

CROSS SECTIONS FOR CHARGE TRANSFER COLLISIONS INVOLVING HYDROGEN ATOMS

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Hydrogen Atoms

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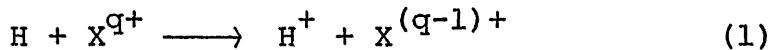
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ABSTRACT

Experimental data on the cross section for $H + X^{q+}$
 $\longrightarrow H^+ + X^{(q-1)+}$ are compiled for any element X and
charge state q. The result is shown in graphs as a
function of collision energy. A scaling law for the
cross section is derived theoretically to provide
quantitative information for highly-stripped ions for
which no data are available. Cross sections for some
related processes are also shown.

INTRODUCTION - SCOPE AND EXPLANATION OF GRAPHS -

An importance of charge transfer collisions in fusion plasmas has increased remarkably in recent years. In particular, the processes involving atomic hydrogen



play fundamental roles in a plasma heated by the injection of fast neutral hydrogen beams. When X^{q+} are impurity ions released from a limiter or first wall, the change in the ionic state of the ion induced by the process (1) affects very much the intensity of impurity radiation. A knowledge of the cross section for (1) enables us to develop fast atomic beam probes providing data on densities and temperatures of ions in a plasma.

On the consideration of this situation, the Research Information Center of the Institute of Plasma Physics, Nagoya University, has organized a working group to collect and compile the cross sections for the process (1). The present report shows the result of the compilation.

All the experimental data published so far (through early 1980) are collected for any element X and any charge state q (> 0). The results are shown in graphs in the increasing order of the atomic number of X. A list is given for the processes in the graphs. The cross section is presented in the unit of cm^2 and the collision energy in kev/amu (e.i., the abscissa being equivalent to the kinetic energy of H). Most of the experimental data

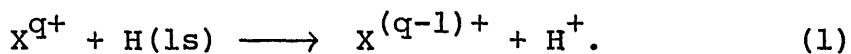
have been obtained by using atomic hydrogen targets produced by thermal dissociation in a furnace. Very few measurements (denoted by * in the list) are based on a fast H beam obtained by a charge transfer of H^+ beam. In the experiments of the latter type, a care should be taken of the effect of long-lived excited atoms present in the H beam.

Although the total number of the experimental data collected here is rather large, there are still many colliding systems, especially including highly stripped ions, for which no data are available. In order to provide some quantitative information on the cross section for such systems, a scaling law has been derived on the theoretical consideration of the process. The result is shown in the next section.

Finally in the Appendix given are the experimental data on some related processes, i.e., collisions of H with H^- or H^- , excitations of H or X^{q+} or electron loss of X^{q+} in the collisions $H + X^{q+}$. The data compilation is not complete for those related processes.

I. SCALING LAW OF TOTAL CROSS SECTION FOR CHARGE TRANSFER
COLLISIONS OF HIGHLY STRIPPED IONS WITH ATOMIC HYDROGEN*

Several authors¹ have proposed scaling laws which are quite useful for theoretical estimates of the cross sections for the title process, ie,



The concensus is that the absolute value of the total cross sections for process (1) is roughly proportional to the ionic charge number q. Ryufuku and Watanabe² have proposed for process (1) a universal curve in the plot of the scaled cross section $\tilde{\sigma}$ ($= \sigma/q^{1.07}$) against the scaled energy \tilde{E} ($= E/q^{0.464}$). The universal curve has been empirically determined from the calculation for fully stripped ions based on the unitarized distorted wave approximation (UDWA). The energy scaling can be physically interpreted as the change of the effective charge which an active electron feels at the instant of the transition.

*Prepared by M. Matsuzawa, H. Ryufuku and T. Watanabe

From a practical point of view, this scaling scheme is quite convenient because one has only to draw a single curve in the plot of $\tilde{\sigma}$ against \tilde{E} . Therefore we have chosen to adopt this scheme for the region of the ionic charge number, $10 \leq q \leq 50$, where experimental data are sparse.

For the high and intermediate energy regions, the universal curve given in ref. 2 describes the energy dependence of the experimental data correctly though it overestimates the absolute magnitude of the cross sections by a factor of two or three for the high energy region, ie, $E \geq 20$ keV/amu. Thus in this region, we have adjusted the absolute value of the universal curve to the existing experimental data³⁻⁶ (including partially stripped ions and H₂ as a target).

For $E \leq 1$ keV/amu, UDWA does not seem to be so reliable as that for higher energy region judging from the spirit of the approximation. At present, there is no experimental data to be compared with the theoretical estimates for this energy region for $q \gtrsim 10$. Therefore we have tested the consistency of other existing theoretical approaches designed to describe collision process (1) for the low energy region, ie, the perturbed stationary state (PSS) method⁷ for $q = 26$, the tunneling effect (TE) models^{8,9} and the absorbing sphere (AS) model¹⁰, with the $\tilde{\sigma}$ - \tilde{E} scaling scheme by replotted these theoretical estimates in the plot of $\tilde{\sigma}$ against \tilde{E} . The results obtained are shown in Fig.1.

The TE cross sections^{8,9} fall into the narrow strip (see the hatched regions in Fig. 1) for $10 \leq q \leq 50$, which shows their consistency with the resent scaling scheme. The AS cross sections lie in the wider strip in the plot of $\tilde{\sigma}$ against \tilde{E} for the same range of q . At present, there is no definite reason to choose one theoretical approach because no experimental data are available to be compared with them. Therefore, we have drawn a single curve, as is shown in Fig.1, to ensure that the above mentioned theoretical estimates for $10 \leq q \leq 50$ agree with it within a factor of two for $E \leq 10$ keV/amu. The resulting universal curve is analytically fitted to the following formulas for the energy regions specified:

a) $1 \leq \log_{10} \tilde{E} \leq 4$

$$\log_{10} \tilde{\sigma} = -15.0706 - 0.0224531 \xi_1 - 0.0144073 \xi_1^2, \quad (2a)$$

$$\xi_1 = \log_{10} \tilde{E} - 1,$$

b) $4 \leq \log_{10} \tilde{E} \leq 5$,

$$\log_{10} \tilde{\sigma} = -15.2676 - 0.474885 \xi_2 - 1.04186 \xi_2^2 - 0.301838 \xi_2^3, \quad (2b)$$

$$\xi_2 = \log_{10} \tilde{E} - 4,$$

c) $5 \leq \log_{10} \tilde{E} \leq 6$

$$\log_{10} \tilde{\sigma} = -17.0862 - 4.39144 \xi_3 - 0.221343 \xi_3^2 \quad (2c)$$

and $\xi_3 = \log_{10} \tilde{E}^{-5}$,

($\tilde{\sigma}$ in cm^2 , \tilde{E} in eV/amu)

We recommend the expression (2) as the reasonable estimate of the cross section compatible within a factor of two with almost all existing theoretical and experimental data available at present for $10 \lesssim q \lesssim 50$.

For $q \lesssim 10$, there is a strong oscillatory dependence of the total charge transfer cross sections on the effective charge due to the diabatic potential curves in the low energy region below 10 keV/amu¹¹. As to more detailed information on each q , the reader may refer to the original references such as the PSS calculation for one electron systems given in Table I.

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TABLE I

The typical PSS or close-coupling calculations
 of the charge transfer cross section for process (1)
 for $q \leq 10$ at present.

Multicharged ion	References
He^{++}	12, 13
Be^{4+}	14
B^{5+}	14
C^{6+}	15, 16
O^{8+}	14, 17

Figure caption

Fig. 1 Scaled charge transfer cross sections

$$\tilde{\sigma} = \sigma/q^{1.07} \text{ plotted against scaled energy}$$

$$\tilde{E} = E/q^{0.464}.$$

The recommended curve shows the one fitted within a factor of two to experimental data at high energies and to theoretical results at low energies: the experimental data

◆ $O^{8+} + H$ (Ref. 3)	● $Fe^{9+\sim 13+} + H$ (Ref. 4)
▽ $Fe^{9+\sim 15+} + H$ (Ref. 3)	○ $Fe^{9+\sim 22+} + \frac{1}{2}H_2$ (Ref. 5)
△ $Fe^{20+\sim 25+} + \frac{1}{2}H_2$ (Ref. 6)	

and the theoretical results

C (Ref. 8, TE)

GJ (Ref. 9, TE)

OS (Ref. 10, AS)

RW (Ref. 2, UDWA)

SO (Ref. 7, PSS)

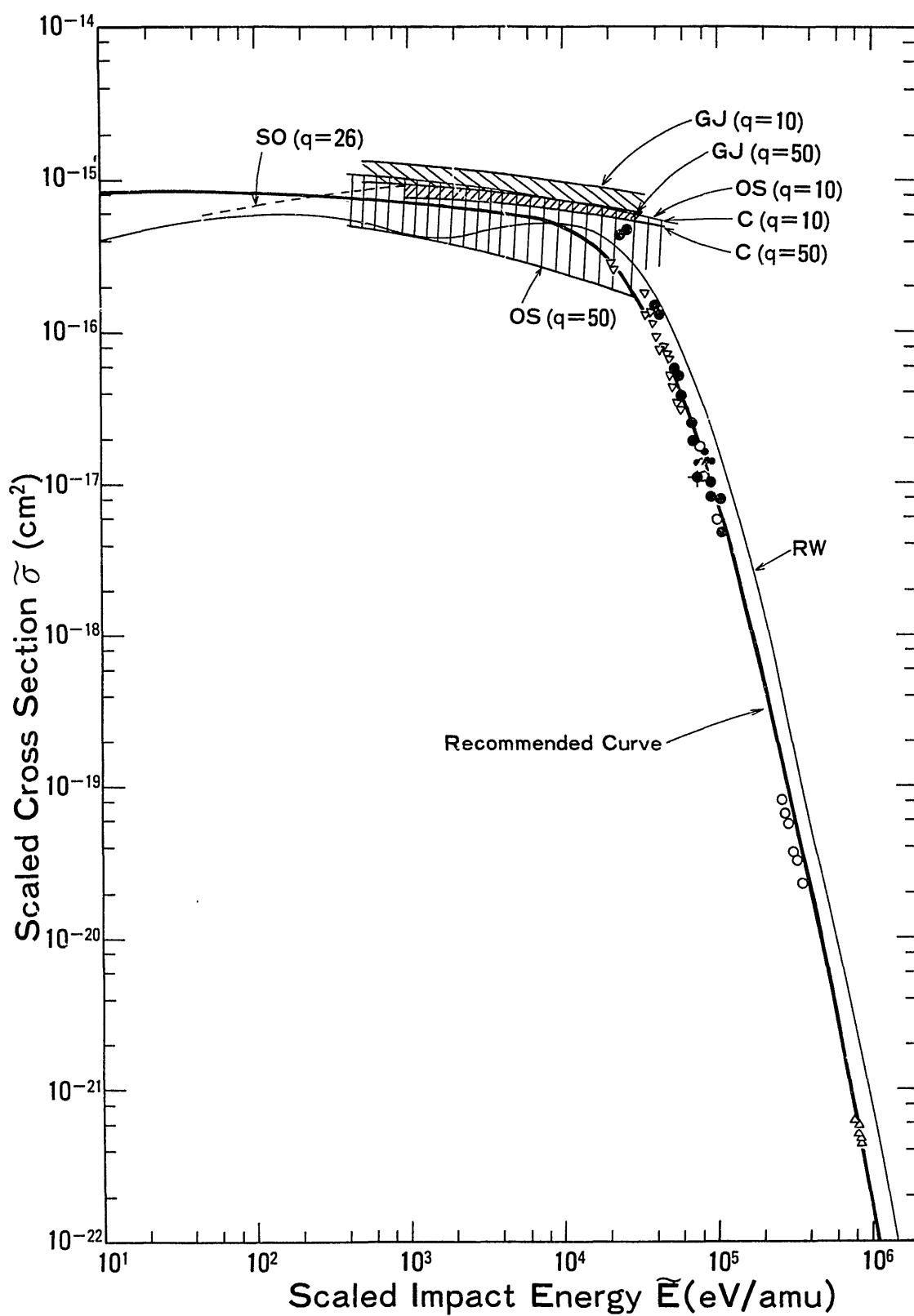


Fig.1

II. LIST OF PROCESSES SHOWN IN GRAPHS

Charge Transfer

Fig. No.	Processes	References
1.	$\underline{H}^+ + H \longrightarrow \underline{H}$	2, 34, 36, 37
	$\underline{H}^+ + H \longrightarrow \underline{H} + H^+$	29, 30, 38*, 42
	$\underline{D}^+ + D \longrightarrow \underline{D} + D^+$	38*
2.	$\underline{H}^+ + H \longrightarrow \underline{H}(2s) + H^+$	23, 45, 42, 43, 47
	$\underline{D}^+ + H \longrightarrow \underline{D}(2s) + H^+$	23
3.	$\underline{H}^+ + H \longrightarrow \underline{H}(2p) + H^+$	33, 43, 45
	$\underline{D}^+ + H \longrightarrow \underline{D}(2p) + H^+$	45
4.	${}^4He^{2+} + H \longrightarrow He^+$	4, 28
	${}^3He^{2+} + H \longrightarrow He^+$	2, 6, 11, 12
5.	${}^3He^{2+} + H \longrightarrow He^+(2s)$	11
	${}^4He^{2+} + H \longrightarrow He^+(2s)$	4
6.	${}^4He^+ + H \longrightarrow He$	6
7.	${}^7Li^+ + H \longrightarrow Li$	10
8.	${}^7Li^{2+} + H \longrightarrow Li^+$	10
9.	${}^7Li^{3+} + H \longrightarrow Li^{2+}$	10
10.	${}^{11}B^+ + H \longrightarrow B$	26
11.	${}^{11}B^{2+} + H \longrightarrow B^+$	26, 54
	$B^{2+} + H \longrightarrow B^+$	16, 25
12.	${}^{11}B^{3+} + H \longrightarrow B^{2+}$	26
	$B^{3+} + H \longrightarrow B^{2+}$	16, 54
13.	$B^{4+} + H \longrightarrow B^{3+}$	16, 26, 54
14.	$B^{5+} + H \longrightarrow B^{4+}$	16
	${}^{11}B^{5+} + H \longrightarrow B^{4+}$	26

Fig. No.	Processes	References
15.	$C^+ + H \longrightarrow C^0$	9,13,26
16.	$C^{2+} + H \longrightarrow C^+$	13,26,18,54
17.	$C^{3+} + H \longrightarrow C^{2+}$	13,16,26,54
18.	$C^{4+} + H \longrightarrow C^{3+}$	13,16,26,54
19.	$C^{5+} + H \longrightarrow C^{4+}$	26
20.	$C^{6+} + H \longrightarrow C^{5+}$	26
21.	$N^+ + H \longrightarrow N^0$	1*,7,9,13
22.	$N^{2+} + H \longrightarrow N^+$	7,13,54
23.	$N^{3+} + H \longrightarrow N^{2+}$	7,13,16,54
24.	$N^{4+} + H \longrightarrow N^{3+}$	7,13,16,54
25.	$N^{5+} + H \longrightarrow N^{4+}$	7,13,54
26.	$N^{7+} + H \longrightarrow N^{6+}$	26
27.	$O^+ + H \longrightarrow O^0$	1*,2*,13
28.	$O^{2+} + H \longrightarrow O^+$	13,54
29.	$O^{3+} + H \longrightarrow O^{2+}$	13,17,54
30.	$O^{4+} + H \longrightarrow O^{3+}$	13,17,54
31.	$O^{5+} + H \longrightarrow O^{4+}$	13,16,17,54
32.	$O^{6+} + H \longrightarrow O^{5+}$	16,17
33.	$O^{7+} + H \longrightarrow O^{6+}$	17
34.	$O^{8+} + H \longrightarrow O^{7+}$	17

Fig. No.	Processes	References
35.	$Mg^{2+} + H \longrightarrow Mg^+$	25
36.	$Si^{2+} + H \longrightarrow Si^+$	14
37.	$Si^{3+} + H \longrightarrow Si^{2+}$	14
38.	$Si^{4+} + H \longrightarrow Si^{3+}$	14,17
39.	$Si^{5+} + H \longrightarrow Si^{4+}$	14,17
40.	$Si^{6+} + H \longrightarrow Si^{5+}$	14,17
41.	$Si^{7+} + H \longrightarrow Si^{6+}$	14,17
42.	$Si^{8+} + H \longrightarrow Si^{7+}$	17
43.	$Si^{9+} + H \longrightarrow Si^{8+}$	17
44.	$Ar^{2+} + H \longrightarrow Ar^+$	50
45.	$Ar^{3+} + H \longrightarrow Ar^{2+}$	50
46.	$Ar^{4+} + H \longrightarrow Ar^{3+}$	50
47.	$Ar^{5+} + H \longrightarrow Ar^{4+}$	50
48.	$Ar^{6+} + H \longrightarrow Ar^{5+}$	50
49.	$Ar^{7+} + H \longrightarrow Ar^{6+}$	50
50.	$Ar^{8+} + H \longrightarrow Ar^{7+}$	50
51.	$Ar^{9+} + H \longrightarrow Ar^{8+}$	50
52.	$Ti^{2+} + H \longrightarrow Ti^+$	9,25
53.	$Fe^{4+} + H \longrightarrow Fe^{3+}$	5,17
54.	$Fe^{5+} + H \longrightarrow Fe^{4+}$	5,17,50
55.	$Fe^{6+} + H \longrightarrow Fe^{5+}$	5,17,50
56.	$Fe^{7+} + H \longrightarrow Fe^{6+}$	5,17
57.	$Fe^{8+} + H \longrightarrow Fe^{7+}$	5,17
58.	$Fe^{9+} + H \longrightarrow Fe^{8+}$	5,17

Fig. No.	Processes	References
59.	$\text{Fe}^{10+} + \text{H} \longrightarrow \text{Fe}^{9+}$	5,17
60.	$\text{Fe}^{11+} + \text{H} \longrightarrow \text{Fe}^{10+}$	5,17
61.	$\text{Fe}^{12+} + \text{H} \longrightarrow \text{Fe}^{11+}$	5,17
62.	$\text{Fe}^{13+} + \text{H} \longrightarrow \text{Fe}^{12+}$	5,17
63.	$\text{Fe}^{14+} + \text{H} \longrightarrow \text{Fe}^{13+}$	17
64.	$\text{Fe}^{15+} + \text{H} \longrightarrow \text{Fe}^{14+}$	17
65.	$\text{Zn}^{2+} + \text{H} \longrightarrow \text{Zn}^+$	25
66.	$\text{Kr}^{2+} + \text{H} \longrightarrow \text{Kr}^+$	25
67.	$\text{Mo}^{4+} + \text{H} \longrightarrow \text{Mo}^{3+}$	17
68.	$\text{Mo}^{5+} + \text{H} \longrightarrow \text{Mo}^{4+}$	17
69.	$\text{Mo}^{6+} + \text{H} \longrightarrow \text{Mo}^{5+}$	17
70.	$\text{Mo}^{7+} + \text{H} \longrightarrow \text{Mo}^{6+}$	17
71.	$\text{Mo}^{8+} + \text{H} \longrightarrow \text{Mo}^{7+}$	17
72.	$\text{Mo}^{9+} + \text{H} \longrightarrow \text{Mo}^{8+}$	17
73.	$\text{Mo}^{10+} + \text{H} \longrightarrow \text{Mo}^{9+}$	17
74.	$\text{Mo}^{11+} + \text{H} \longrightarrow \text{Mo}^{10+}$	17
75.	$\text{Mo}^{12+} + \text{H} \longrightarrow \text{Mo}^{11+}$	17
76.	$\text{Mo}^{13+} + \text{H} \longrightarrow \text{Mo}^{12+}$	17
77.	$\text{Mo}^{14+} + \text{H} \longrightarrow \text{Mo}^{13+}$	17
78.	$\text{Mo}^{15+} + \text{H} \longrightarrow \text{Mo}^{14+}$	17
79.	$\text{Mo}^{16+} + \text{H} \longrightarrow \text{Mo}^{15+}$	17
80.	$\text{Mo}^{17+} + \text{H} \longrightarrow \text{Mo}^{16+}$	17
81.	$\text{Mo}^{18+} + \text{H} \longrightarrow \text{Mo}^{17+}$	17
82.	$\text{Cd}^{2+} + \text{H} \longrightarrow \text{Cd}^+$	25
83.	$\text{Xe}^{2+} + \text{H} \longrightarrow \text{Xe}^+$	50
84.	$\text{Xe}^{3+} + \text{H} \longrightarrow \text{Xe}^{2+}$	50
85.	$\text{Xe}^{4+} + \text{H} \longrightarrow \text{Xe}^{3+}$	50

Fig. No.	Processes			References
86.	Xe^{5+}	+	H	$\longrightarrow Xe^{4+}$
87.	Xe^{6+}	+	H	$\longrightarrow Xe^{5+}$
88.	Xe^{7+}	+	H	$\longrightarrow Xe^{6+}$
89.	Xe^{8+}	+	H	$\longrightarrow Xe^{7+}$
90.	Xe^{9+}	+	H	$\longrightarrow Xe^{8+}$
91.	Xe^{10+}	+	H	$\longrightarrow Xe^{9+}$
92.	Xe^{11+}	+	H	$\longrightarrow Xe^{10+}$
93.	Xe^{12+}	+	H	$\longrightarrow Xe^{11+}$
94.	Ba^+	+	H	$\longrightarrow Ba^+$
95.	Ta^{3+}	+	H	$\longrightarrow Ta^{2+}$
96.	Ta^{4+}	+	H	$\longrightarrow Ta^{3+}$
97.	Ta^{5+}	+	H	$\longrightarrow Ta^{4+}$
98.	Ta^{6+}	+	H	$\longrightarrow Ta^{5+}$
99.	Ta^{7+}	+	H	$\longrightarrow Ta^{6+}$
100.	Ta^{8+}	+	H	$\longrightarrow Ta^{7+}$
101.	Ta^{9+}	+	H	$\longrightarrow Ta^{8+}$
102.	Ta^{10+}	+	H	$\longrightarrow Ta^{9+}$
103.	Ta^{11+}	+	H	$\longrightarrow Ta^{10+}$
104.	Ta^{12+}	+	H	$\longrightarrow Ta^{11+}$
105.	Ta^{13+}	+	H	$\longrightarrow Ta^{12+}$
106.	Ta^{14+}	+	H	$\longrightarrow Ta^{13+}$
107.	Ta^{15+}	+	H	$\longrightarrow Ta^{14+}$
108.	Ta^{16+}	+	H	$\longrightarrow Ta^{15+}$
109.	Ta^{17+}	+	H	$\longrightarrow Ta^{16+}$
110.	Ta^{18+}	+	H	$\longrightarrow Ta^{17+}$
111.	Ta^{19+}	+	H	$\longrightarrow Ta^{18+}$
112.	W^{4+}	+	H	$\longrightarrow W^{3+}$

Fig. No.	Processes	References
113.	$W^{5+} + H \longrightarrow W^{4+}$	17
114.	$W^{6+} + H \longrightarrow W^{5+}$	17
115.	$W^{7+} + H \longrightarrow W^{6+}$	17
116.	$W^{8+} + H \longrightarrow W^{7+}$	17
117.	$W^{9+} + H \longrightarrow W^{8+}$	17
118.	$W^{10+} + H \longrightarrow W^{9+}$	17
119.	$W^{11+} + H \longrightarrow W^{10+}$	17
120.	$W^{12+} + H \longrightarrow W^{11+}$	17
121.	$W^{13+} + H \longrightarrow W^{12+}$	17
122.	$W^{14+} + H \longrightarrow W^{13+}$	17
123.	$W^{15+} + H \longrightarrow W^{14+}$	17
124.	$Au^{5+} + H \longrightarrow Au^{4+}$	17
125.	$Au^{6+} + H \longrightarrow Au^{5+}$	17
126.	$Au^{7+} + H \longrightarrow Au^{6+}$	17
127.	$Au^{8+} + H \longrightarrow Au^{7+}$	17
128.	$Au^{9+} + H \longrightarrow Au^{8+}$	17
129.	$Au^{10+} + H \longrightarrow Au^{9+}$	17
130.	$Au^{11+} + H \longrightarrow Au^{10+}$	17
131.	$Au^{12+} + H \longrightarrow Au^{11+}$	17
132.	$Au^{13+} + H \longrightarrow Au^{12+}$	17
133.	$Au^{14+} + H \longrightarrow Au^{13+}$	17
134.	$Au^{15+} + H \longrightarrow Au^{14+}$	17
135.	$Au^{16+} + H \longrightarrow Au^{15+}$	17

Related Processes (Appendix)

Fig. No.	Processes	References
A1.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(2p)$	33, 43, 45
	$\underline{D}^+ + H \longrightarrow \underline{D}^+ + H(2p)$	45
A2.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(2s)$	43, 47
A3.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(n=2)$	52
A4.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(n=3)$	52
A5.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(n=4)$	52
A6.	$\underline{H}^+ + H \longrightarrow \underline{H}^+ + H^+ + e$	30, 32, 46
A7.	$\underline{H}^- + H \longrightarrow \underline{H}^-$	28, 39, 40
A8.	$\underline{H}^- + H \longrightarrow \underline{H}(2s)$	44
	$\underline{H}(1s) + H(1s) \longrightarrow \underline{H}(2s)$	24
A9.	$\underline{H}^- + H \longrightarrow \underline{H}(2p)$	44
A10.	$\underline{H}^- + H \longrightarrow \underline{H}^- + H^+$	40
A11.	$\underline{H}^- + H \longrightarrow \underline{H}$	28, 48
	$\underline{H}^- + H \longrightarrow \underline{H} + H^-$	31
A12.	$\underline{H}^- + H \longrightarrow \underline{H}^+$	48
A13.	${}^4He^+ + H \longrightarrow He^{2+}$	8, 28
A14.	${}^4He^+ + H \longrightarrow He^+ + H(2p)$	27
A15.	${}^3He^+ + H \longrightarrow He^+(2s)$	11
A16.	${}^4He + H \longrightarrow He^+$	28
A17.	${}^4He^- + H \longrightarrow He$	28
A18.	$C^+ + H \longrightarrow C^{2+}$	26
A19.	$C^{2+} + H \longrightarrow C^{3+}$	26
A20.	$C^{3+} + H \longrightarrow C^{4+}$	26

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IV. GRAPHS

- CROSS SECTIONS FOR $H + X^{q+} \rightarrow H^+ + X^{(q-1)+}$ -

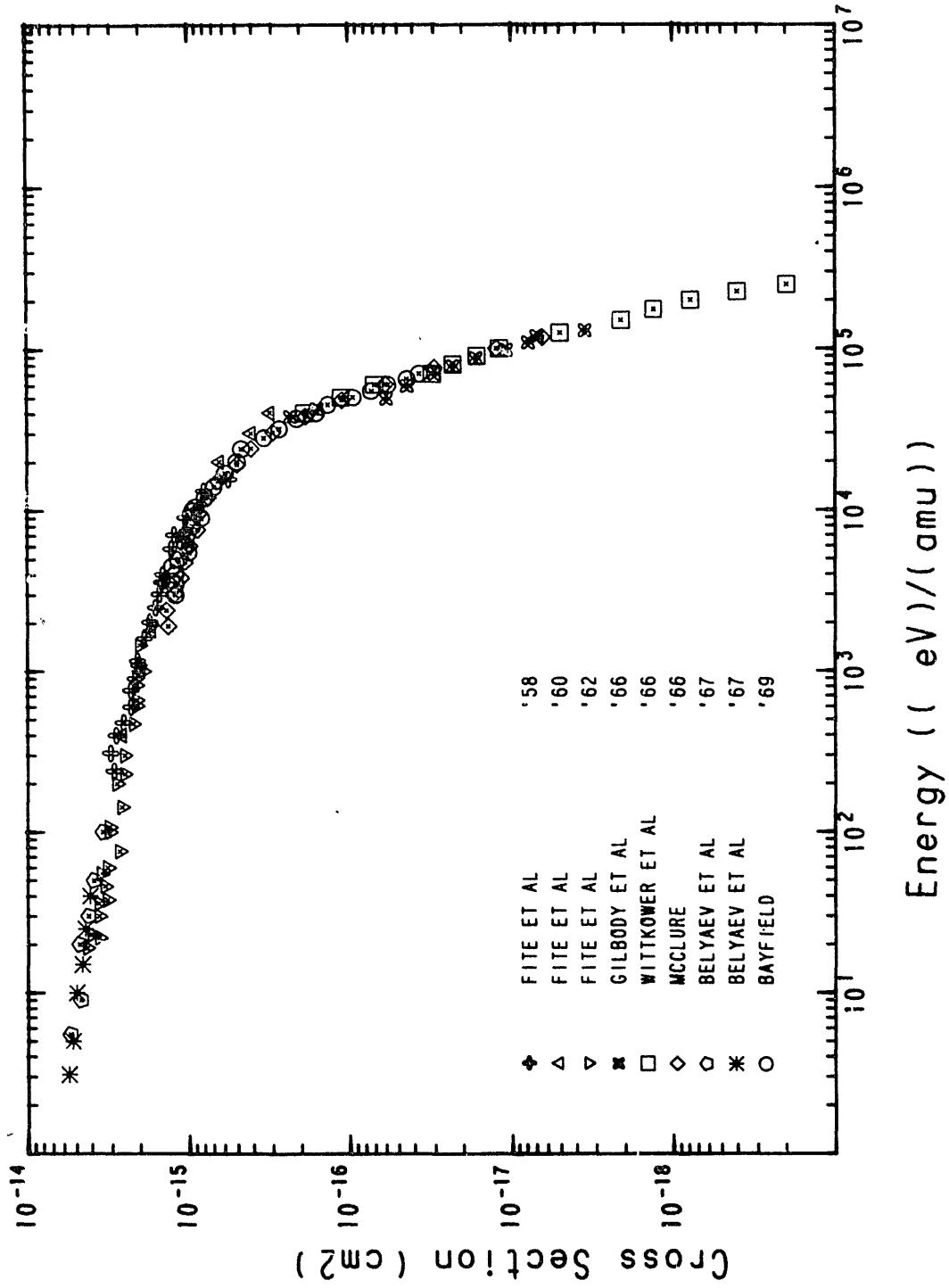


Fig.1 $\underline{\text{H}}^+ + \text{H} \longrightarrow \underline{\text{H}} + \text{H}^+$

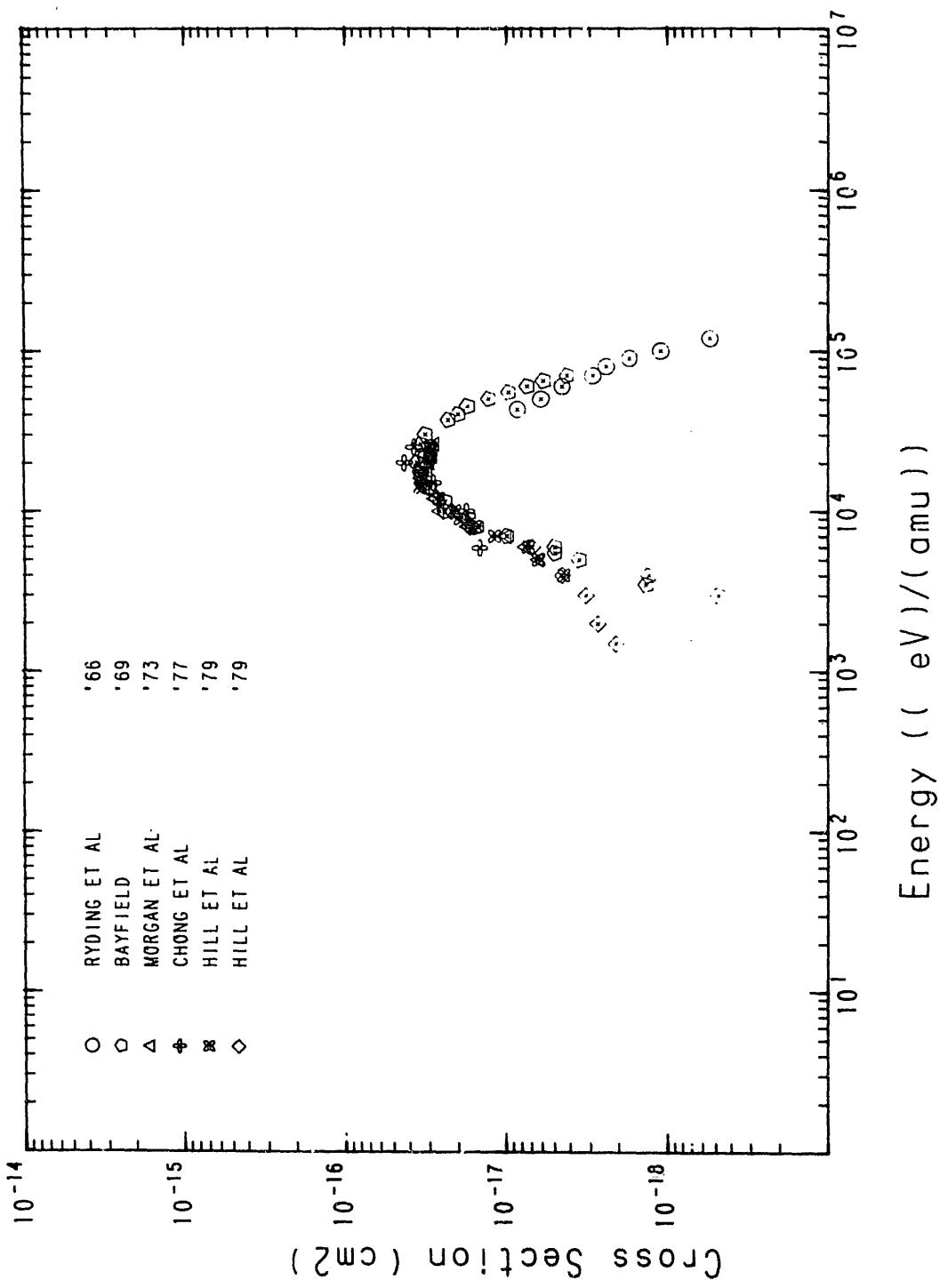


Fig.2 $\underline{\text{H}}^+ + \text{H} \rightarrow \underline{\text{H}}(2\text{s}) + \text{H}^+$

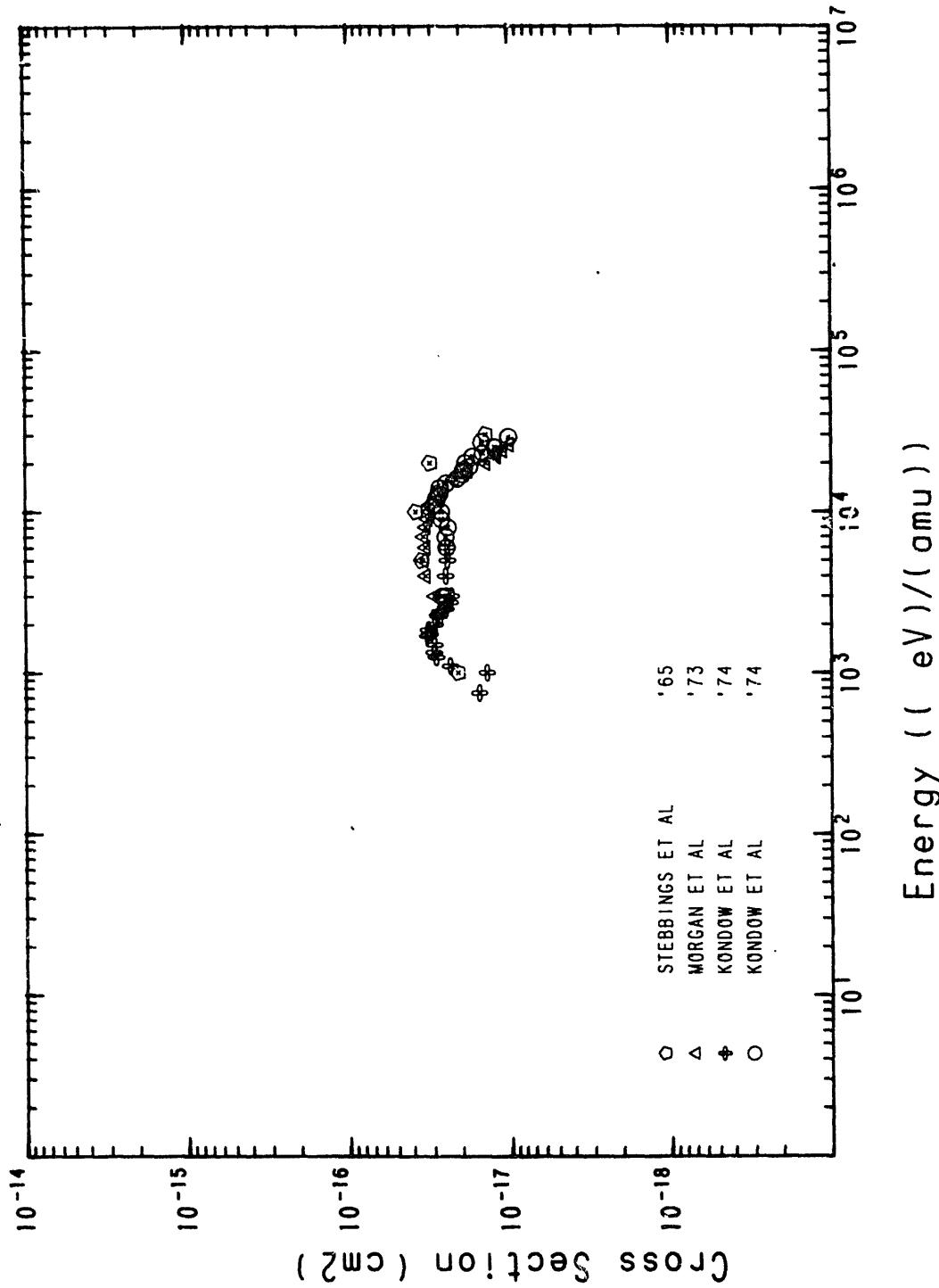


Fig.3 $\underline{\text{H}}^+ + \text{H} \longrightarrow \underline{\text{H}}(2\text{p}) + \text{H}^+$

