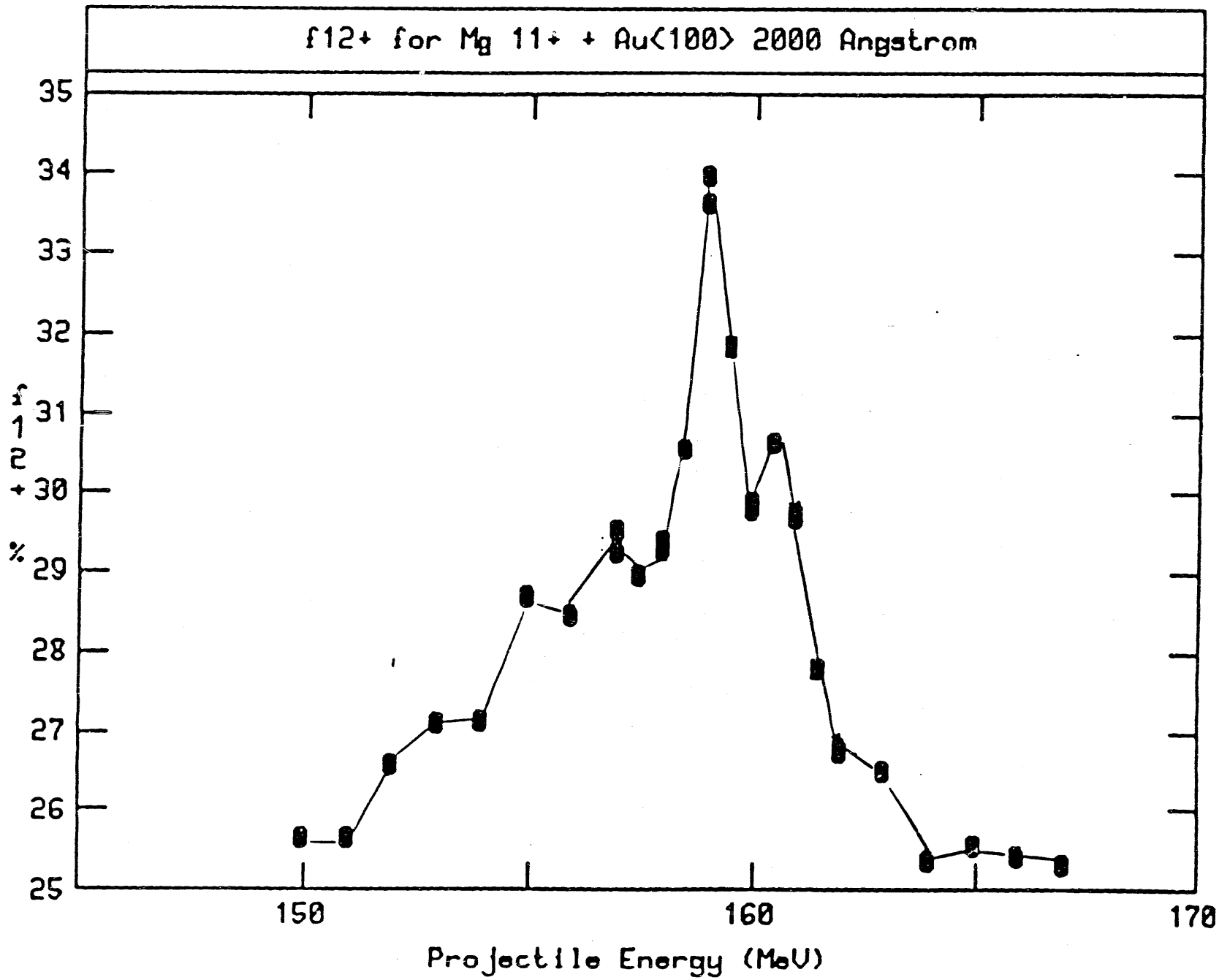
14.5
f12+ %
150
160
170
Projectile Energy (MeV)