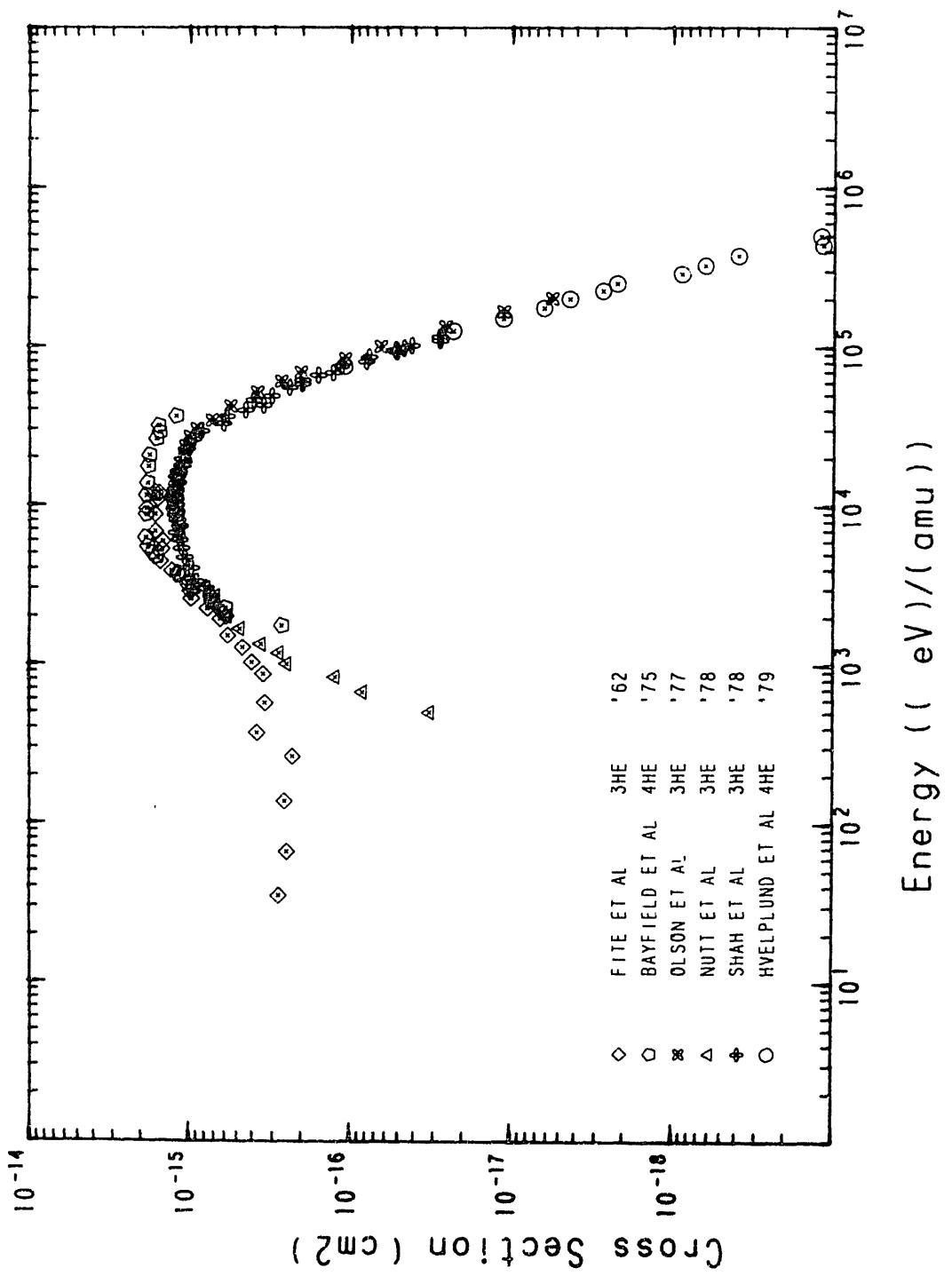


Fig.4 $\text{He}^{2+} + \text{H} \rightarrow \text{He}^+$

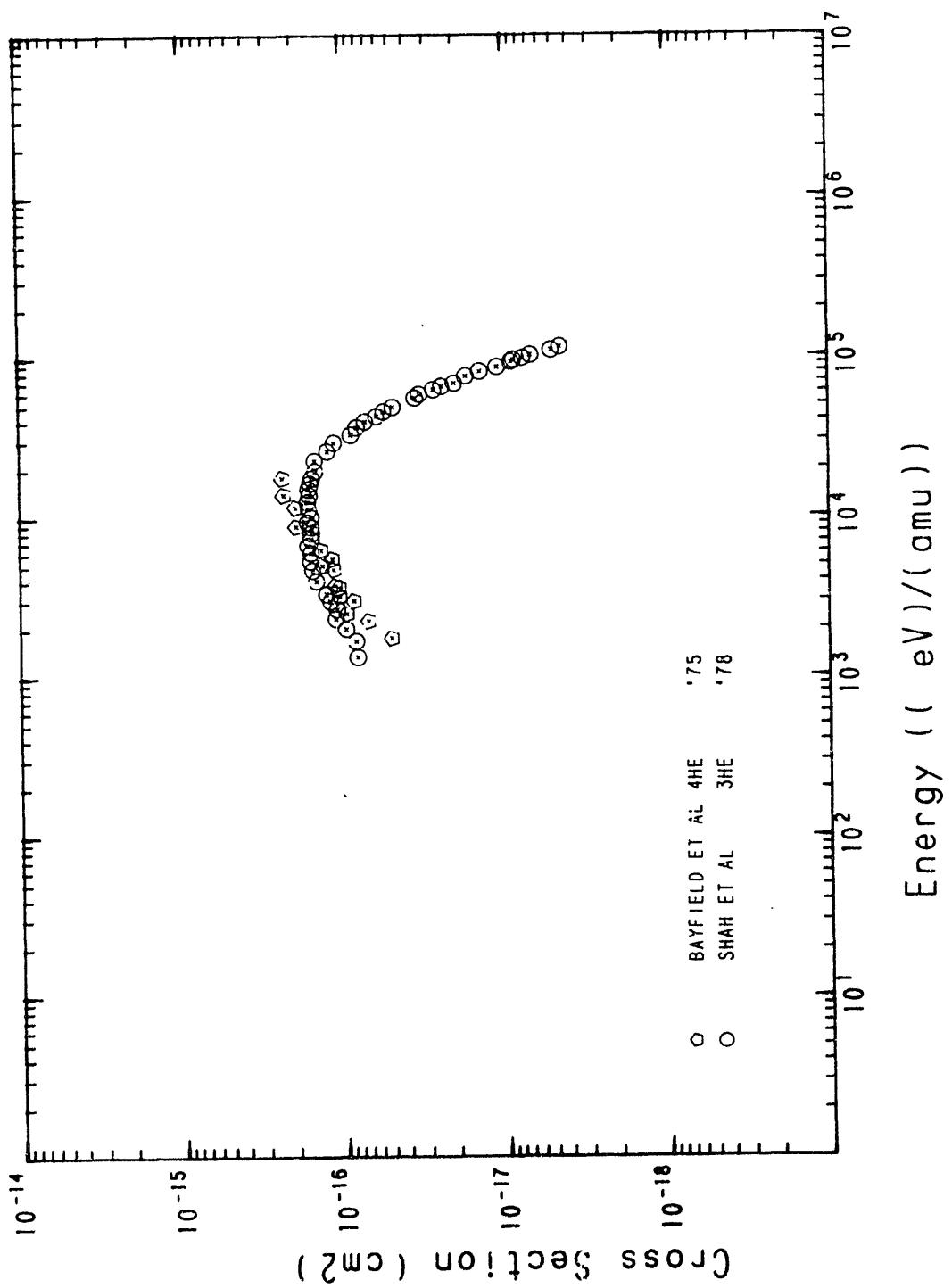


Fig.5 $\text{He}^{2+} + \text{H} \rightarrow \text{He}^+(2s)$

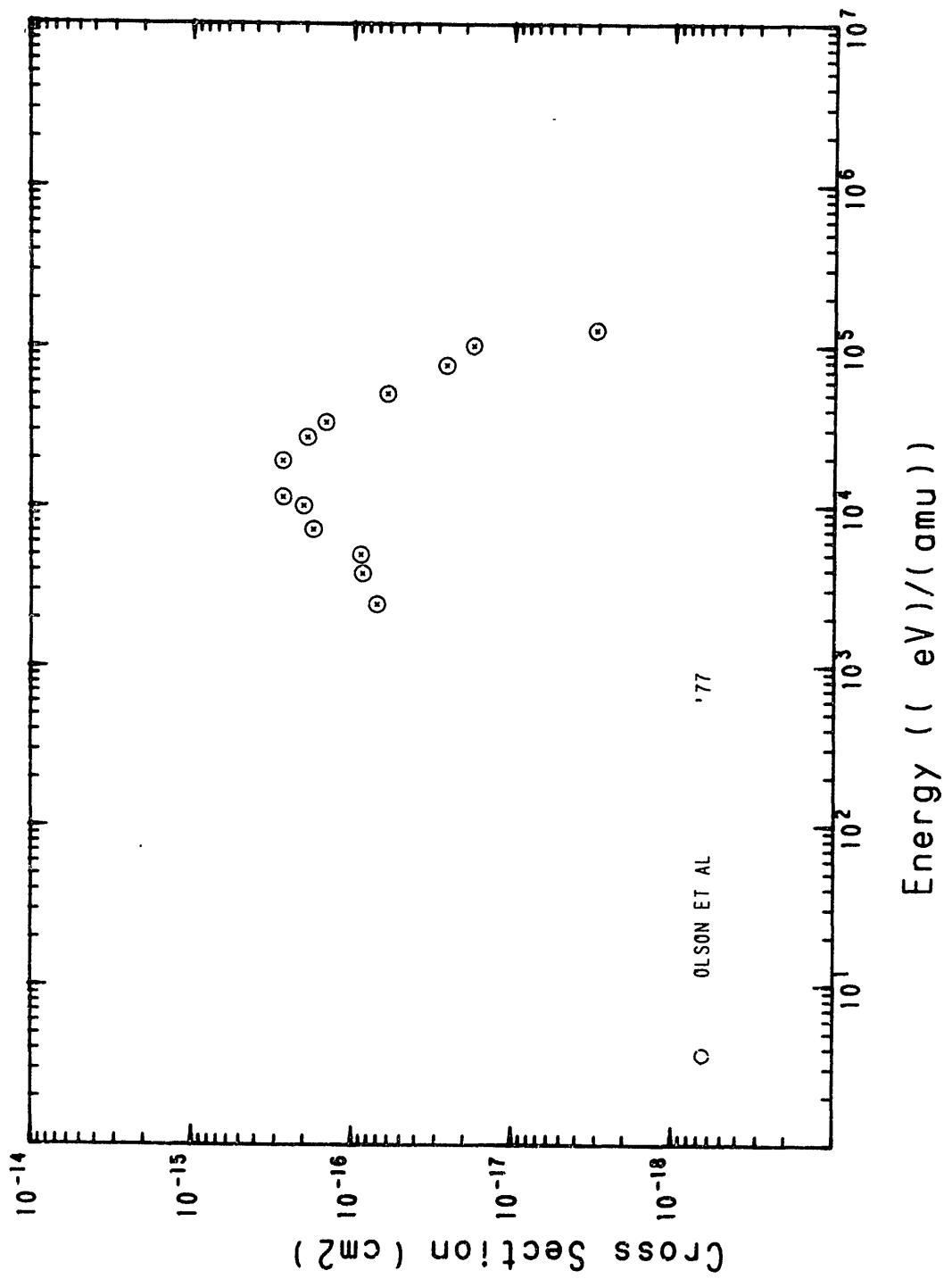


Fig.6 $\text{He}^+ + \text{H} \rightarrow \text{He}$

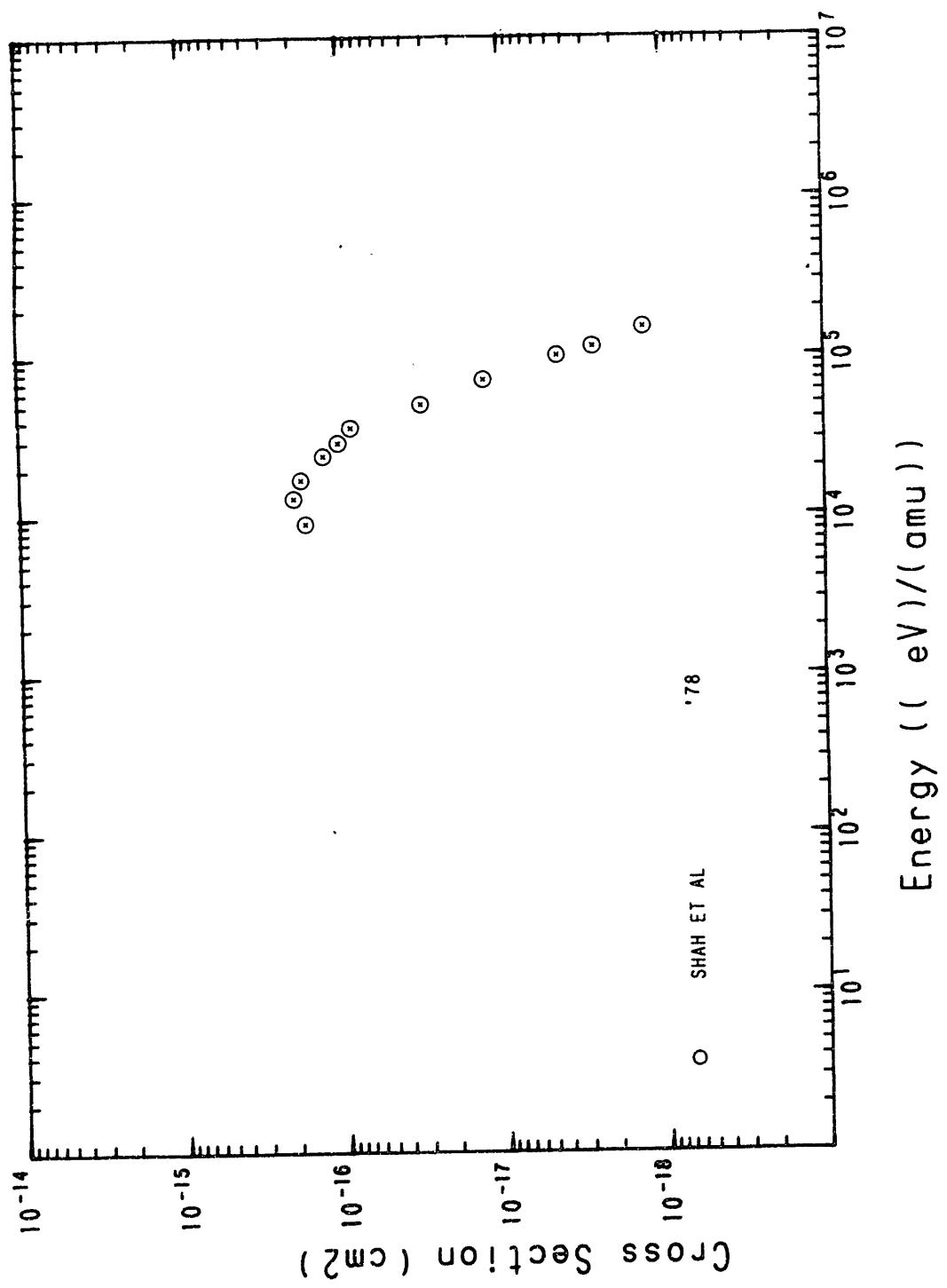


Fig.7 $\text{Li}^+ + \text{H} \rightarrow \text{Li}$

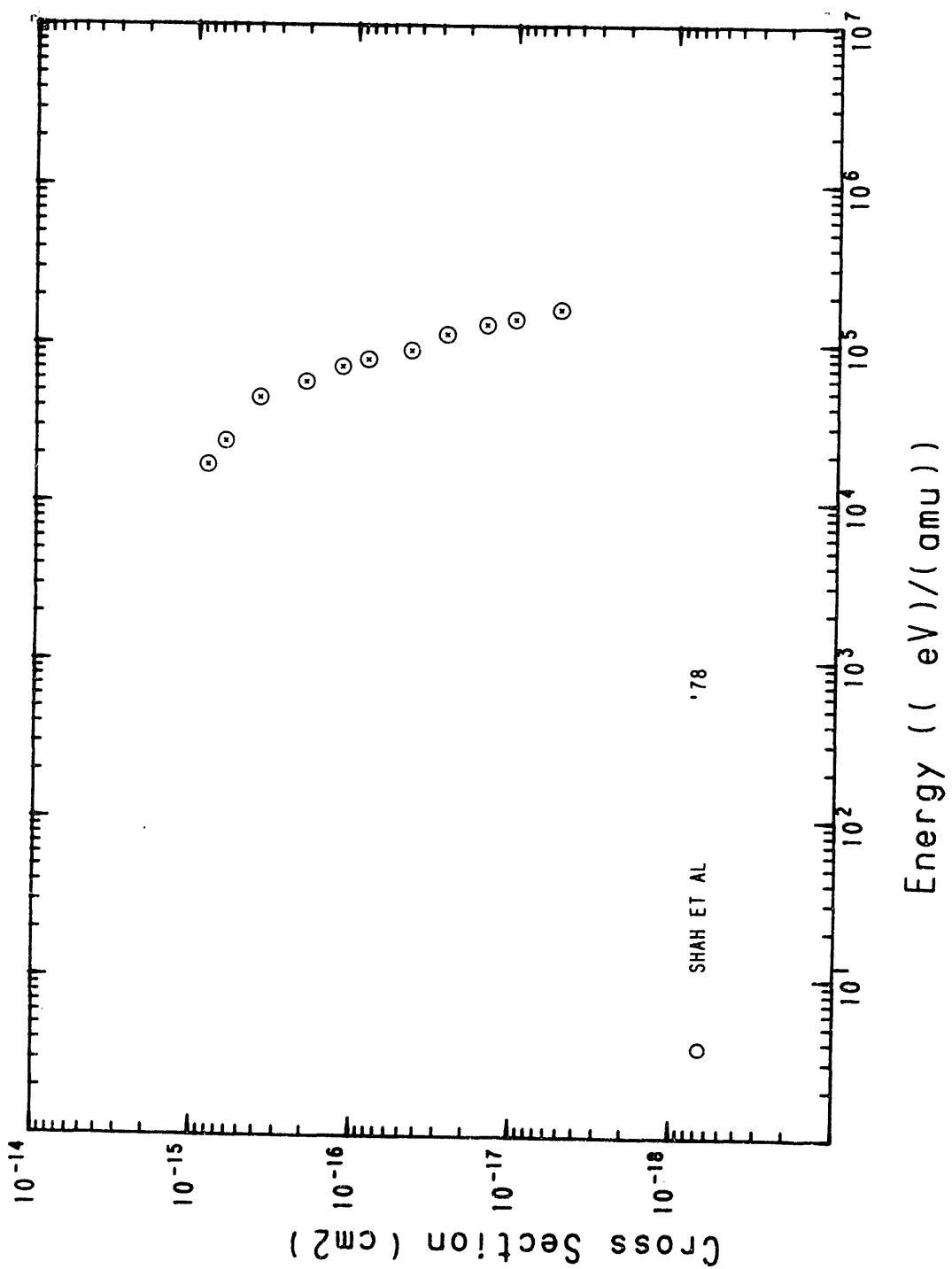


Fig.8 $\text{Li}^{2+} + \text{H} \rightarrow \text{Li}^+$

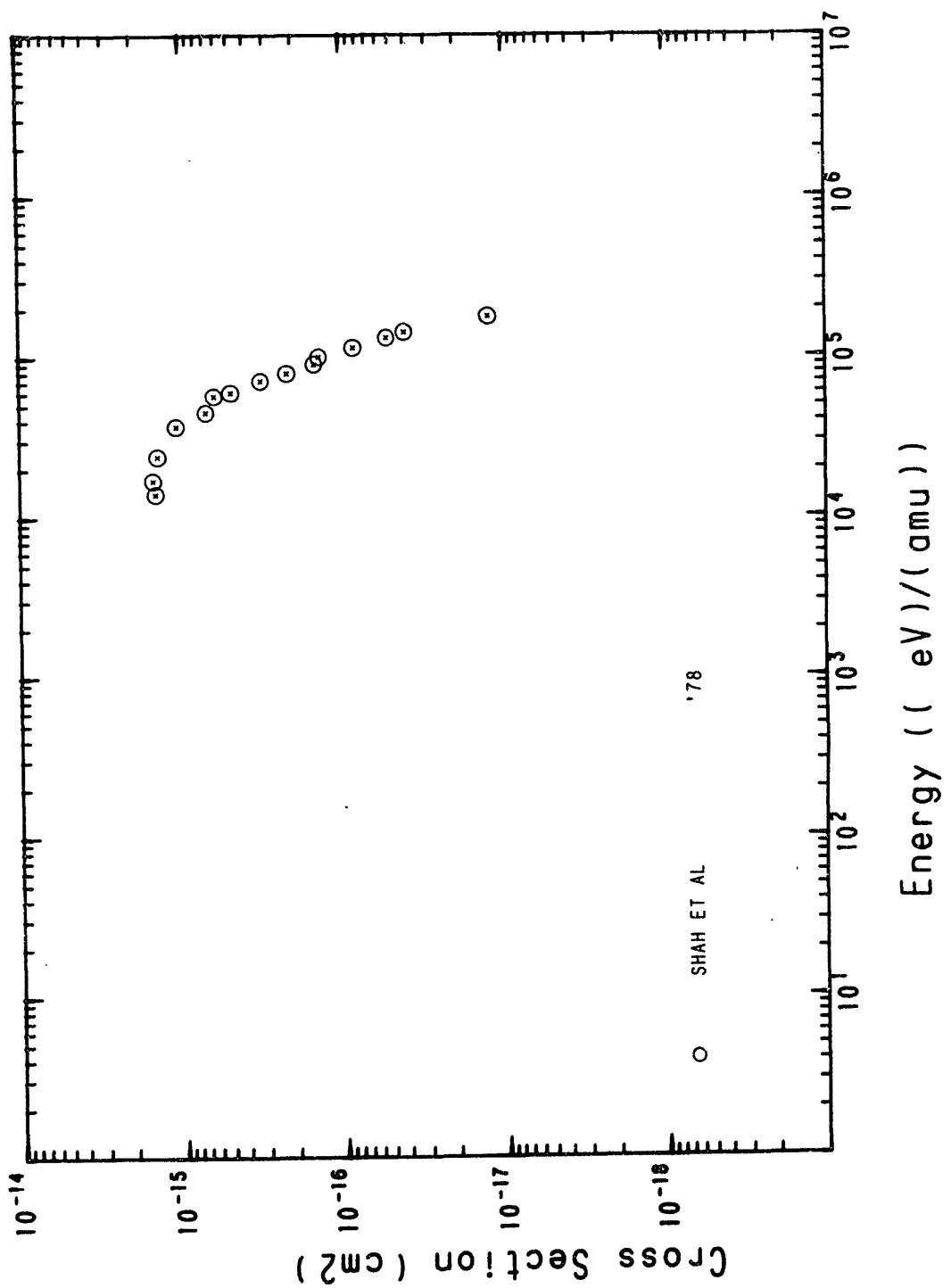


Fig.9 $\text{Li}^{3+} + \text{H} \rightarrow \text{Li}^{2+}$

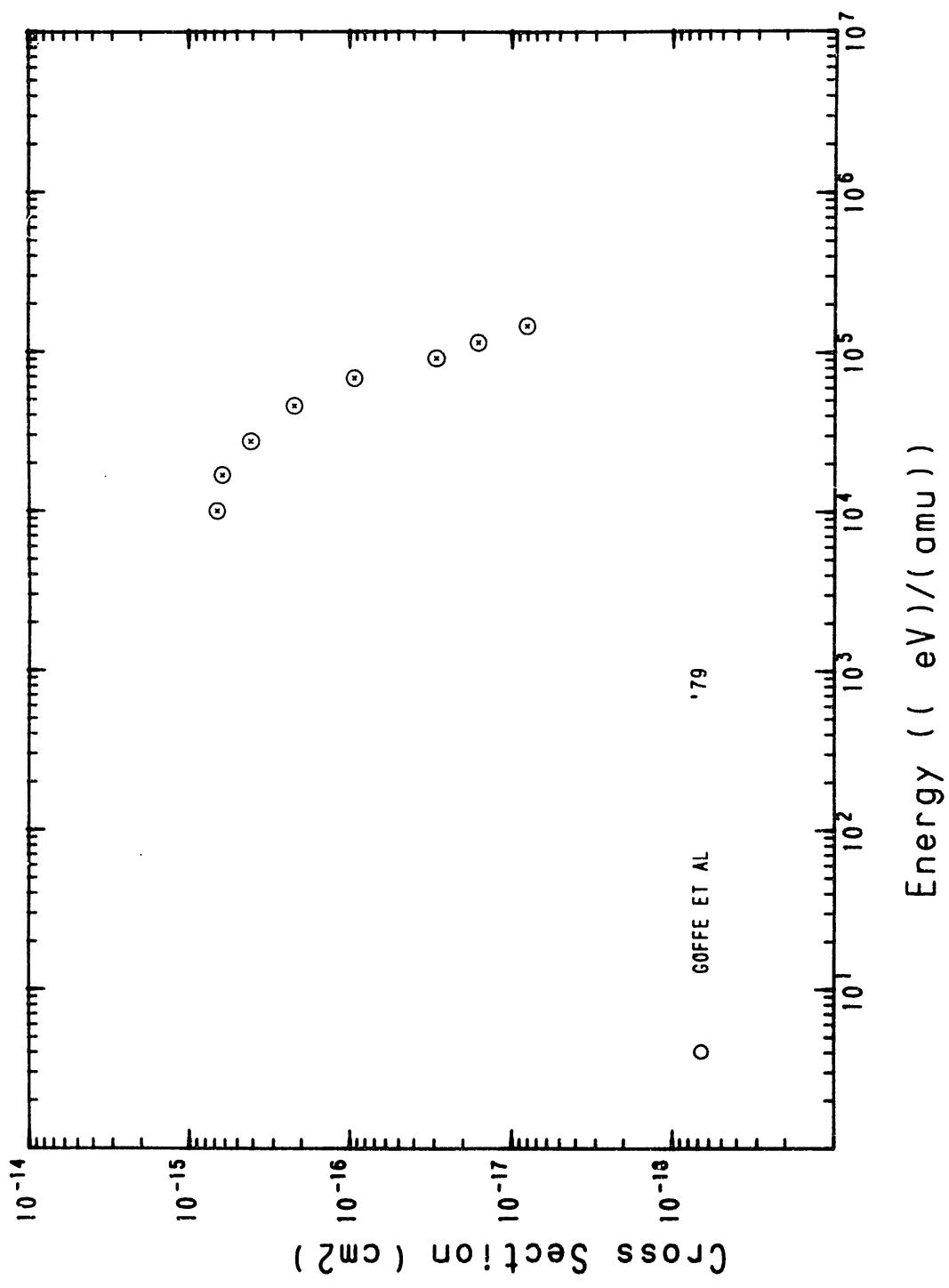


Fig.10 $B^+ + H \rightarrow B$

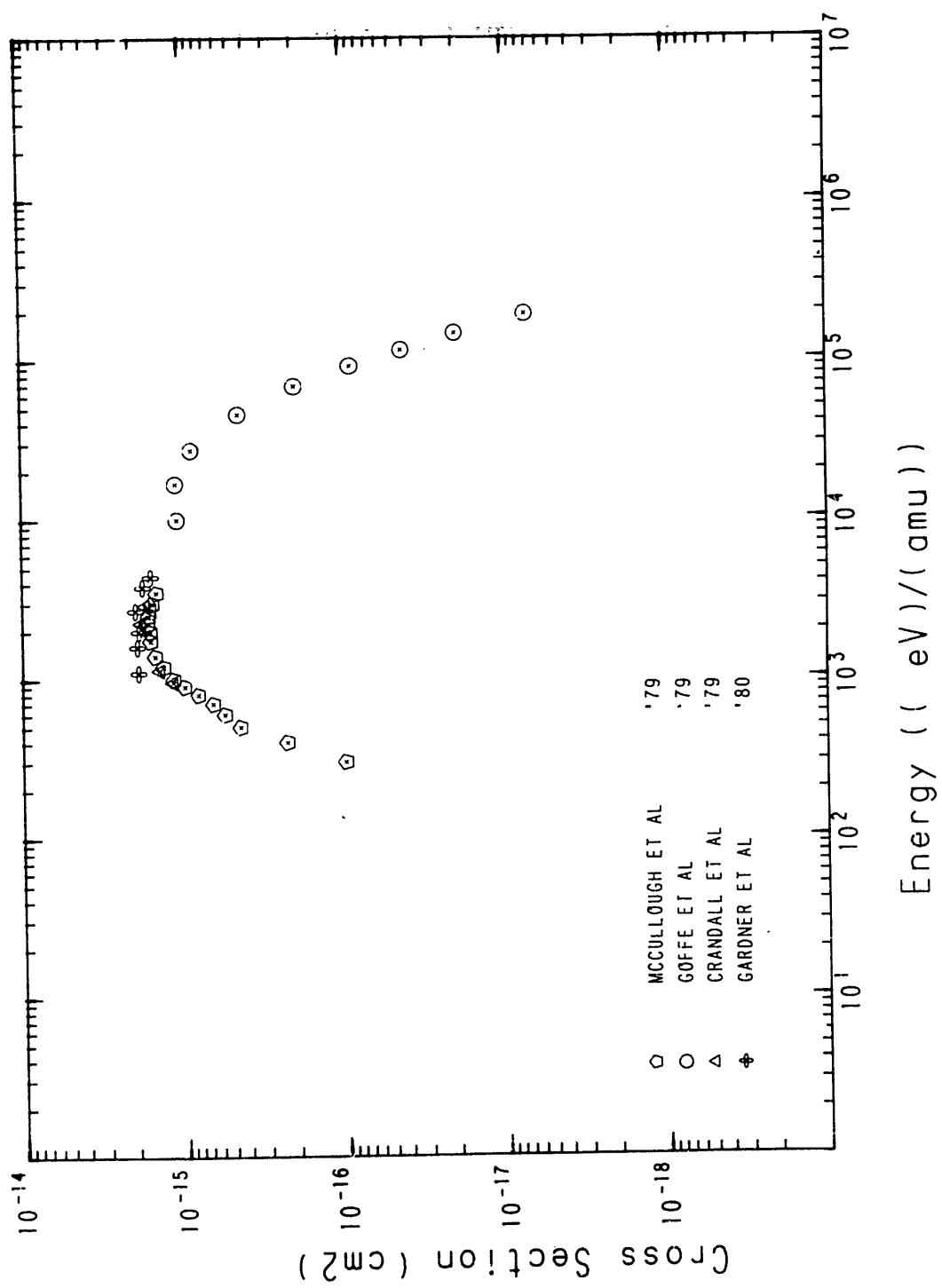


Fig.11 $\text{B}^{2+} + \text{H} \rightarrow \text{B}^+$

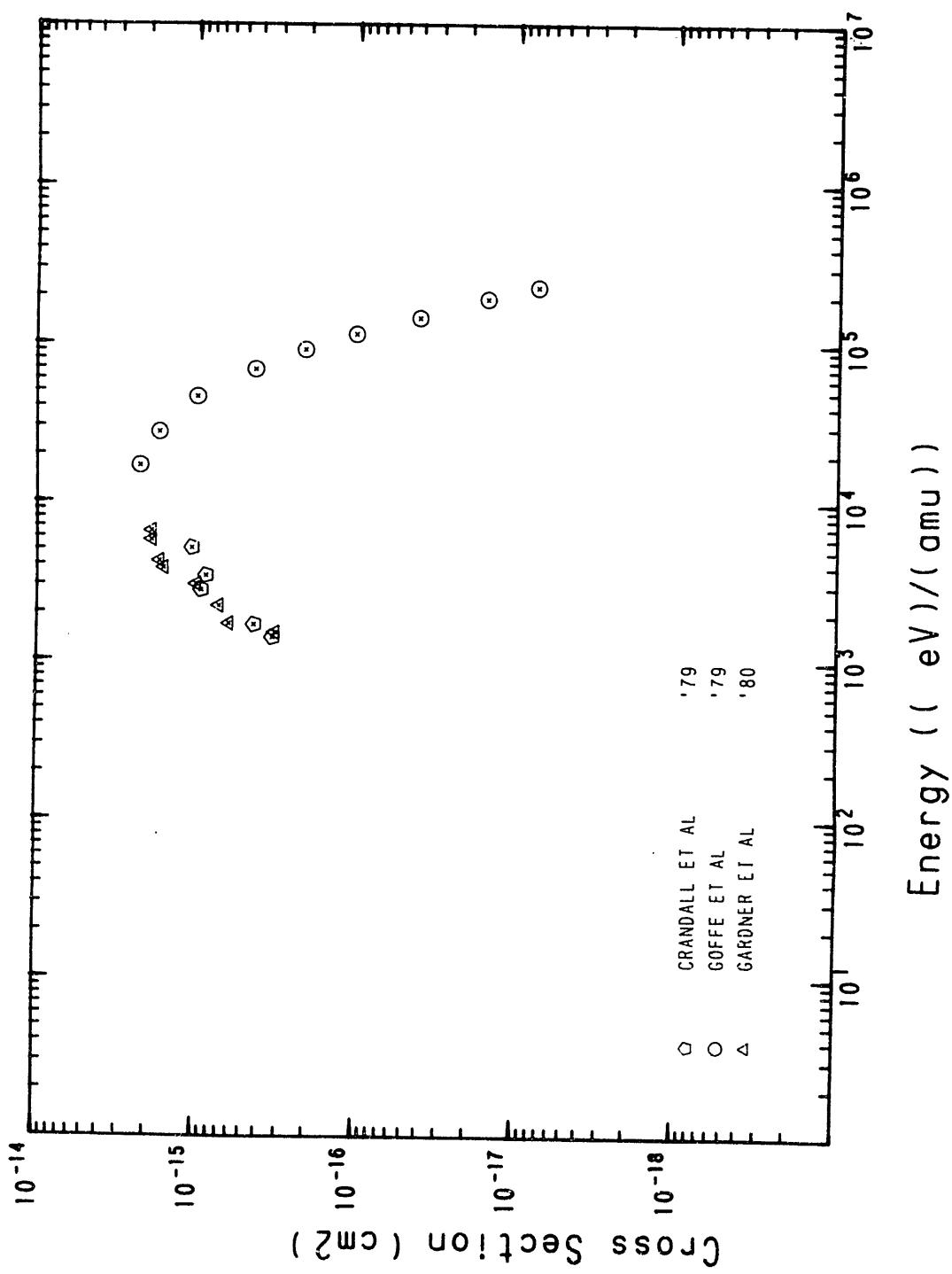


Fig.12 $B^{3+} + H \rightarrow B^{2+}$

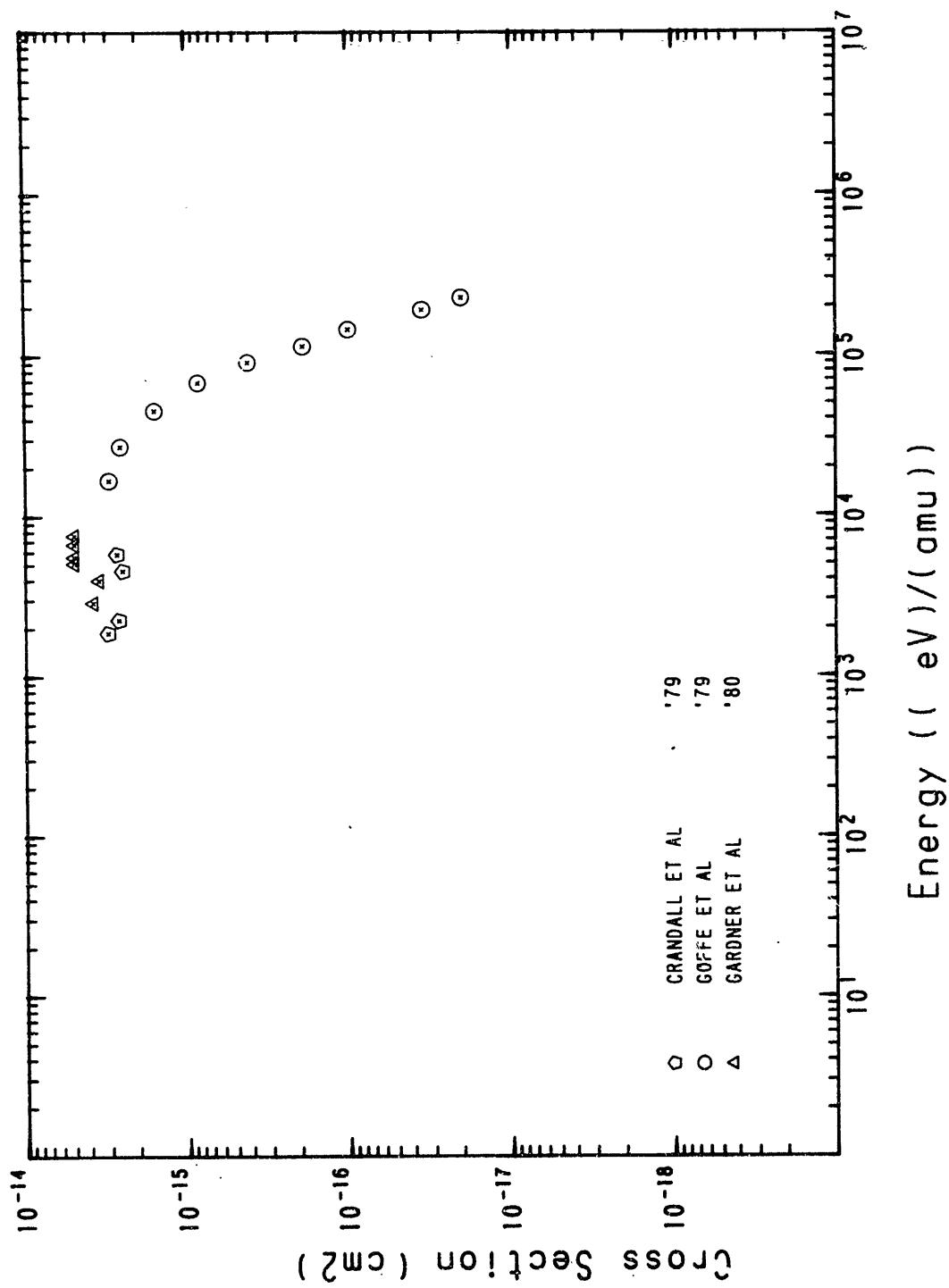


Fig.13 $\text{B}^{4+} + \text{H} \rightarrow \text{B}^{3+}$

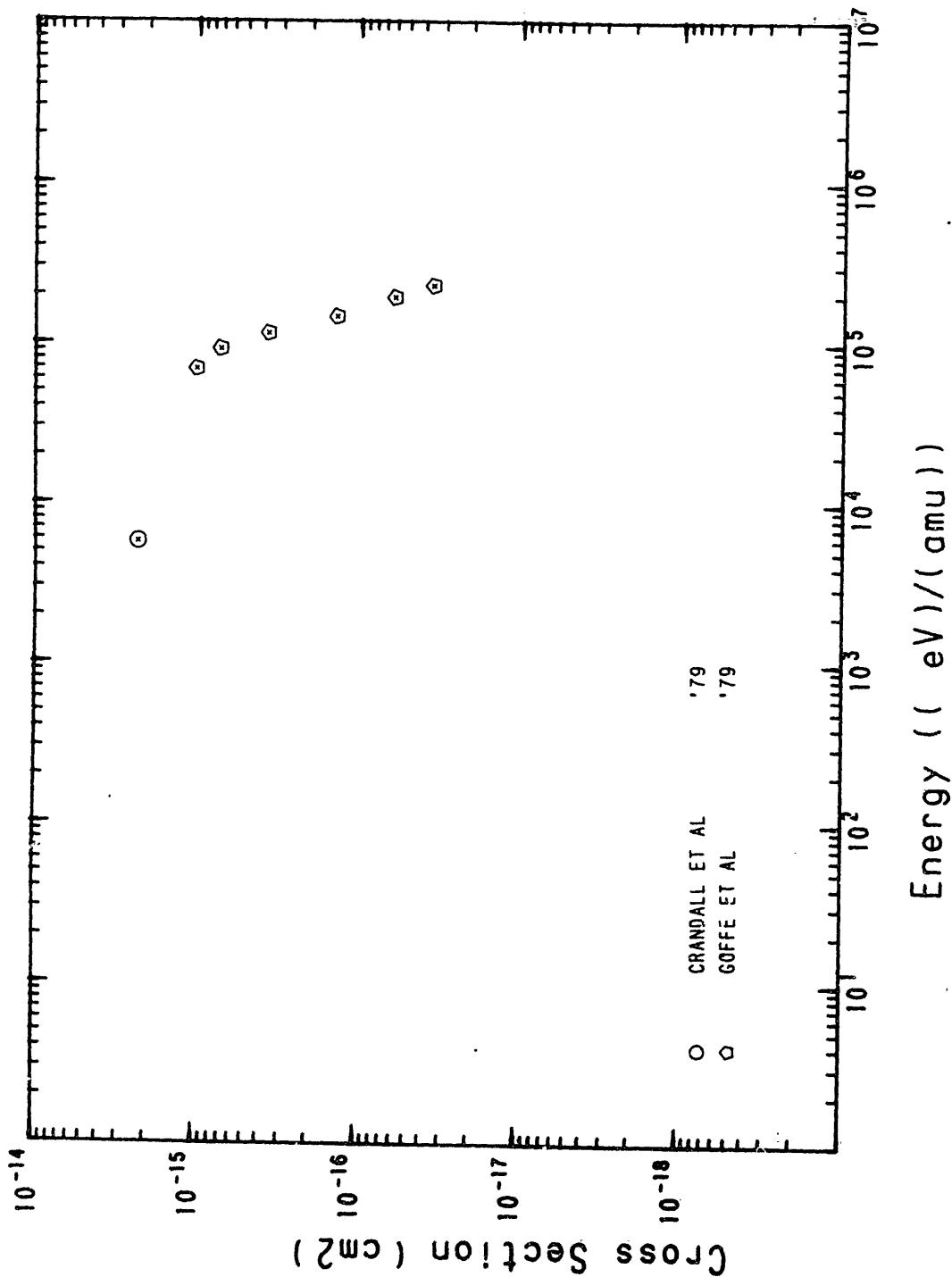


Fig.14 $\text{B}^{5+} + \text{H} \rightarrow \text{B}^{4+}$

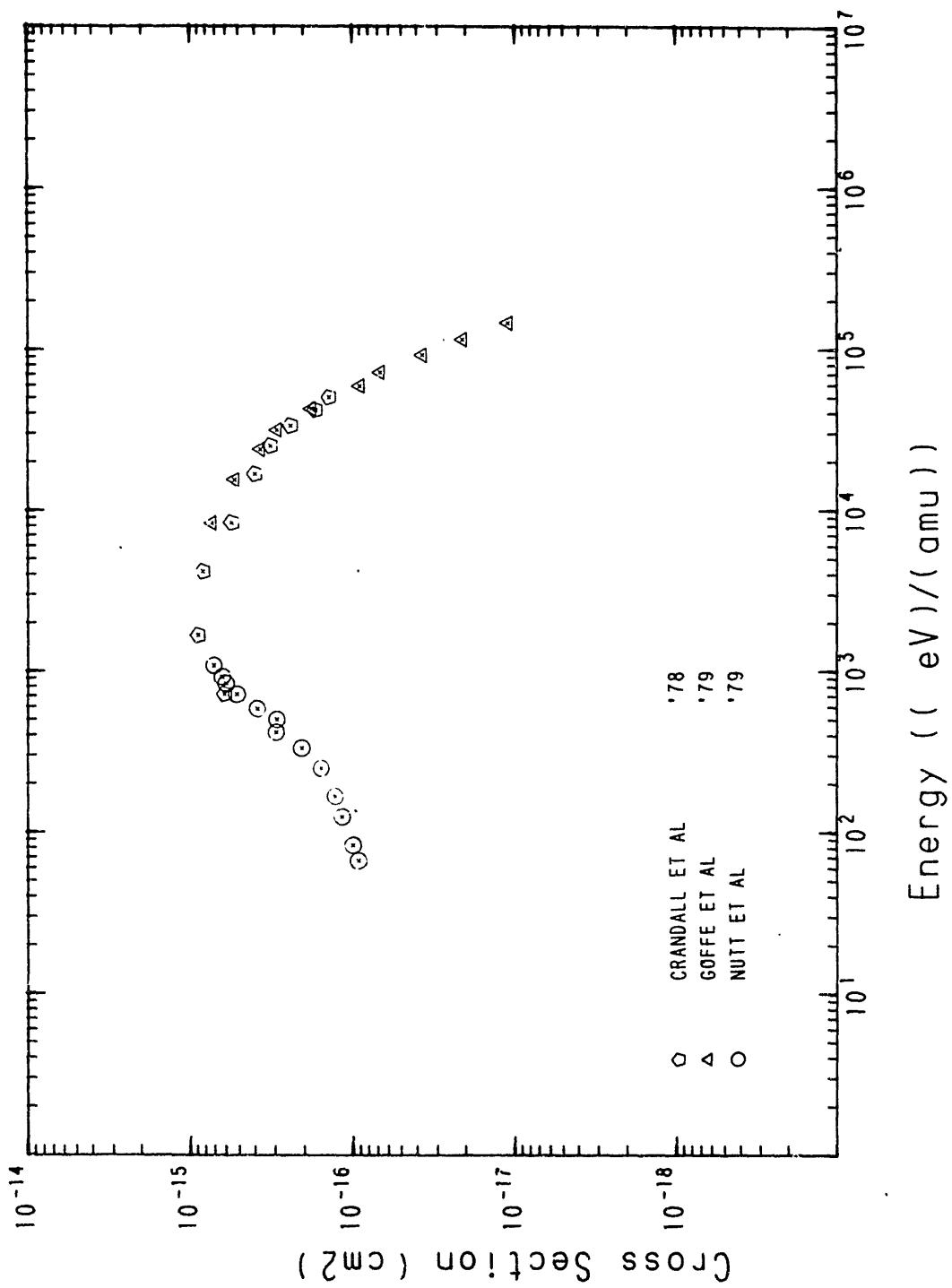


Fig.15 $\text{C}^+ + \text{H} \rightarrow \text{C}^0$

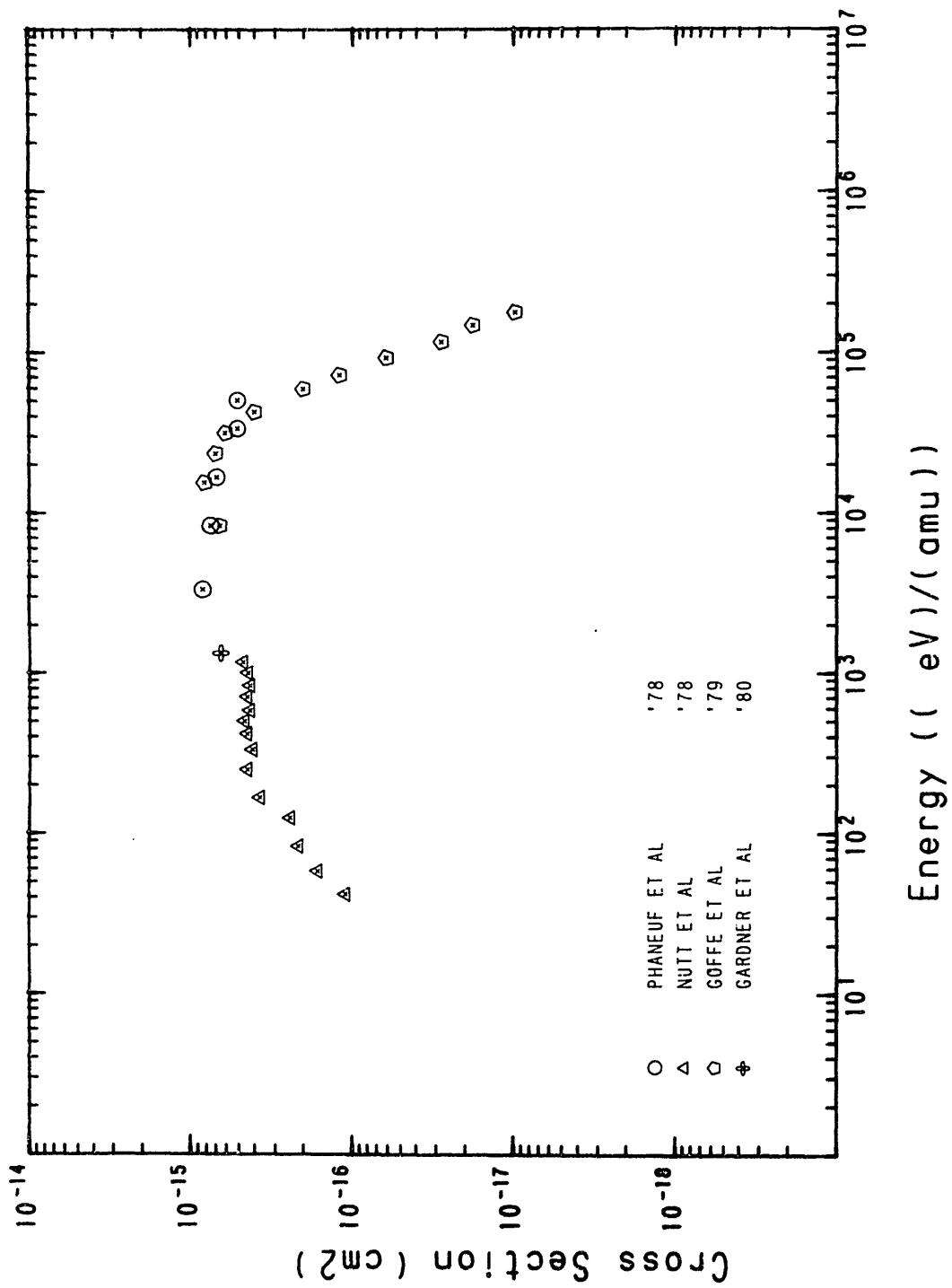


Fig.16 $\text{C}^{2+} + \text{H} \rightarrow \text{C}^+$

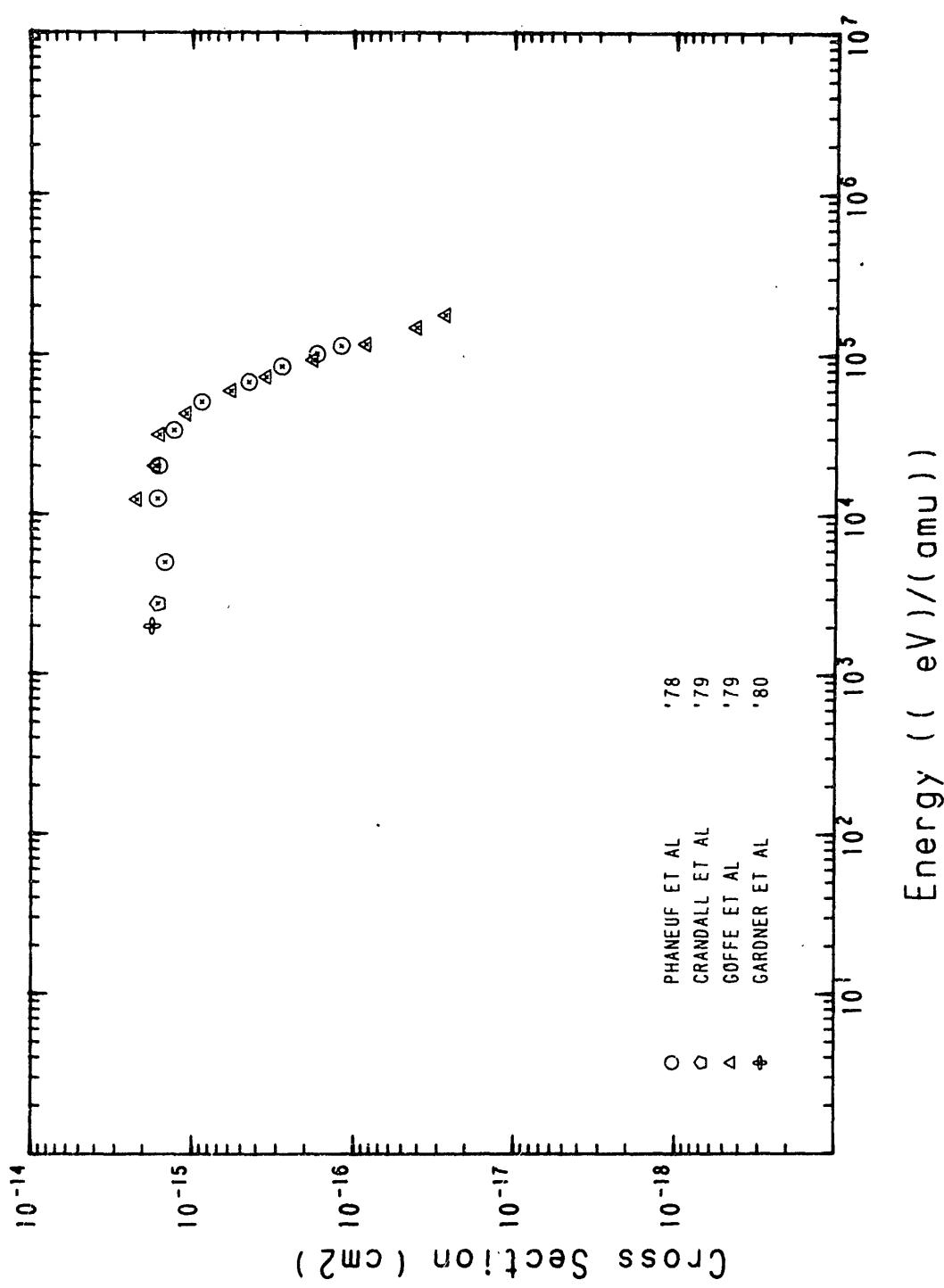


Fig.17 $\text{C}^{3+} + \text{H} \longrightarrow \text{C}^{2+}$

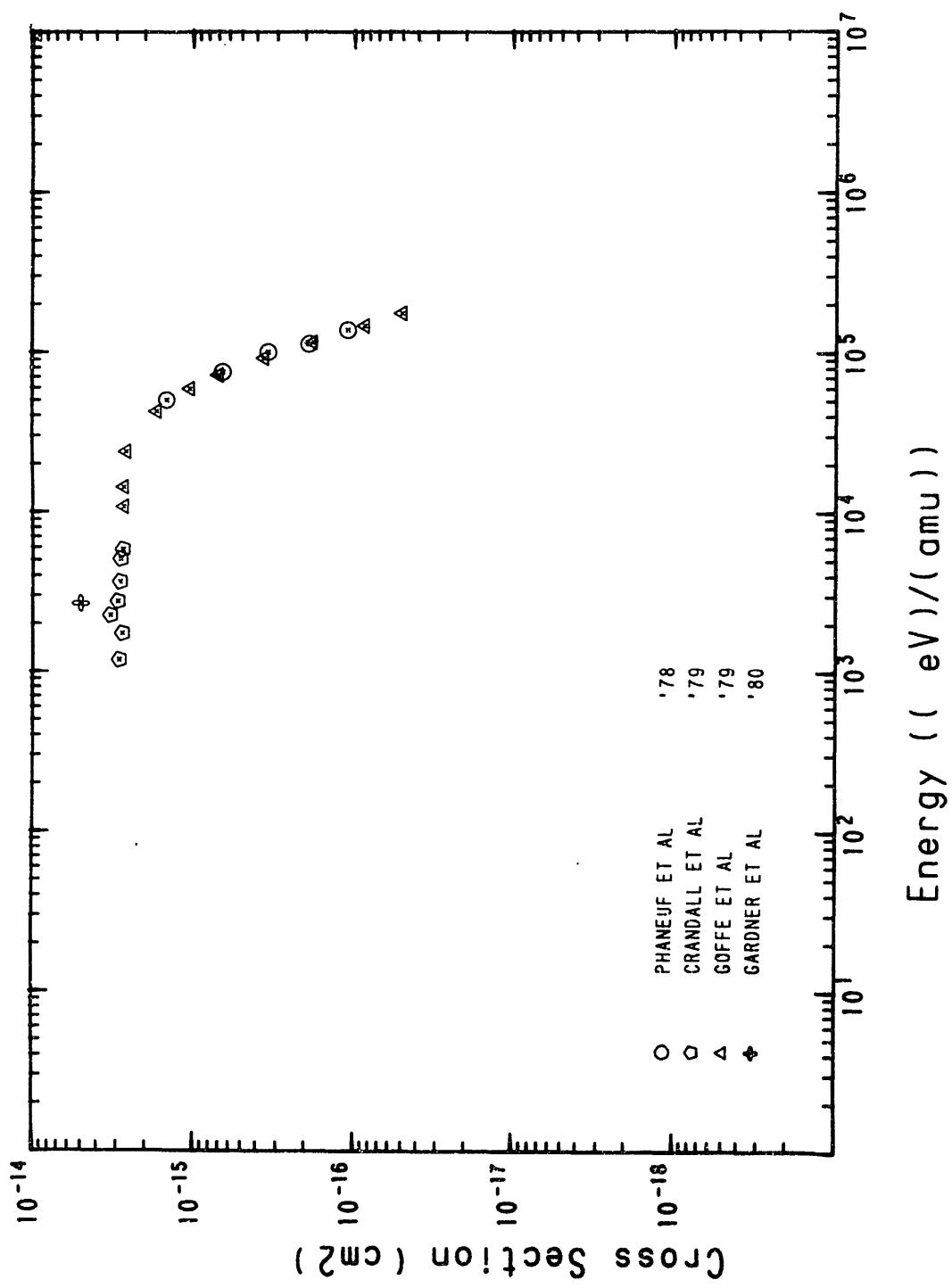


Fig.18 $\text{C}^{4+} + \text{H} \rightarrow \text{C}^{3+}$

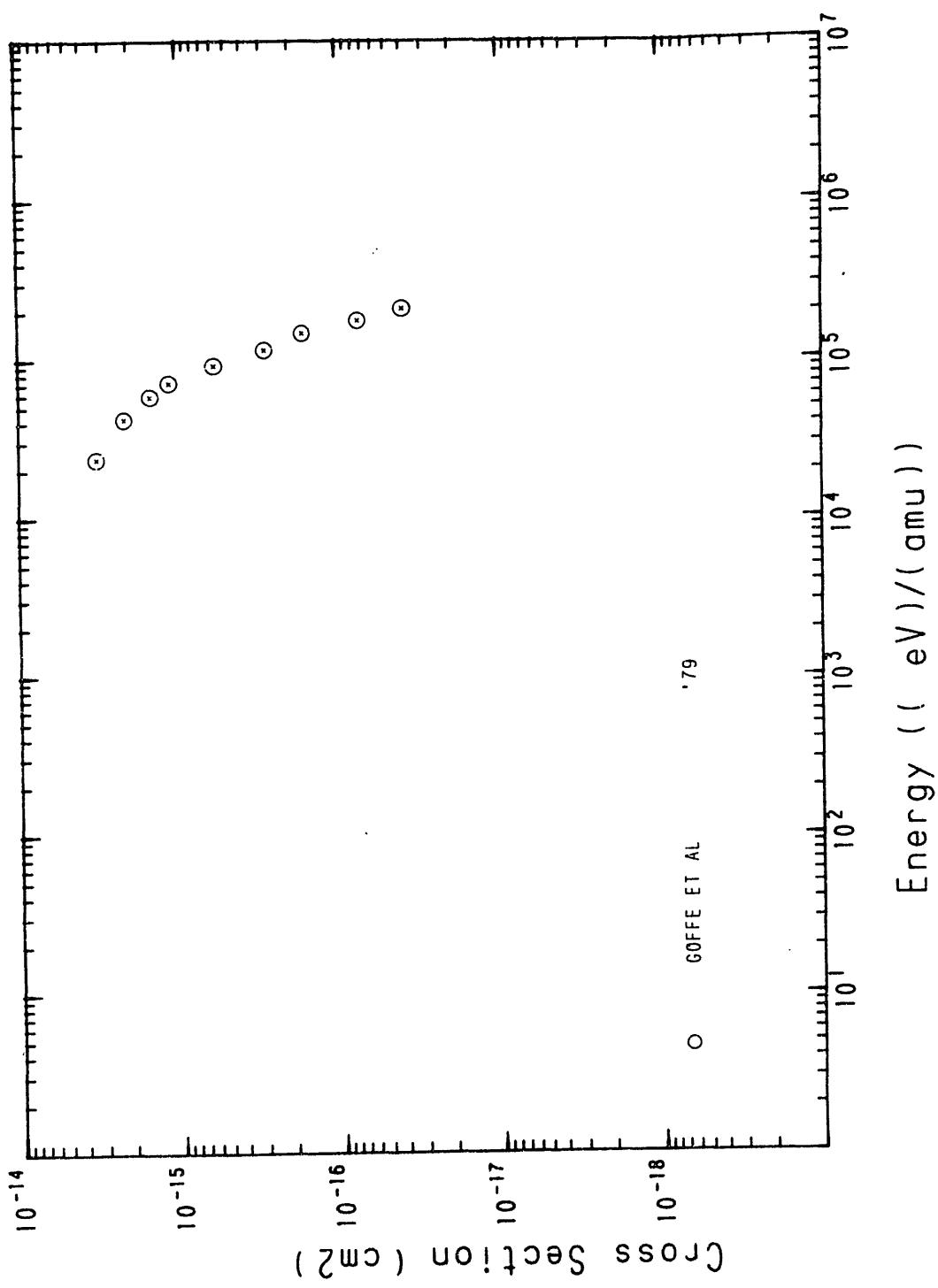


Fig.19 $\text{C}^{5+} + \text{H} \rightarrow \text{C}^{4+}$

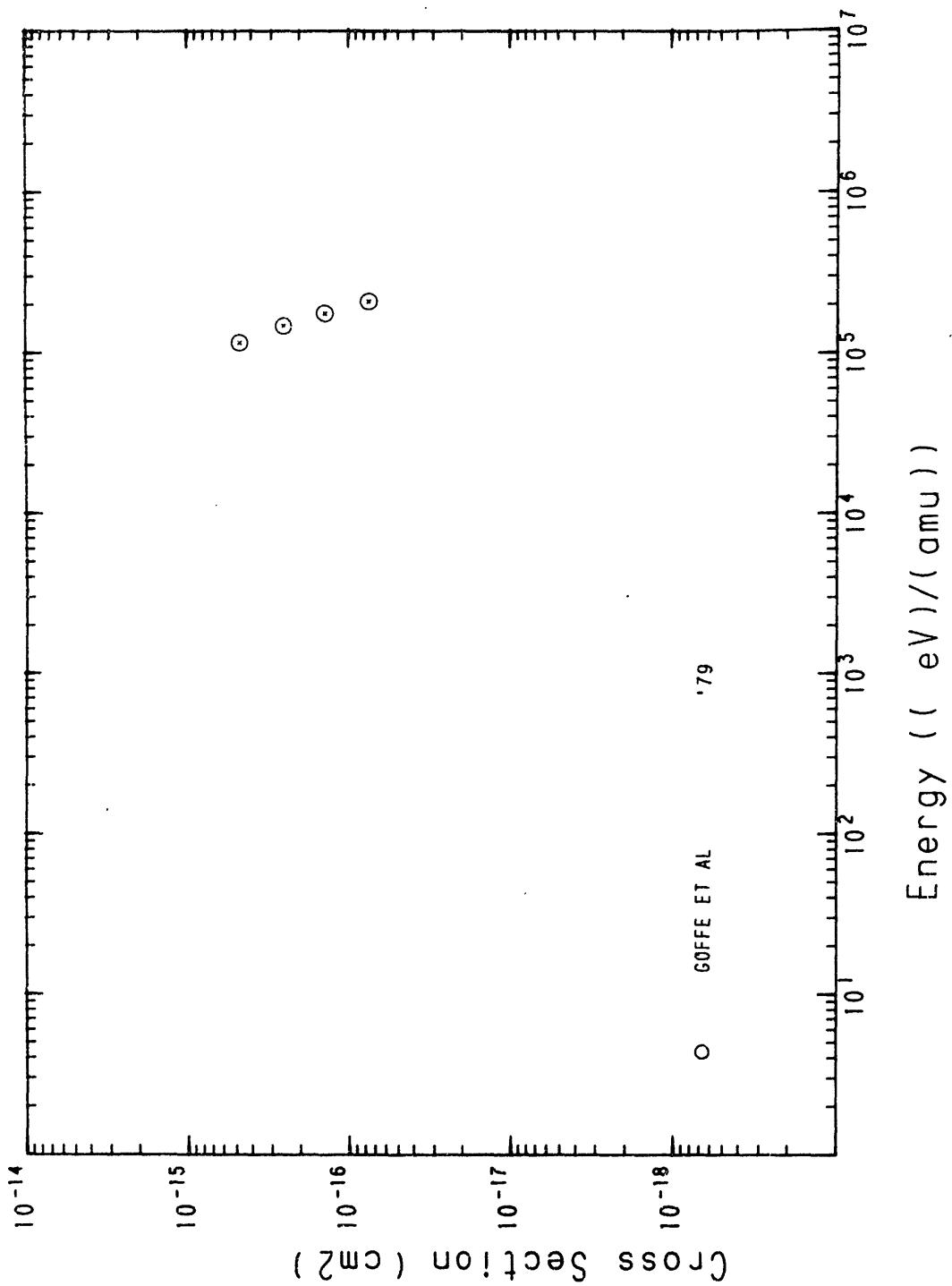


Fig.20 $\text{C}^{6+} + \text{H} \longrightarrow \text{C}^{5+}$

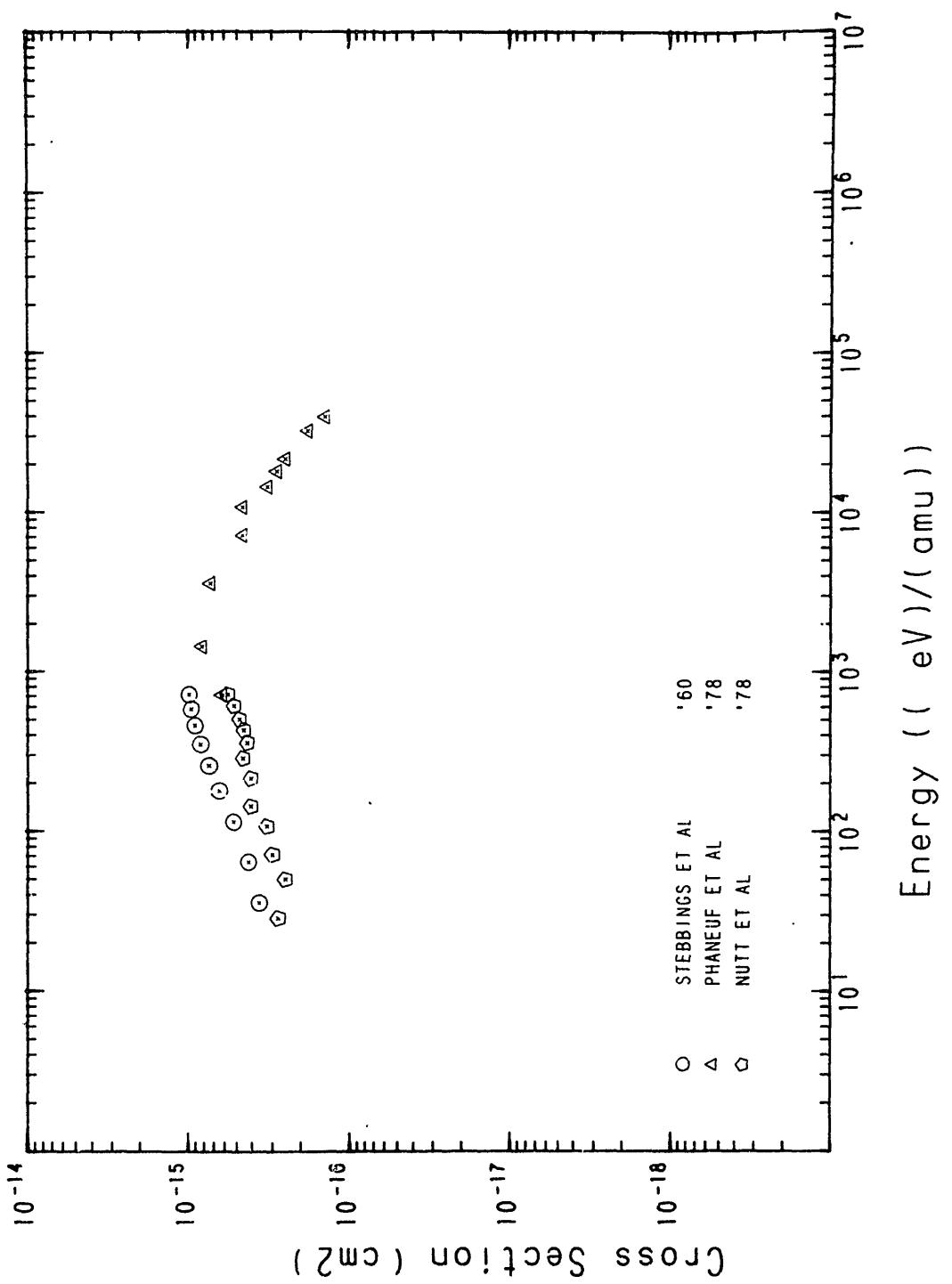


Fig.21 $\text{N}^+ + \text{H} \longrightarrow \text{N}^0$

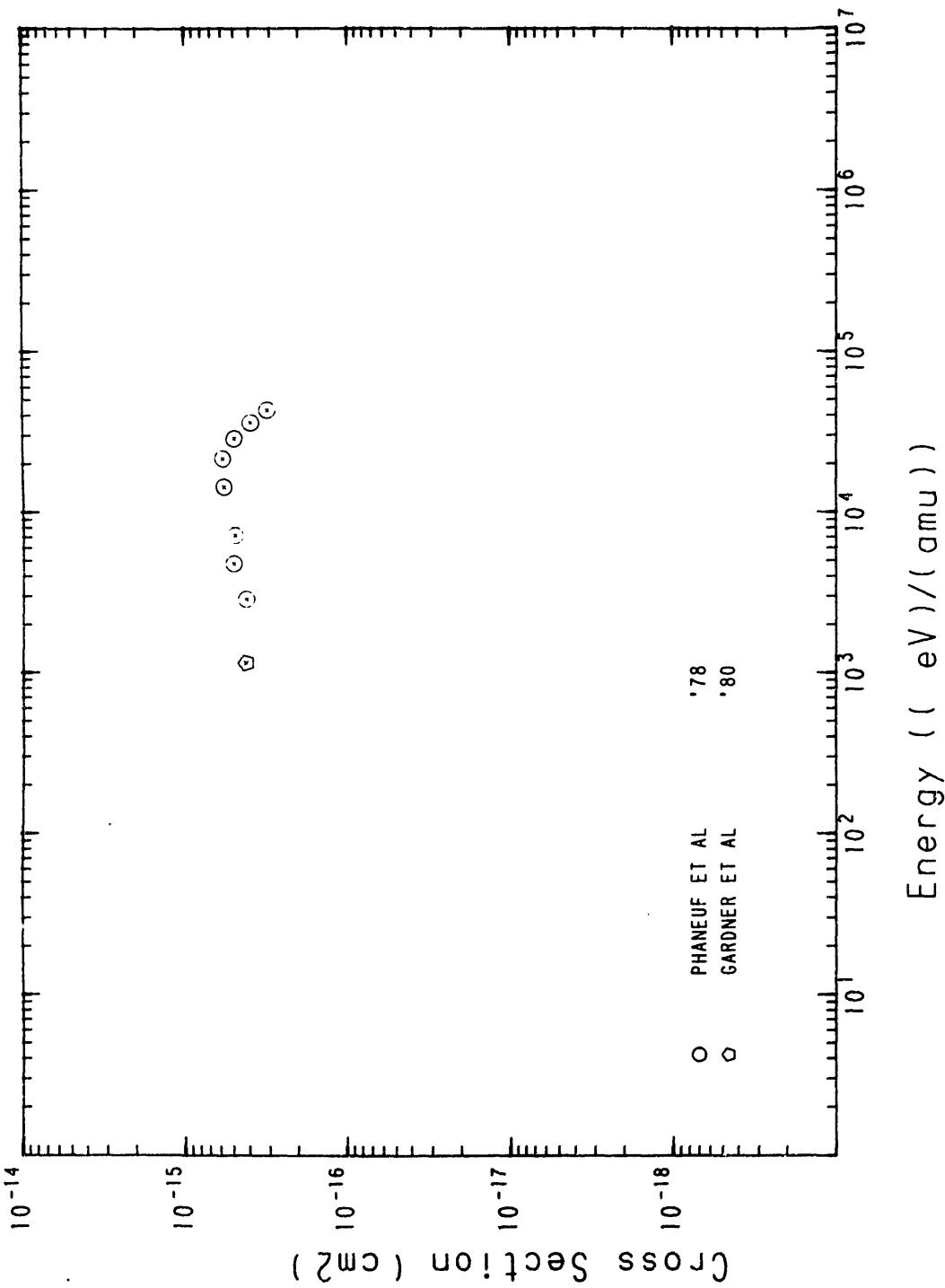


Fig.22 $\text{N}^{2+} + \text{H} \rightarrow \text{N}^+$

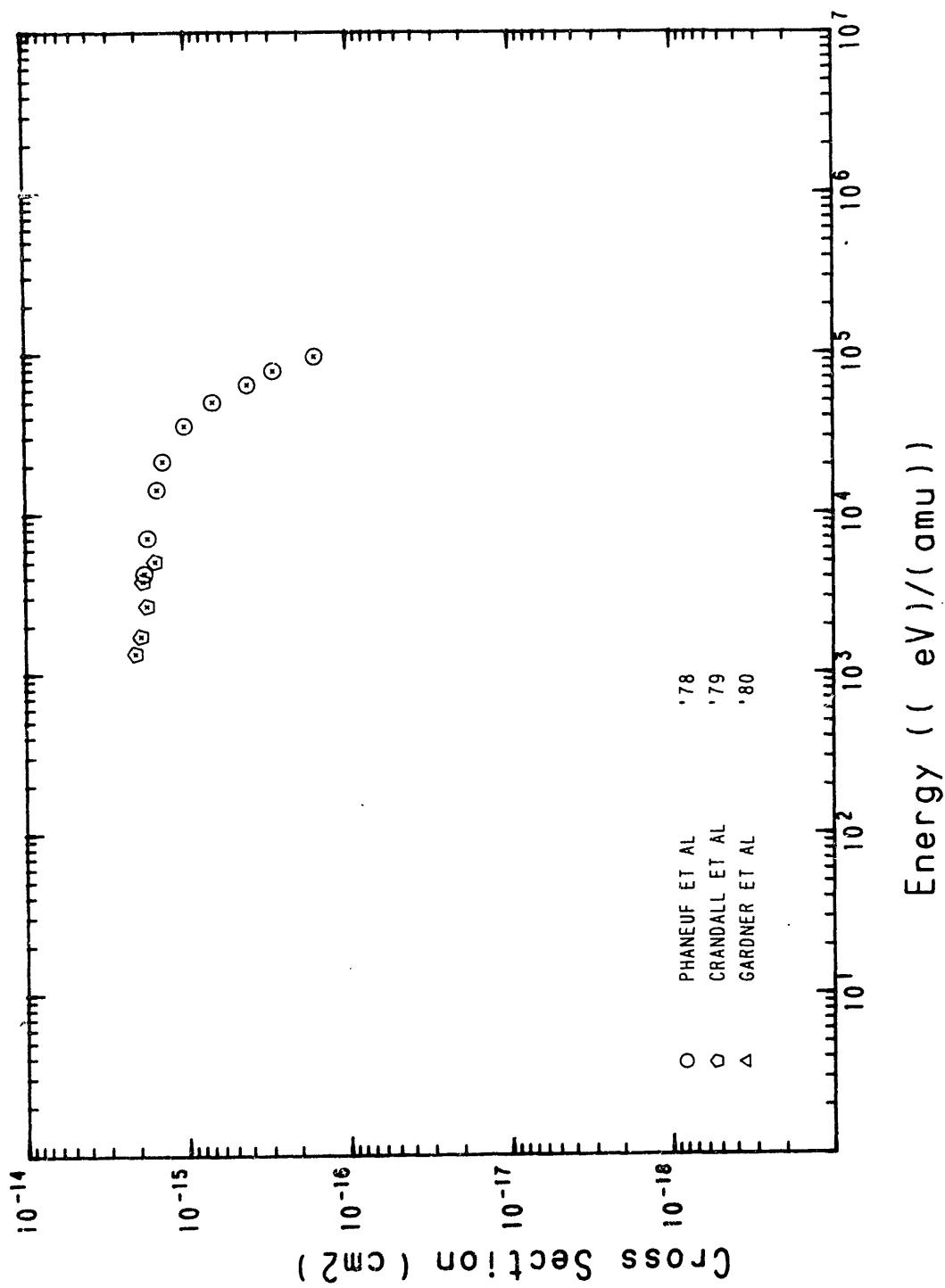


Fig.23 $\text{N}^{3+} + \text{H} \rightarrow \text{N}^{2+}$

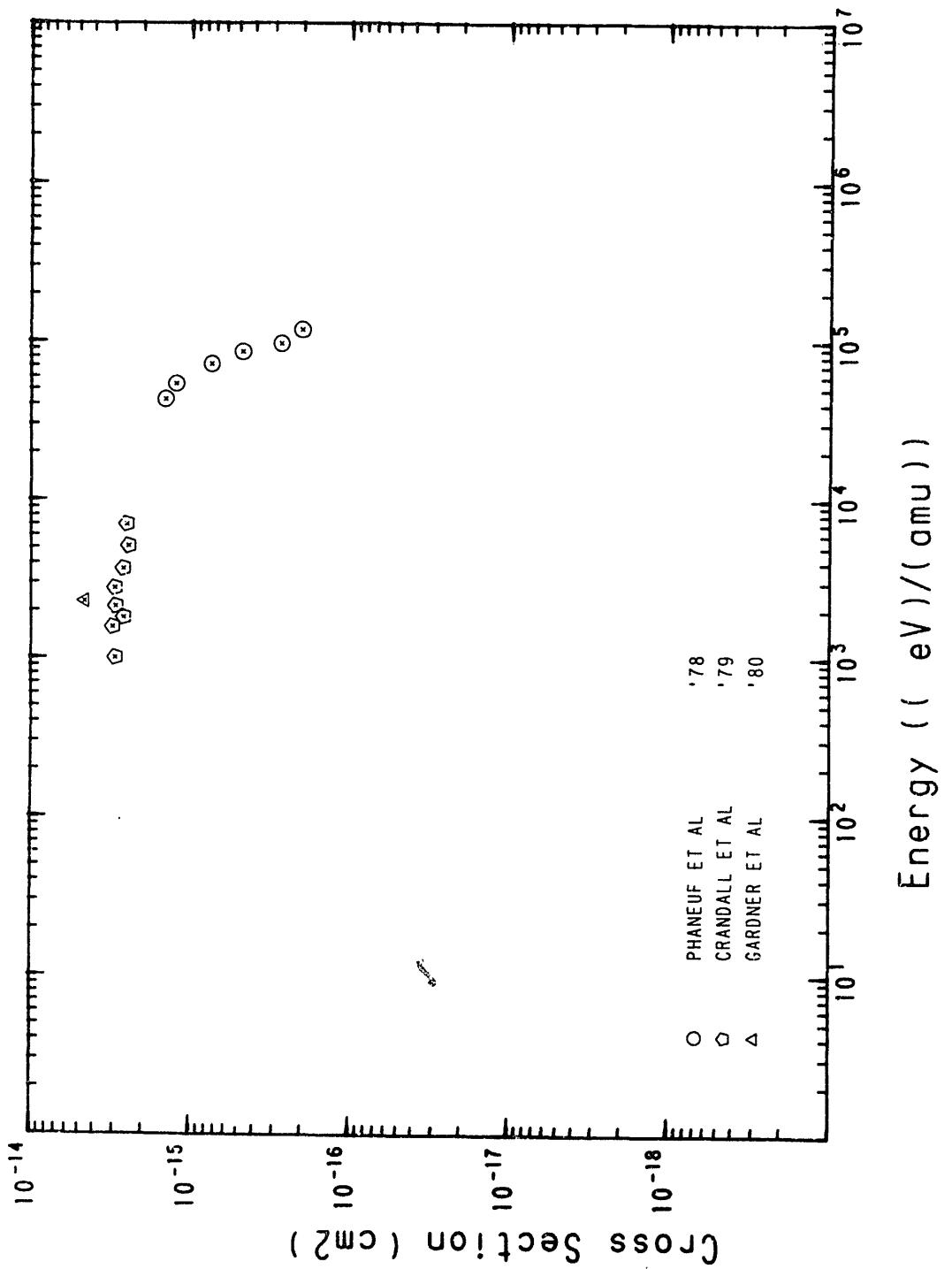


Fig.24 $\text{N}^{4+} + \text{H} \rightarrow \text{N}^{3+}$

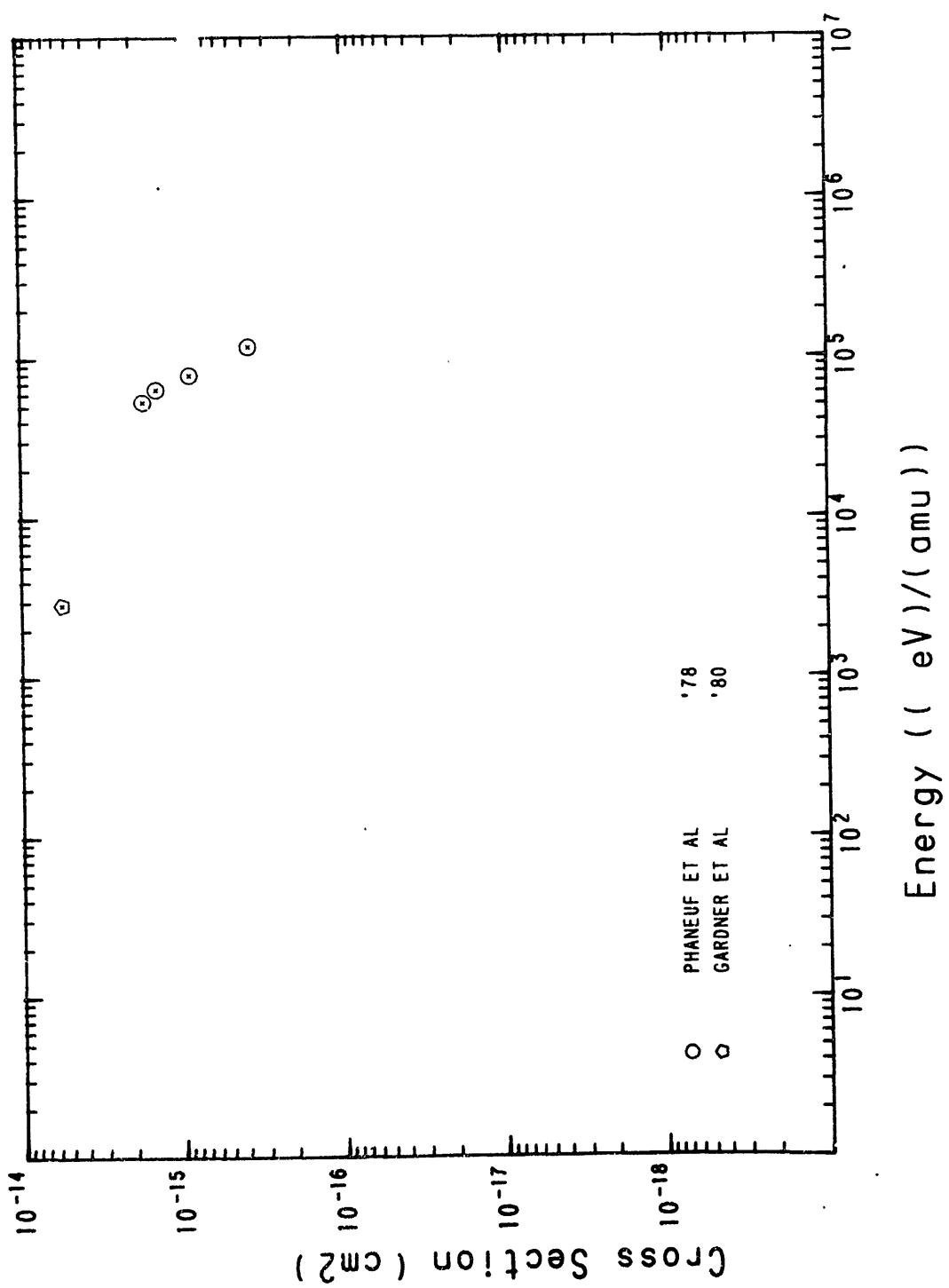


Fig.25 $\text{N}^{5+} + \text{H} \longrightarrow \text{N}^{4+}$

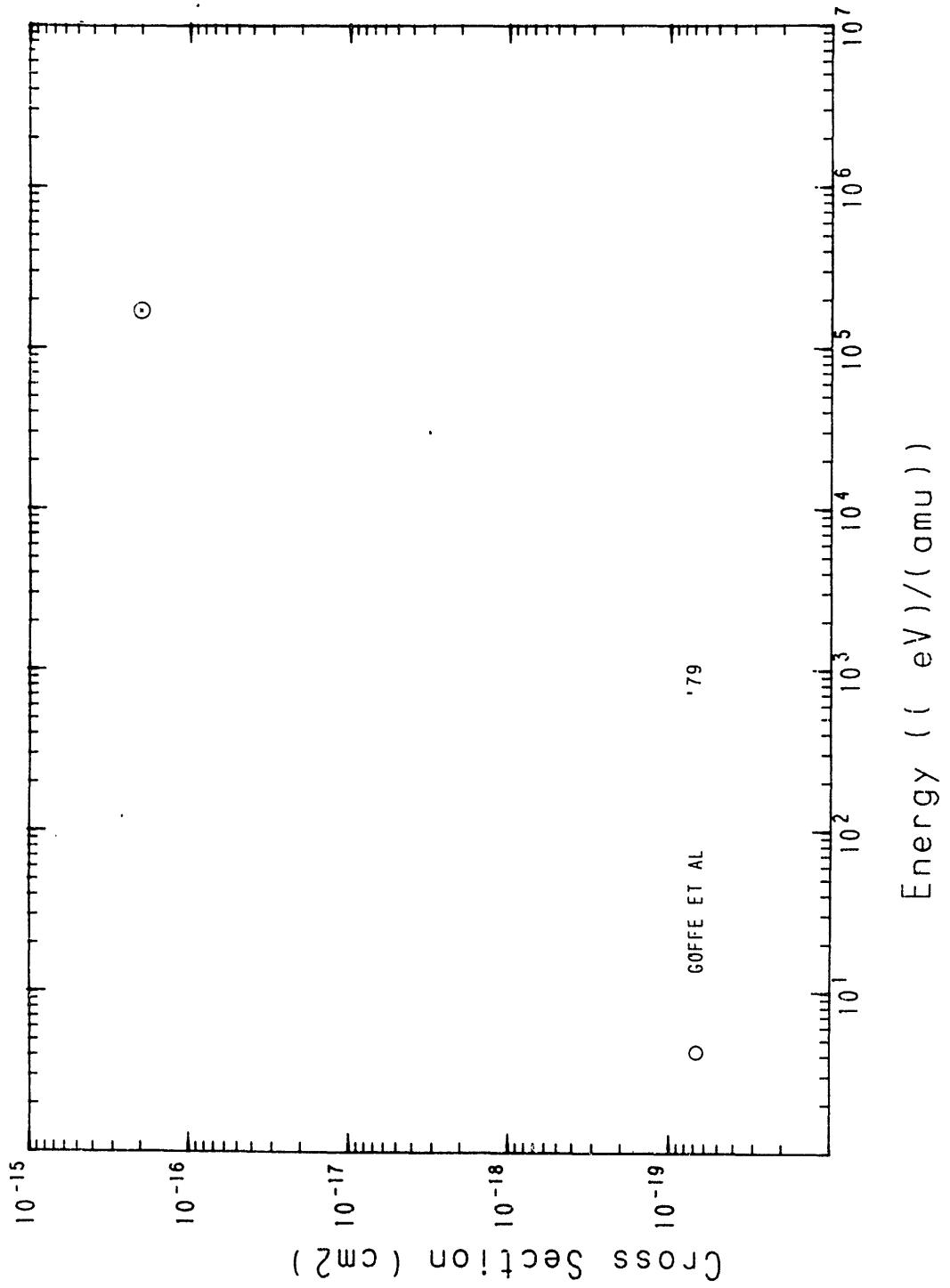


Fig.26 $\text{N}^{7+} + \text{H} \longrightarrow \text{N}^{6+}$

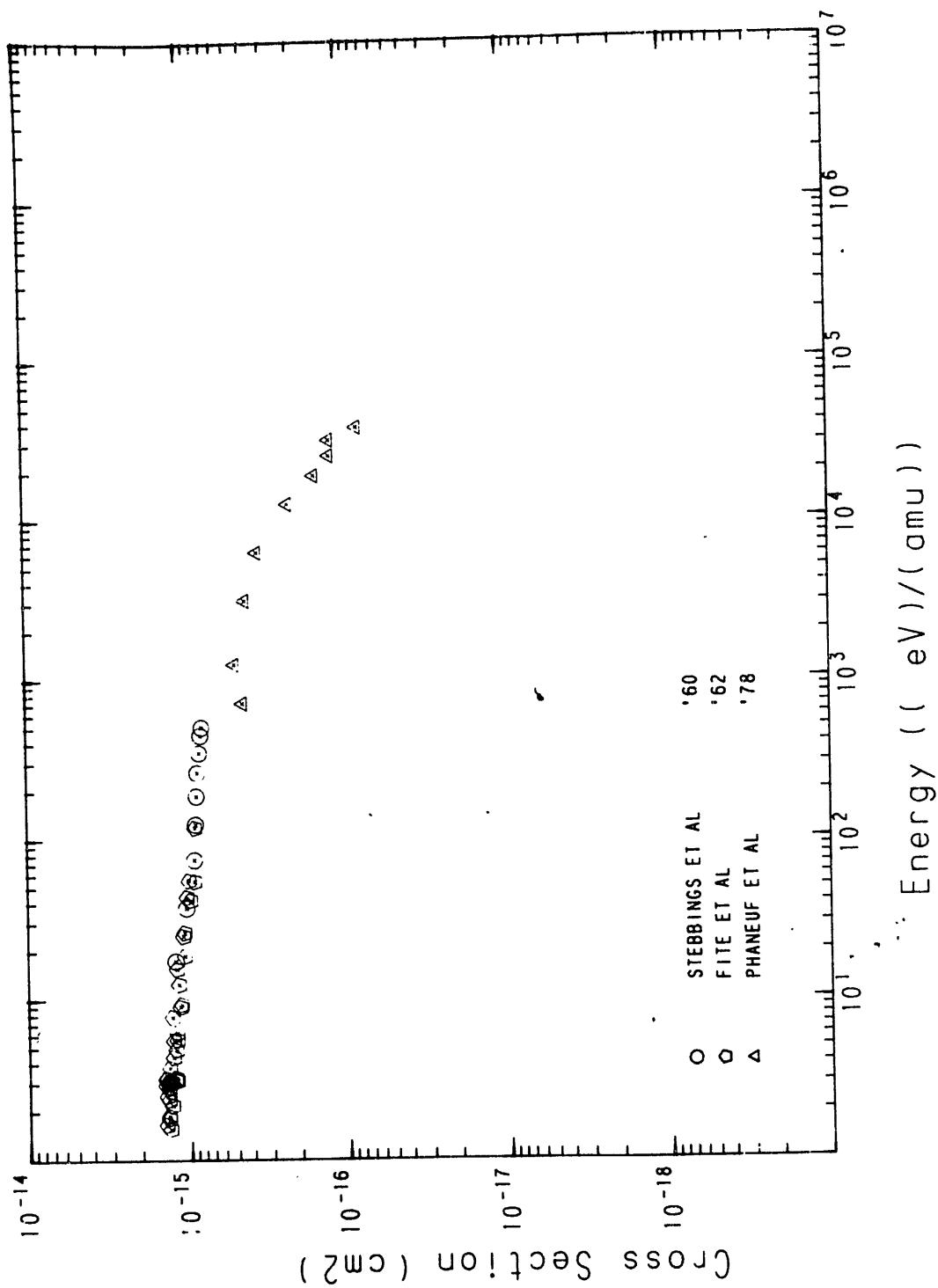


Fig.27 $O^+ + H \rightarrow O^0$

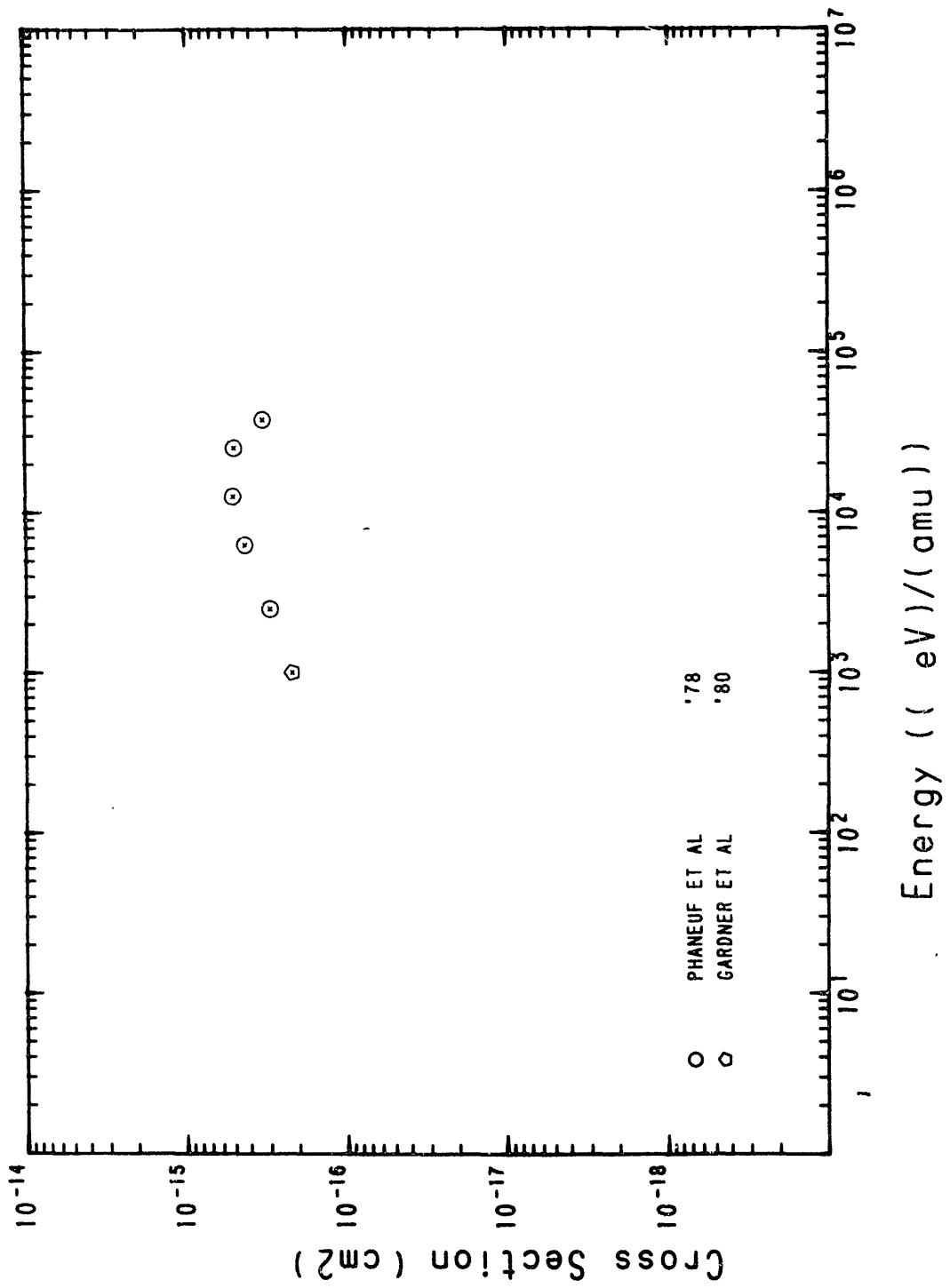


Fig.28 $\text{O}^{2+} + \text{H} \rightarrow \text{O}^+$

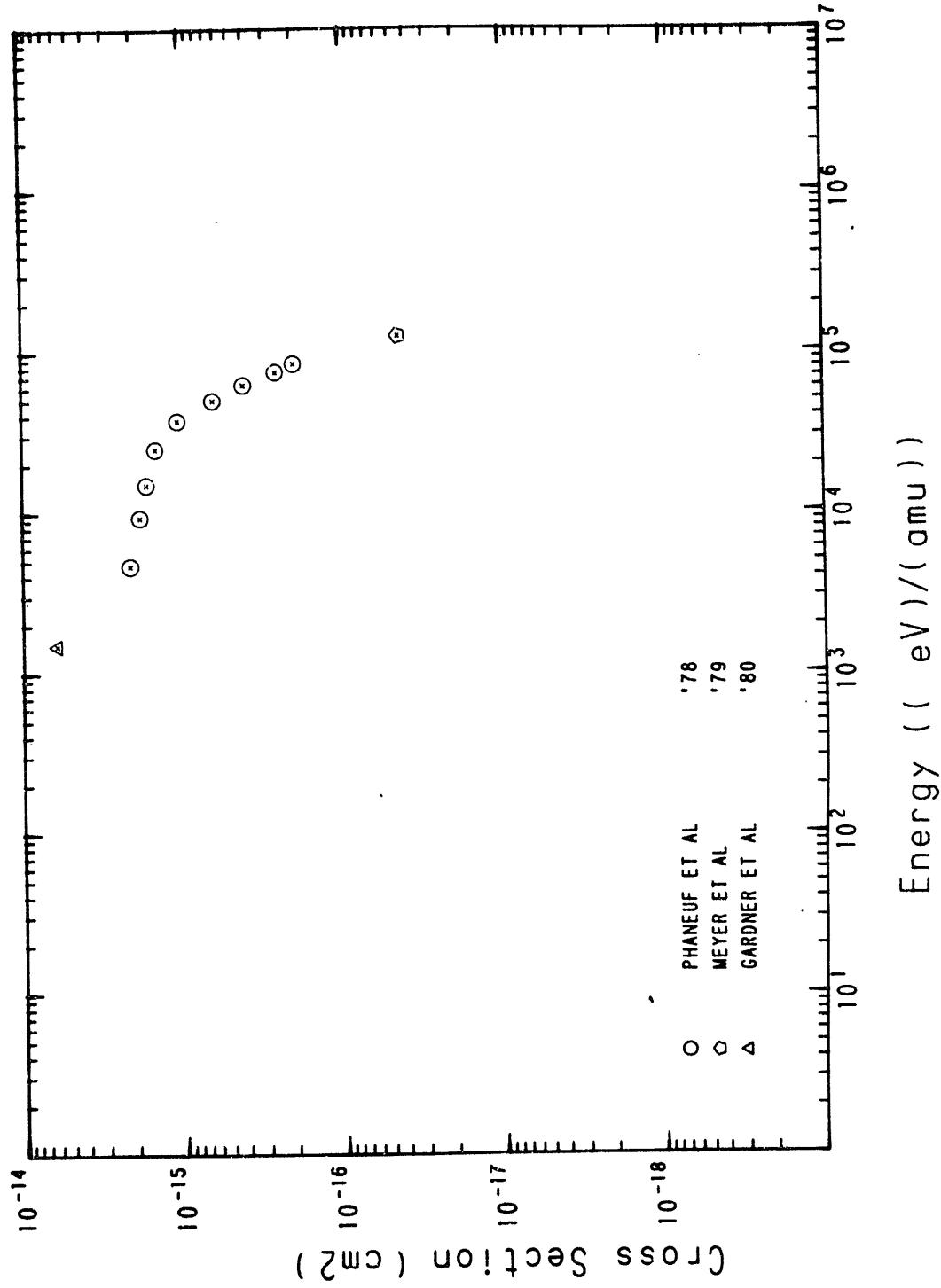


Fig.29 $O^{3+} + H \rightarrow O^{2+}$

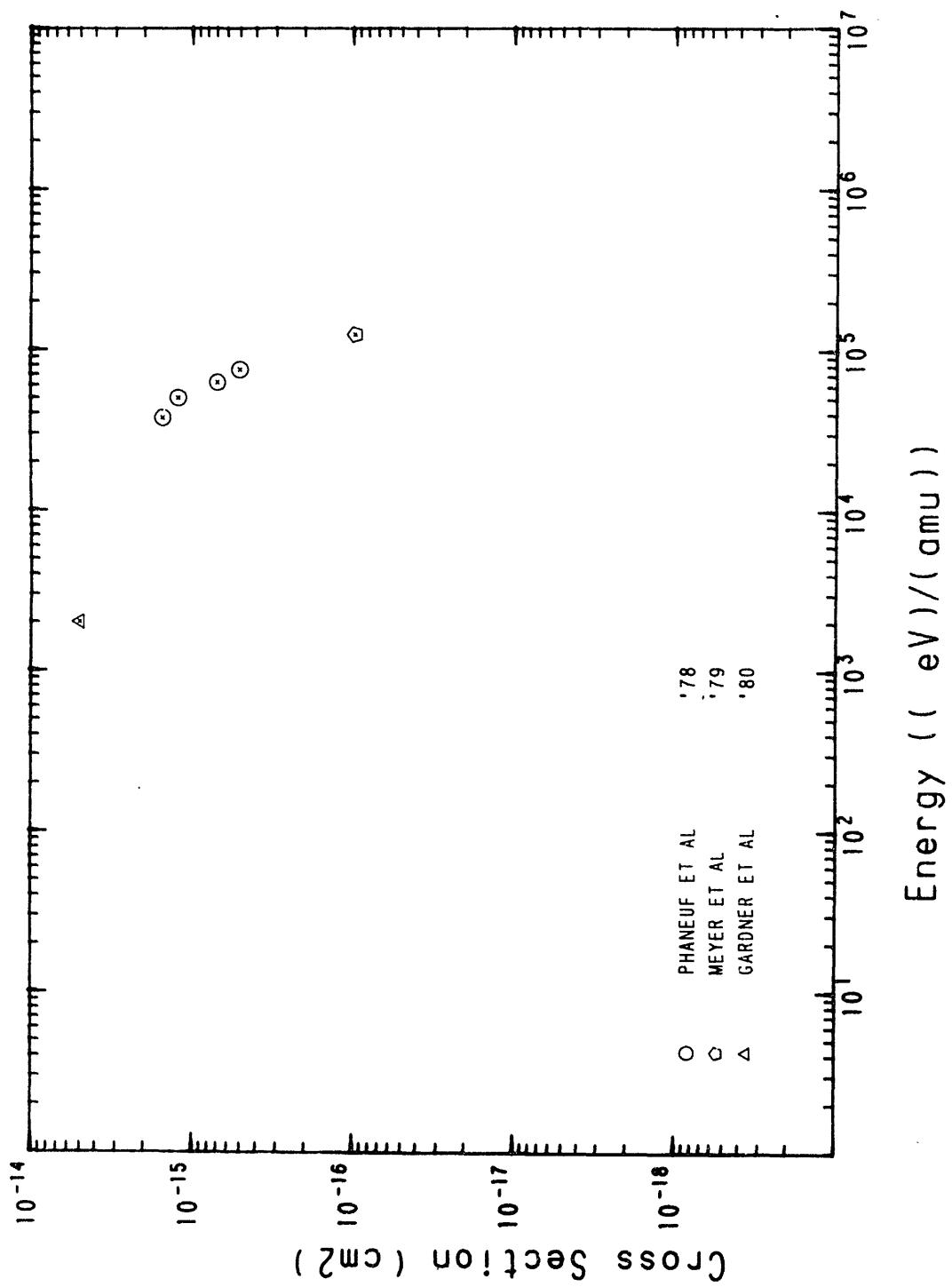


Fig.30 $\text{O}^{4+} + \text{H} \rightarrow \text{O}^{3+}$

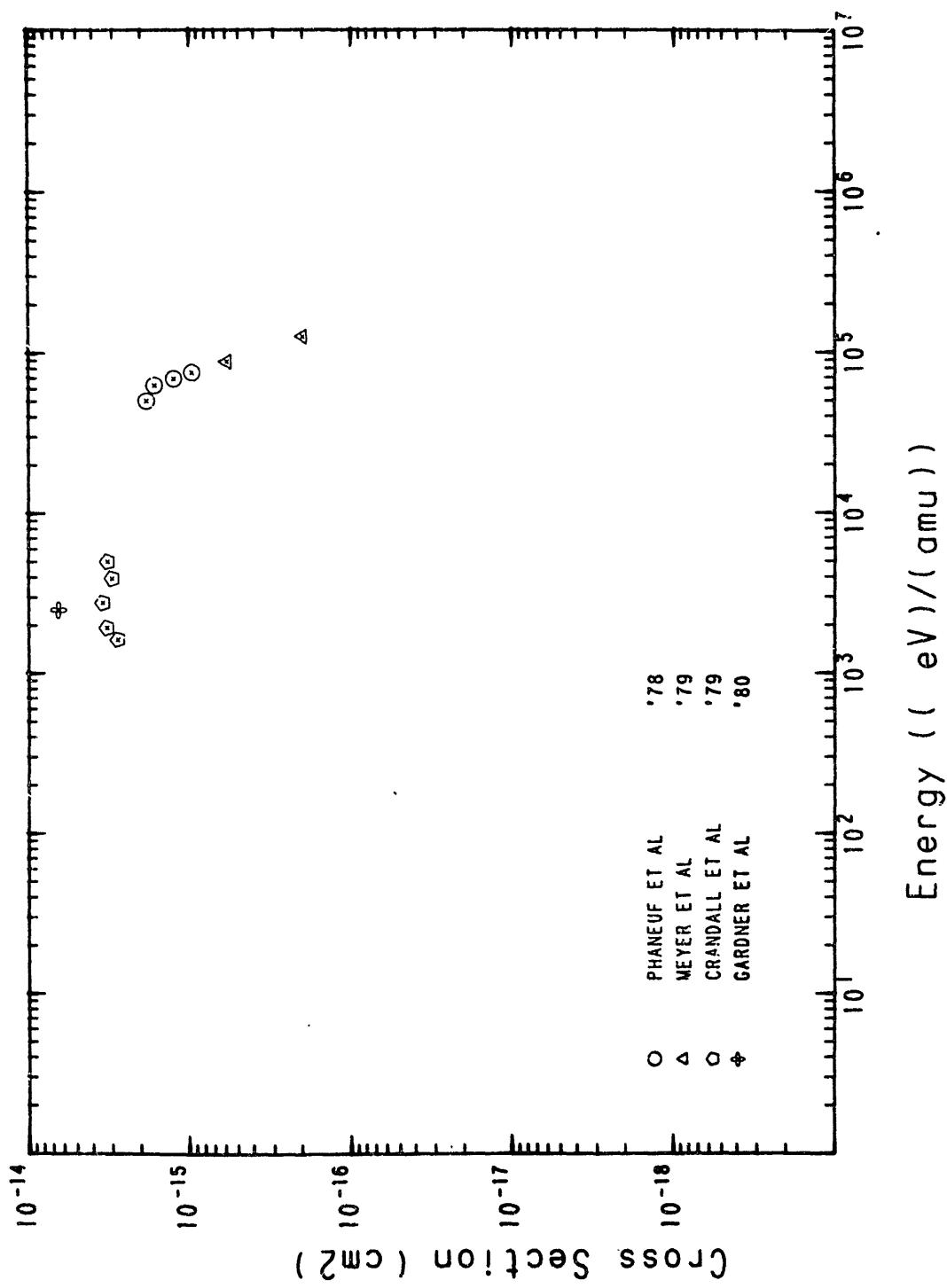


Fig.31 $O^{5+} + H \rightarrow O^{4+}$

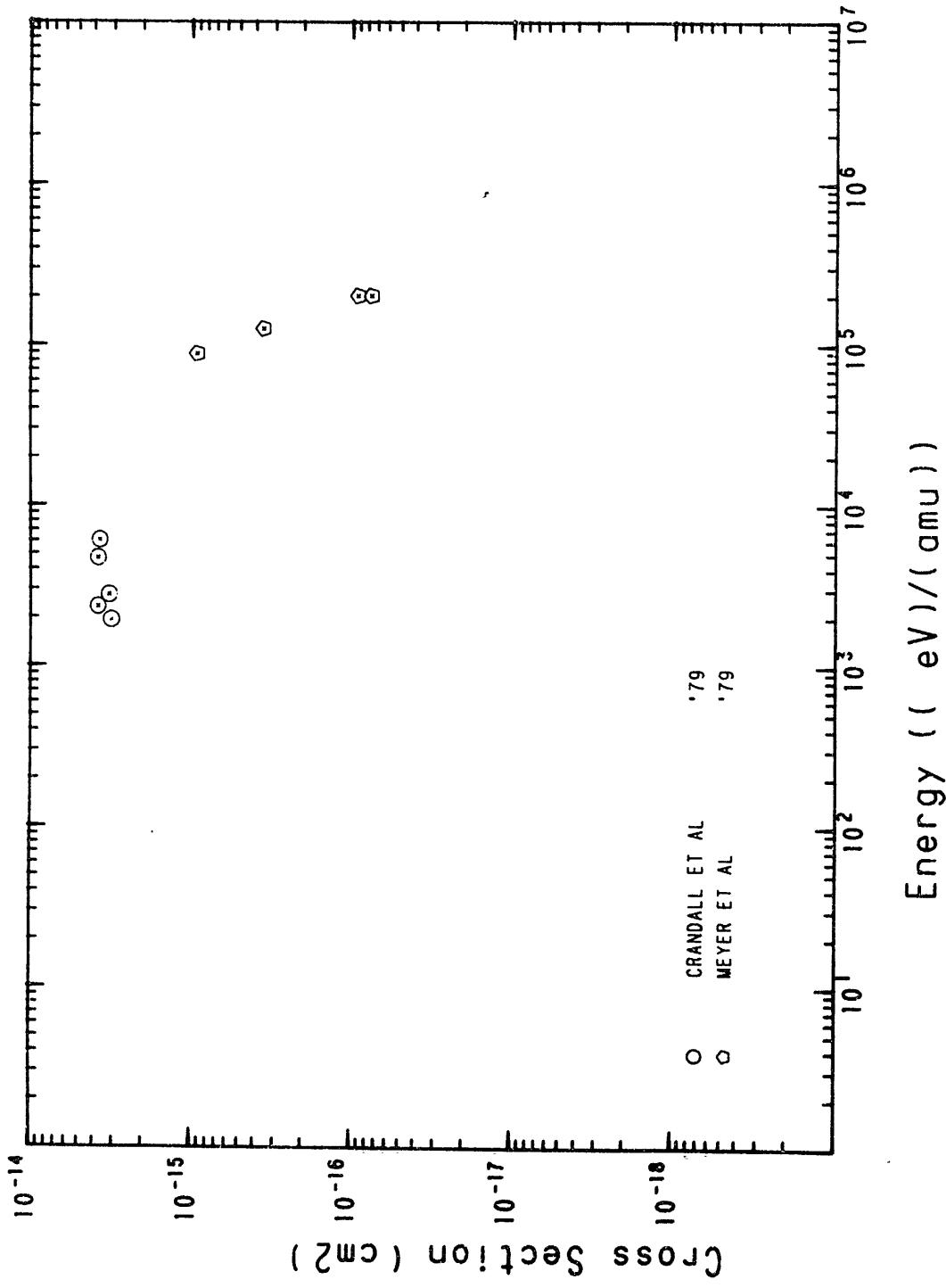


Fig.32 $\text{O}^{6+} + \text{H} \rightarrow \text{O}^{5+}$

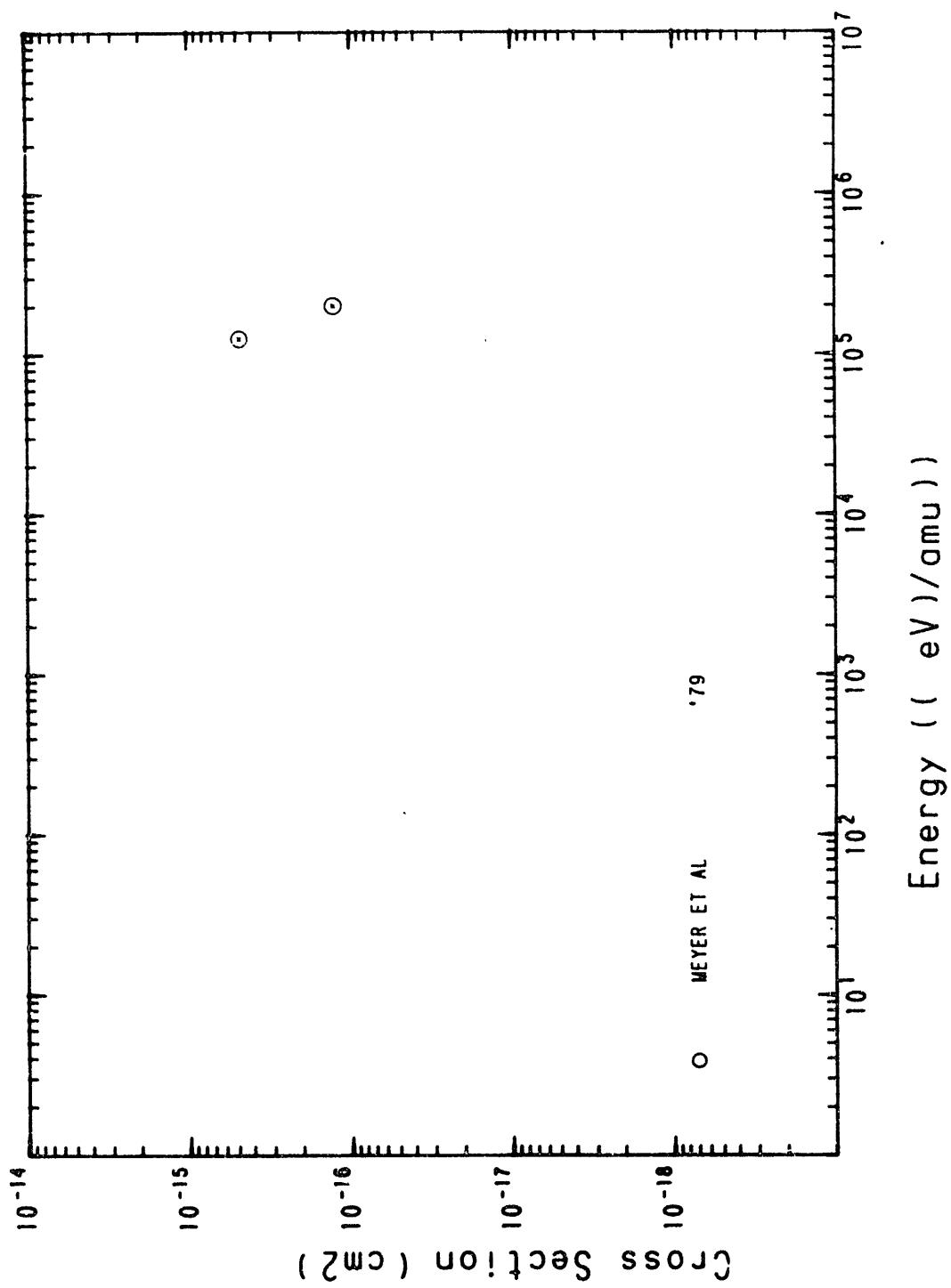


Fig.33 $\text{O}^{7+} + \text{H} \rightarrow \text{O}^{6+}$