Fig. 1

Fig 2


f12+ for Mg 11+ + Au<100> 2000 Angstrom
35
34
33
32
31
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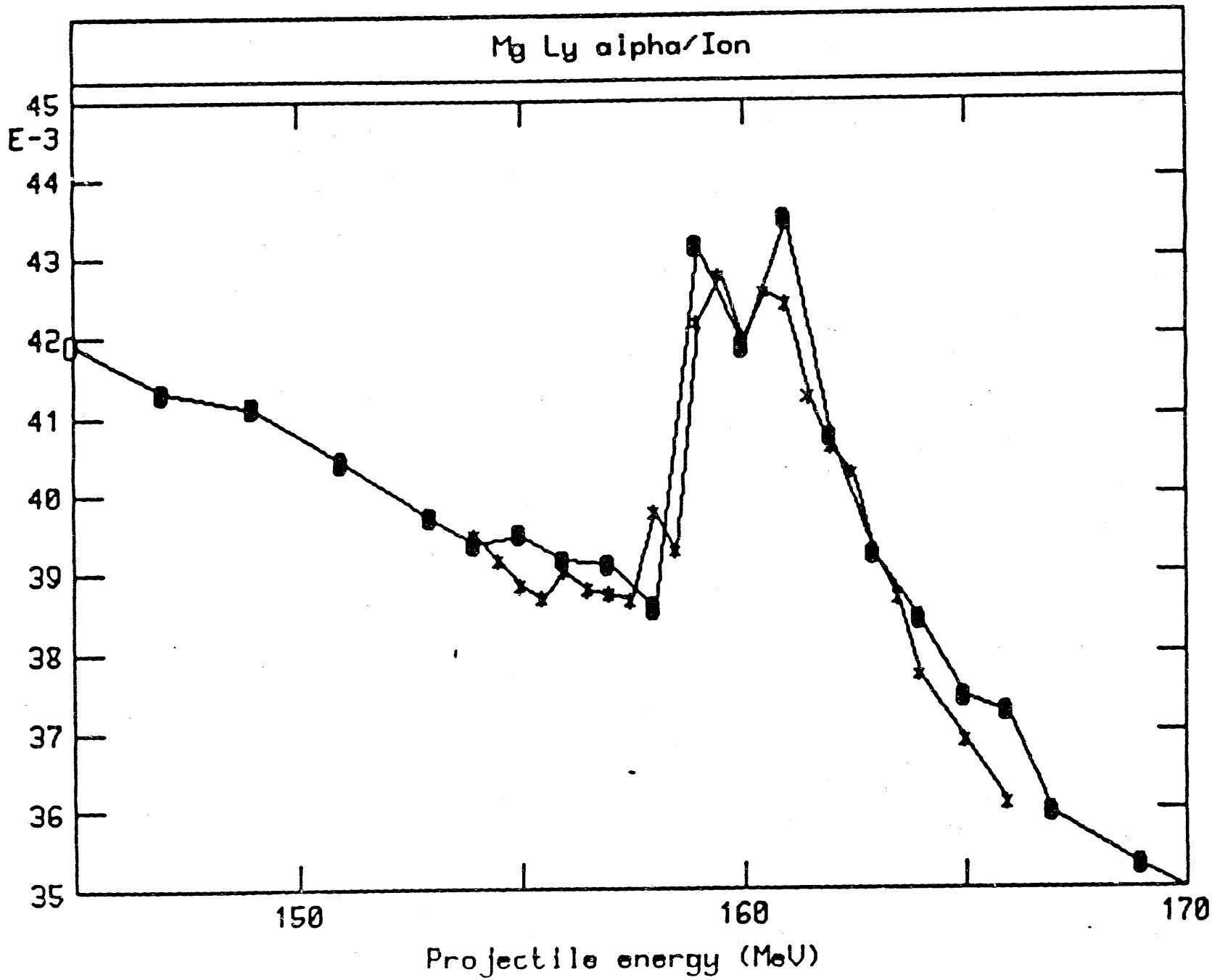
28
27
26
25
f12+ %
150
160
170
Projectile Energy (MeV)

Fig 3


Mg Ly alpha/Ion
45
E-3
44
43
42
41
40
39
38
37
36
35
150
160
170
Projectile energy (MeV)

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