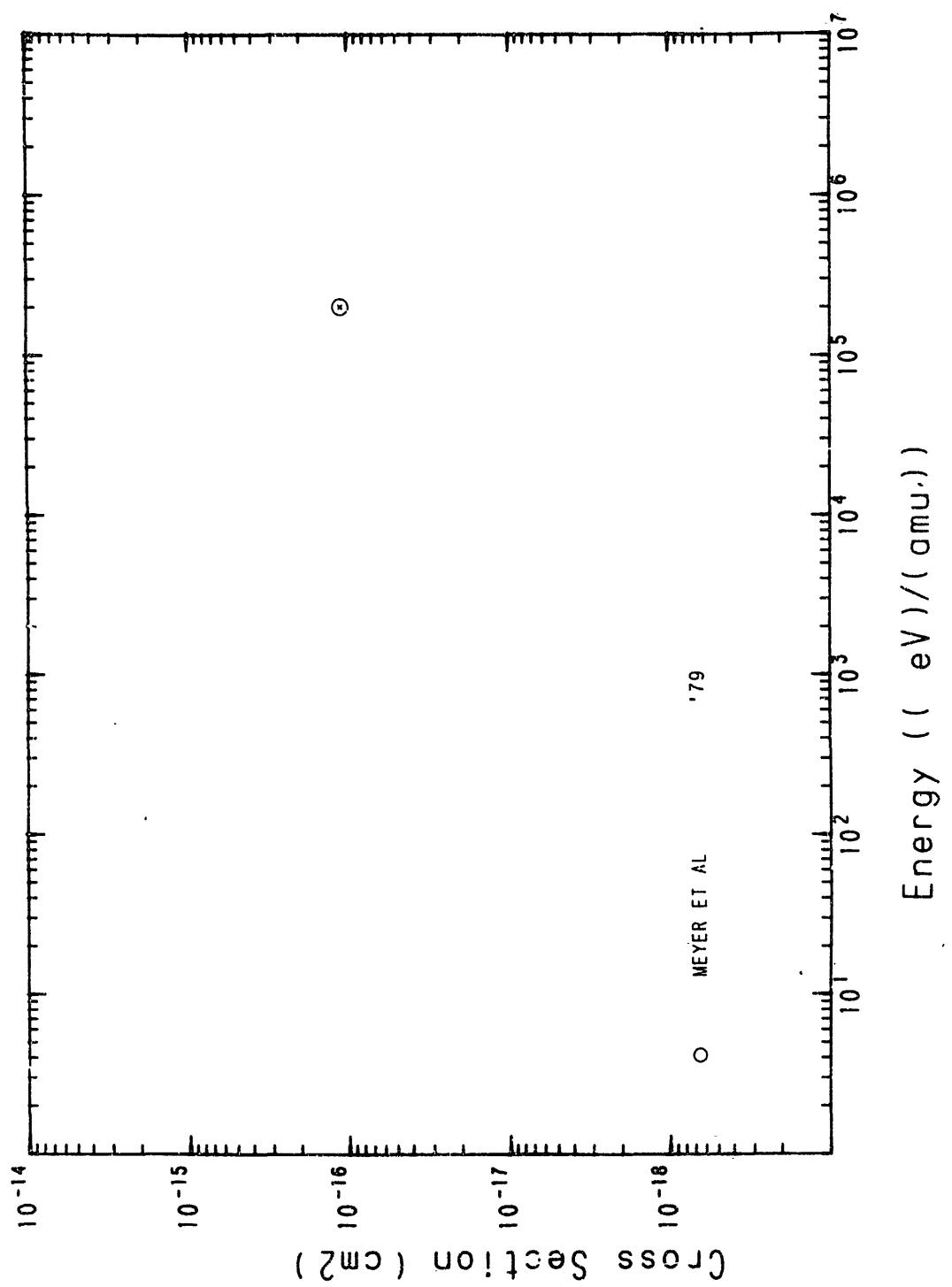


Fig.34 $O^{8+} + H \rightarrow O^{7+}$

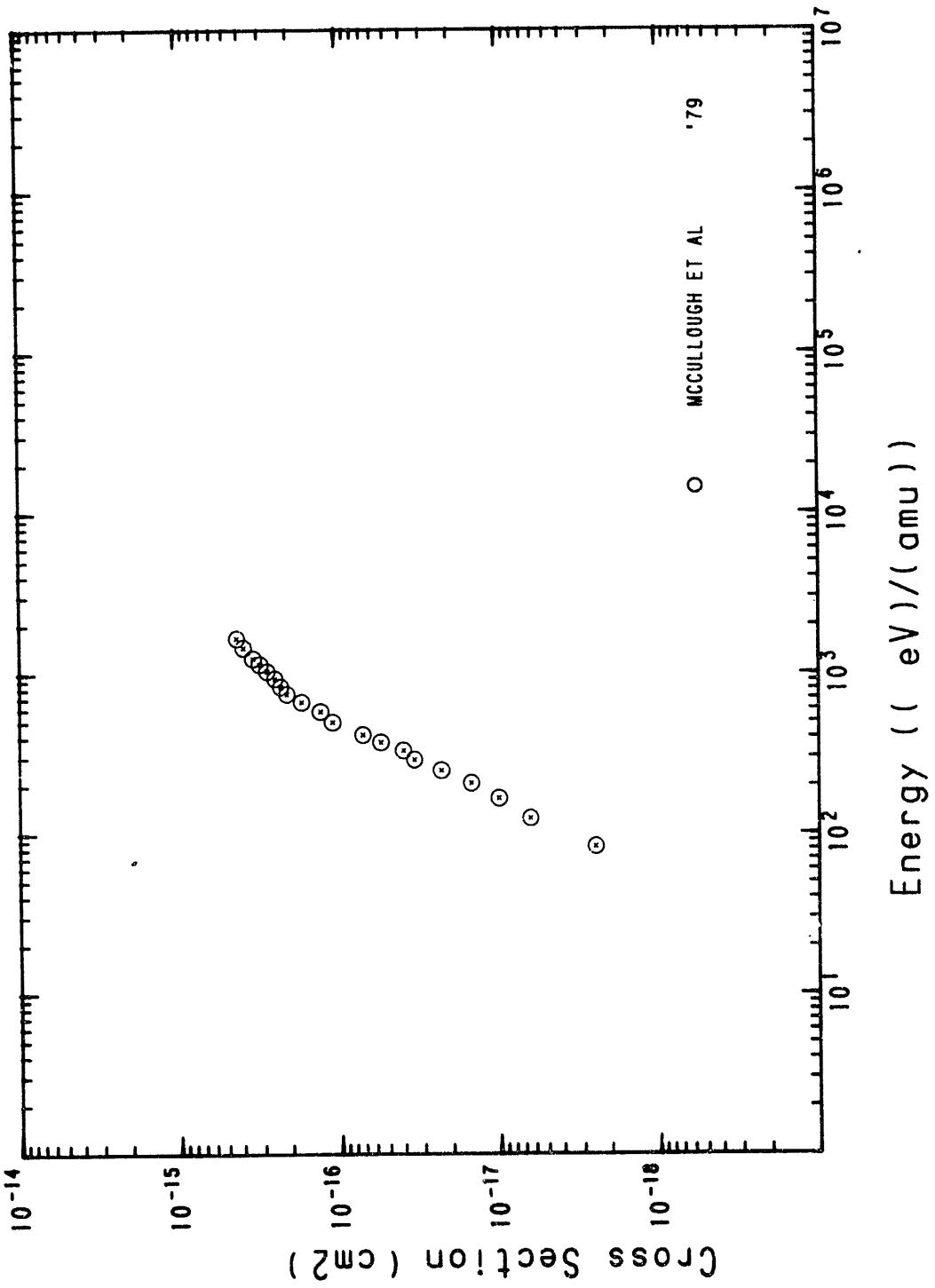


Fig.35 $\text{Mg}^{2+} + \text{H} \rightarrow \text{Mg}^+$

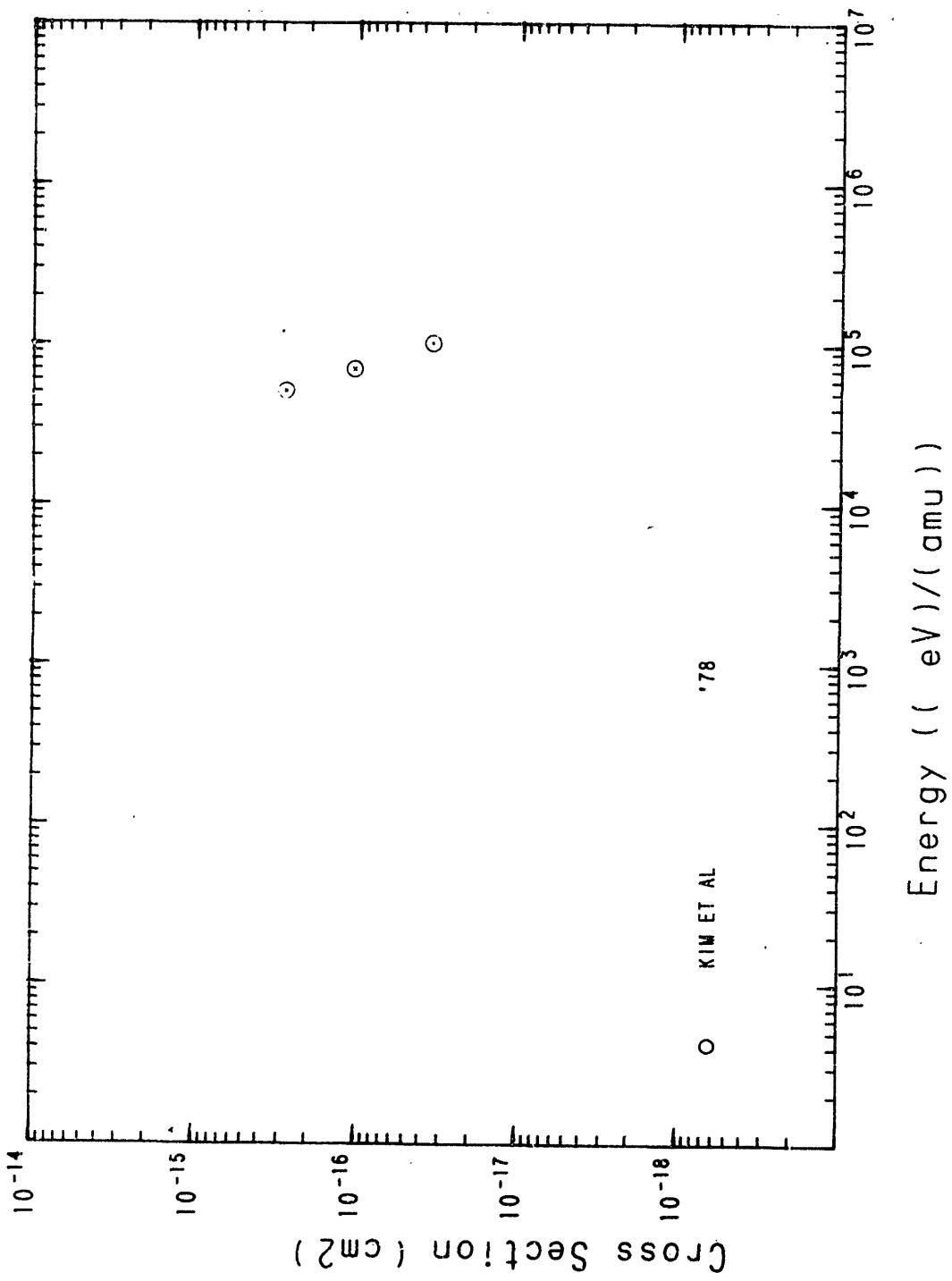


Fig.36 $\text{Si}^{2+} + \text{H} \rightarrow \text{Si}^+$

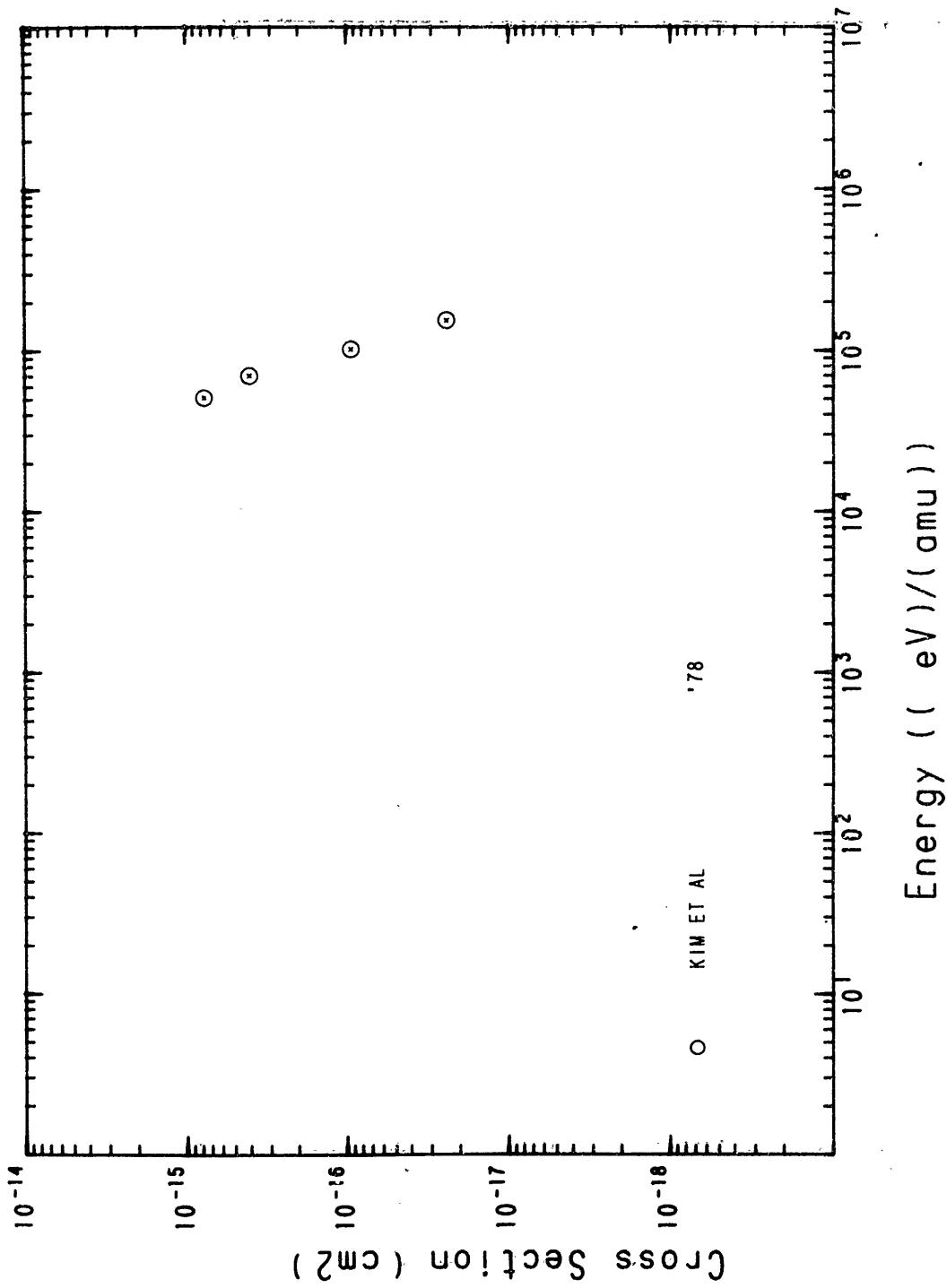


Fig.37 $\text{Si}^{3+} + \text{H} \rightarrow \text{Si}^{2+}$

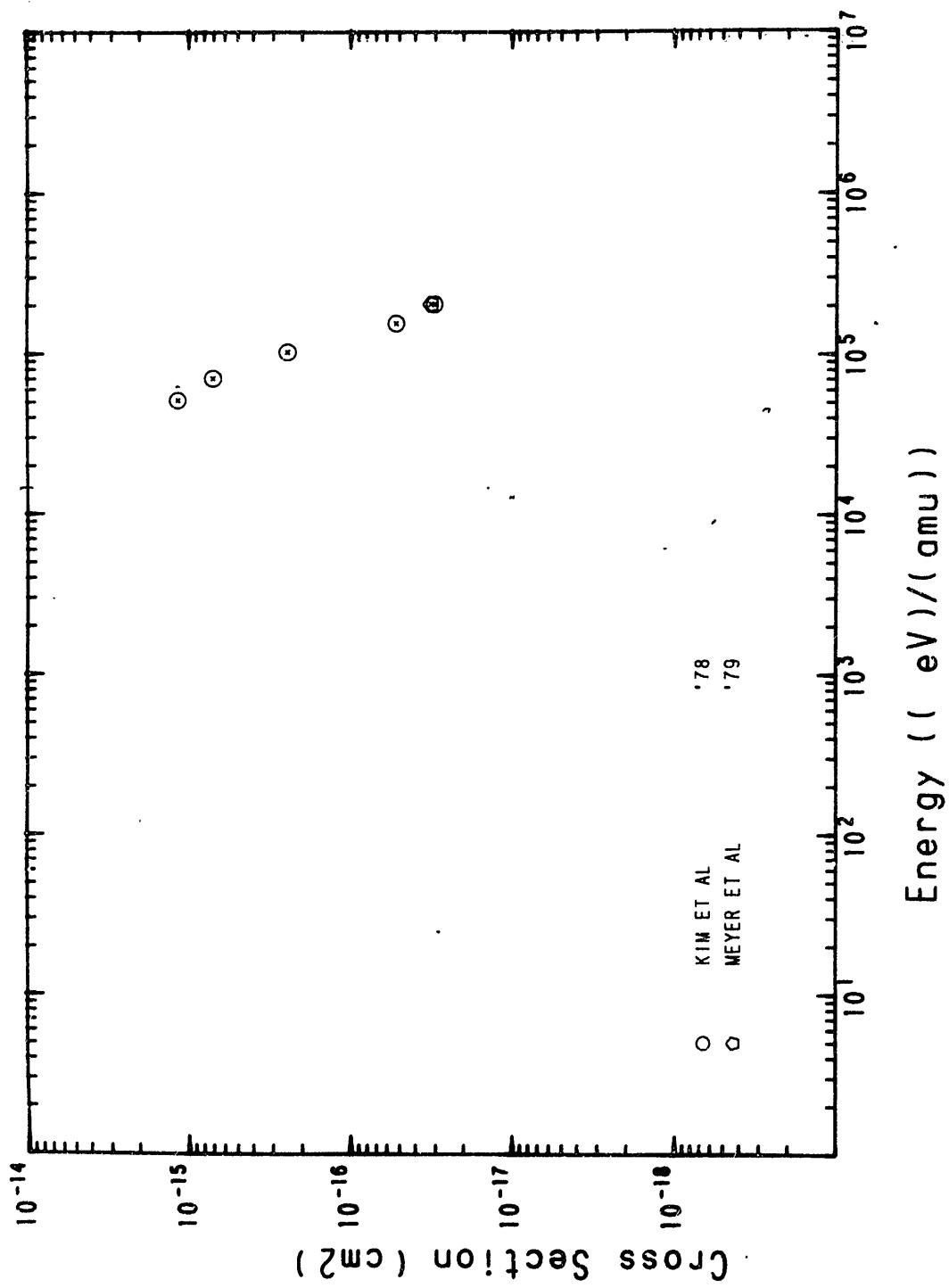


Fig.38 $\text{Si}^{4+} + \text{H} \longrightarrow \text{Si}^{3+}$

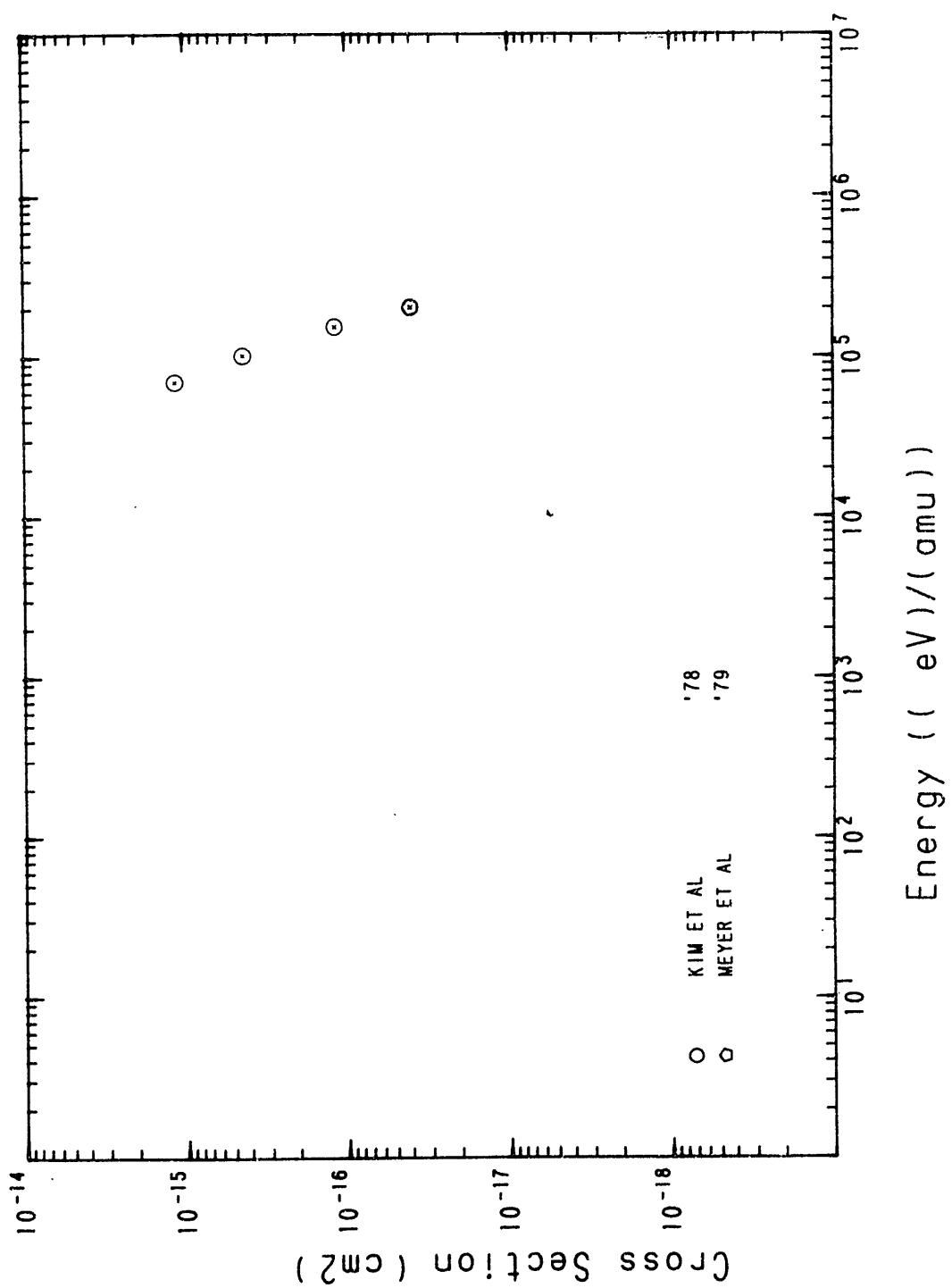


Fig.39 $\text{Si}^{5+} + \text{H} \rightarrow \text{Si}^{4+}$

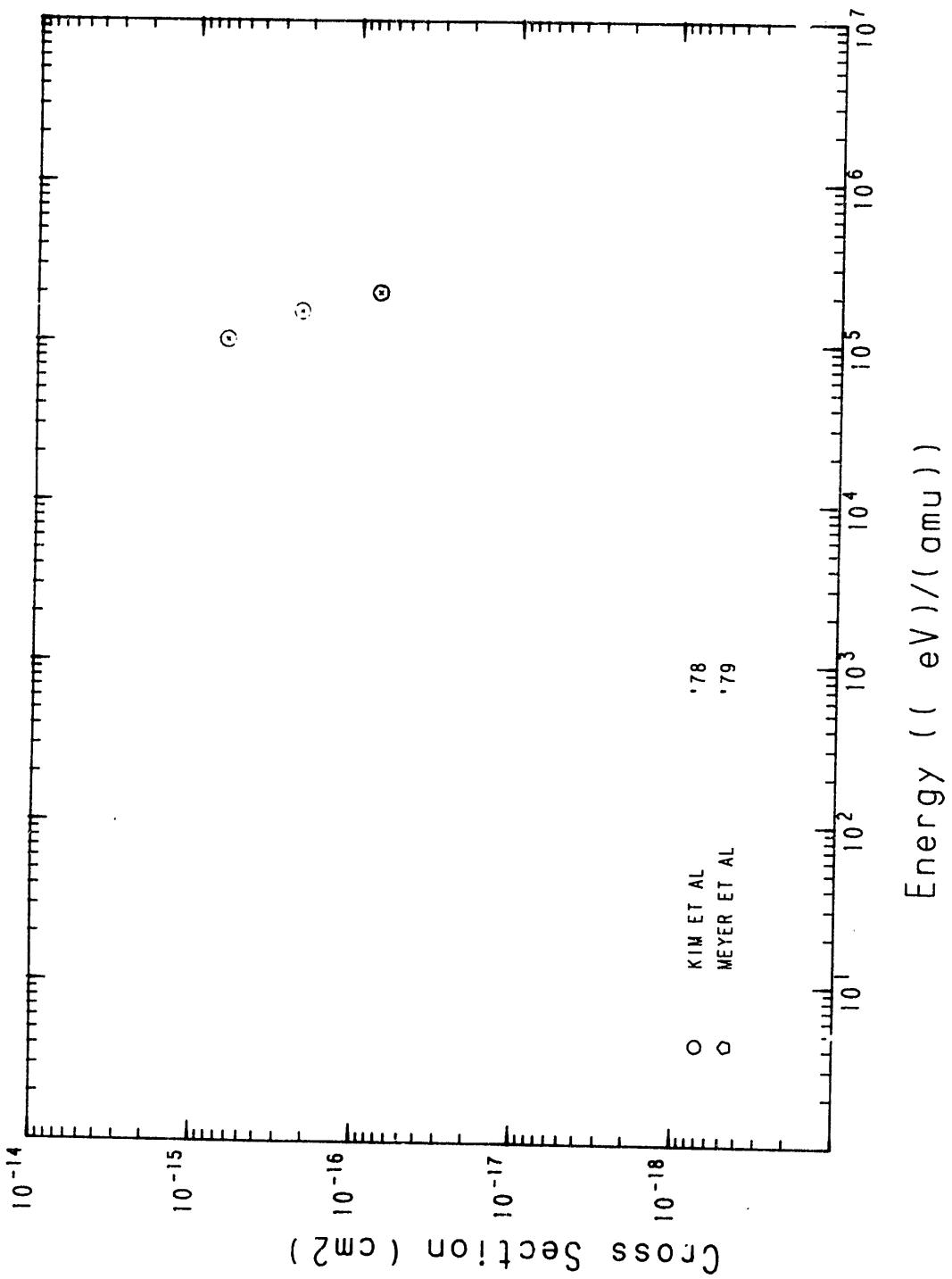


Fig.40 $\text{Si}^{6+} + \text{H} \rightarrow \text{Si}^{5+}$

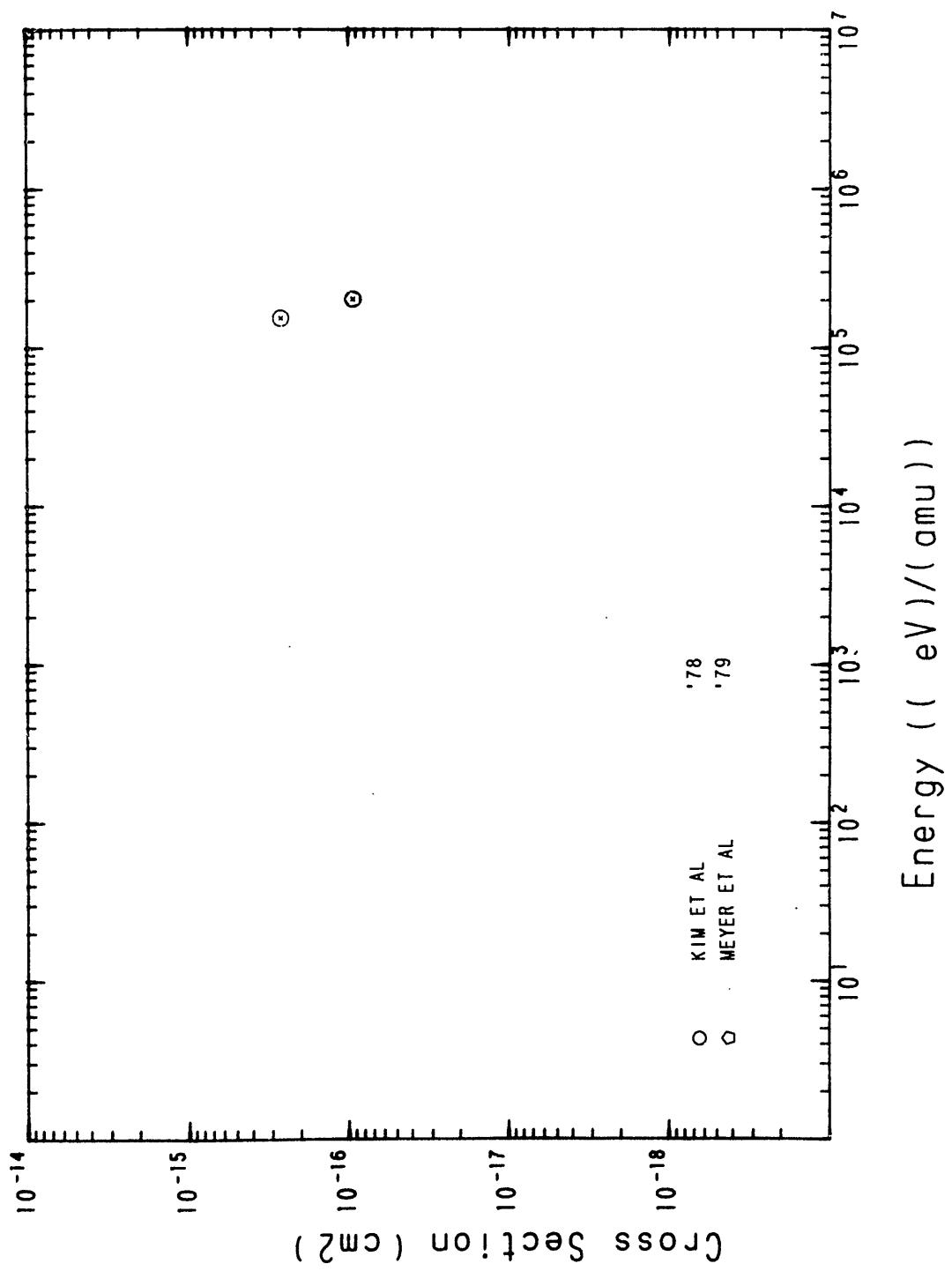


Fig.41 $\text{Si}^{7+} + \text{H} \rightarrow \text{Si}^{6+}$

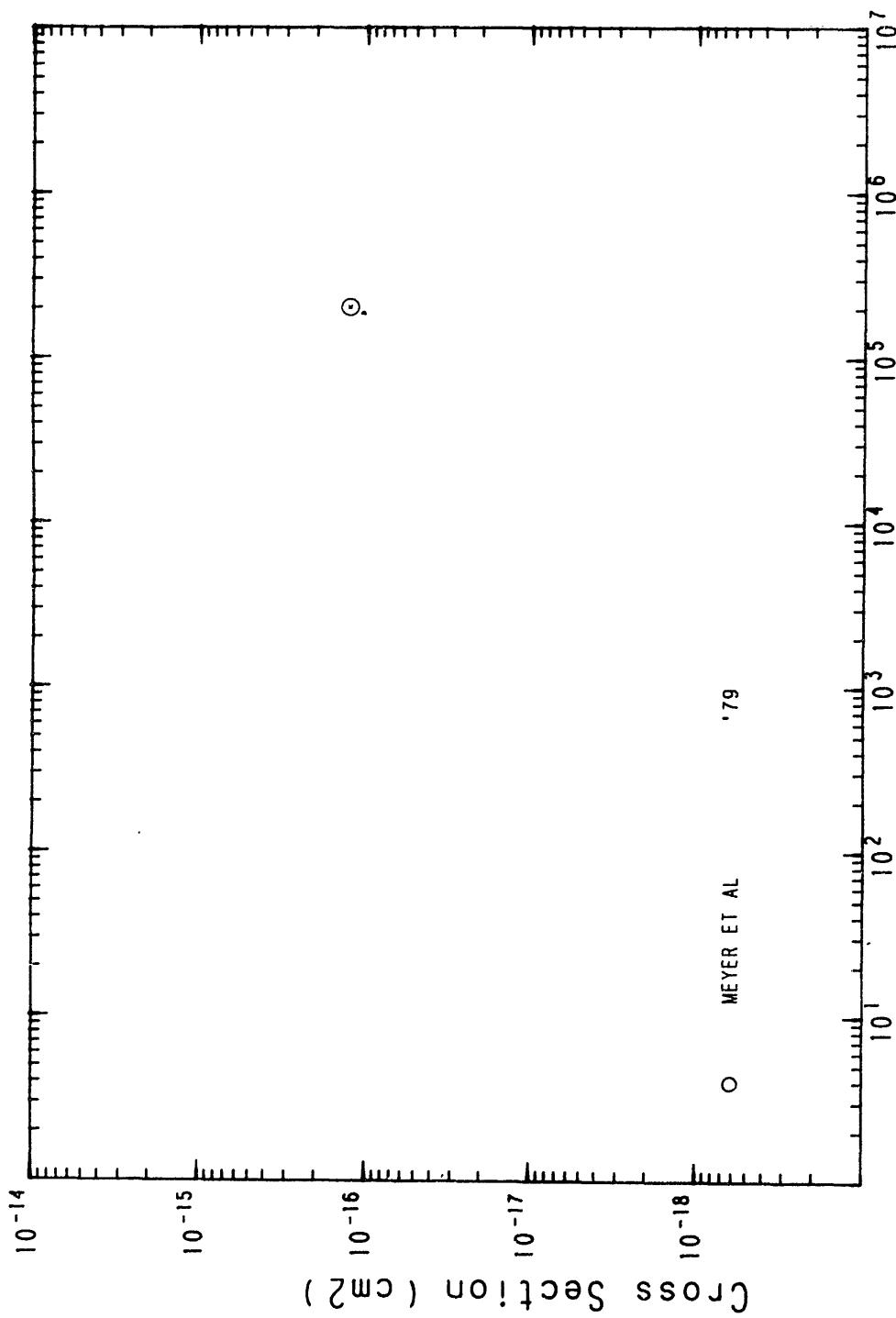


Fig.42 $\text{Si}^{8+} + \text{H} \rightarrow \text{Si}^{7+}$

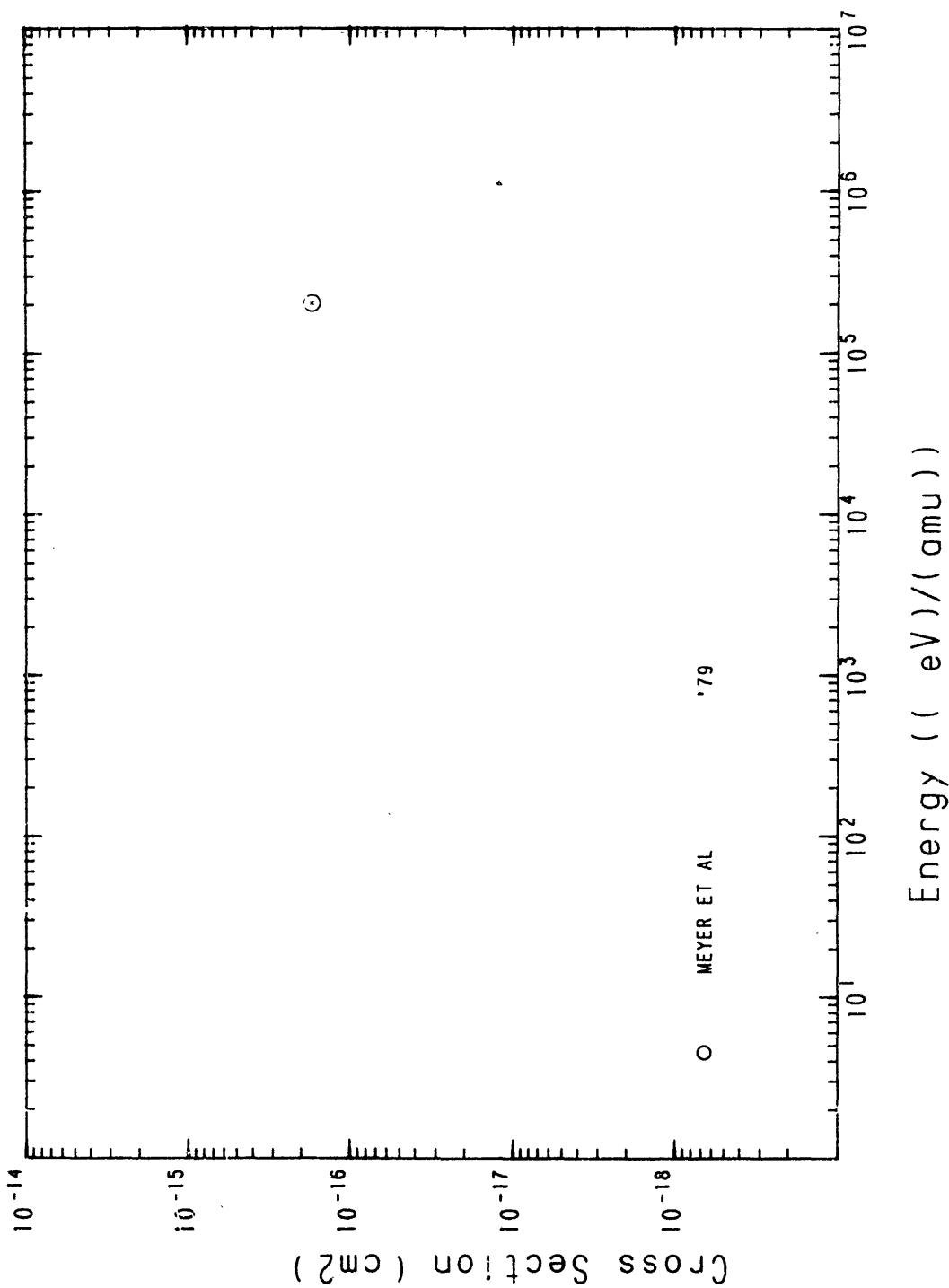


Fig.43 $\text{Si}^{9+} + \text{H} \rightarrow \text{Si}^{8+}$

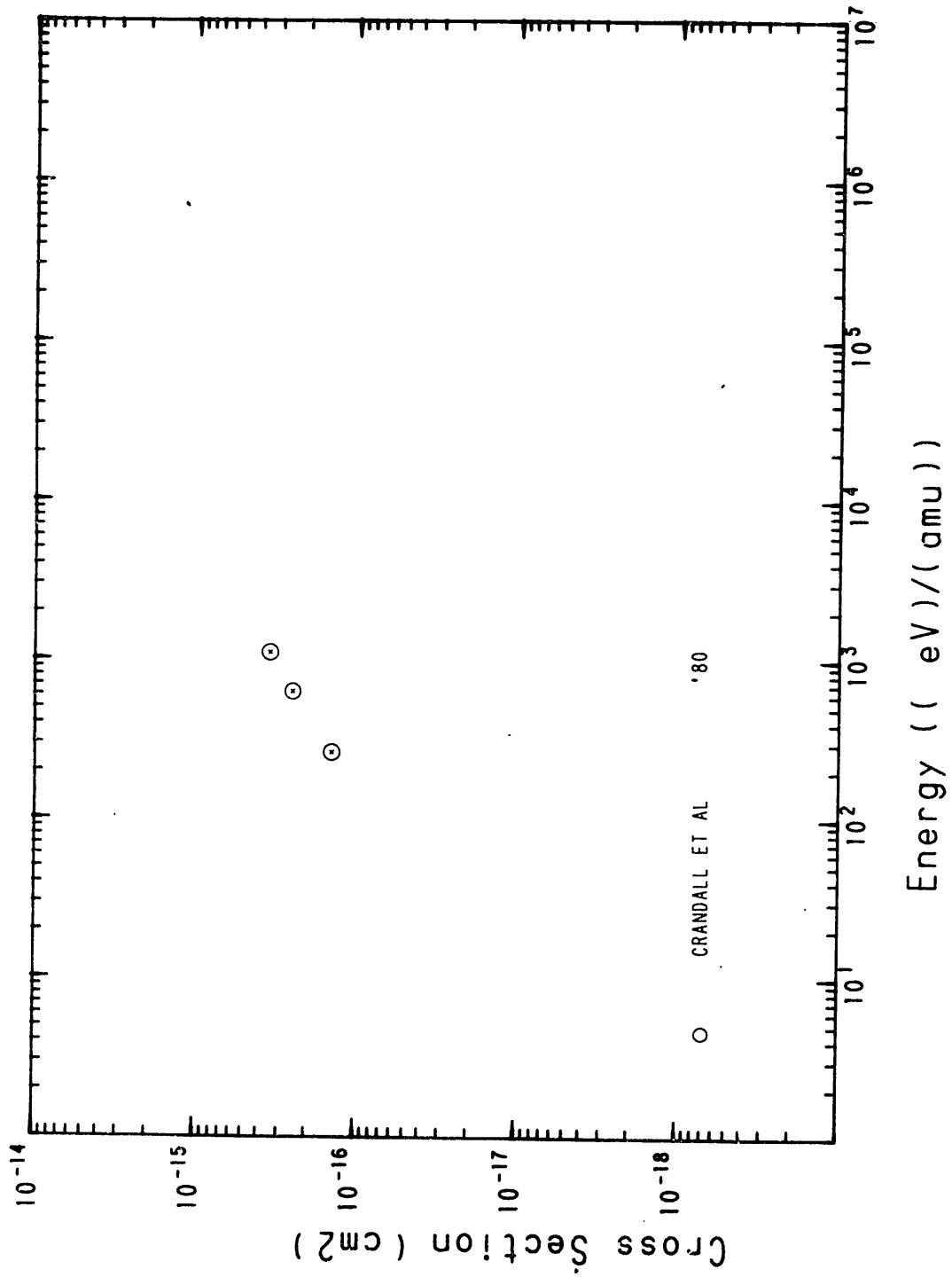


Fig.44 $\text{Ar}^{2+} + \text{H} \longrightarrow \text{Ar}^+$

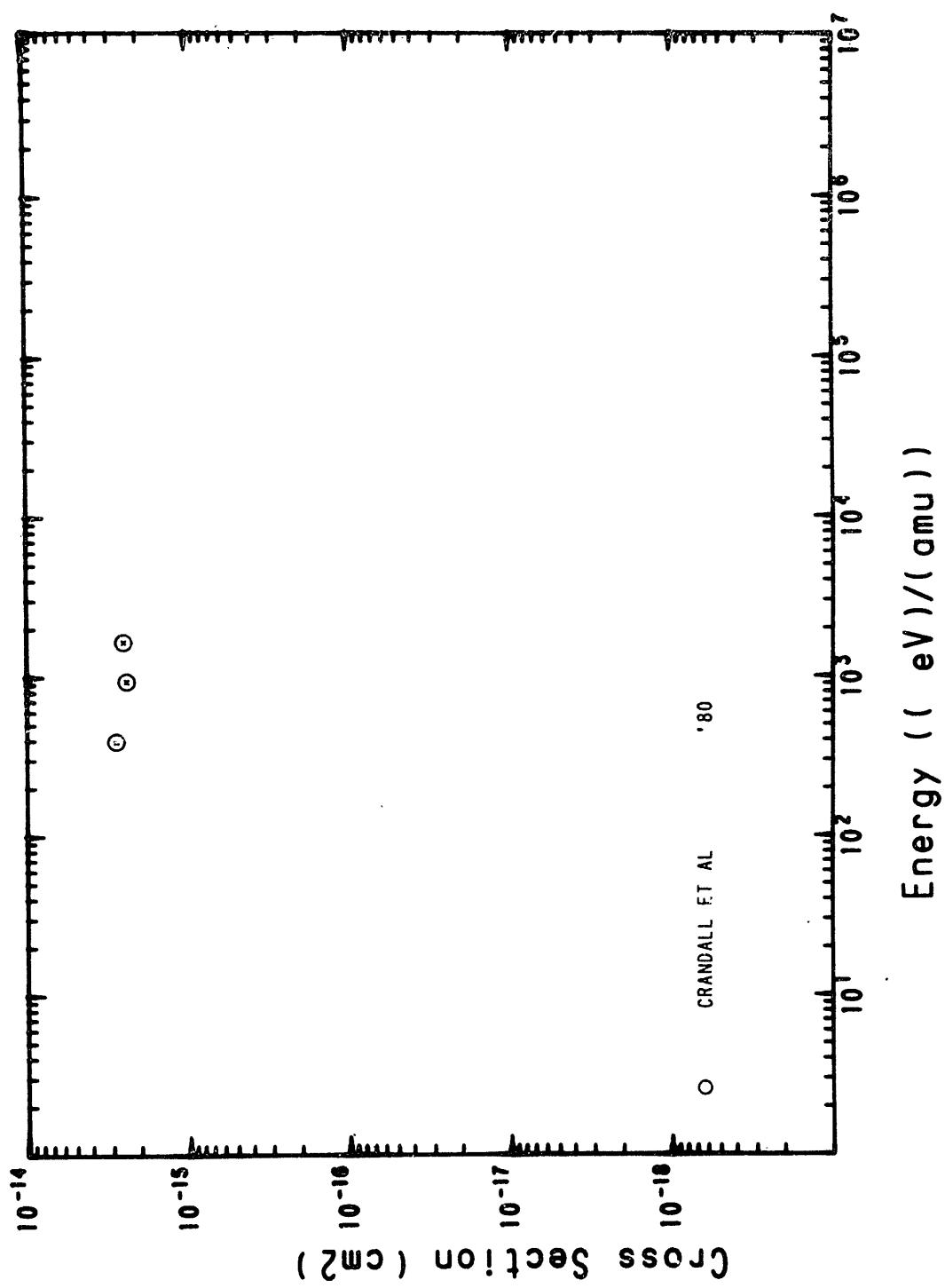


Fig.45 $\text{Ar}^{3+} + \text{H} \longrightarrow \text{Ar}^{2+}$

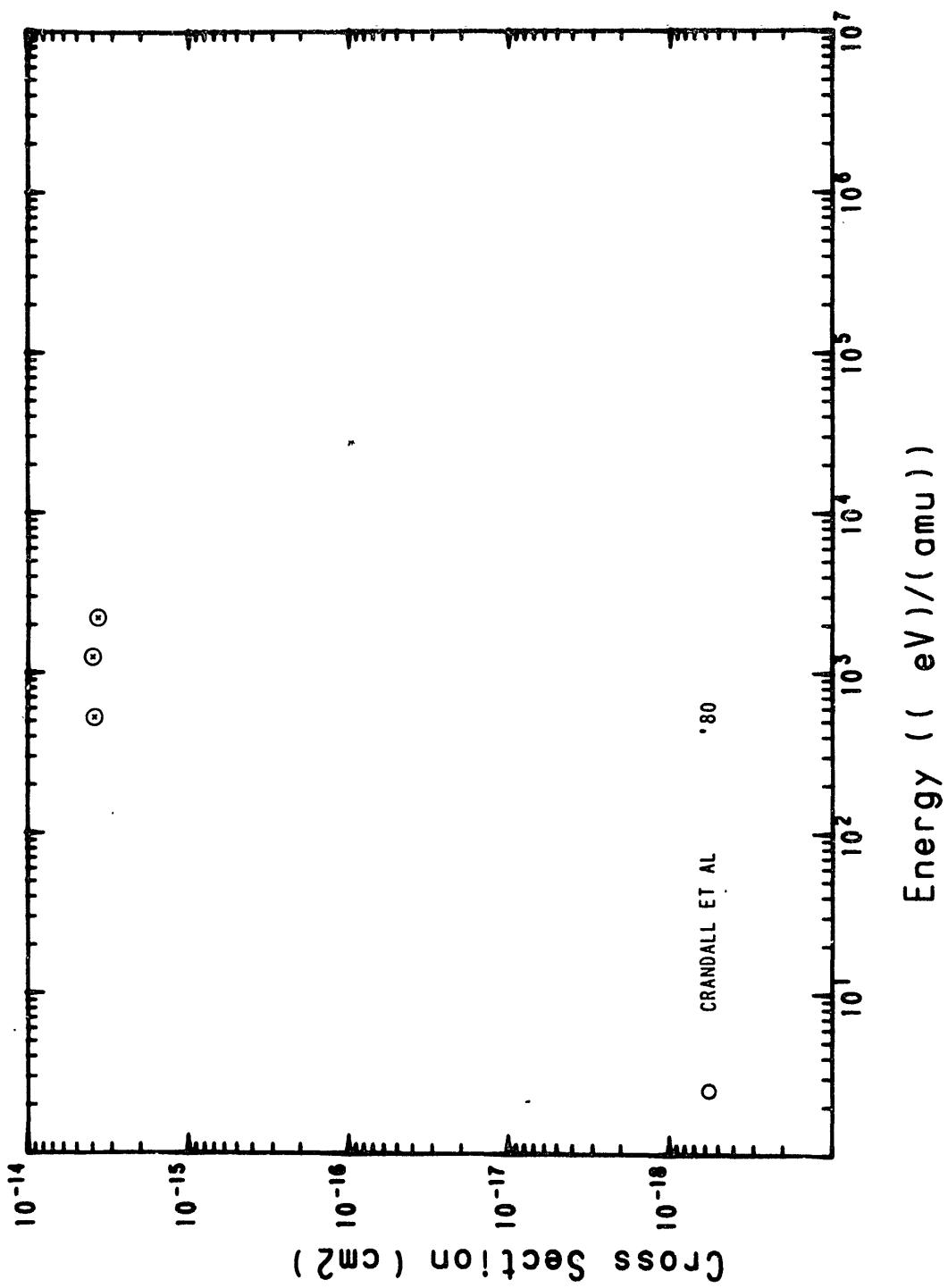


Fig.46 $\text{Ar}^{4+} + \text{H} \longrightarrow \text{Ar}^{3+}$

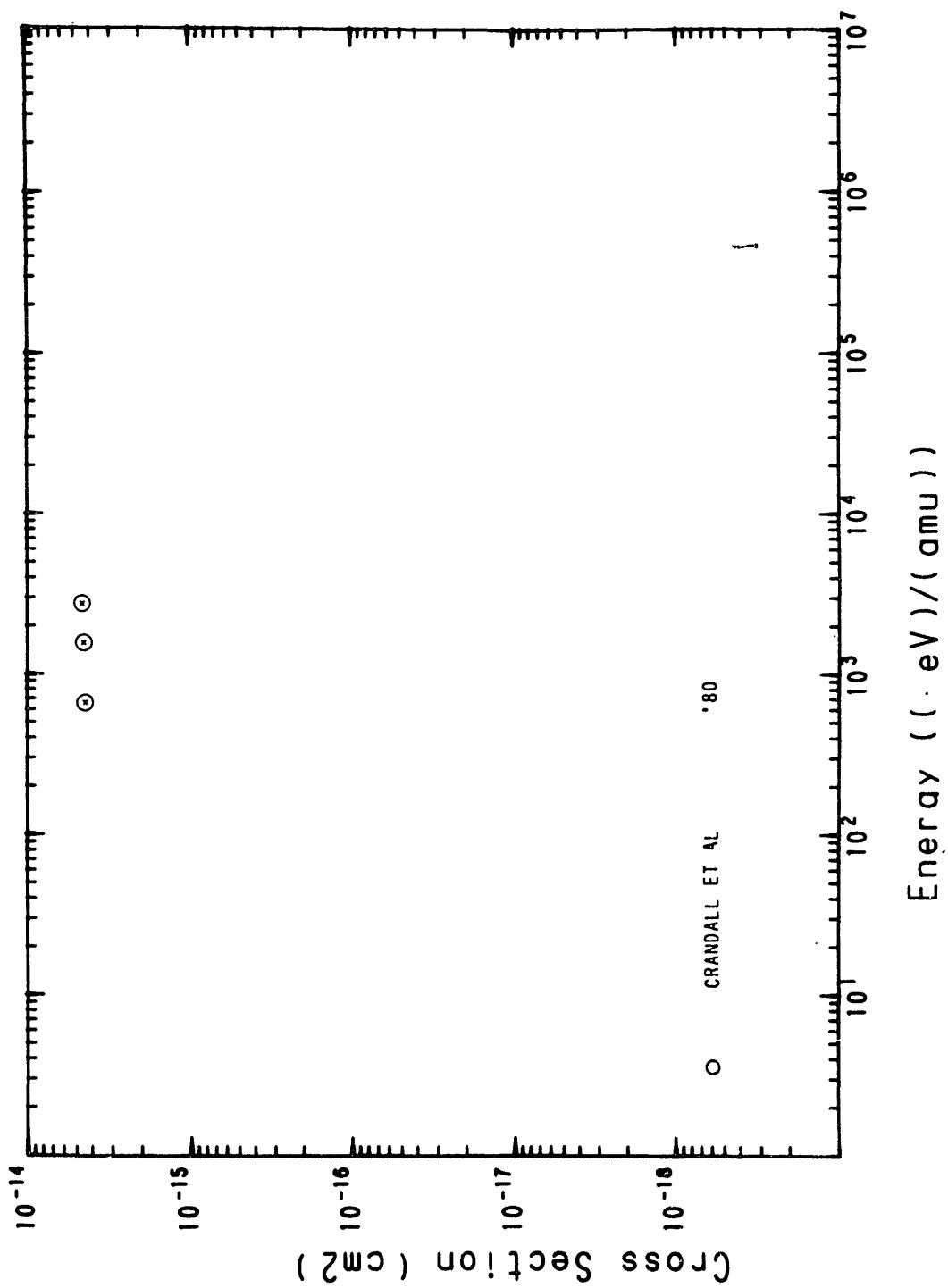


Fig. 47 $\text{Ar}^{5+} + \text{H} \rightarrow \text{Ar}^{4+}$

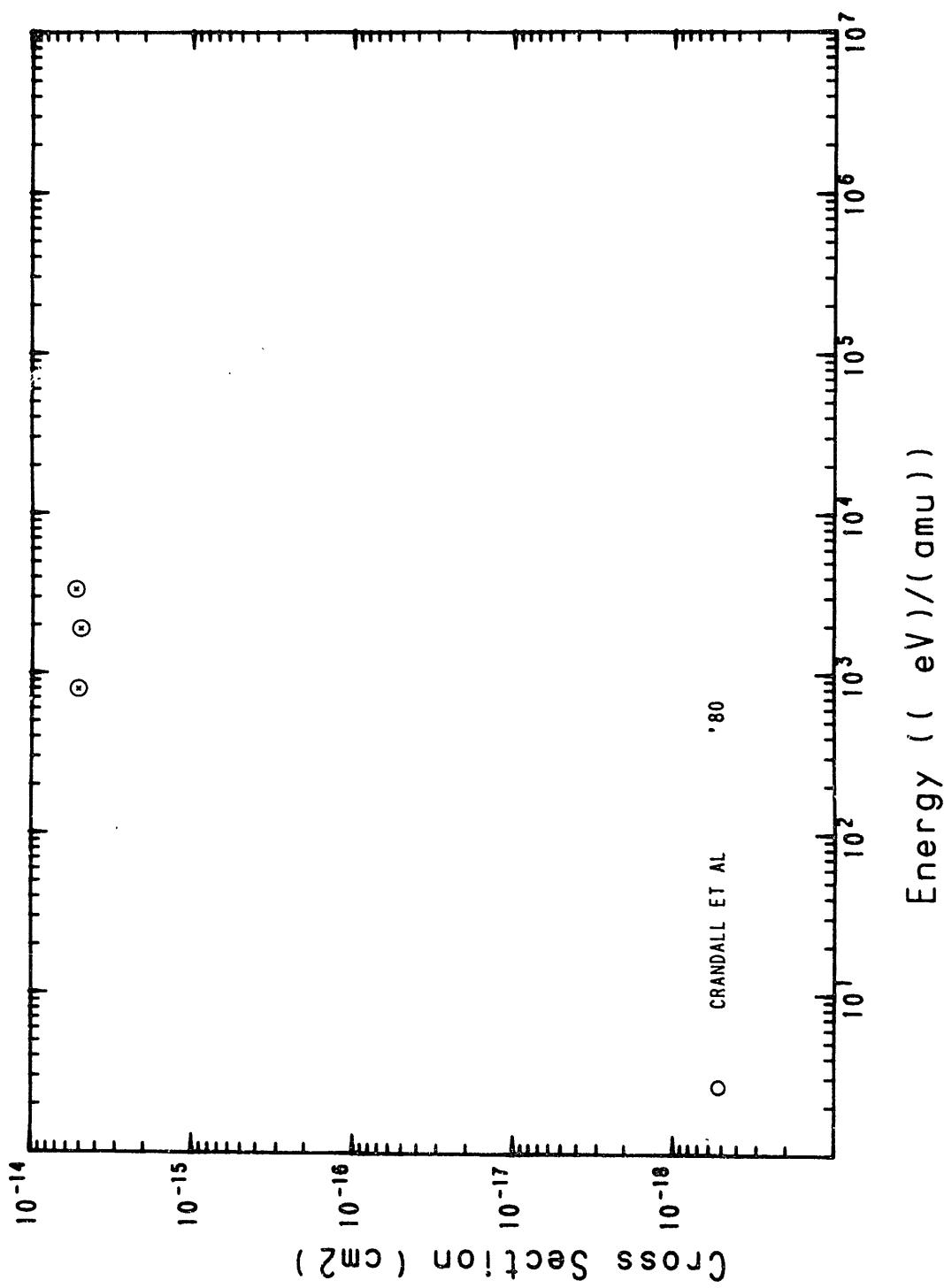


Fig.48 $\text{Ar}^{6+} + \text{H} \longrightarrow \text{Ar}^{5+}$

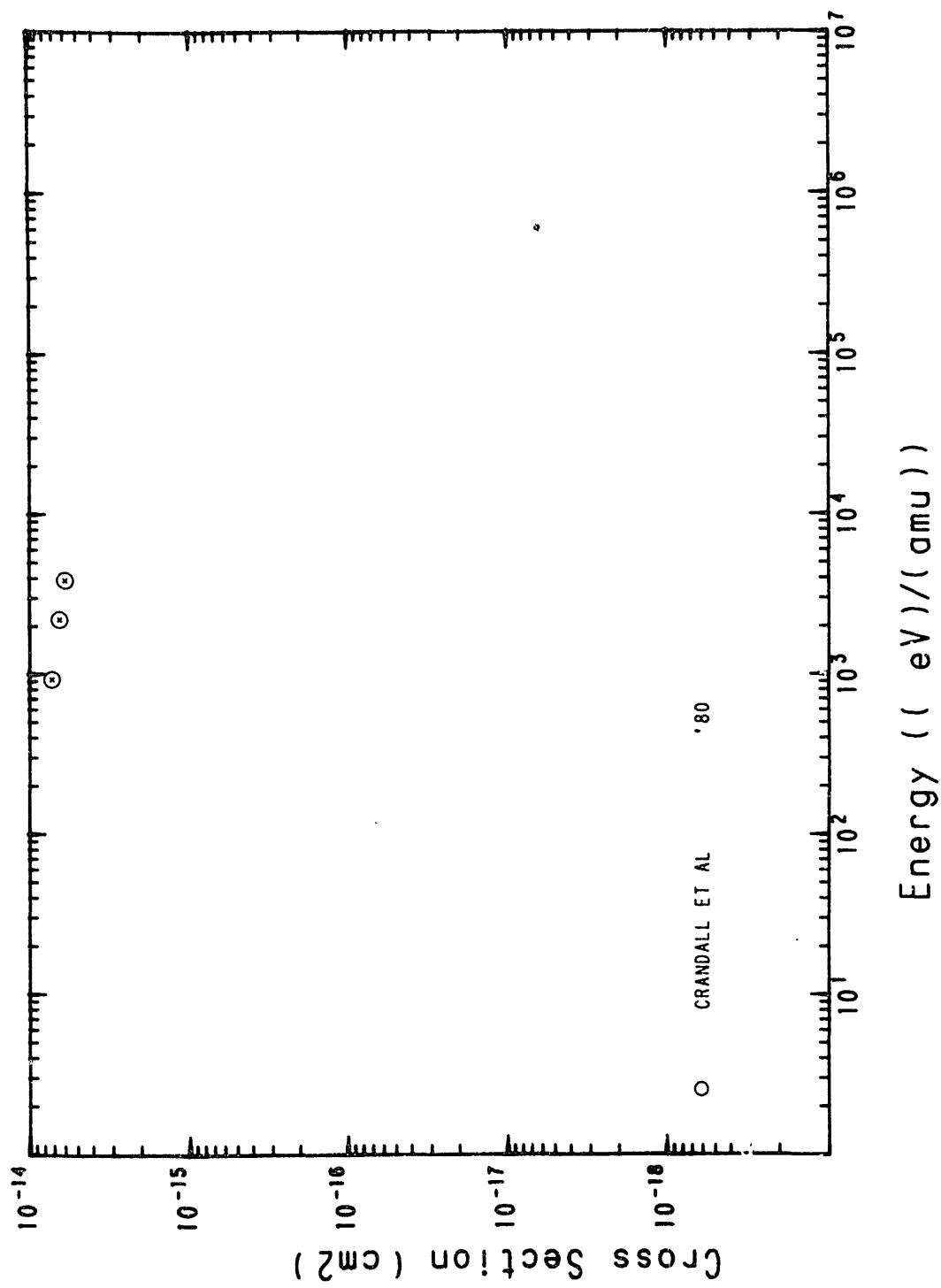


Fig.49 $\text{Ar}^{7+} + \text{H} \rightarrow \text{Ar}^{6+}$

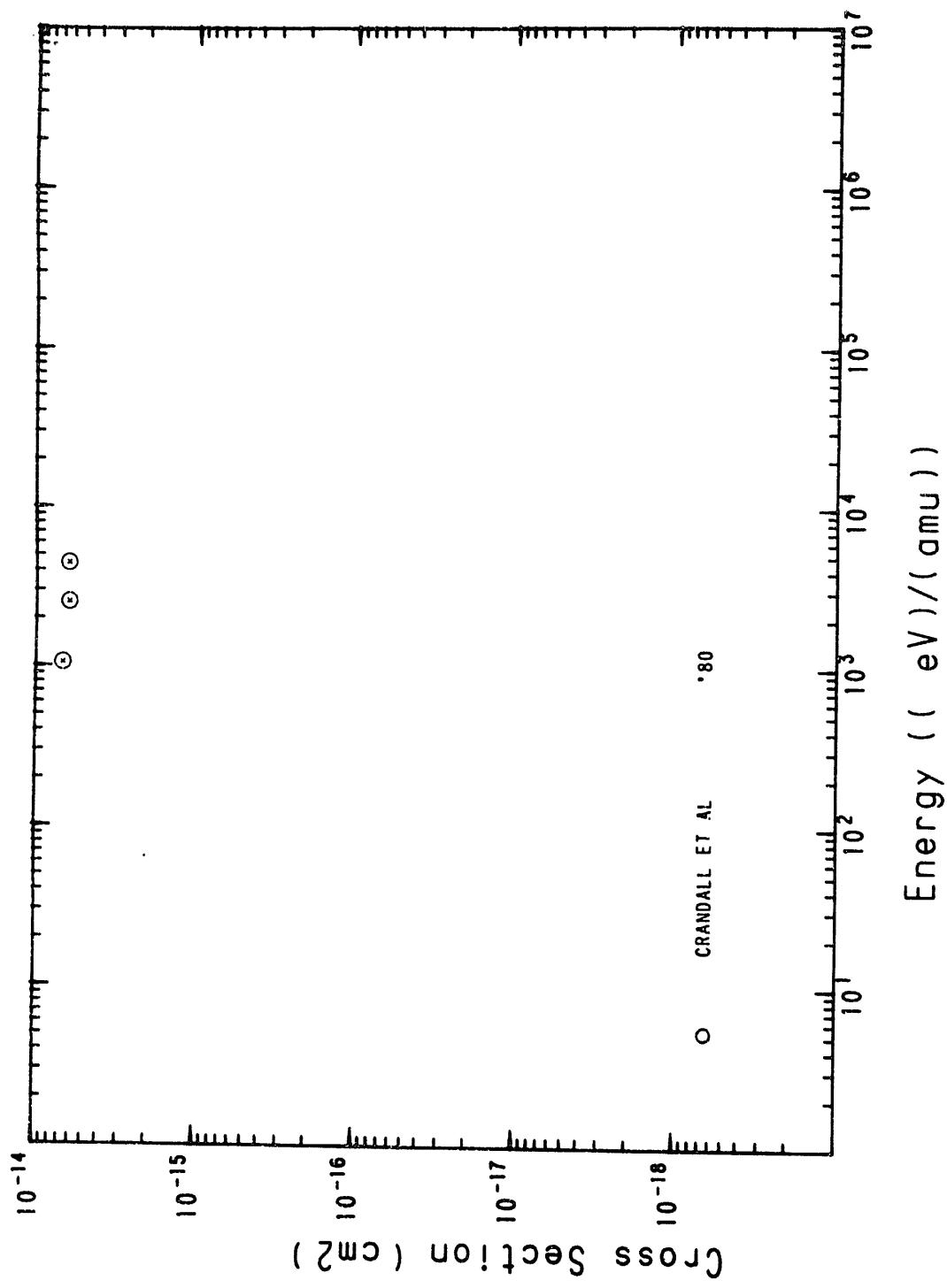


Fig.50 $\text{Ar}^{8+} + \text{H} \longrightarrow \text{Ar}^{7+}$

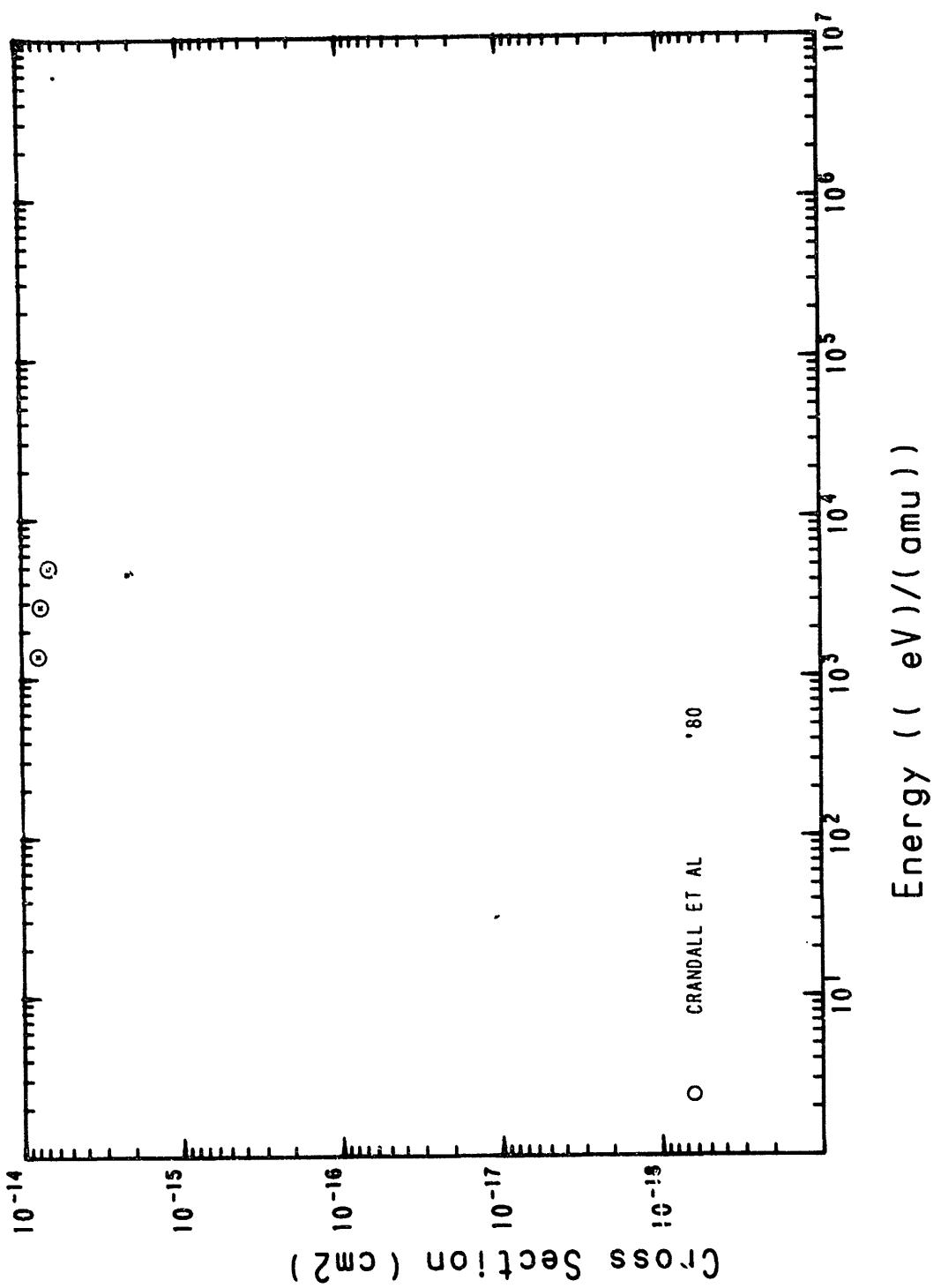


Fig.51 $\text{Ar}^{9+} + \text{H} \longrightarrow \text{Ar}^{8+}$

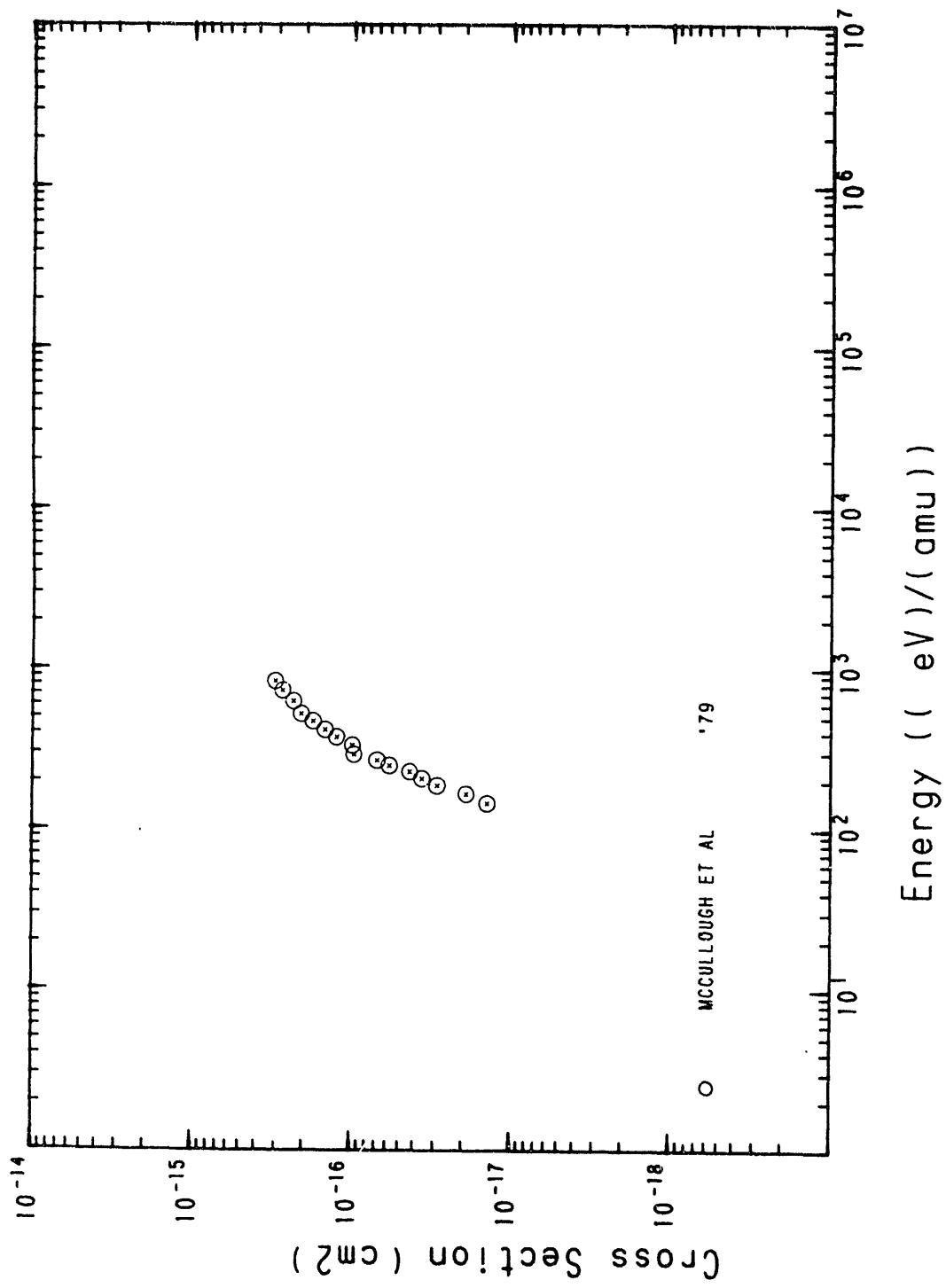


Fig.52 $\text{Ti}^{2+} + \text{H} \rightarrow \text{Ti}^+$

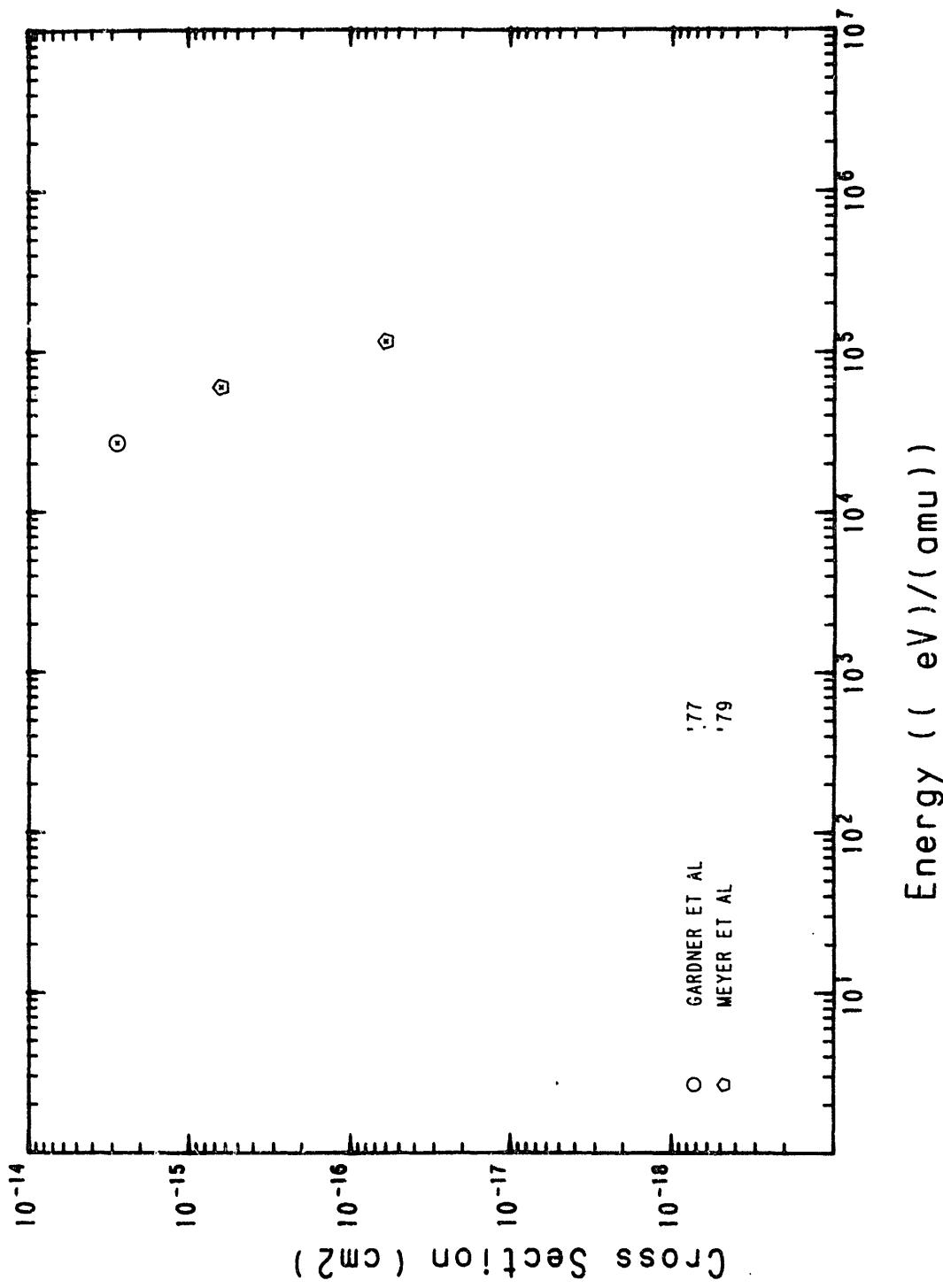


Fig.53 $\text{Fe}^{4+} + \text{H} \rightarrow \text{Fe}^{3+}$

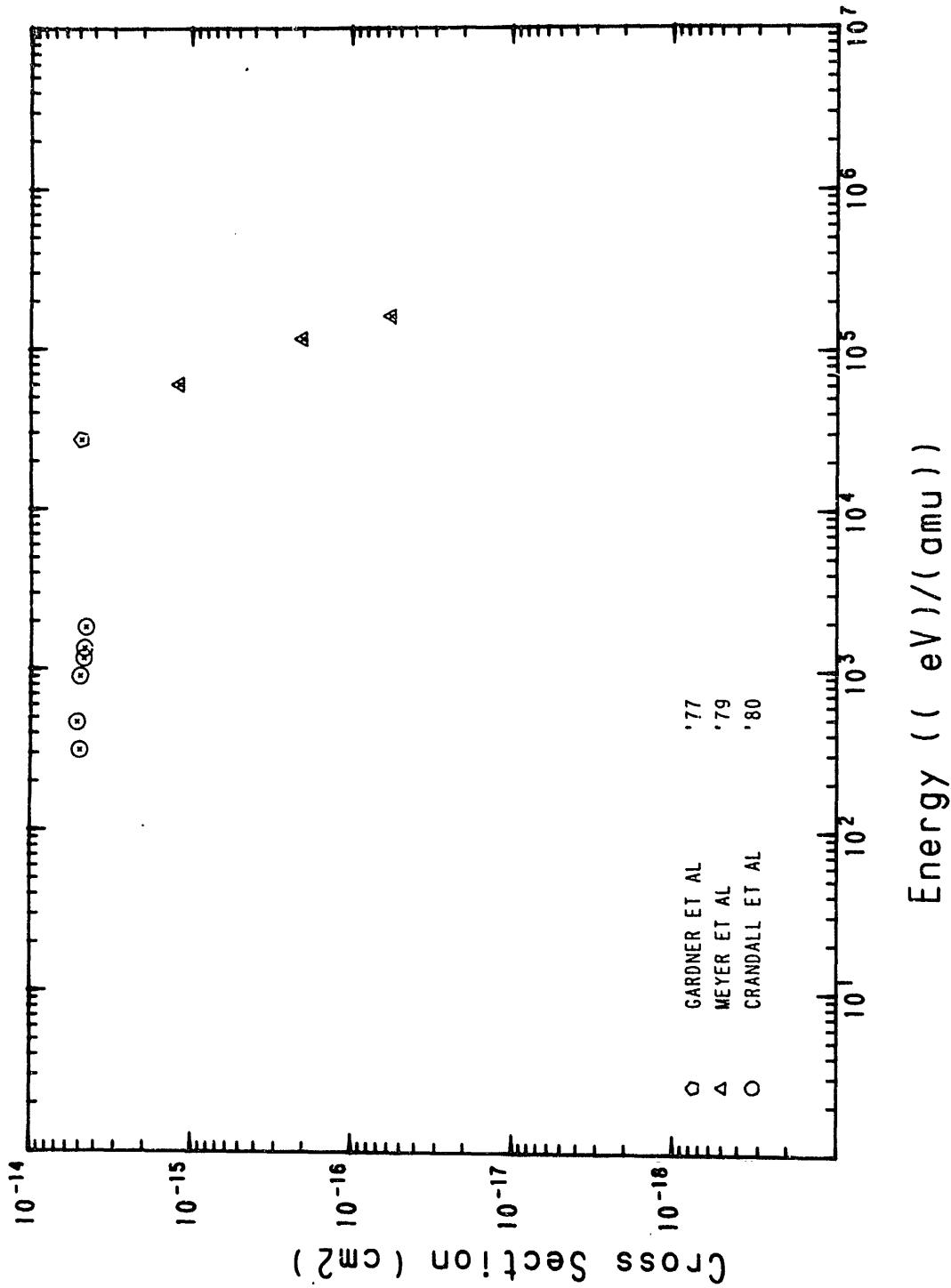


Fig.54 $\text{Fe}^{5+} + \text{H} \longrightarrow \text{Fe}^{4+}$

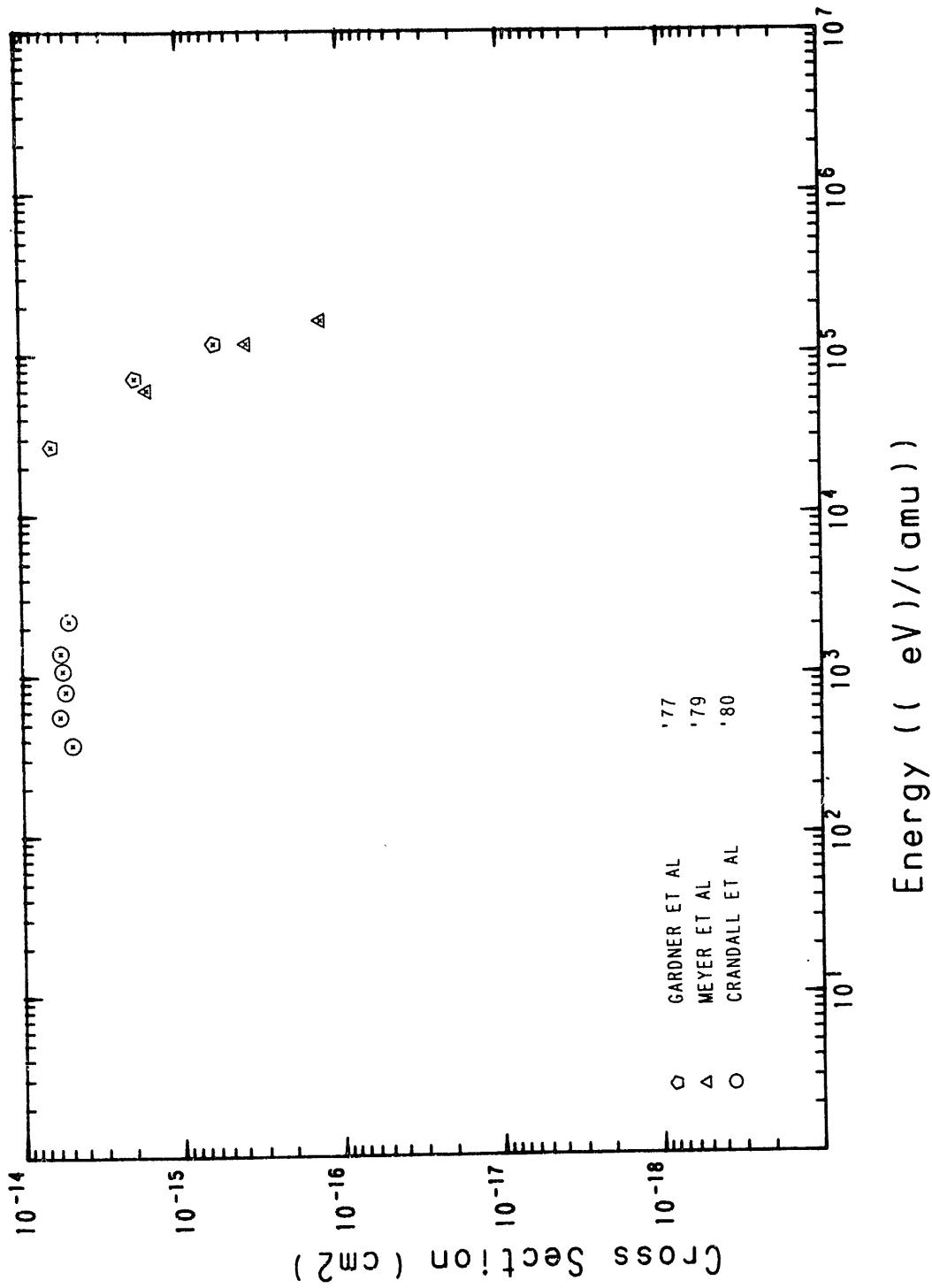


Fig.55 $\text{Fe}^{6+} + \text{H} \rightarrow \text{Fe}^{5+}$

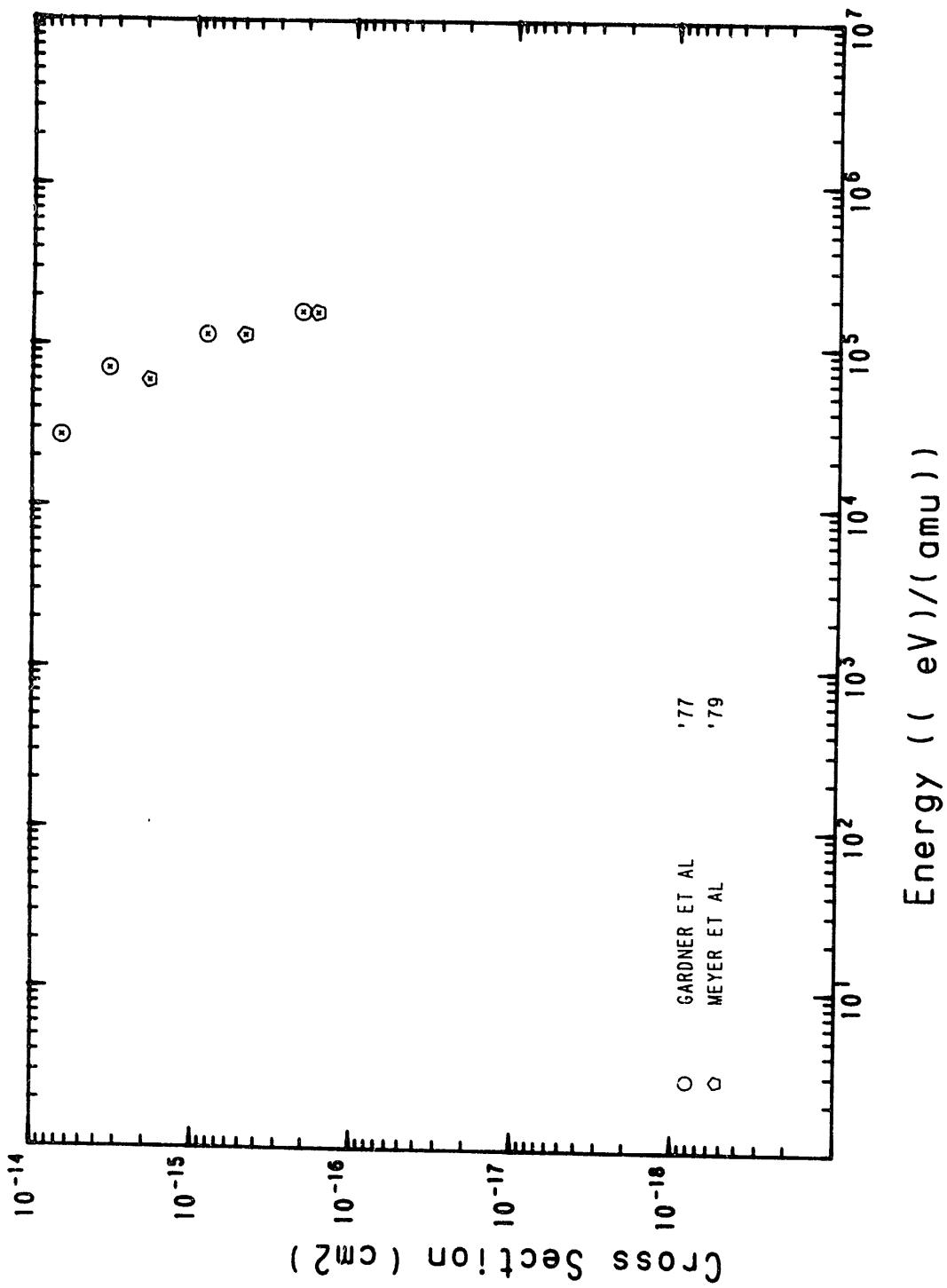


Fig.56 $\text{Fe}^{7+} + \text{H} \rightarrow \text{Fe}^{6+}$

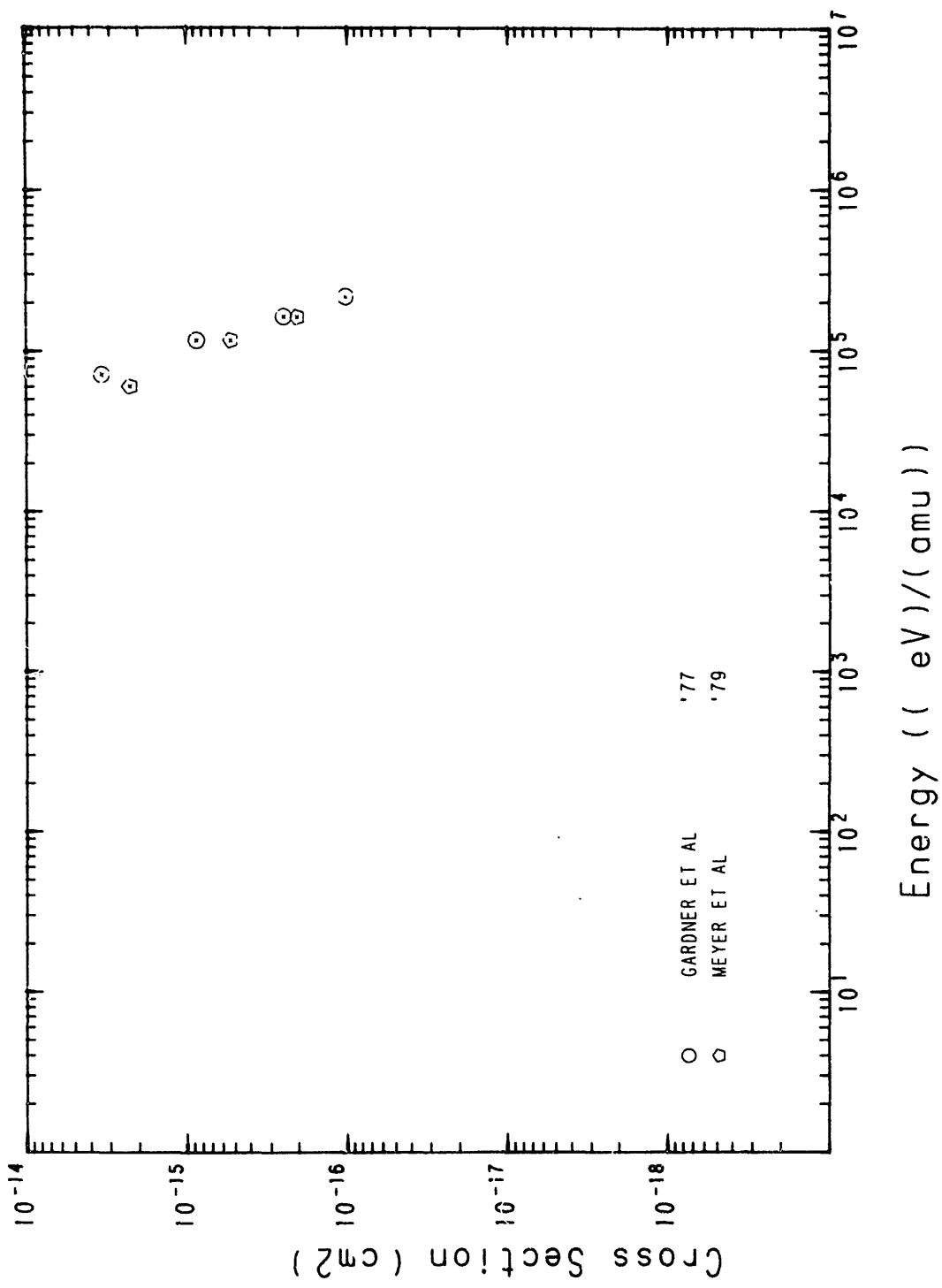


Fig.57 $\text{Fe}^{8+} + \text{H} \rightarrow \text{Fe}^{7+}$

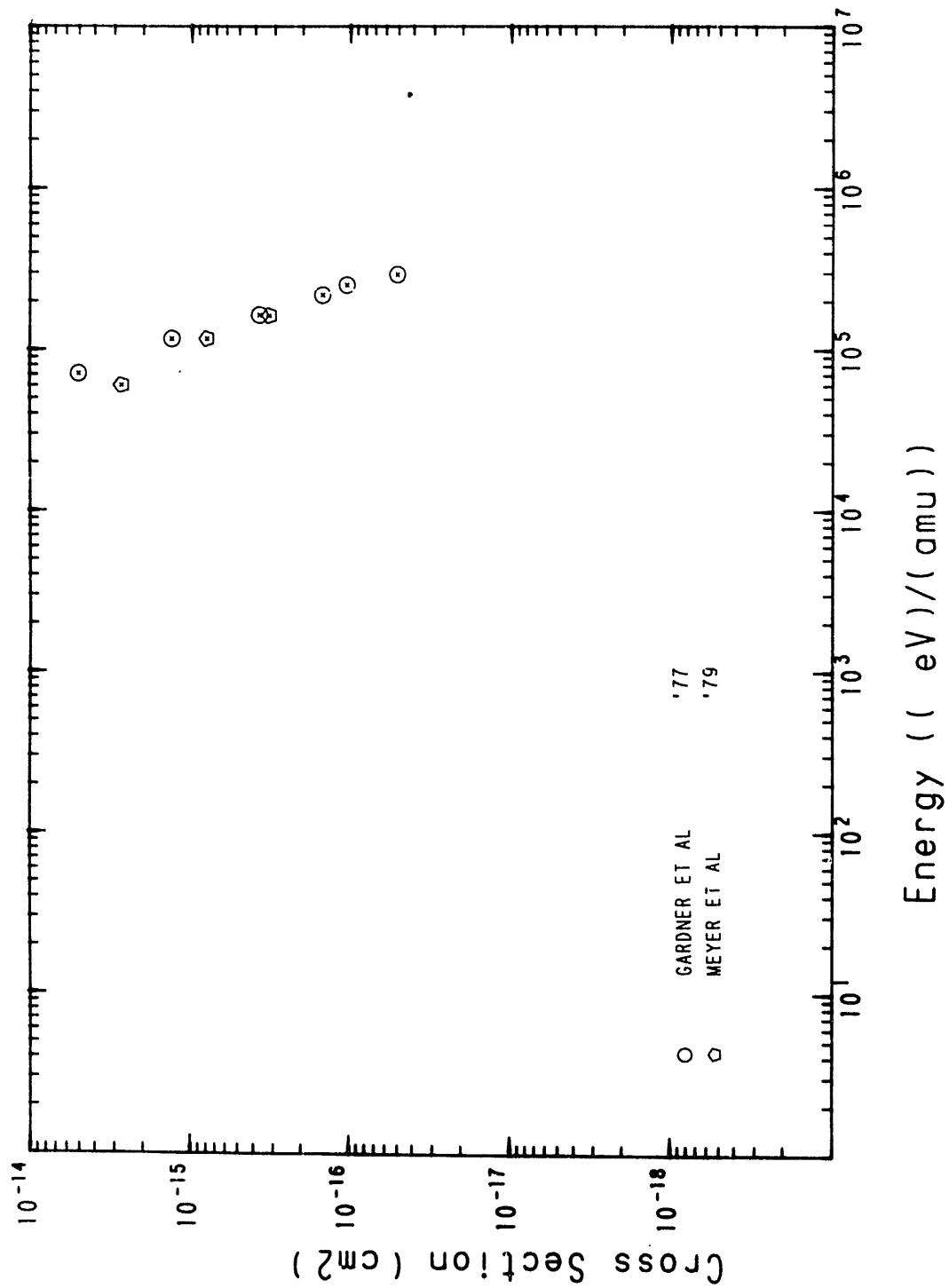


Fig.58 $\text{Fe}^{9+} + \text{H} \rightarrow \text{Fe}^{8+}$

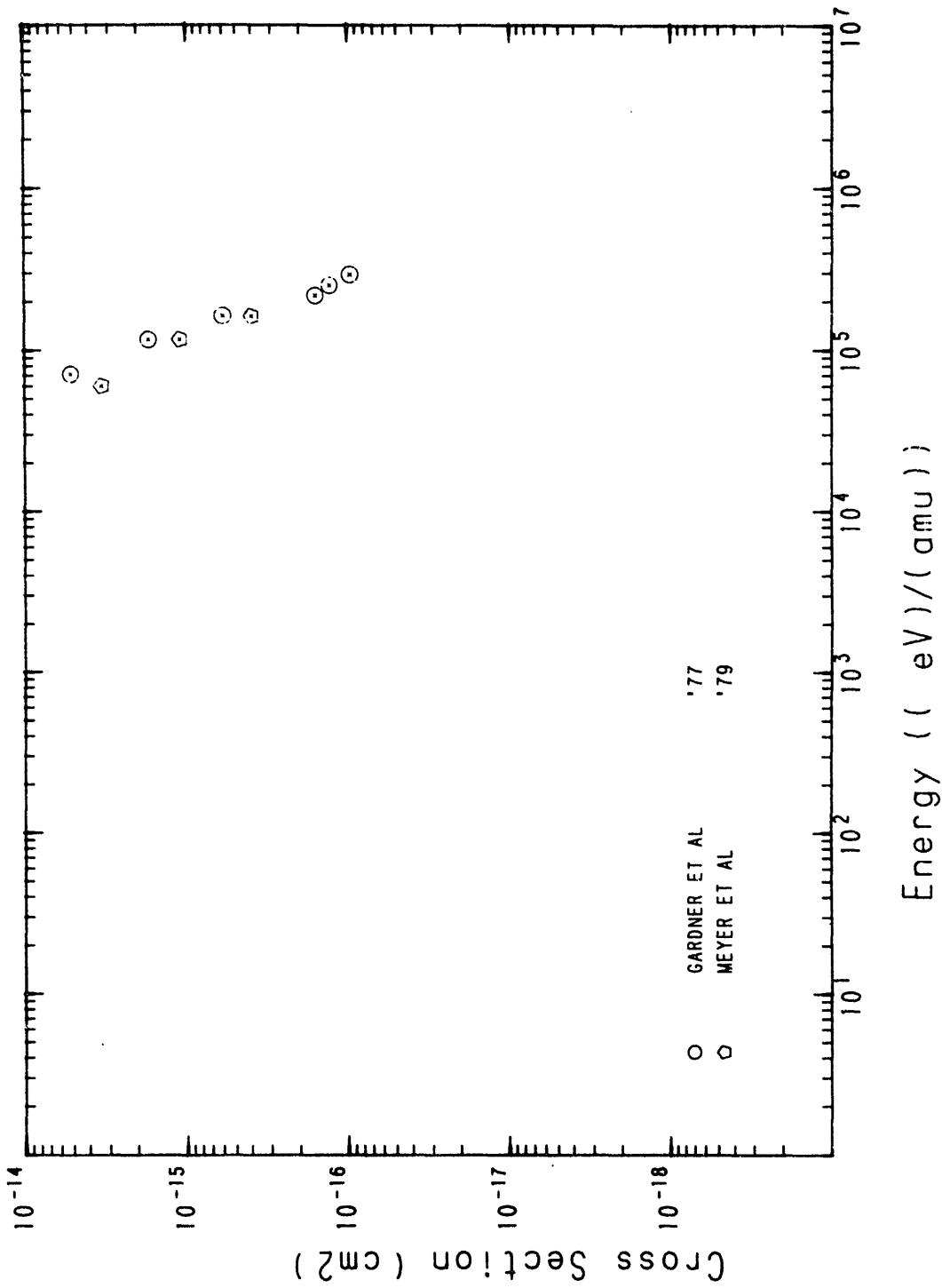


Fig.59 $\text{Fe}^{10+} + \text{H} \rightarrow \text{Fe}^{9+}$

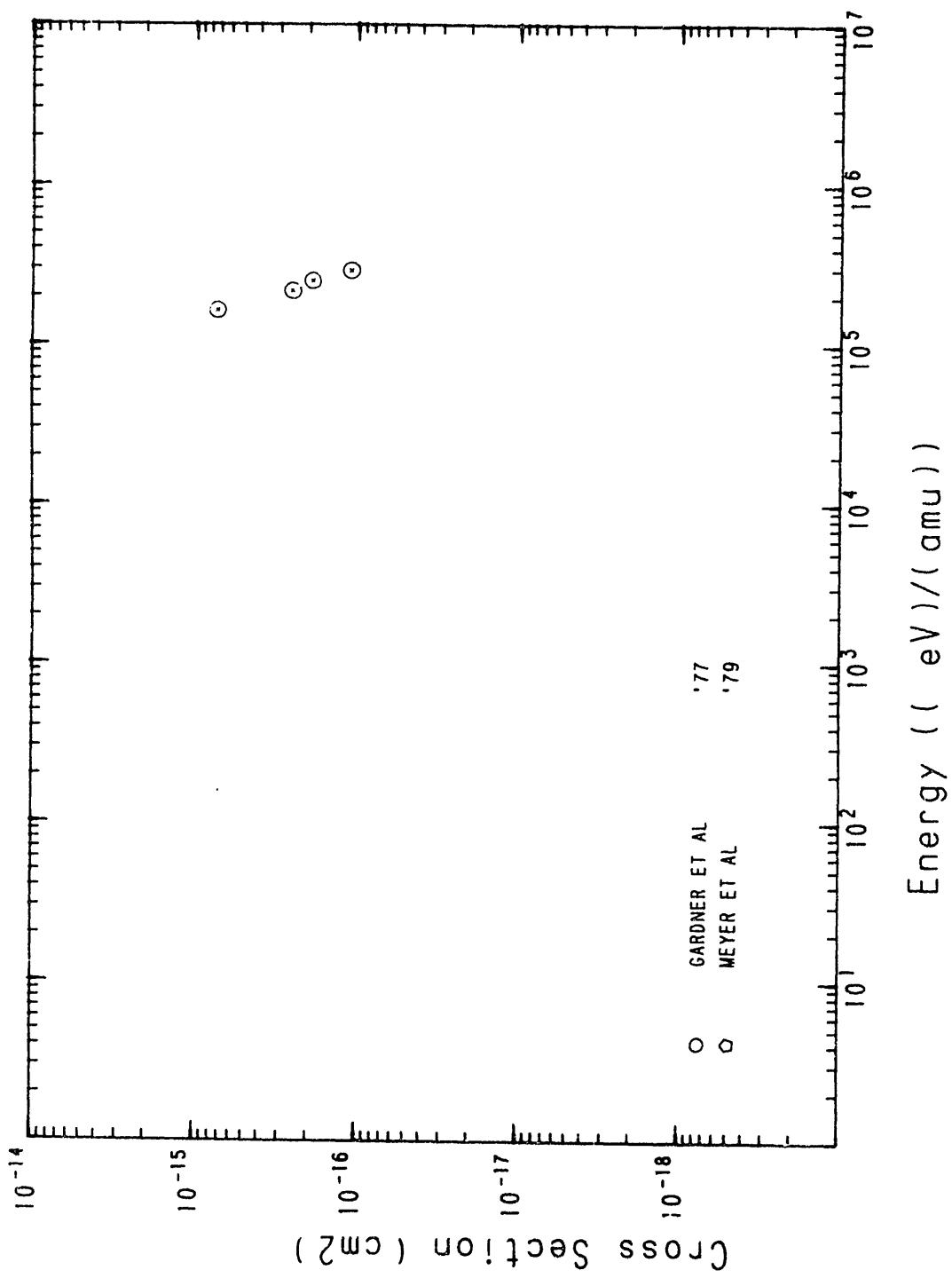


Fig.60 $\text{Fe}^{11+} + \text{H} \rightarrow \text{Fe}^{10+}$

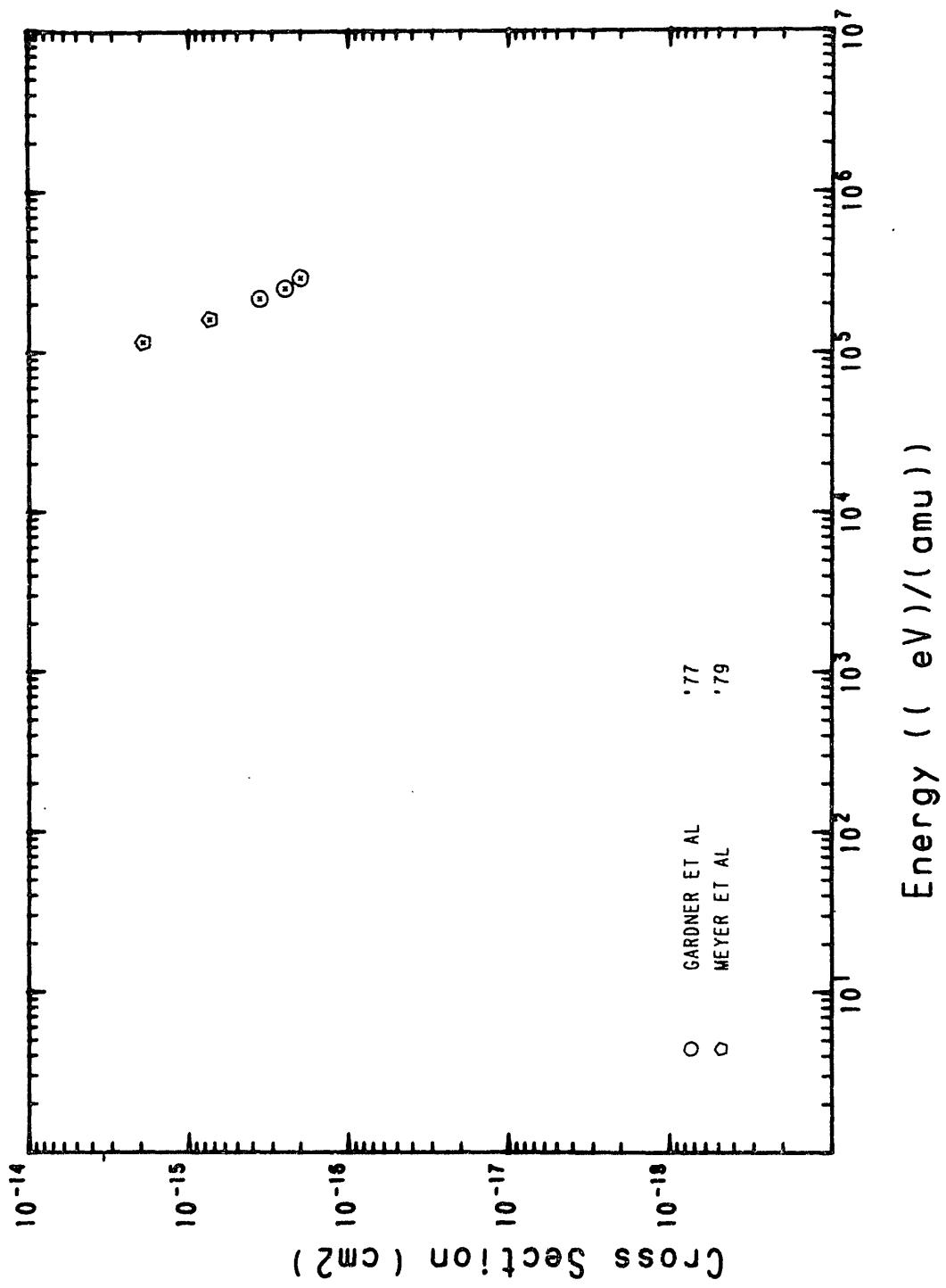


Fig.61 $\text{Fe}^{12+} + \text{H} \longrightarrow \text{Fe}^{11+}$

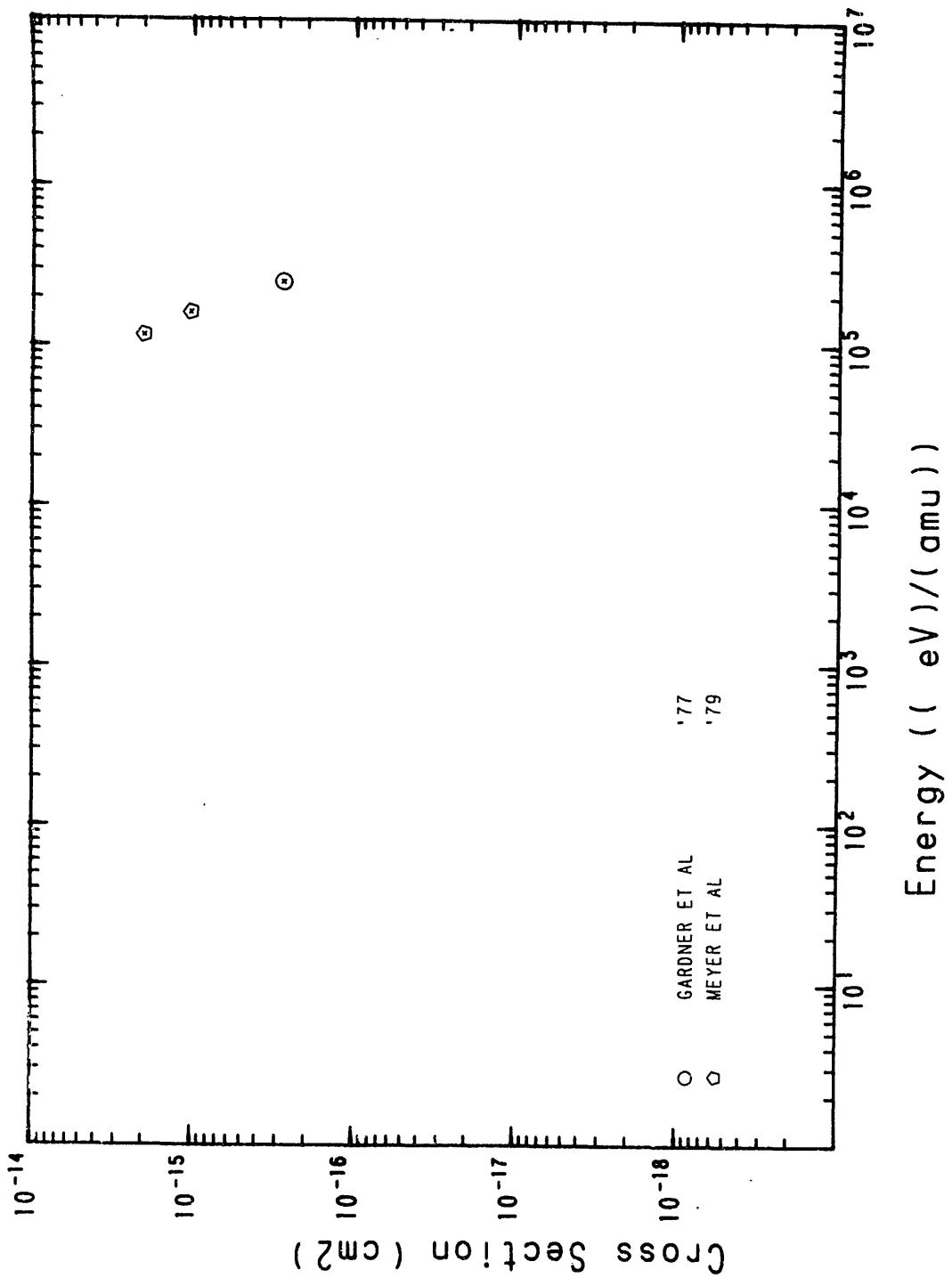


Fig.62 $\text{Fe}^{13+} + \text{H} \rightarrow \text{Fe}^{12+}$

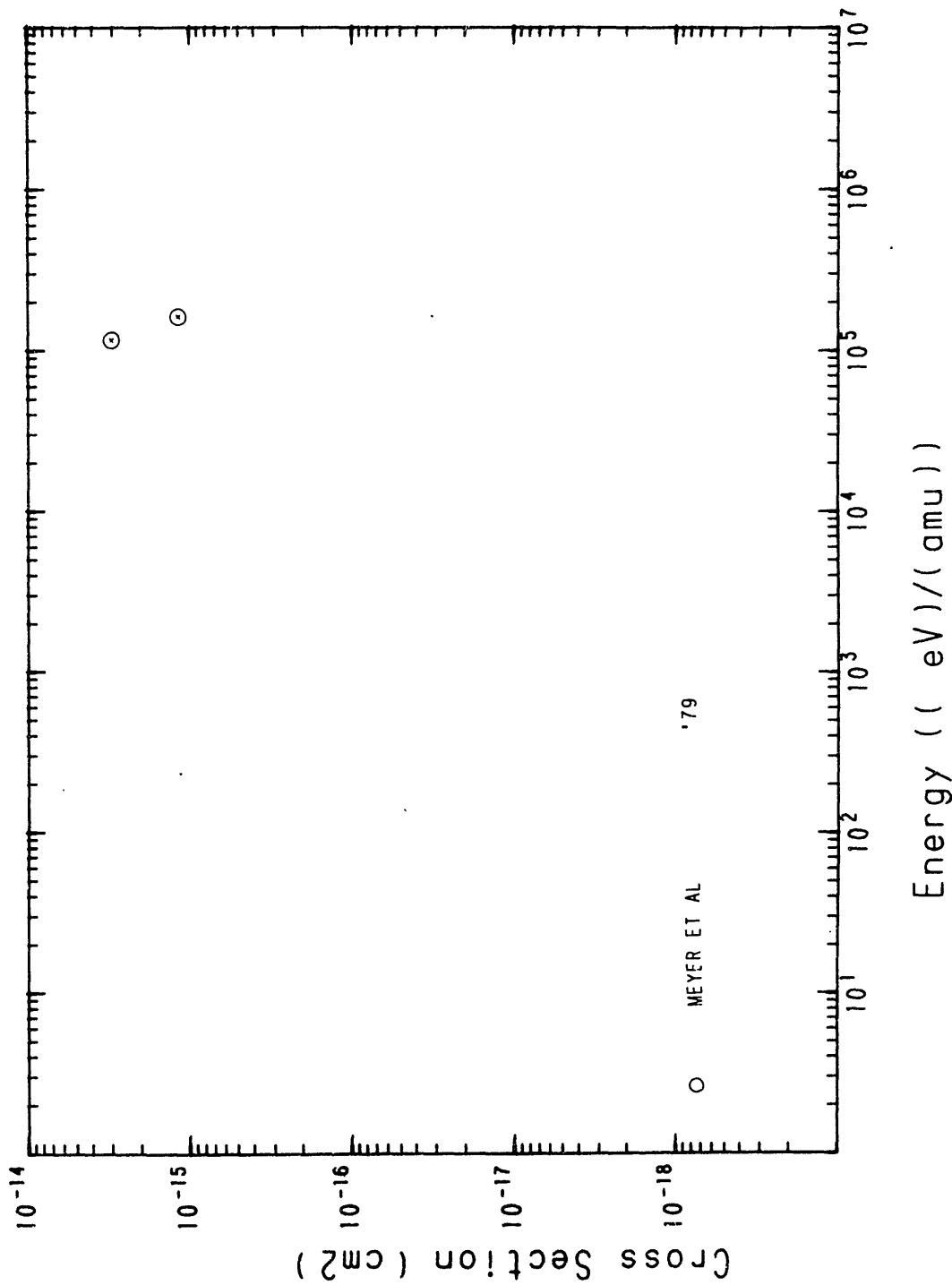


Fig.63 $\text{Fe}^{14+} + \text{H} \rightarrow \text{Fe}^{13+}$

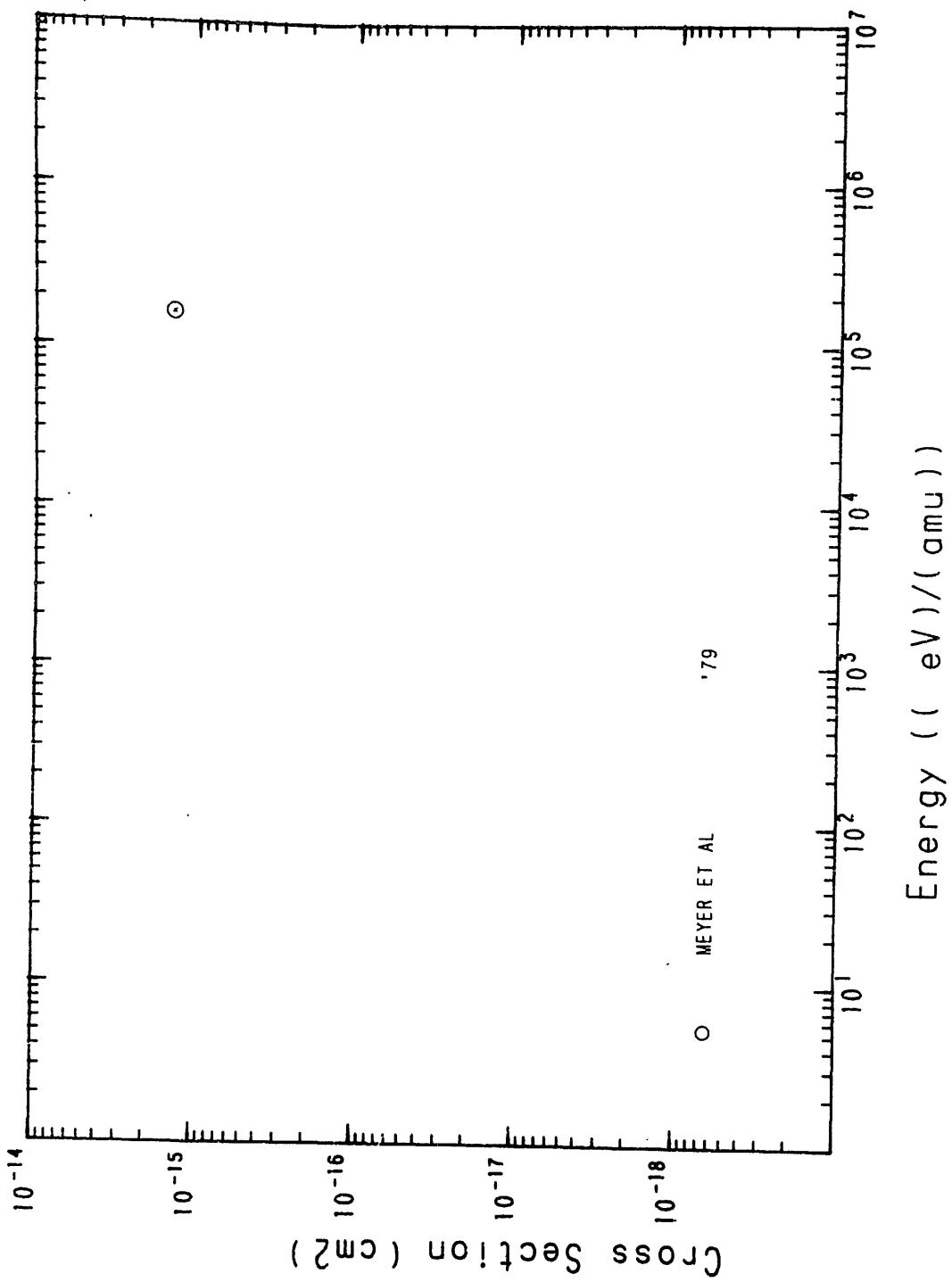


Fig.64 $\text{Fe}^{15+} + \text{H} \rightarrow \text{Fe}^{14+}$

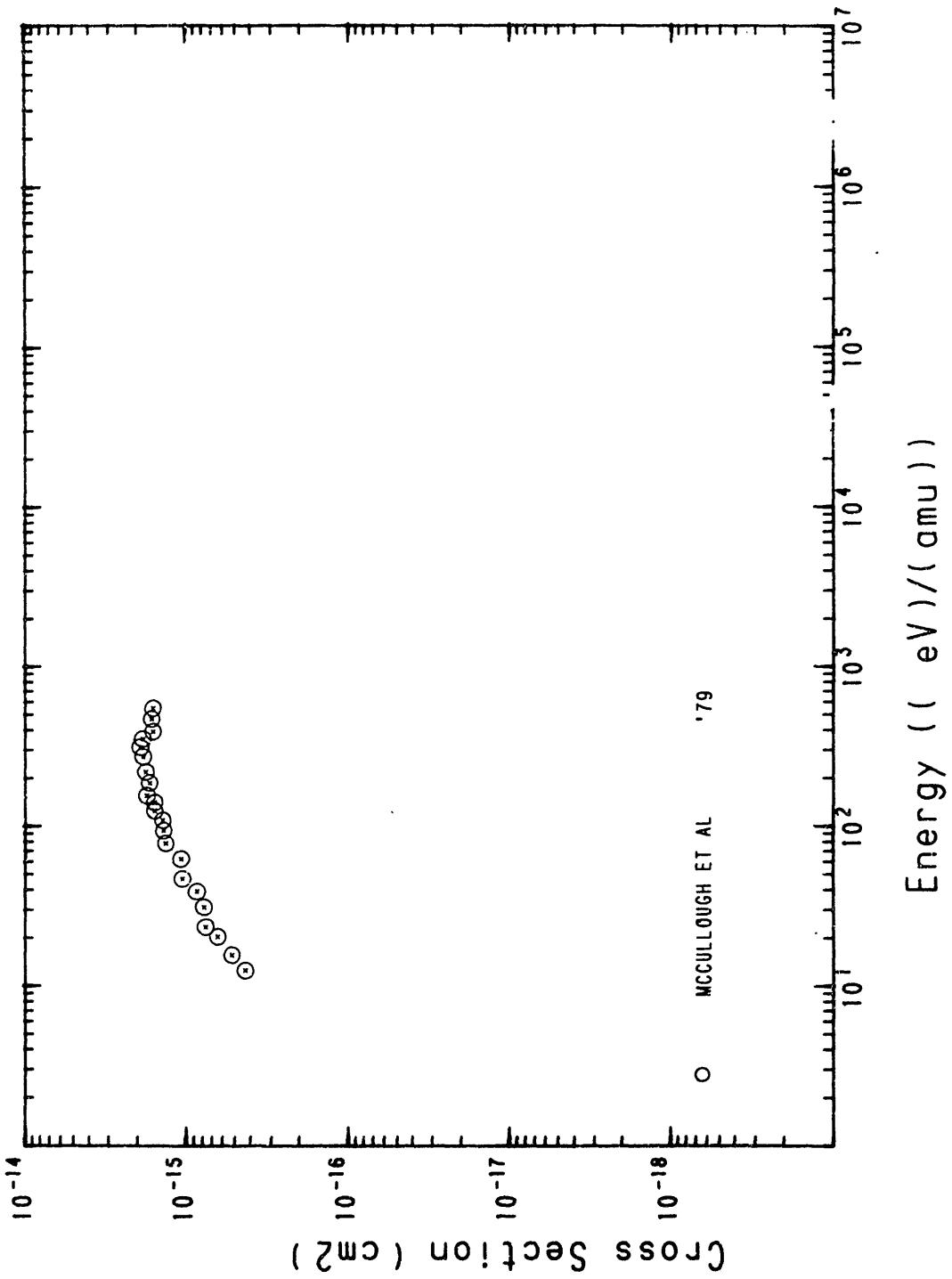


Fig.65 $\text{Zn}^{2+} + \text{H} \rightarrow \text{Zn}^+$

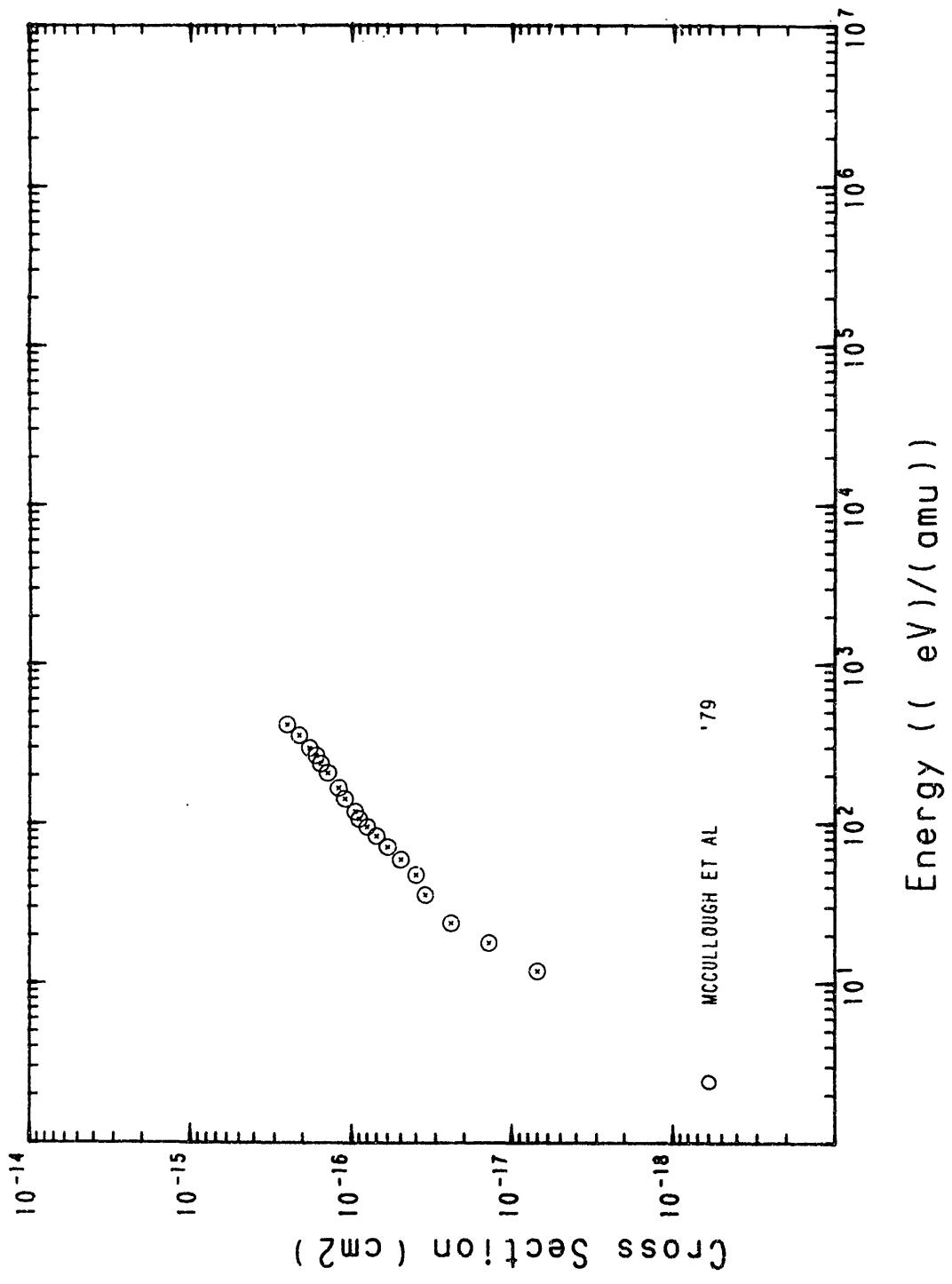


Fig.66 $\text{Kr}^{2+} + \text{H} \longrightarrow \text{Kr}^+$

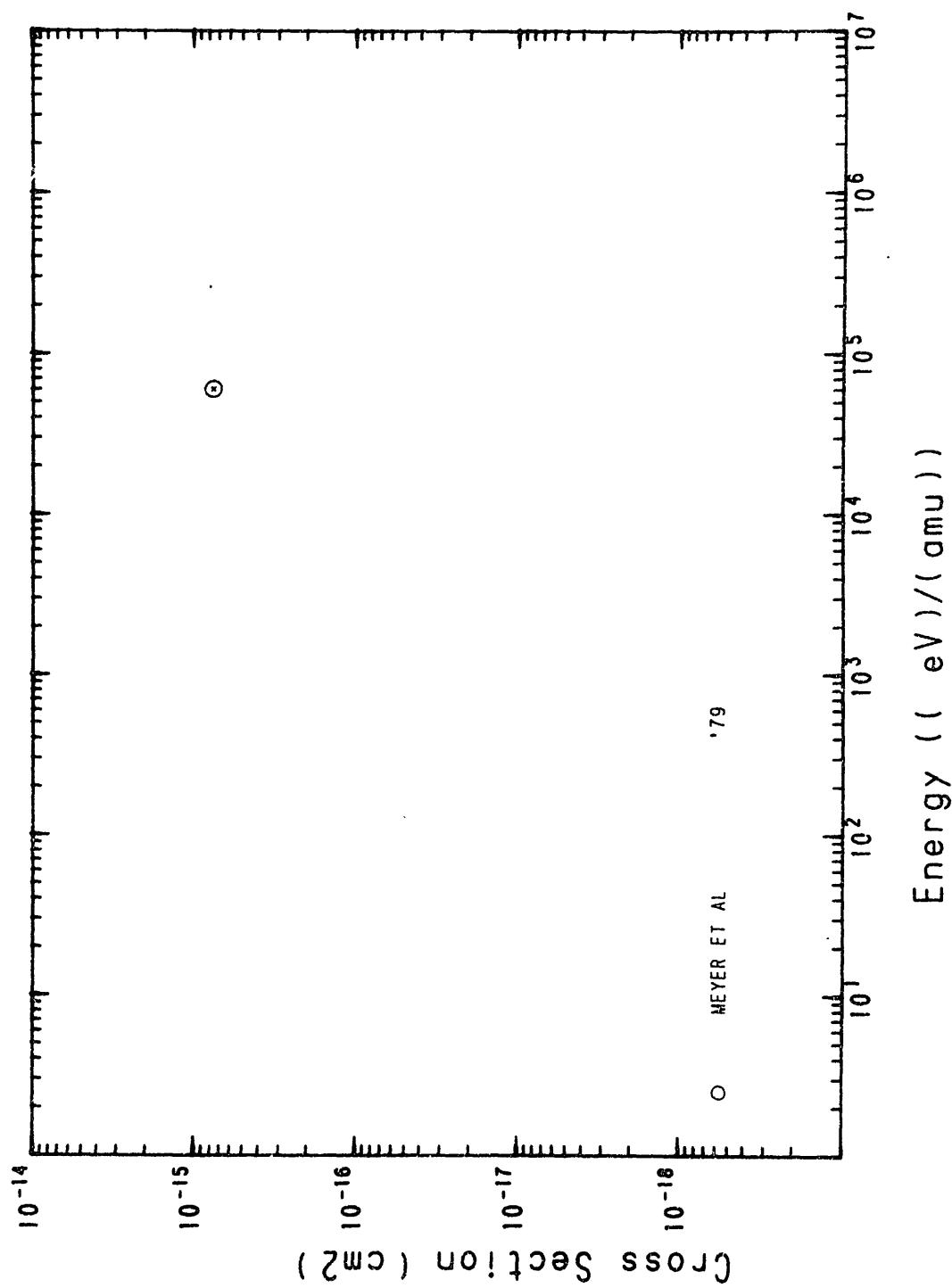


Fig. 67 $\text{Mo}^{4+} + \text{H} \rightarrow \text{Mo}^{3+}$

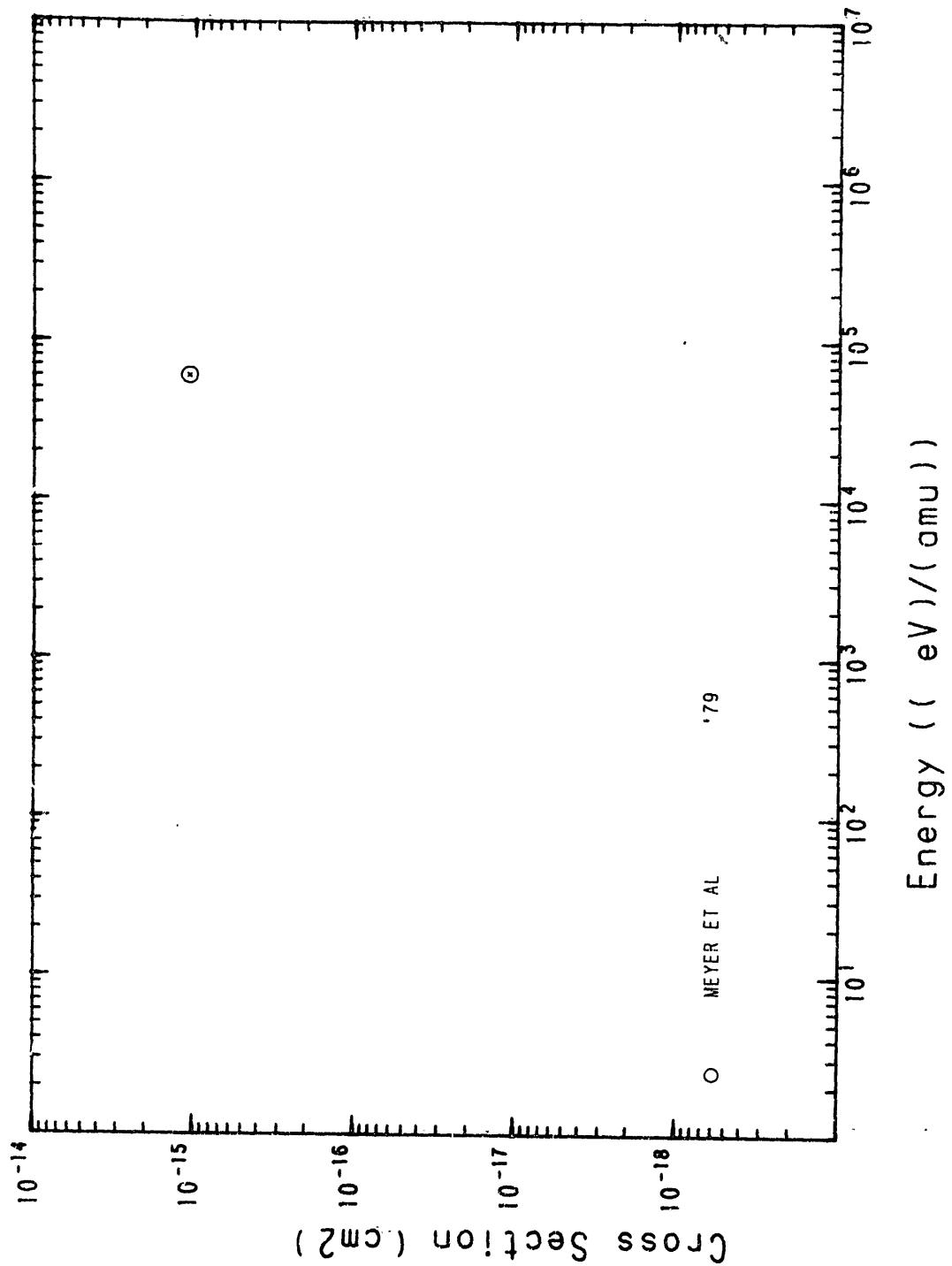


Fig.68 $\text{Mo}^{5+} + \text{H} \longrightarrow \text{Mo}^{4+}$

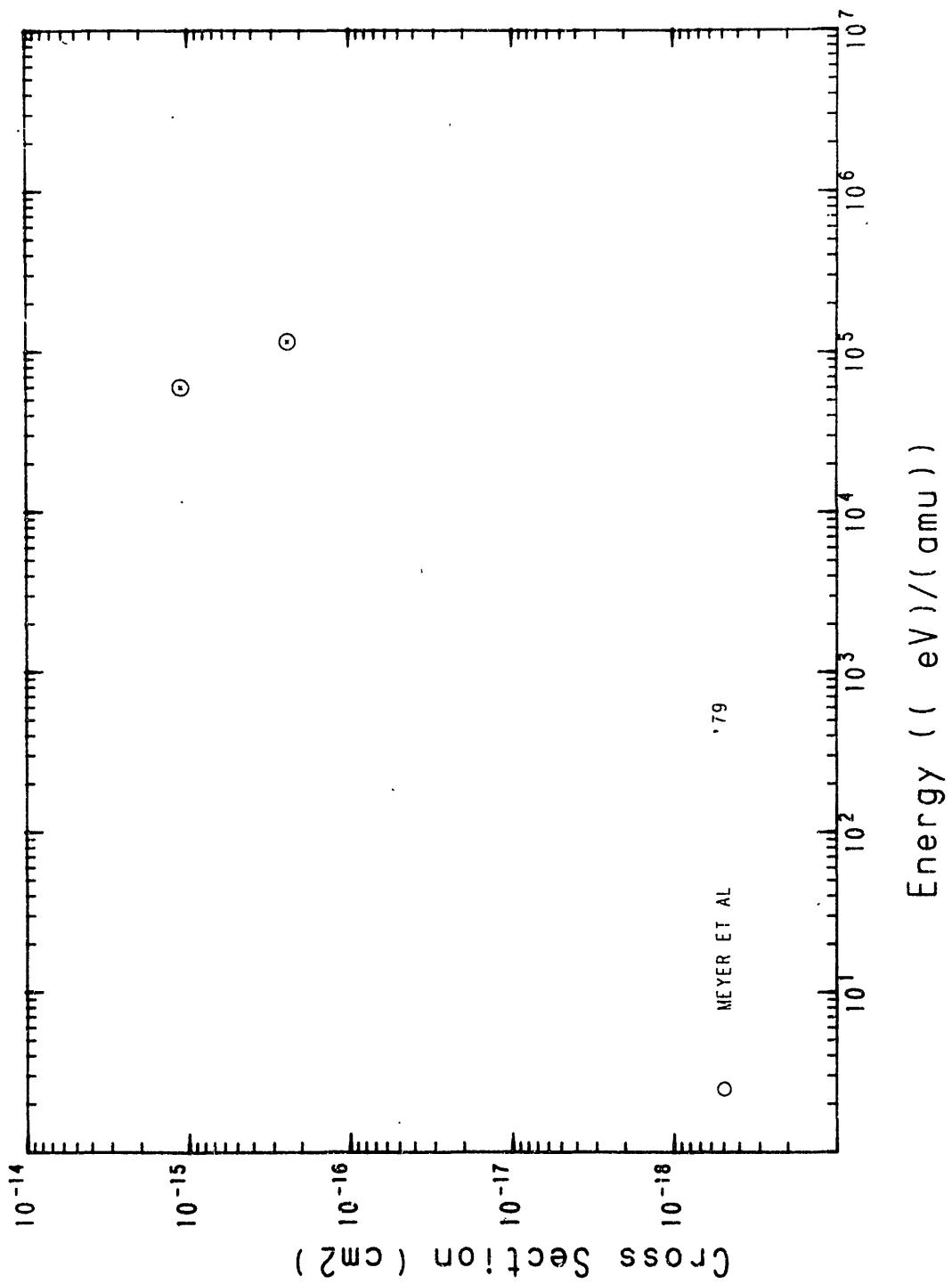


Fig.69 $\text{Mo}^{6+} + \text{H} \rightarrow \text{Mo}^{5+}$

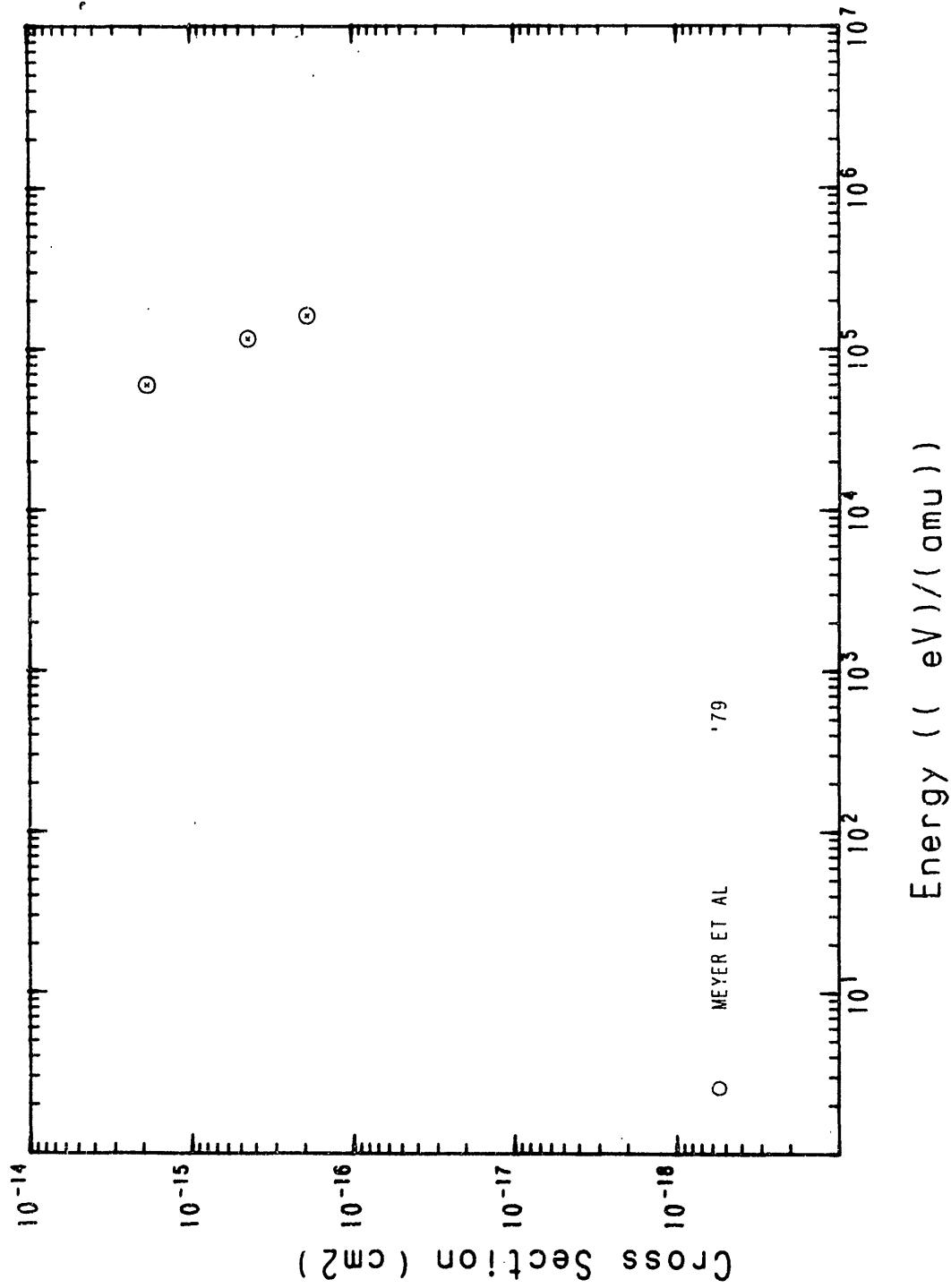


Fig.70 $\text{Mo}^{7+} + \text{H} \longrightarrow \text{Mo}^{6+}$

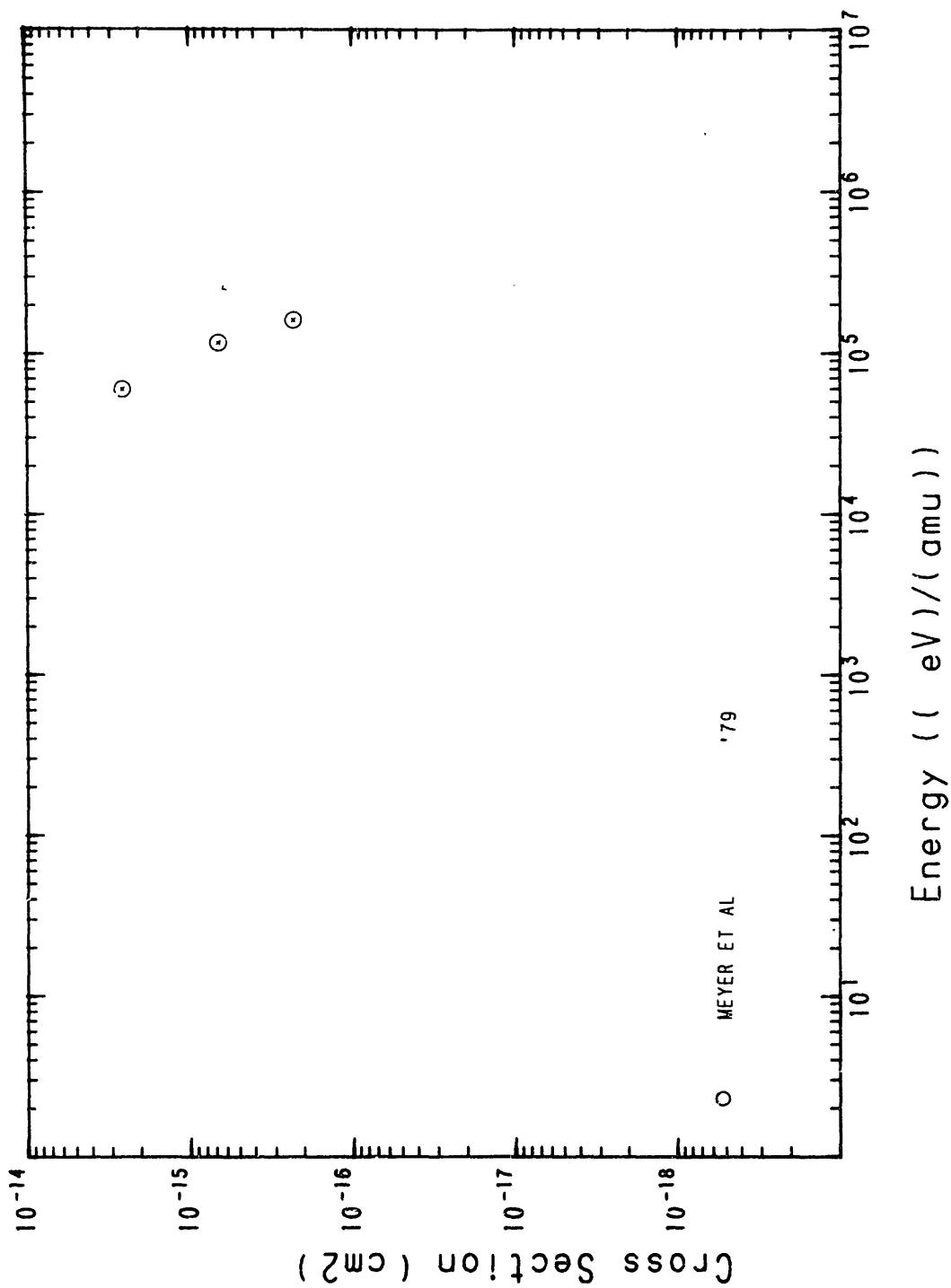


Fig.71 $\text{Mo}^{8+} + \text{H} \rightarrow \text{Mo}^{7+}$

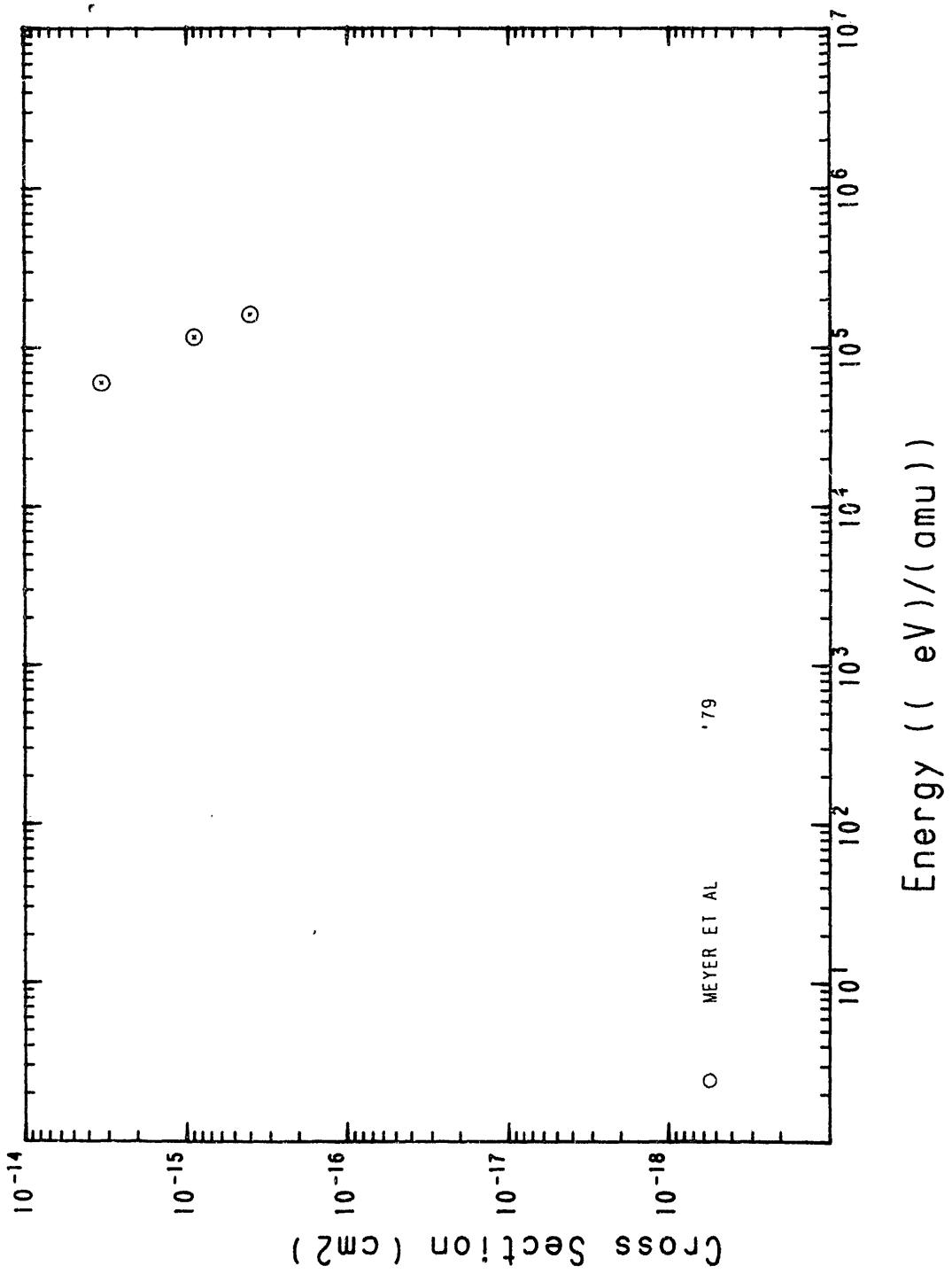


Fig.72 $\text{Mo}^{9+} + \text{H} \longrightarrow \text{Mo}^{8+}$

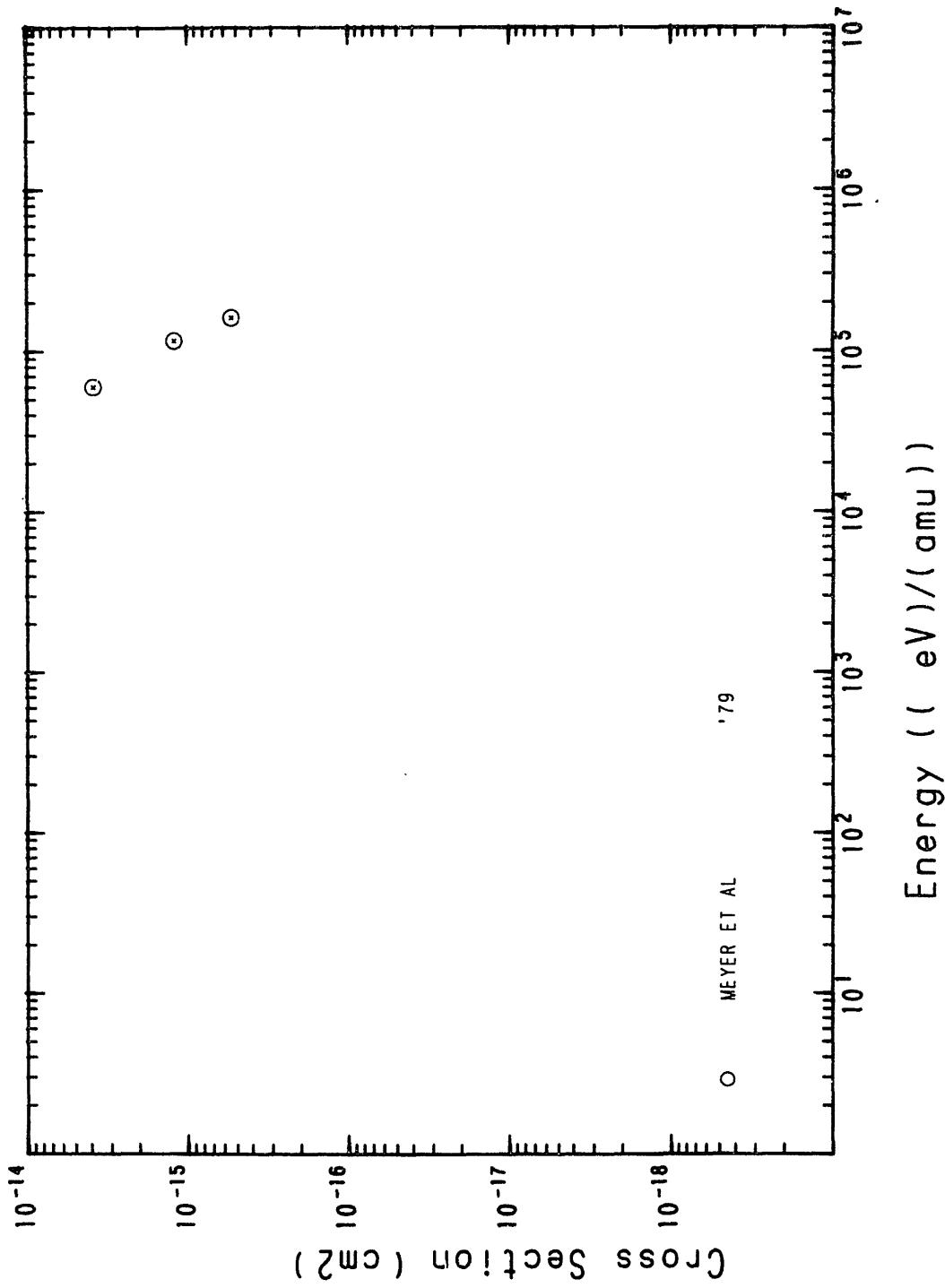


Fig.73 $\text{Mo}^{10+} + \text{H} \rightarrow \text{Mo}^{9+}$

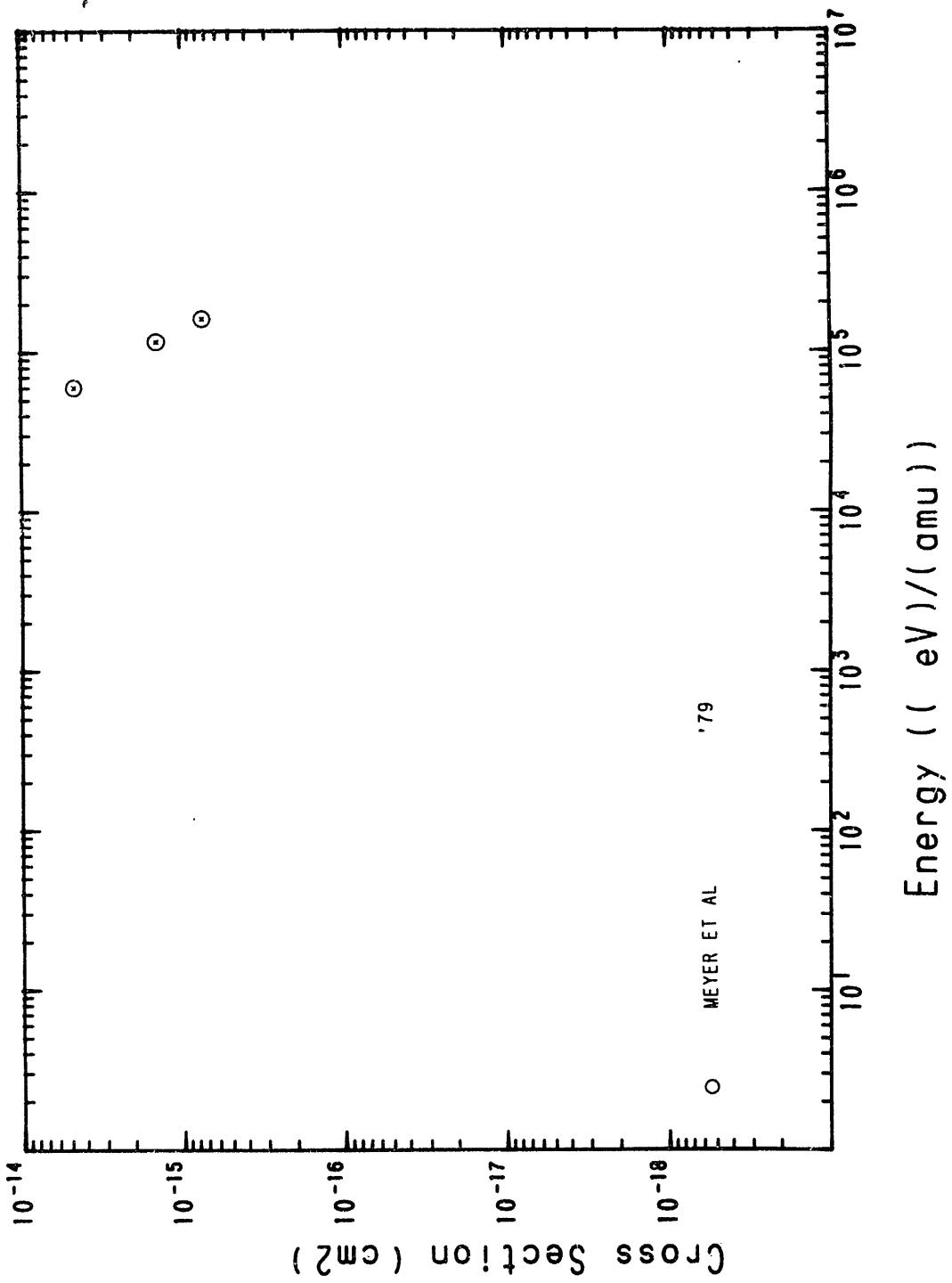


Fig.74 $\text{Mo}^{11+} + \text{H} \rightarrow \text{Mo}^{10+}$

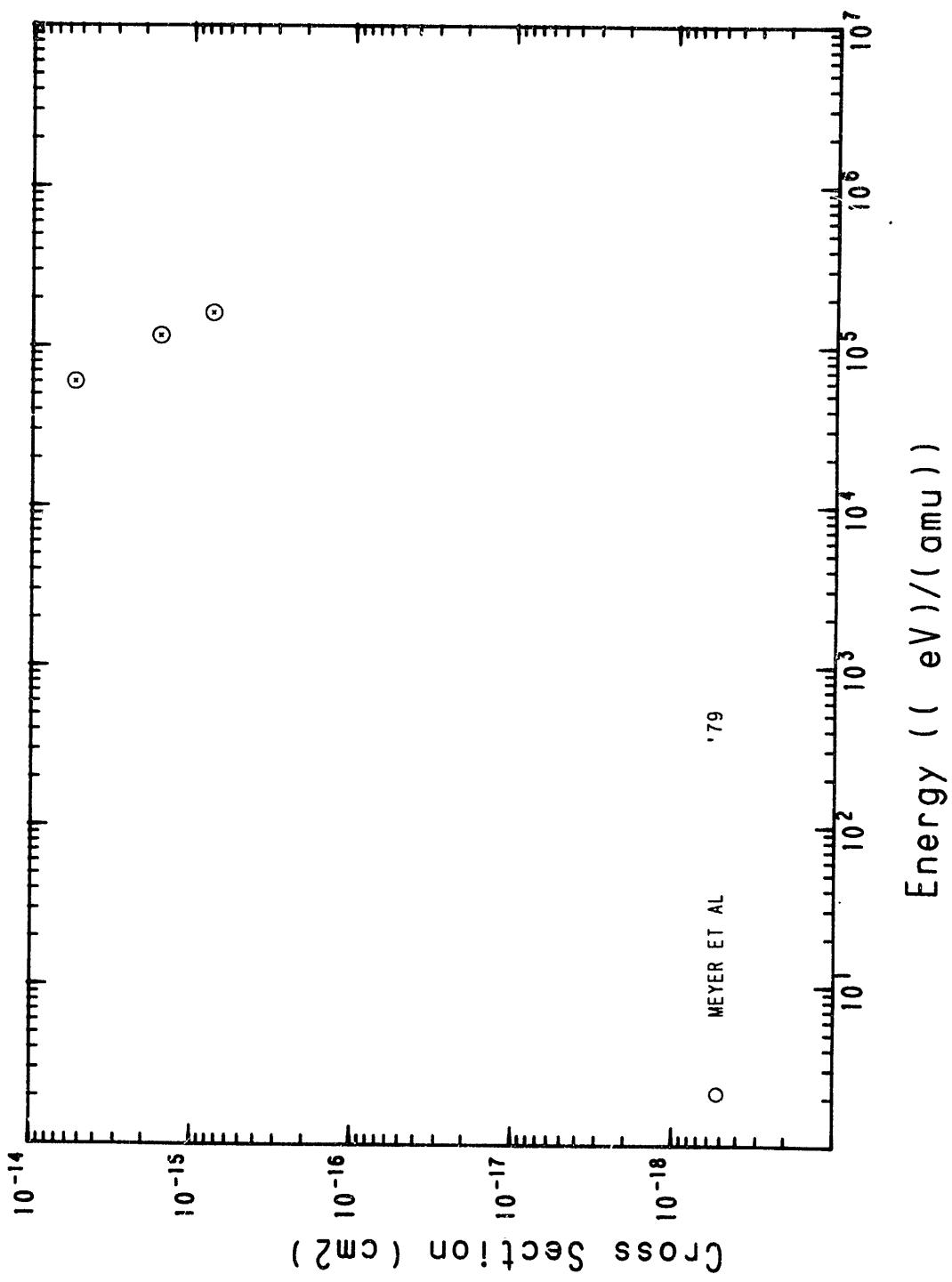


Fig. 75 $\text{Mo}^{12+} + \text{H} \rightarrow \text{Mo}^{11+}$

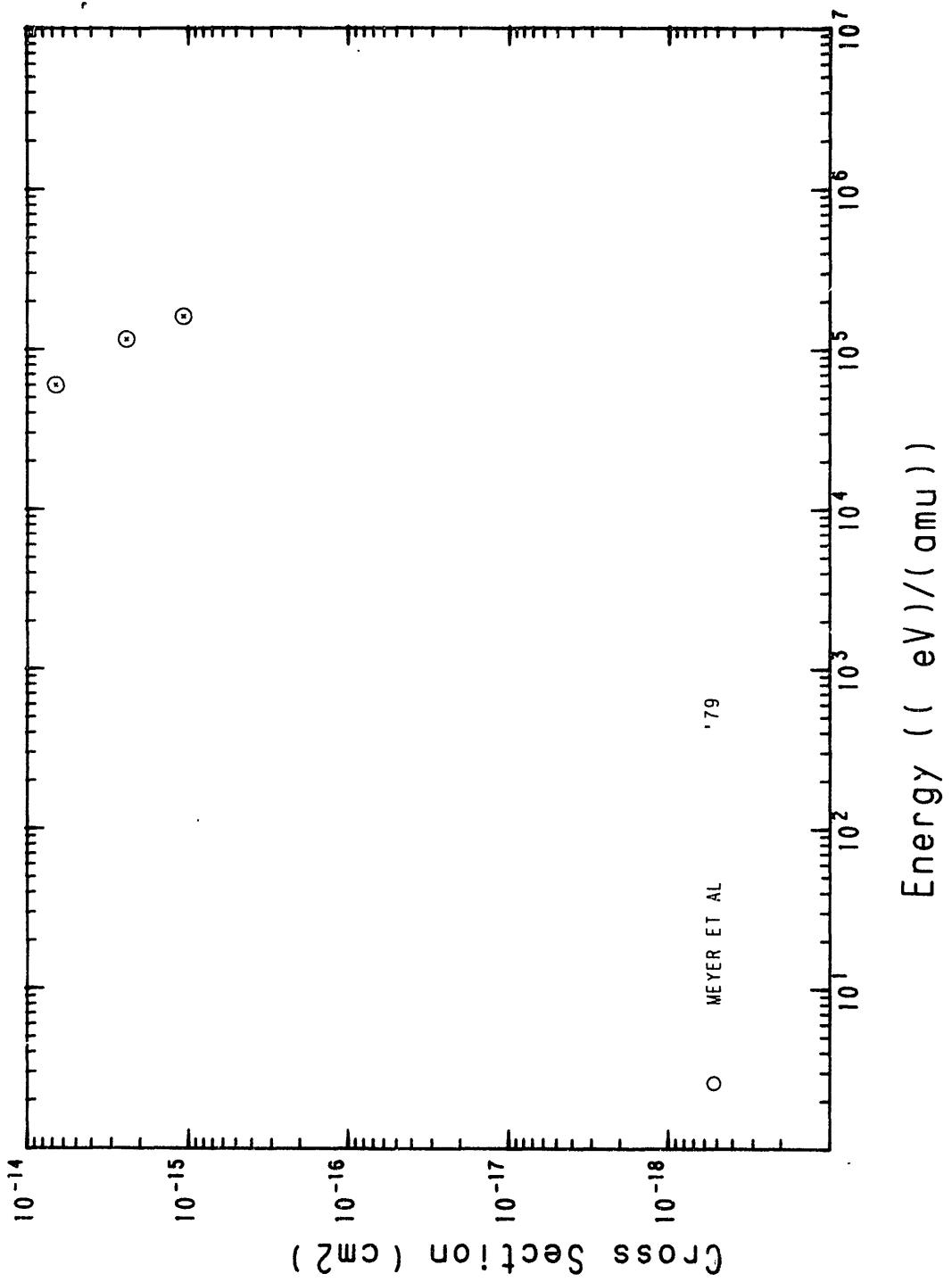


Fig.76 $\text{Mo}^{13+} + \text{H} \rightarrow \text{Mo}^{12+}$

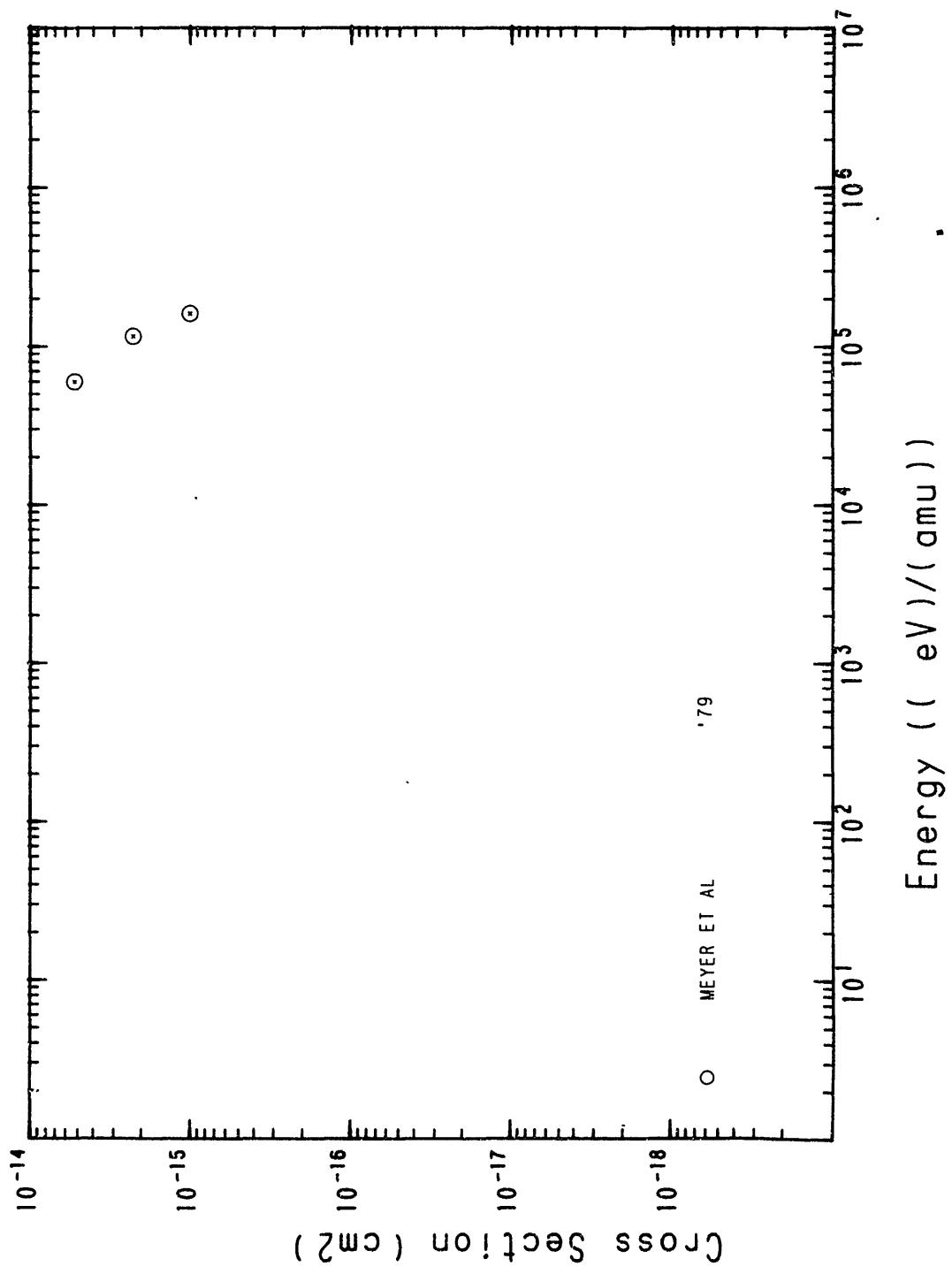


Fig.77 $\text{Mo}^{14+} + \text{H} \rightarrow \text{Mo}^{13+}$

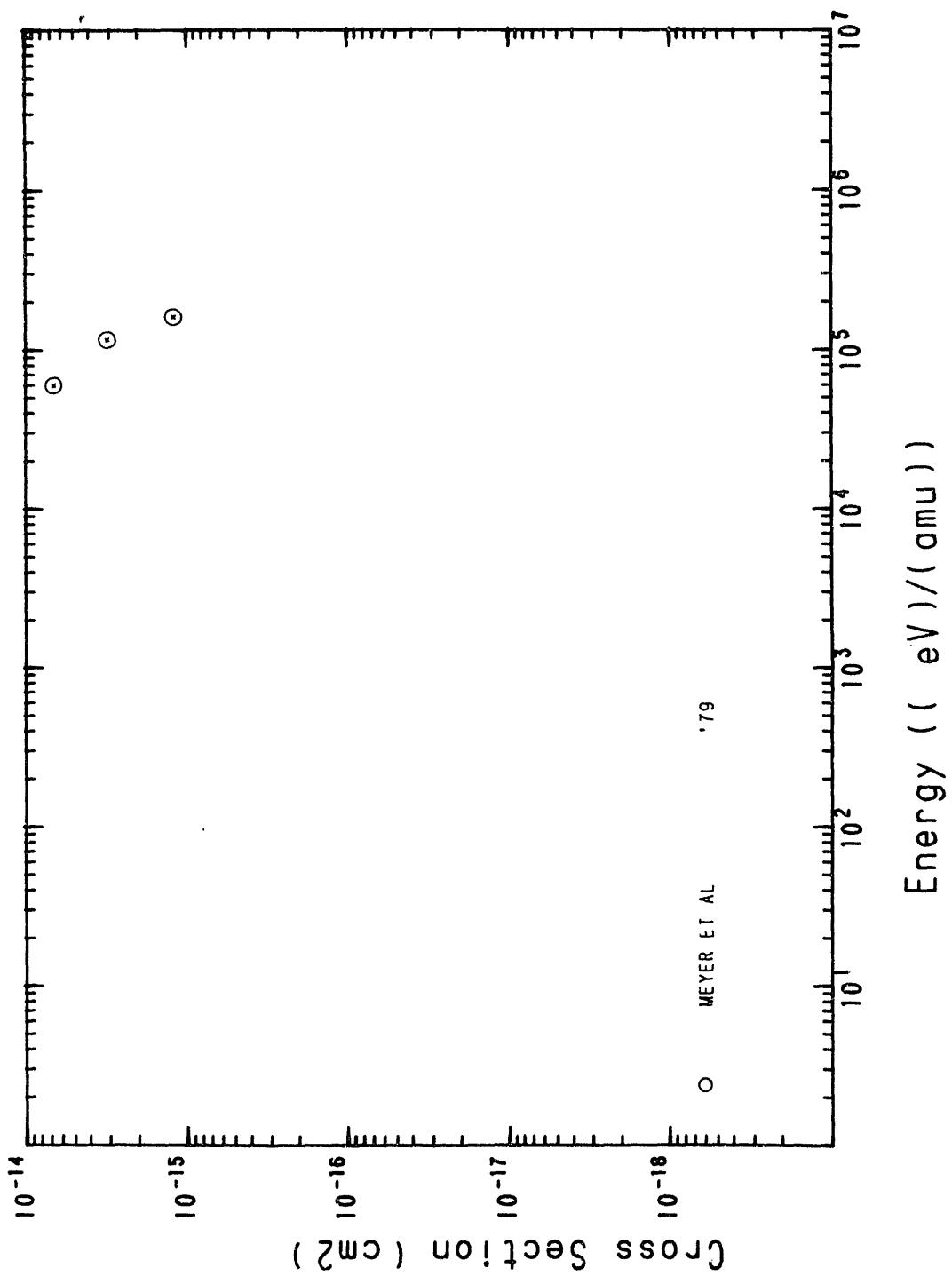


Fig.78 $\text{Mo}^{15+} + \text{H} \longrightarrow \text{Mo}^{14+}$

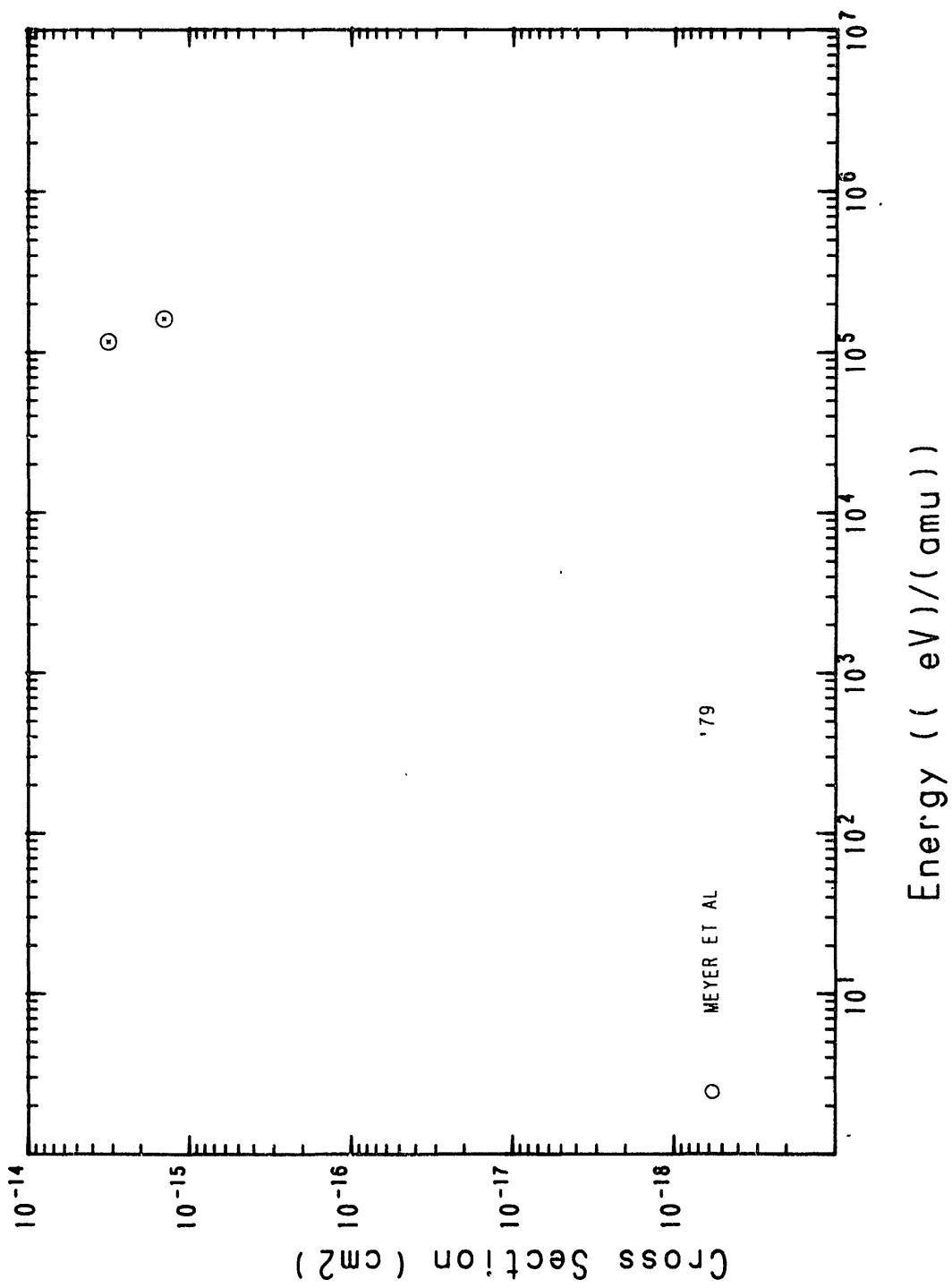


Fig.79 $\text{Mo}^{16+} + \text{H} \longrightarrow \text{Mo}^{15+}$

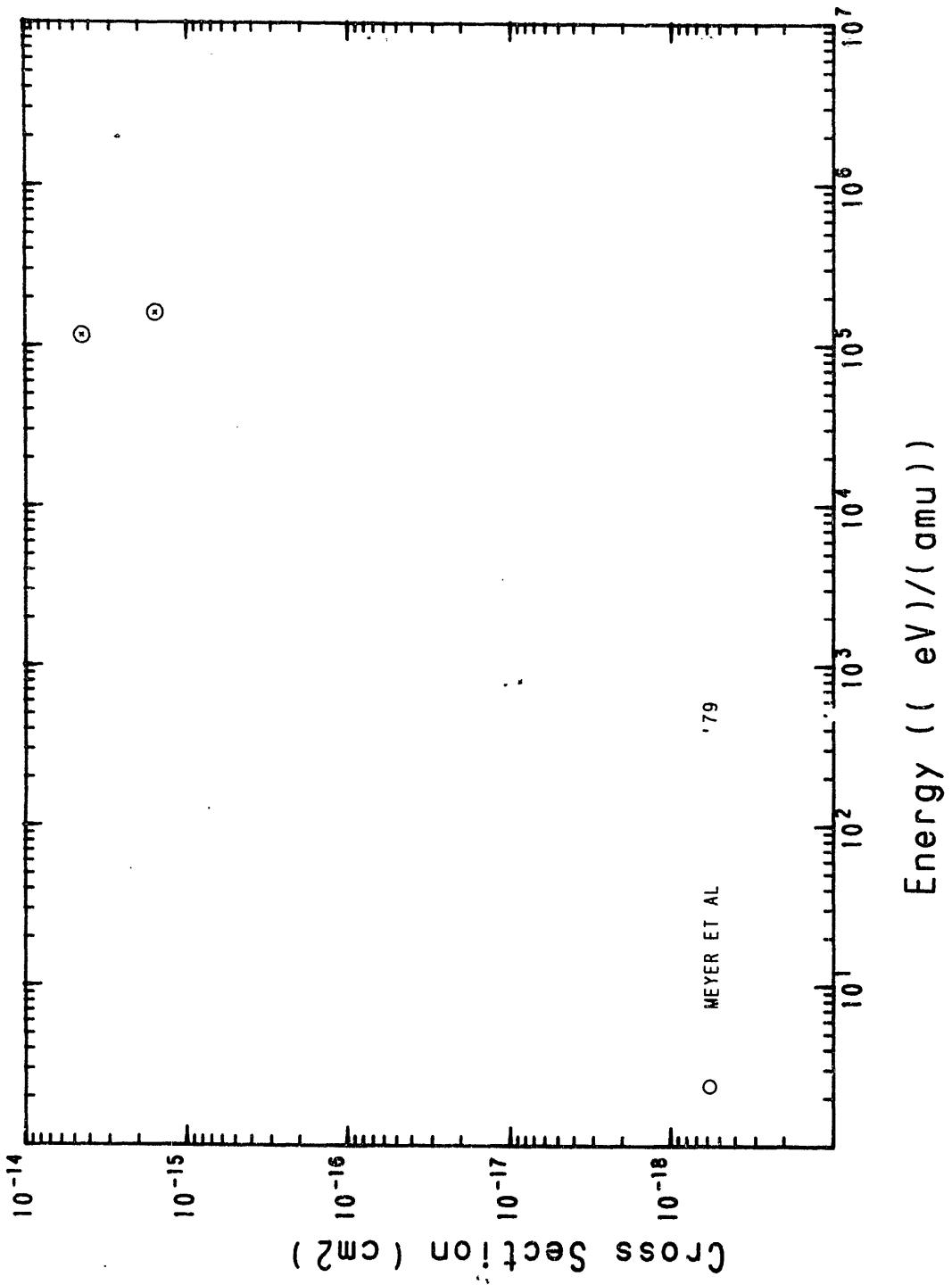


Fig.80 $\text{Mo}^{17+} + \text{H} \rightarrow \text{Mo}^{16+}$

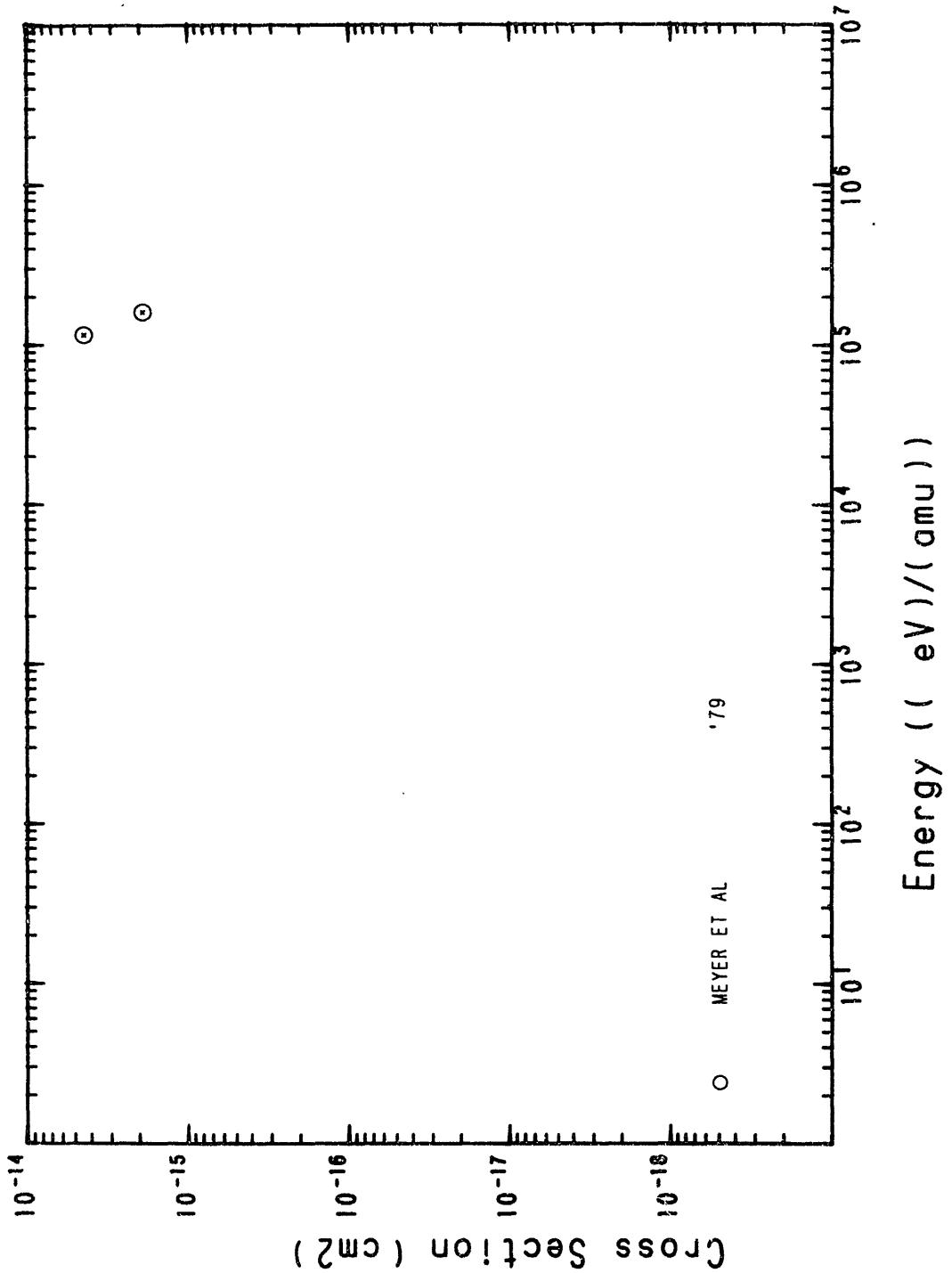


Fig.81 $\text{Mo}^{18+} + \text{H} \rightarrow \text{Mo}^{17+}$

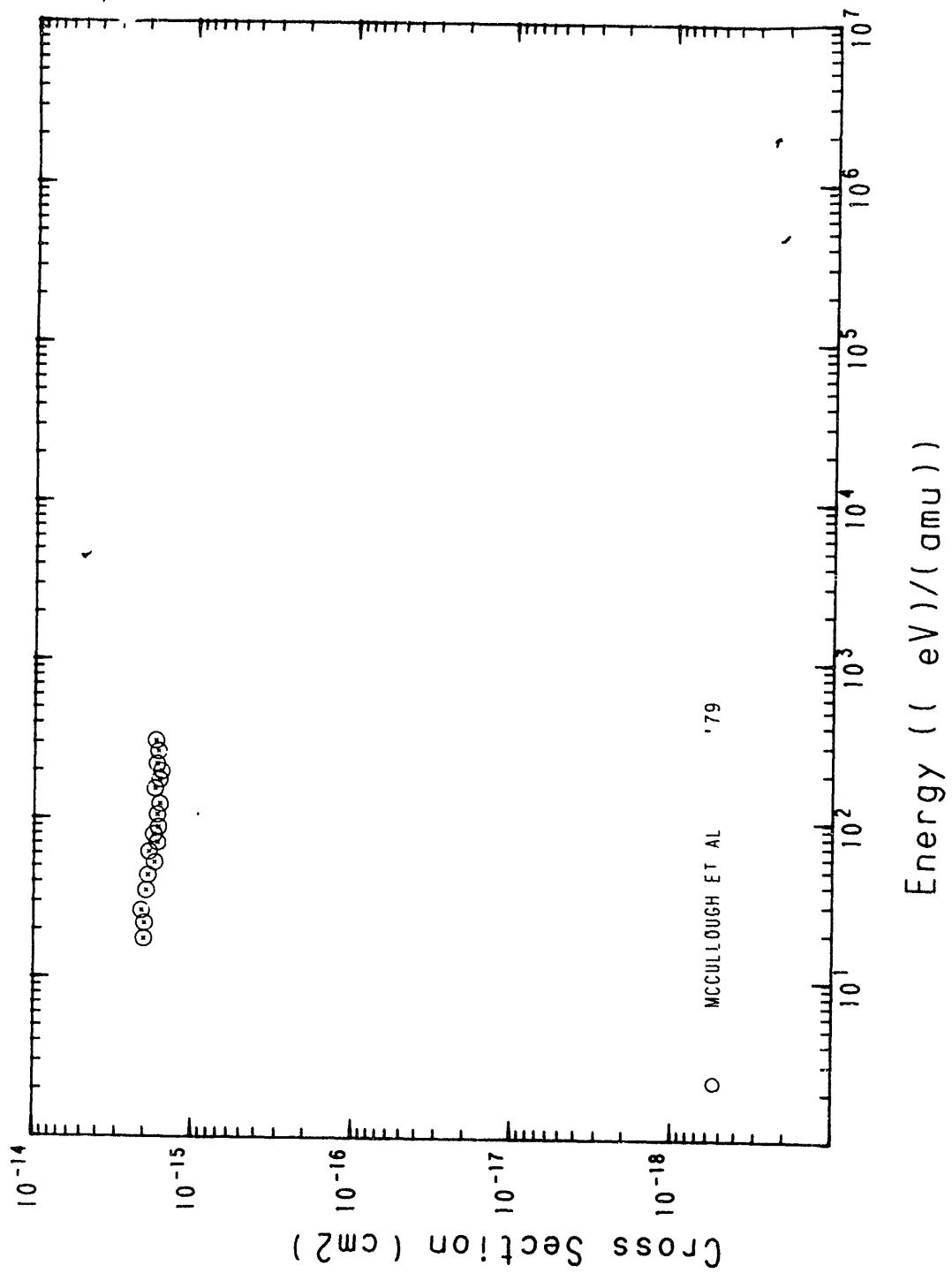


Fig.82 $\text{Cd}^{2+} + \text{H} \longrightarrow \text{Cd}^+$

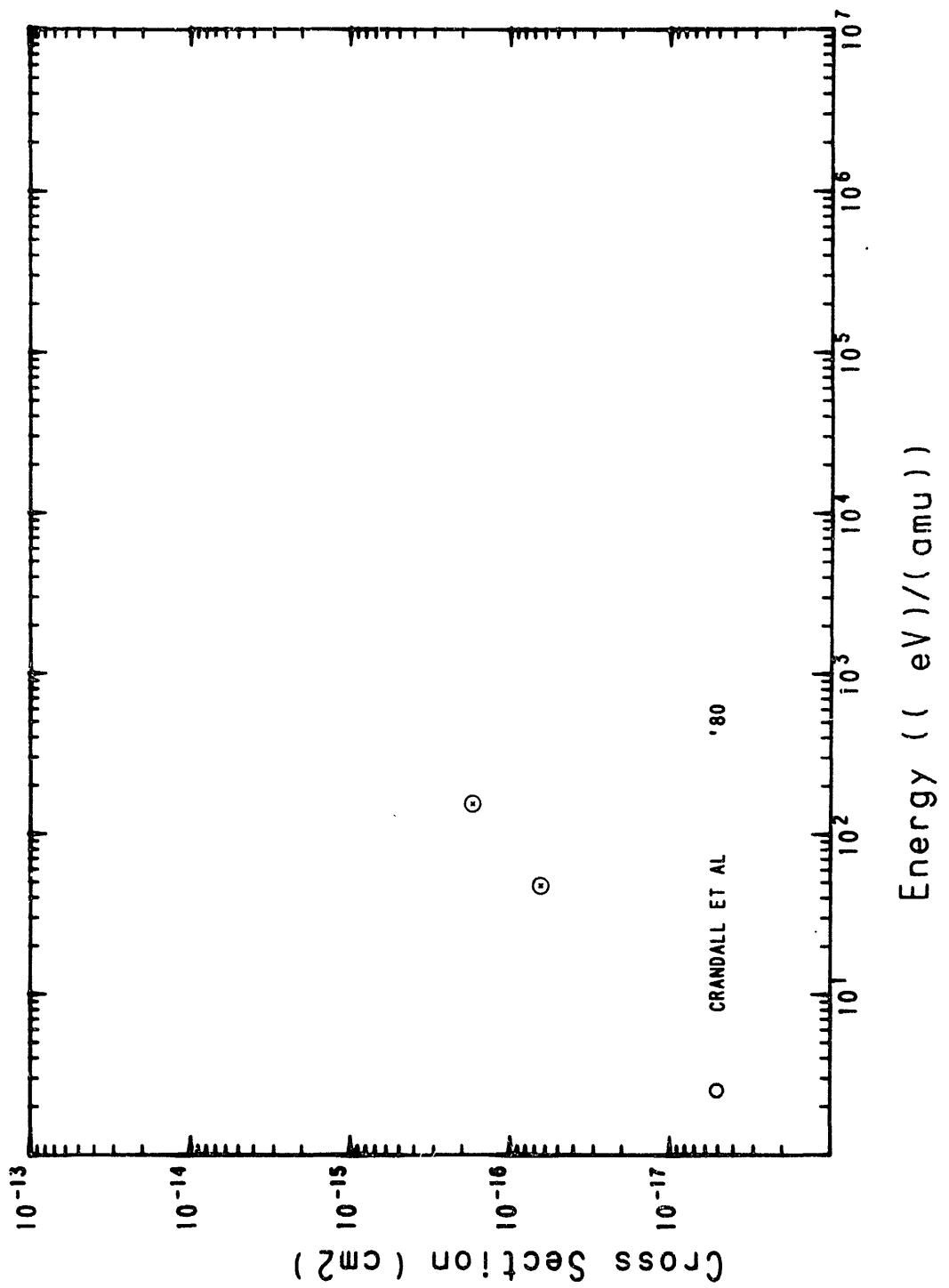


Fig.83 $\text{Xe}^{2+} + \text{H} \rightarrow \text{Xe}^+$

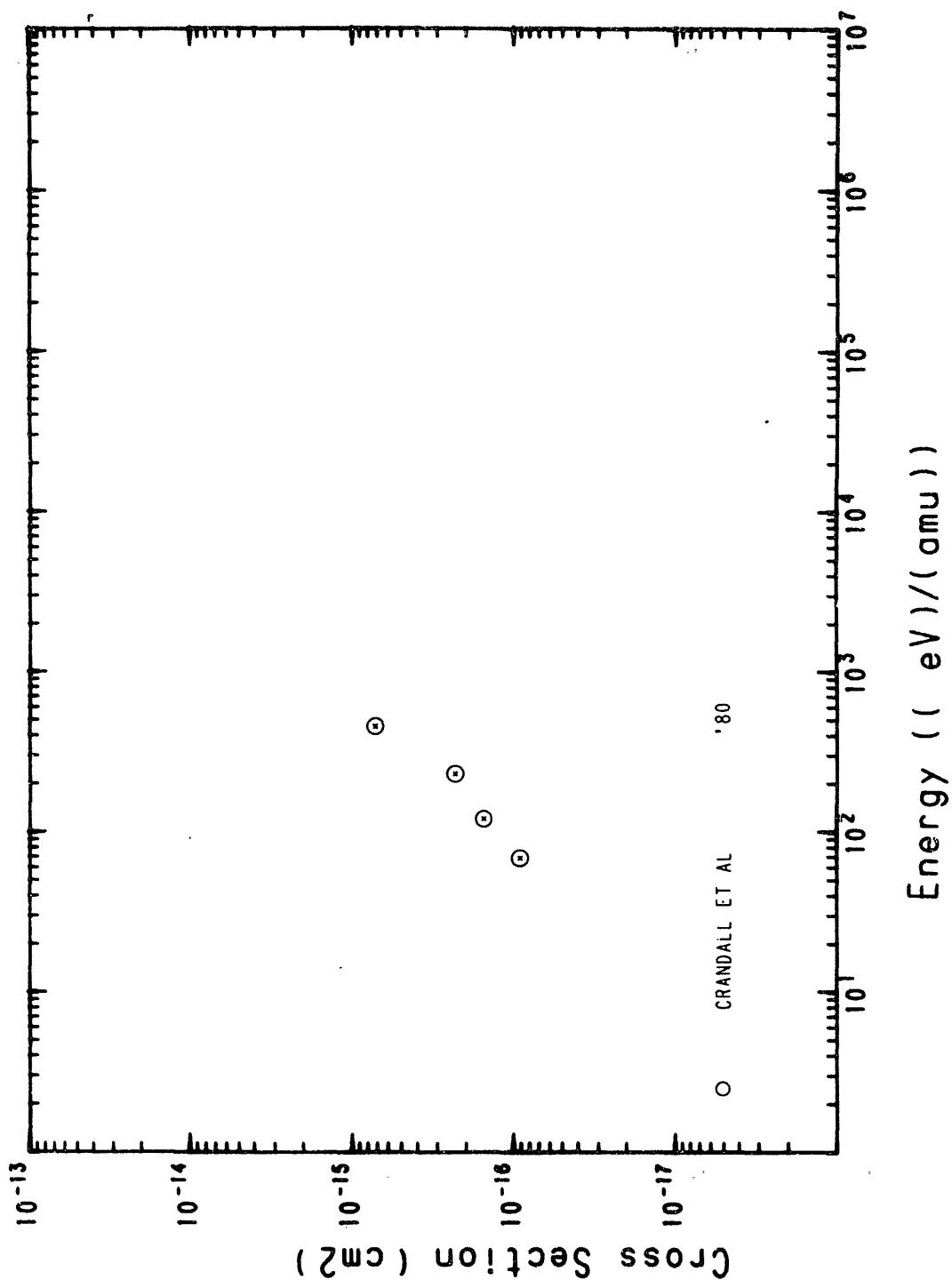


Fig.84 $\text{Xe}^{3+} + \text{H} \rightarrow \text{Xe}^{2+}$

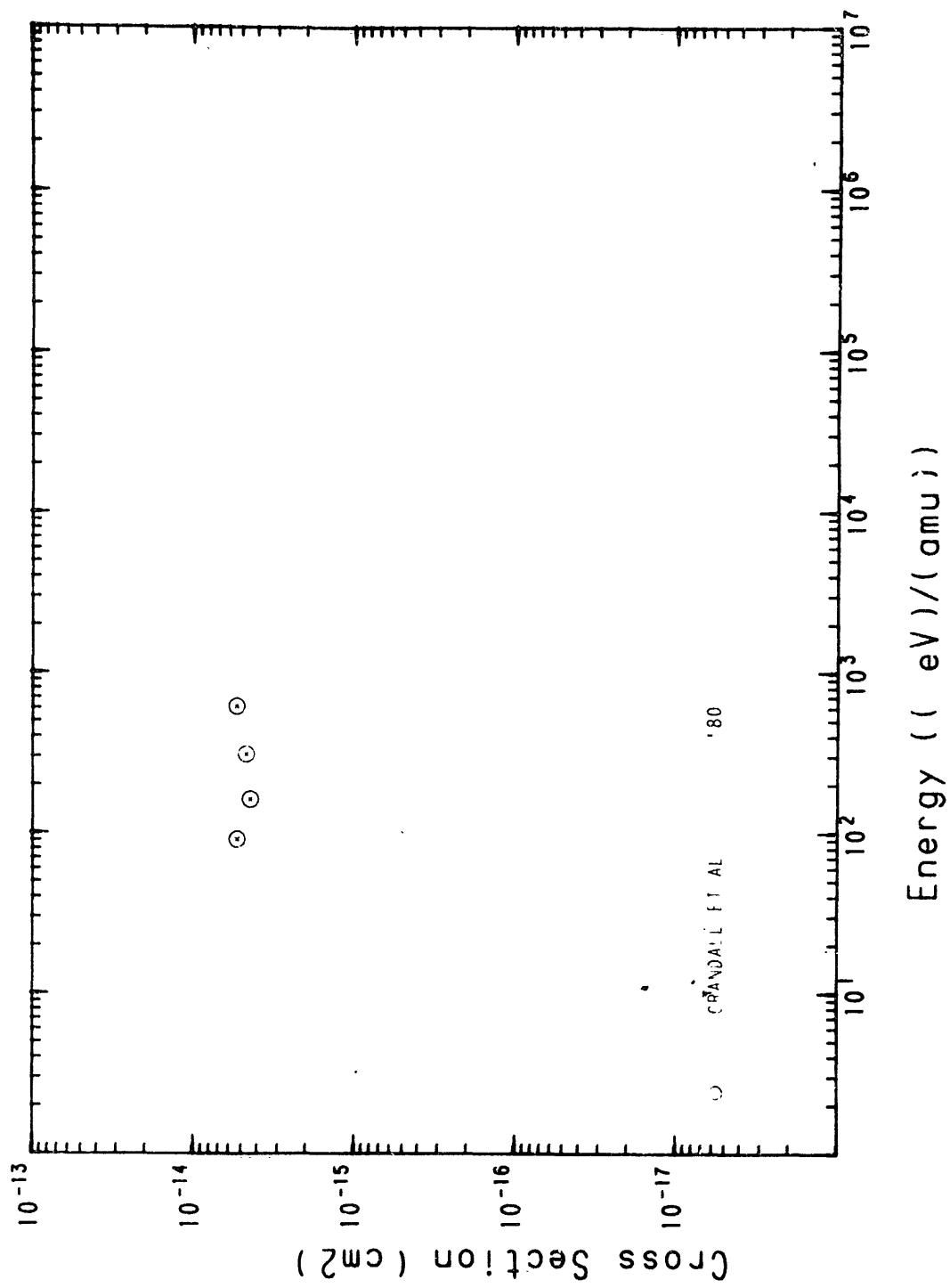


Fig.85 $\text{Xe}^{4+} + \text{H} \rightarrow \text{Xe}^{3+}$

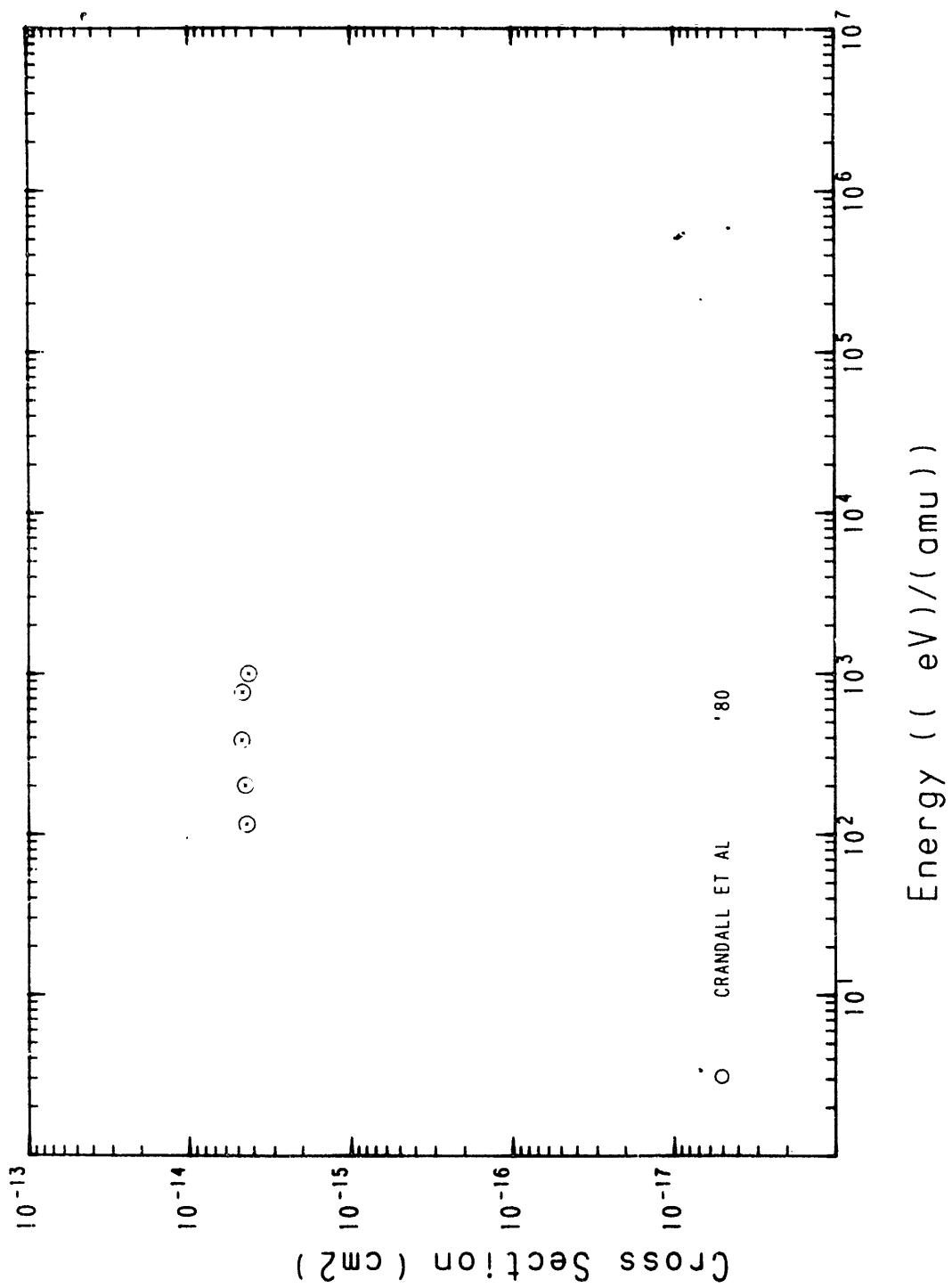


Fig.86 $\text{Xe}^{5+} + \text{H} \rightarrow \text{Xe}^{4+}$

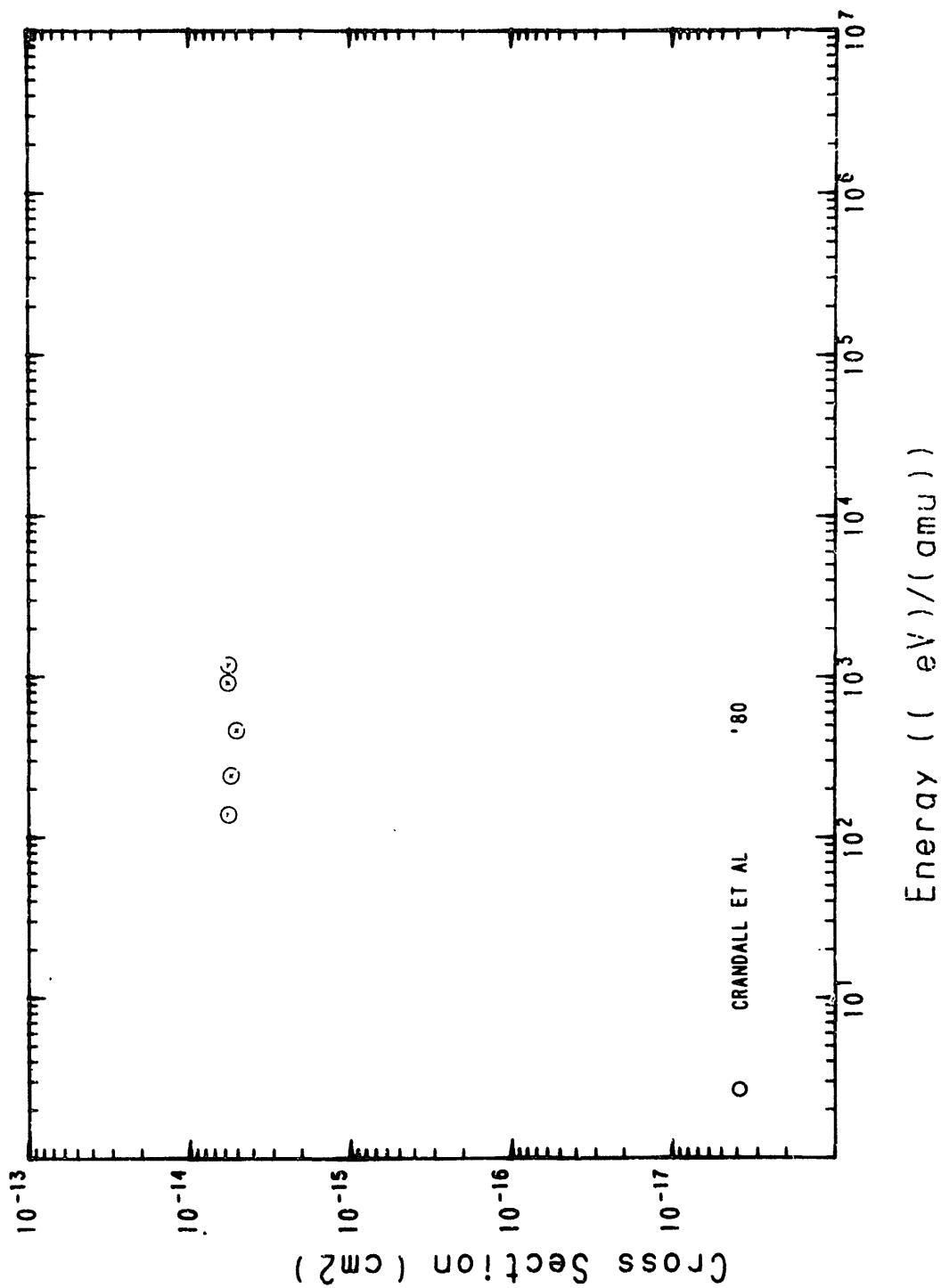


Fig.87 $\text{Xe}^{6+} + \text{H} \longrightarrow \text{Xe}^{5+}$

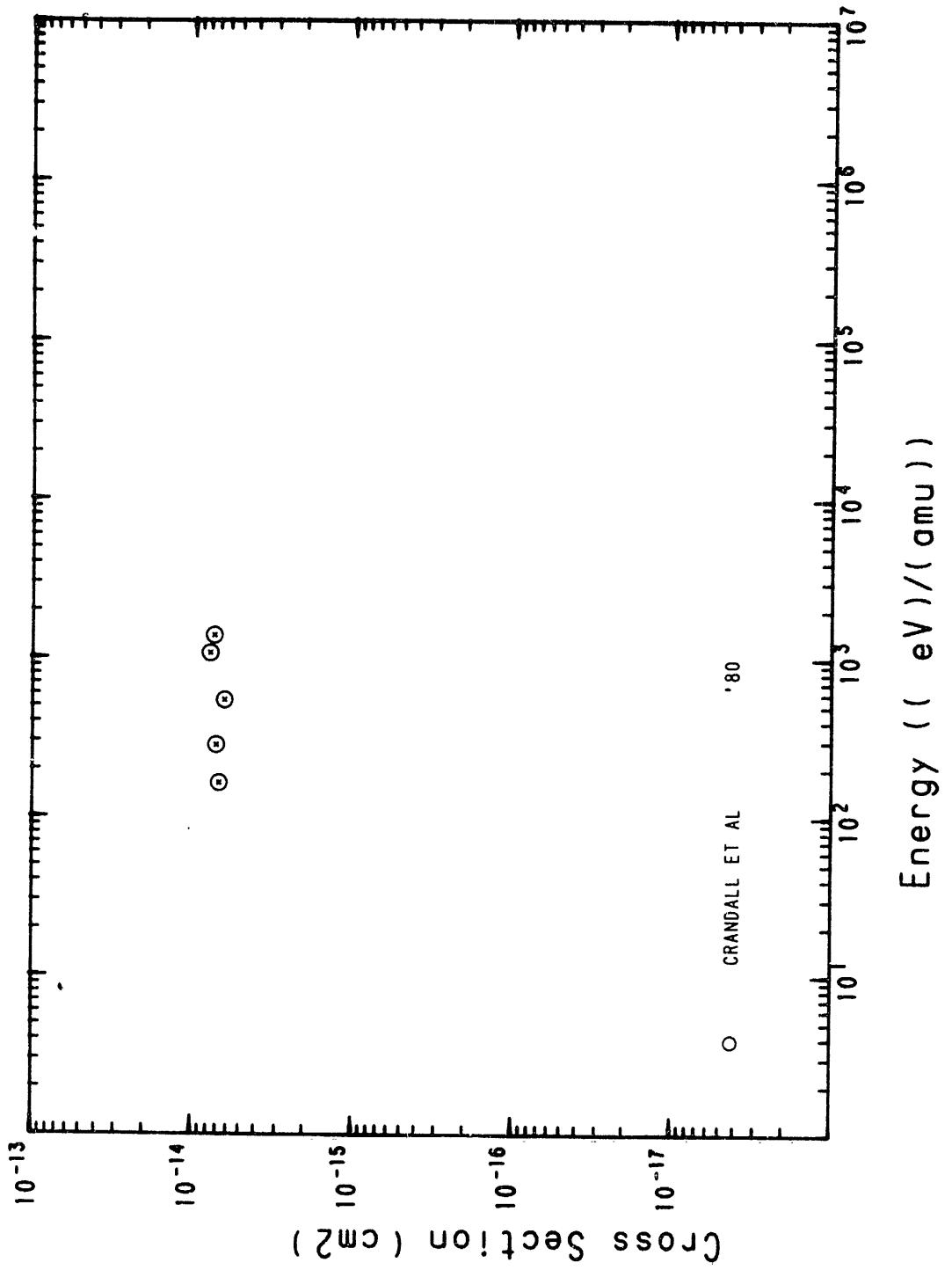


Fig.88 $\text{Xe}^{7+} + \text{H} \longrightarrow \text{Xe}^{6+}$

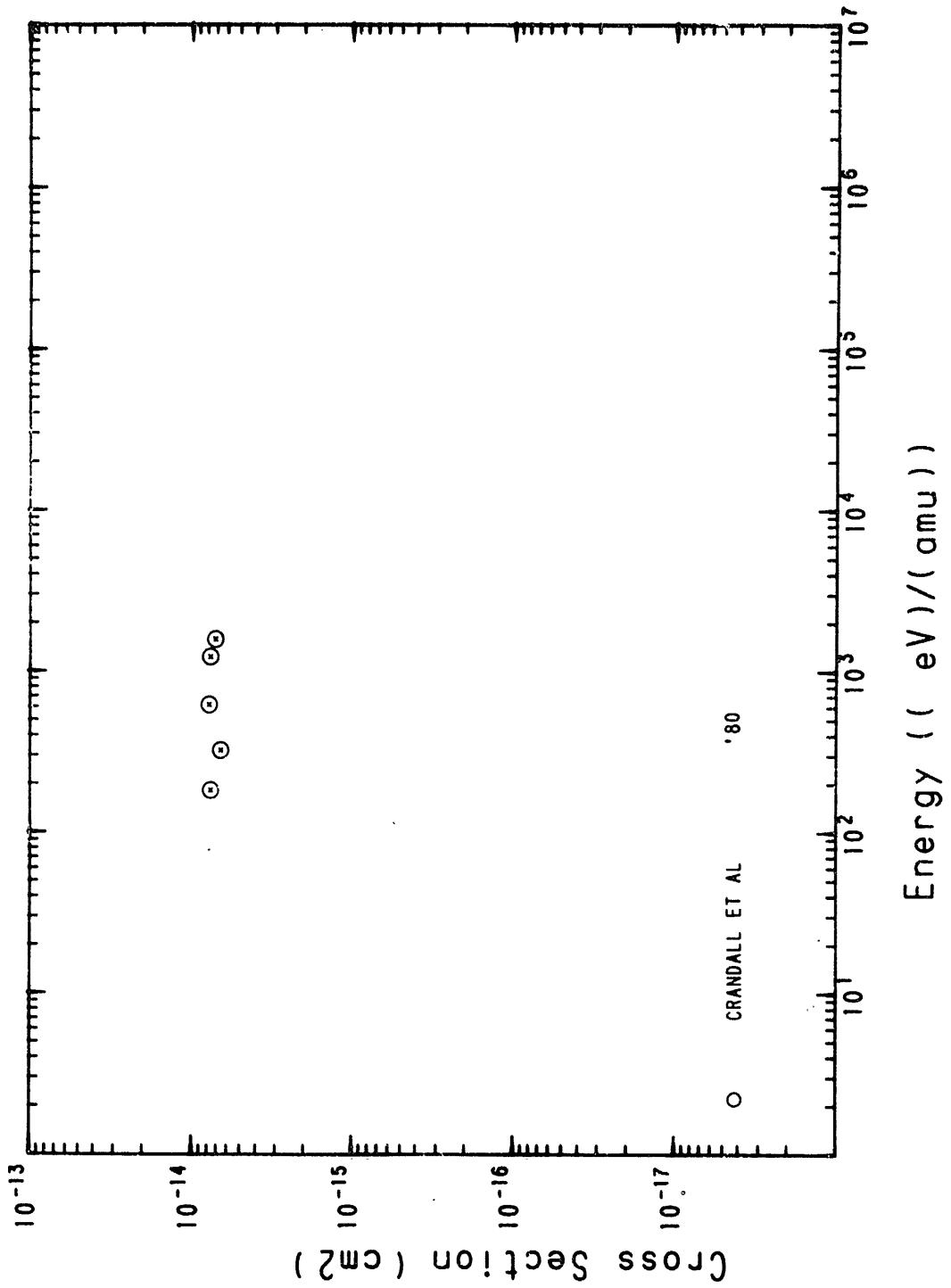


Fig.89 $Xe^{8+} + H \rightarrow Xe^{7+}$

Energy ((eV) / (amu))

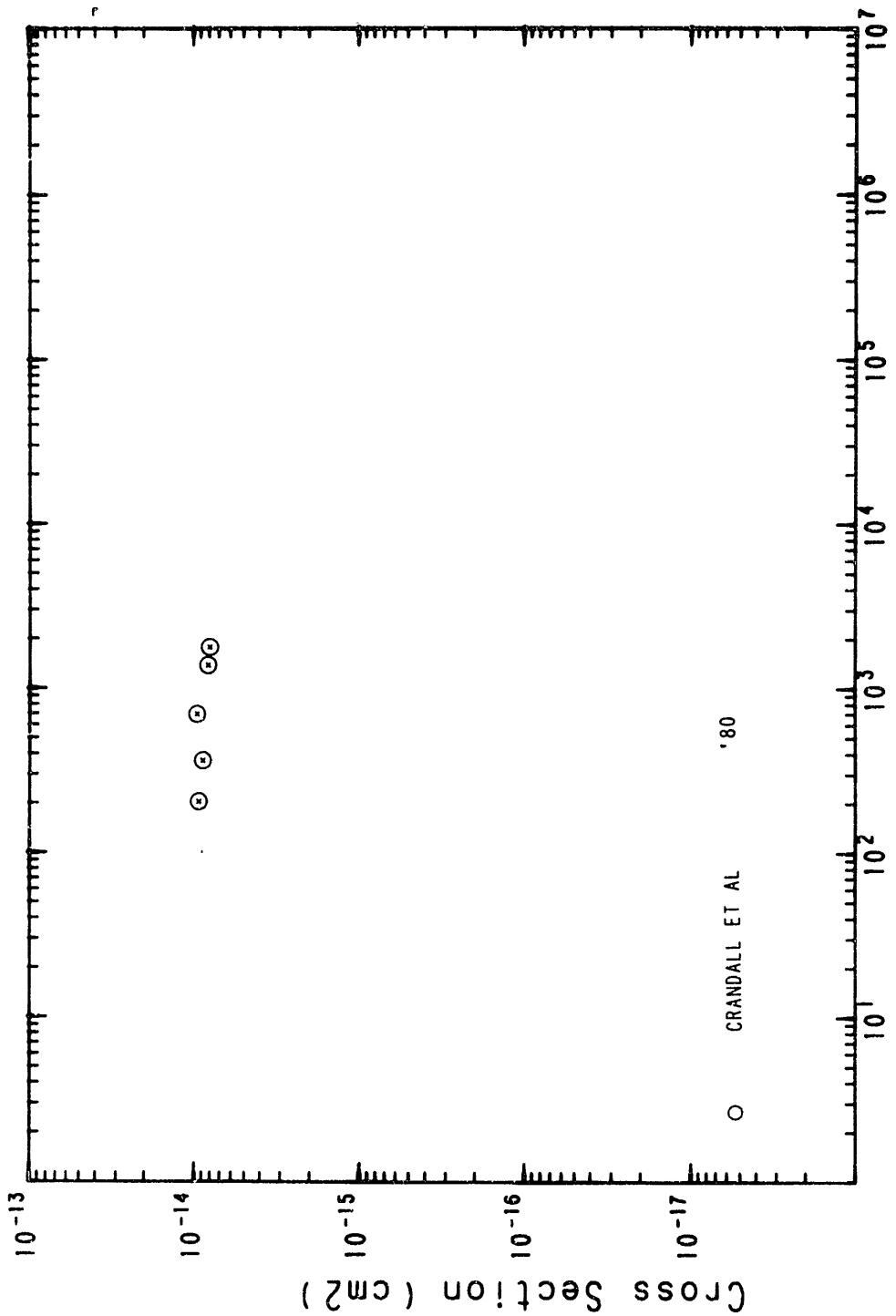


Fig.90 $\text{Xe}^{9+} + \text{H} \rightarrow \text{Xe}^{8+}$

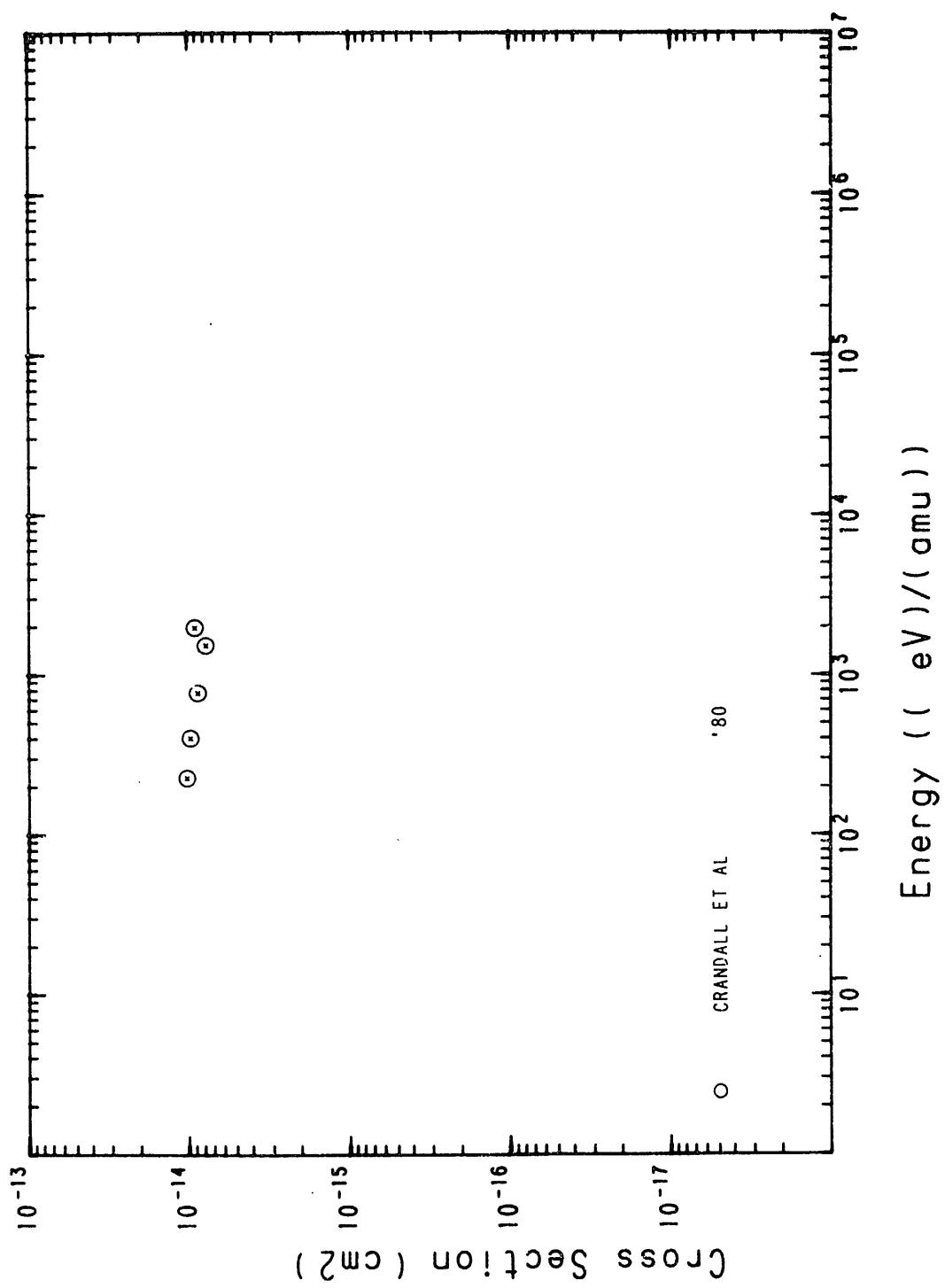


Fig.91 $\text{Xe}^{10+} + \text{H} \longrightarrow \text{Xe}^{9+}$

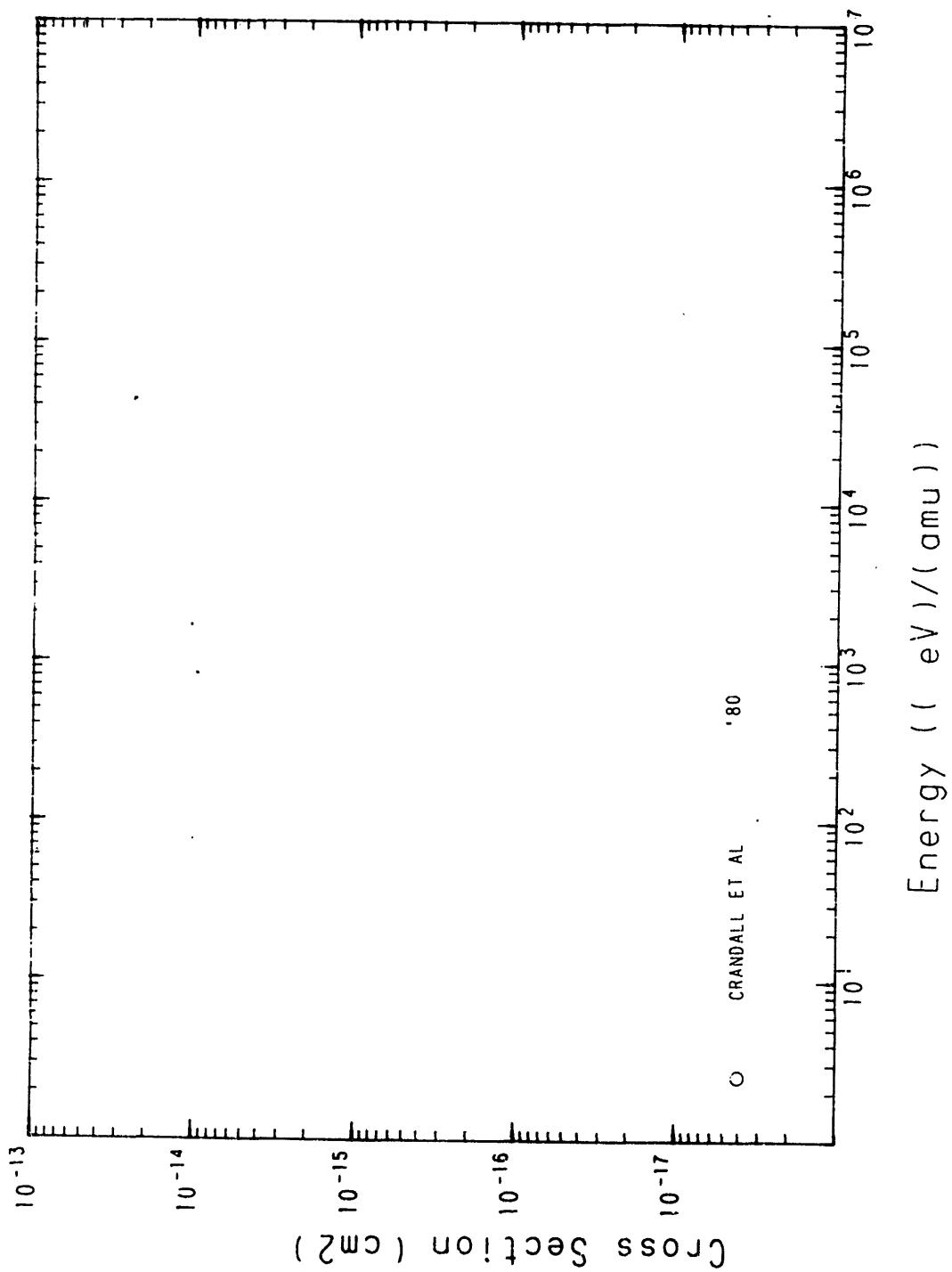


Fig.92 $\text{Xe}^{11+} + \text{H} \rightarrow \text{Xe}^{10+}$

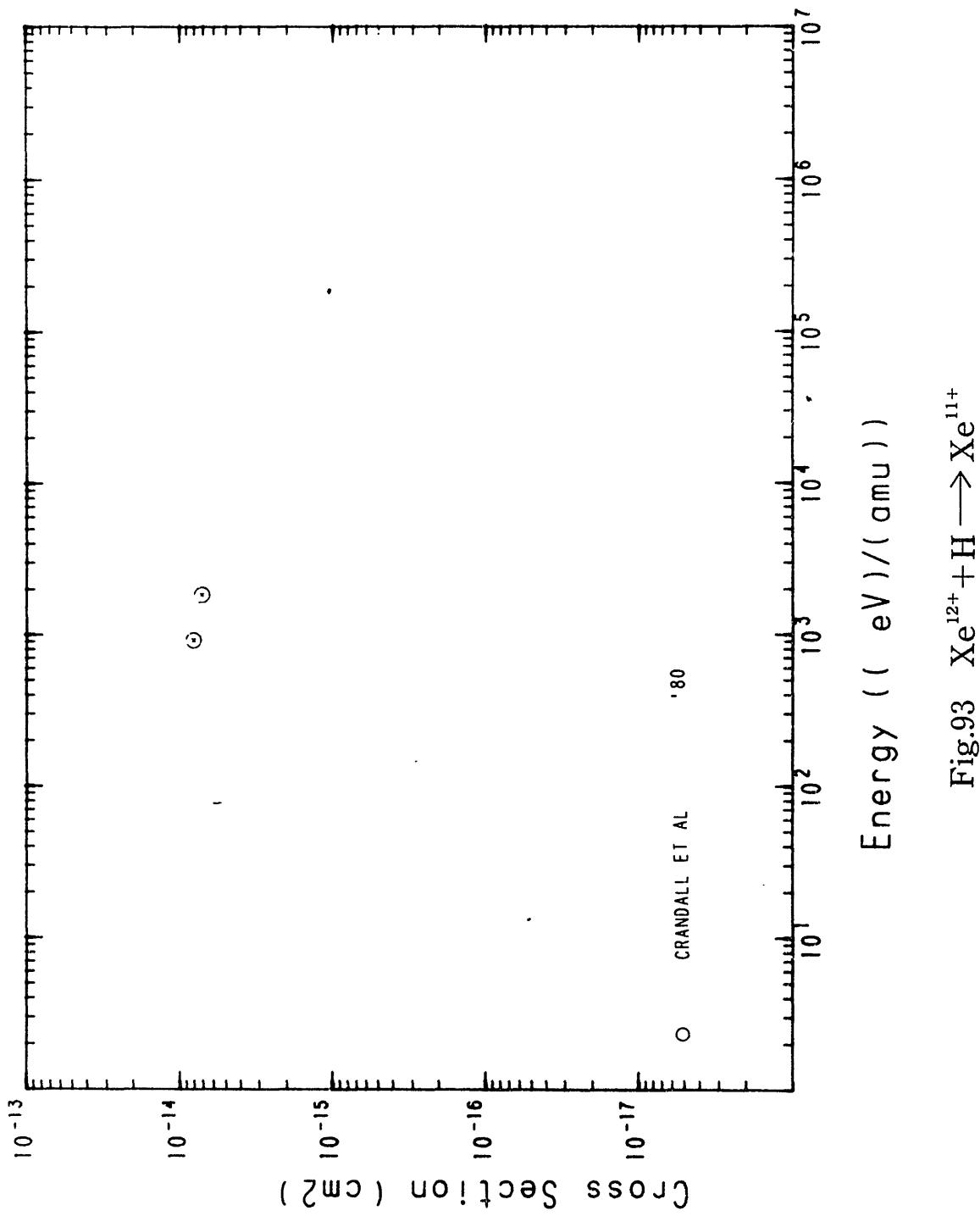


Fig.93 $\text{Xe}^{12+} + \text{H} \rightarrow \text{Xe}^{11+}$

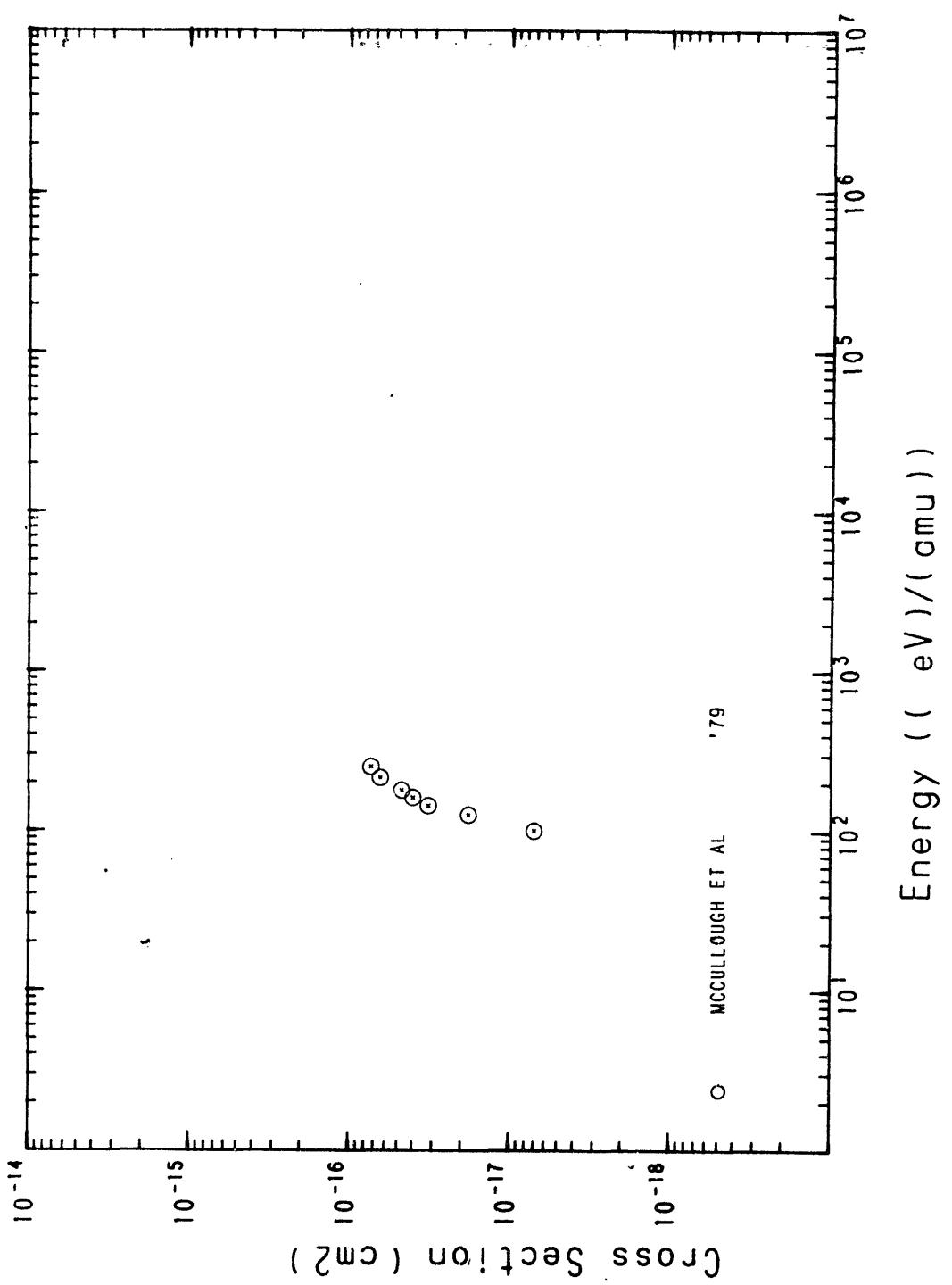


Fig.94 $\text{Ba}^+ + \text{H} \rightarrow \text{Ba}^+$

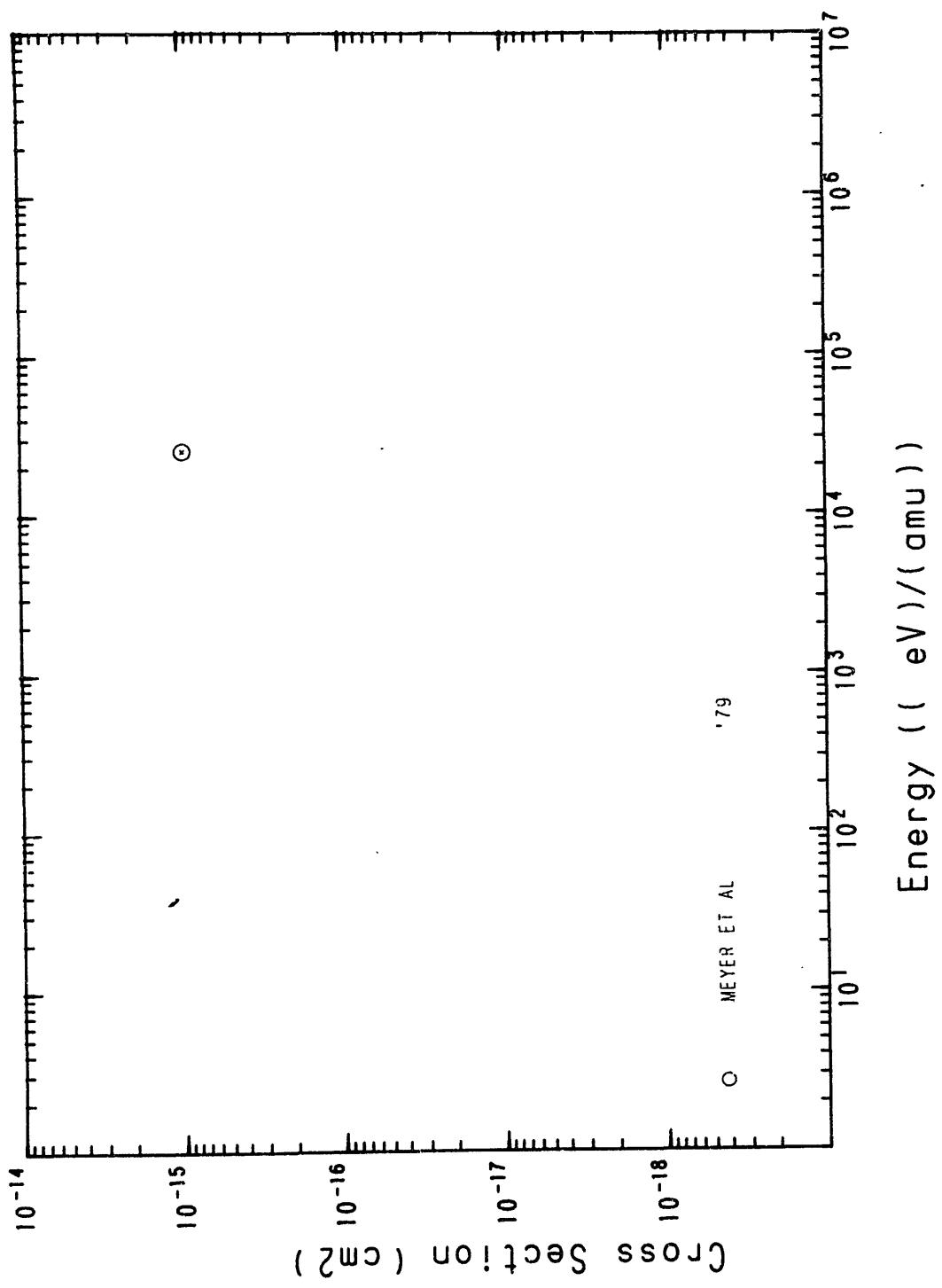


Fig.95 $\text{Ta}^{3+} + \text{H} \longrightarrow \text{Ta}^{2+}$

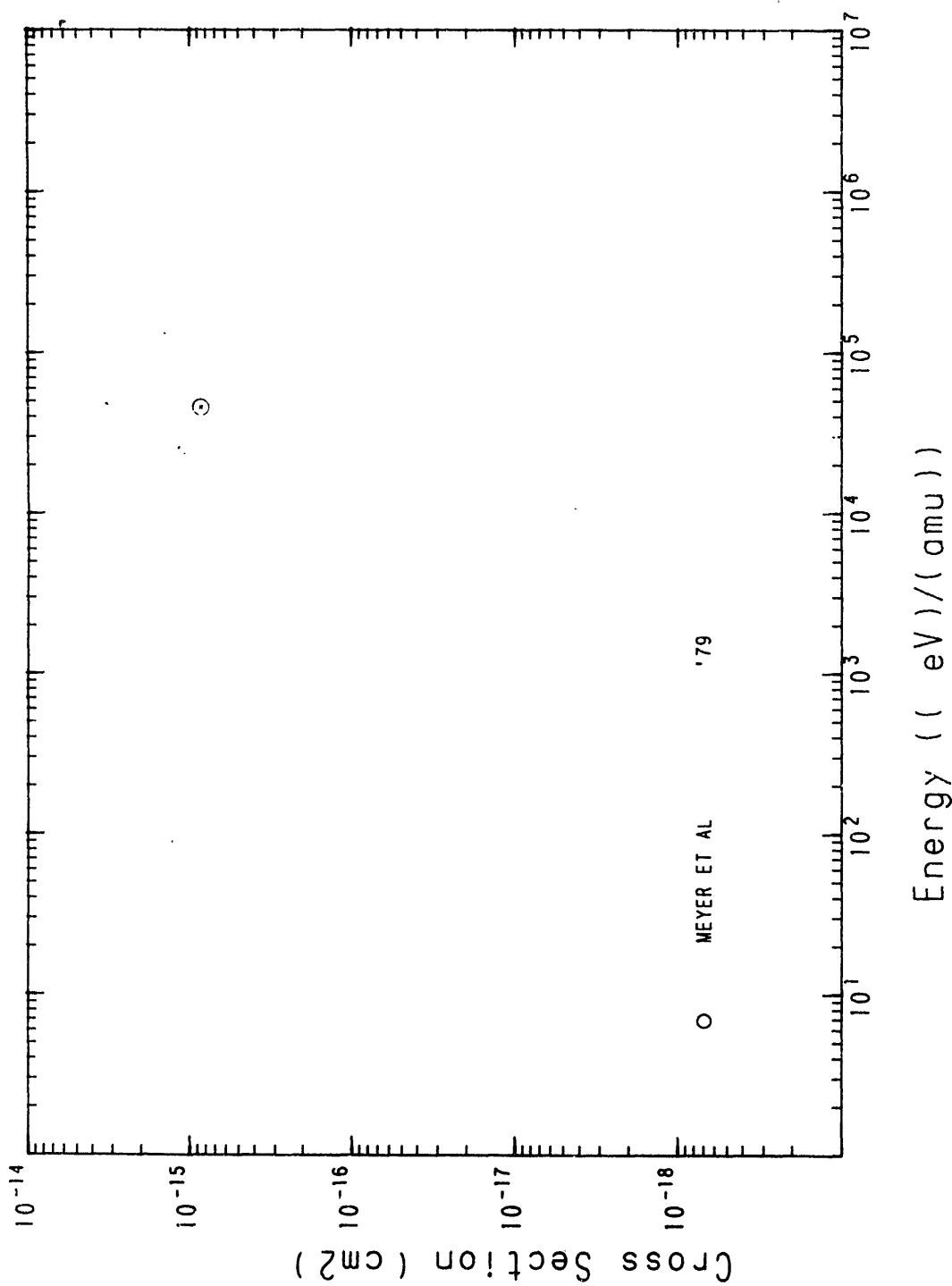


Fig.96 $\text{Ta}^{4+} + \text{H} \rightarrow \text{Ta}^{3+}$

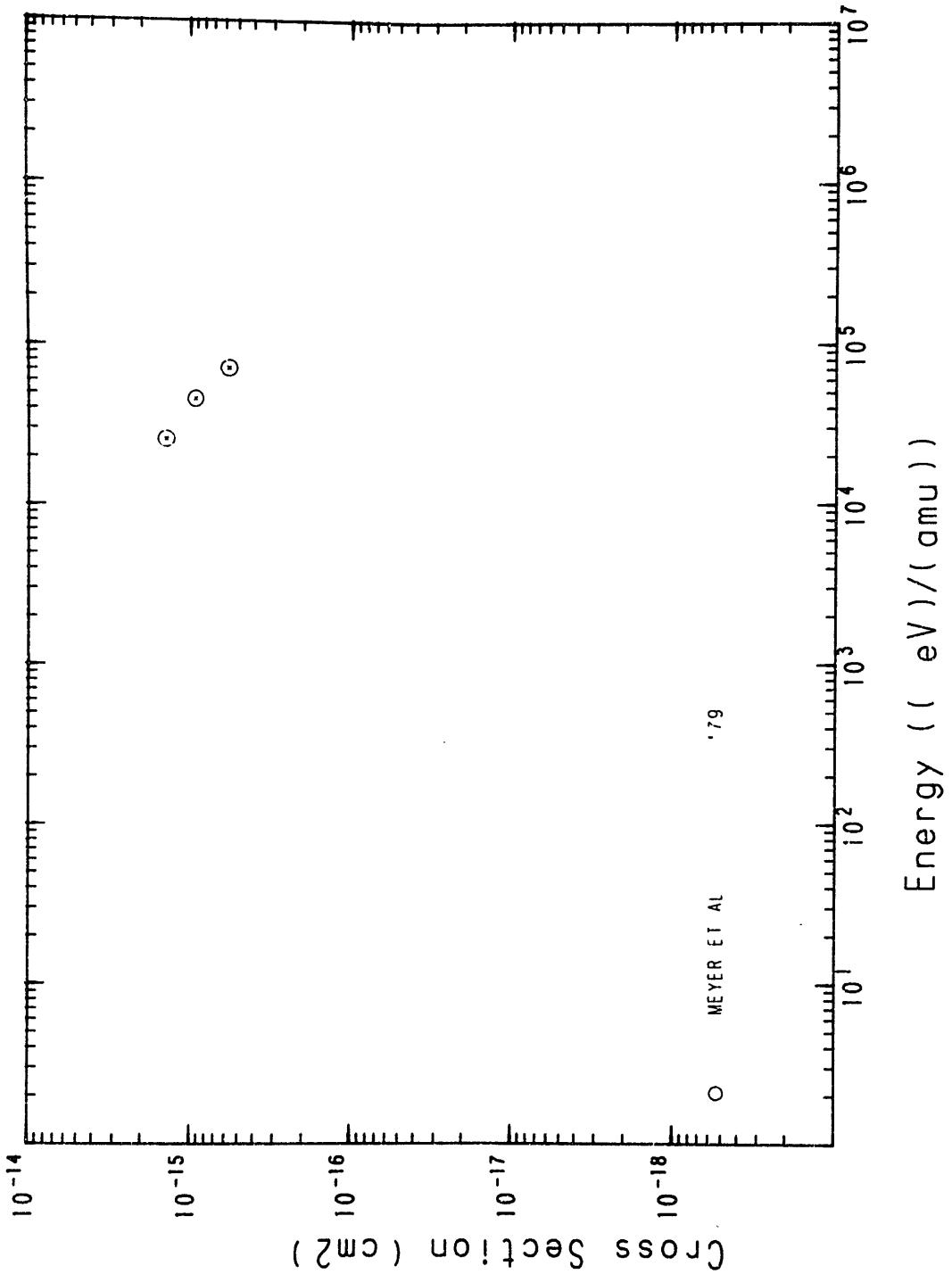


Fig.97 $\text{Ta}^{5+} + \text{H} \longrightarrow \text{Ta}^{4+}$

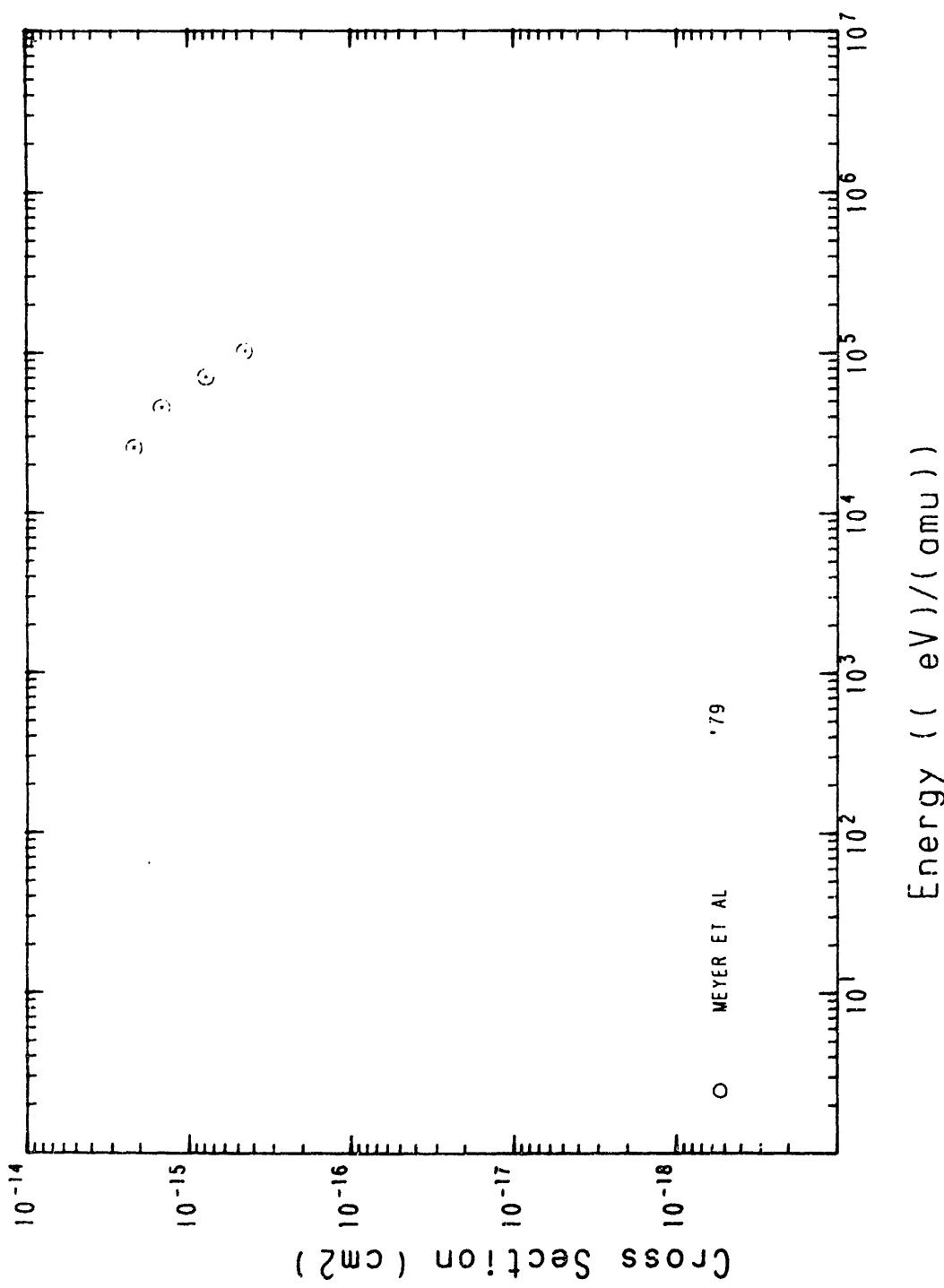


Fig.98 $\text{Ta}^{6+} + \text{H} \rightarrow \text{Ta}^{5+}$

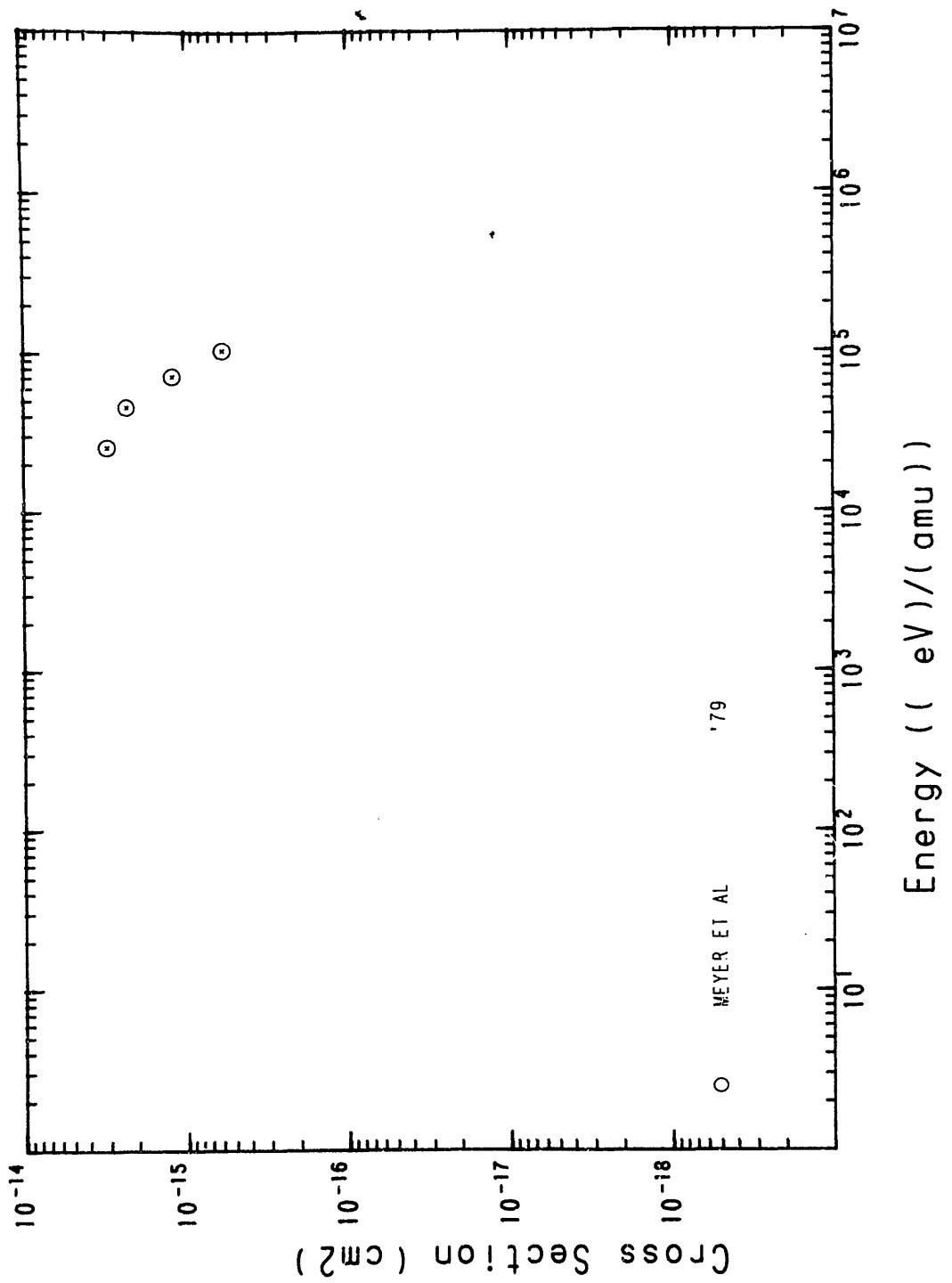


Fig.99 $\text{Ta}^{7+} + \text{H} \rightarrow \text{Ta}^{6+}$

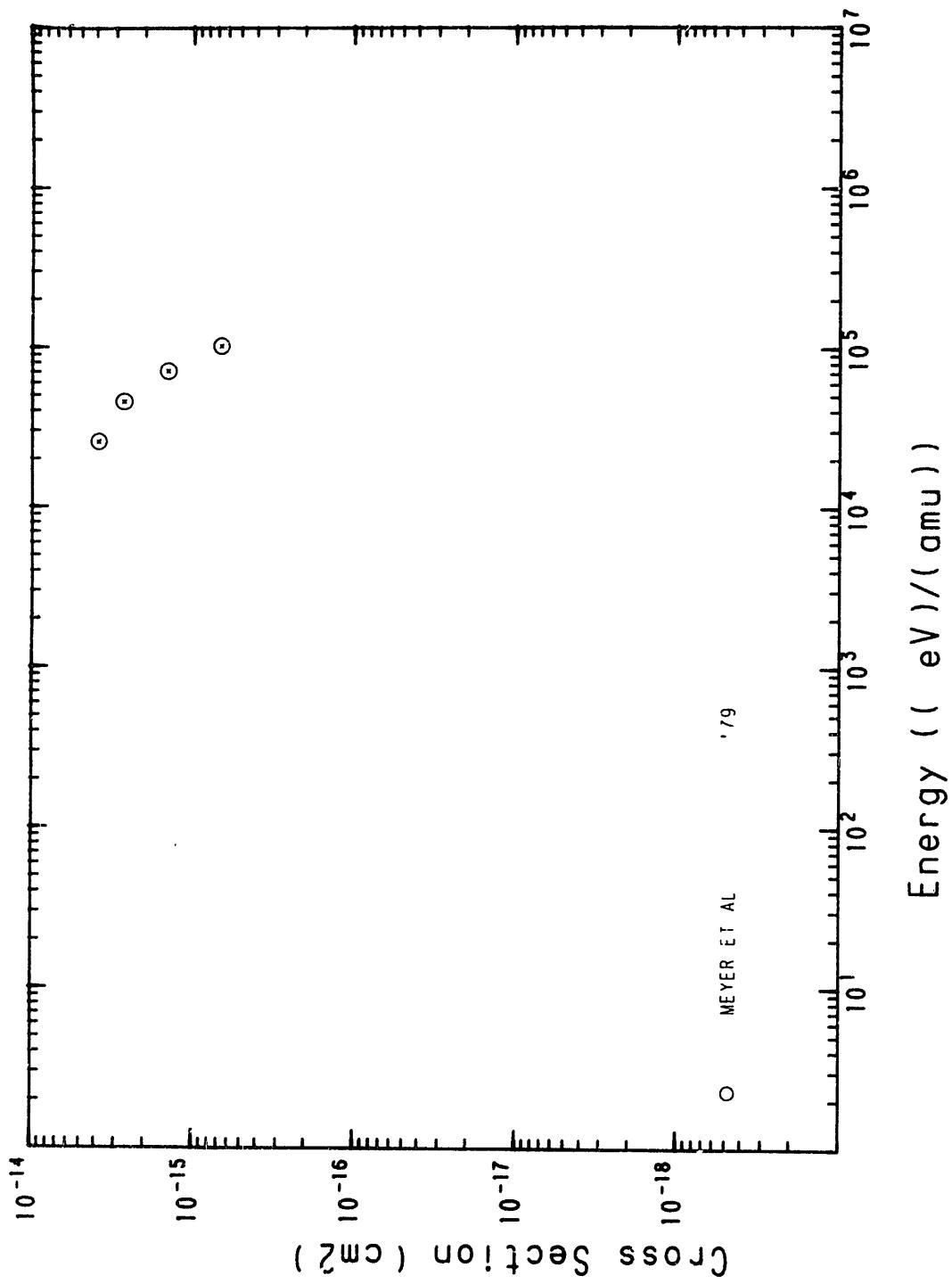


Fig.100 $\text{Ta}^{8+} + \text{H} \longrightarrow \text{Ta}^{7+}$

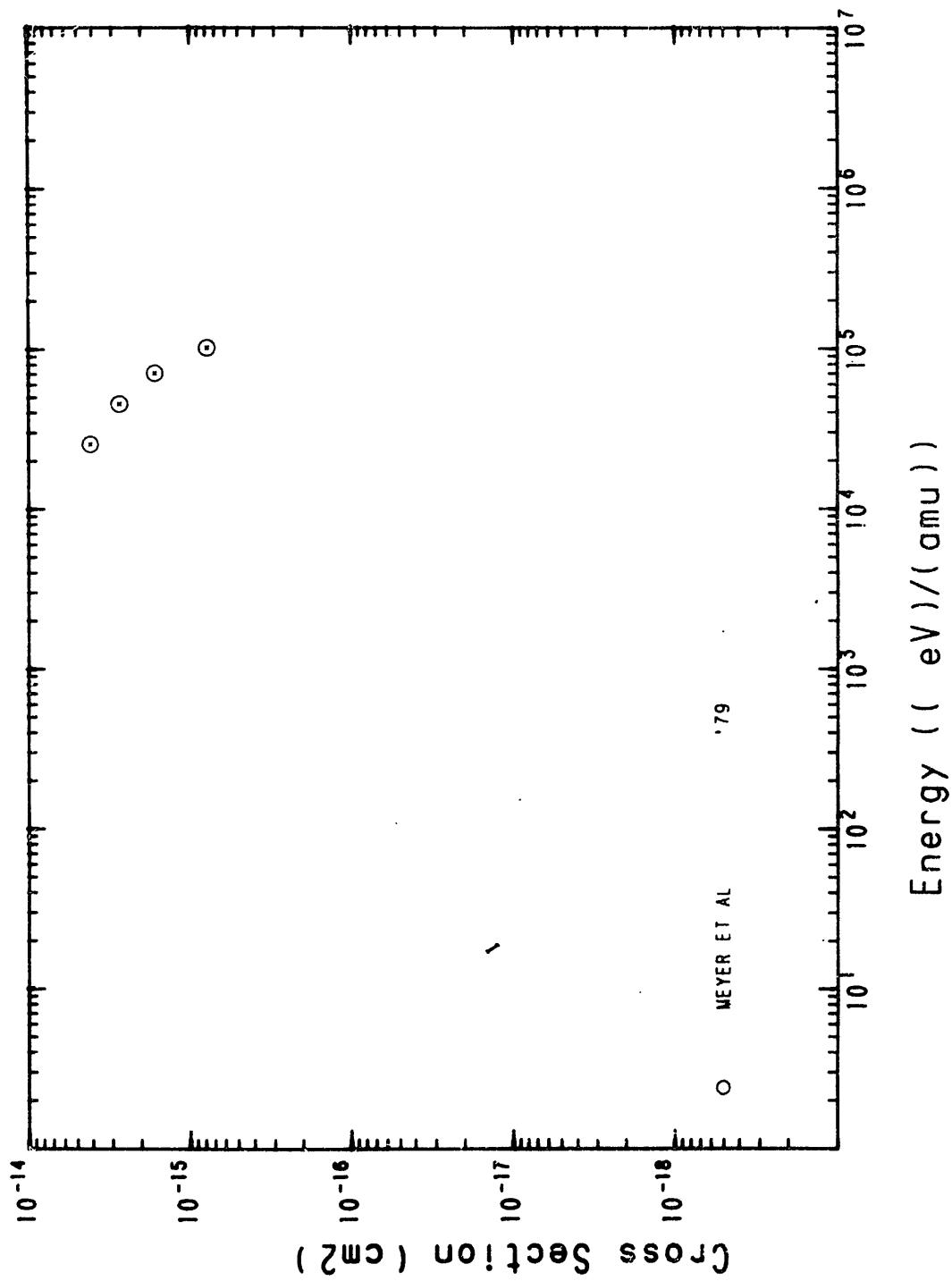


Fig.101 $\text{Ta}^{9+} + \text{H} \rightarrow \text{Ta}^{8+}$

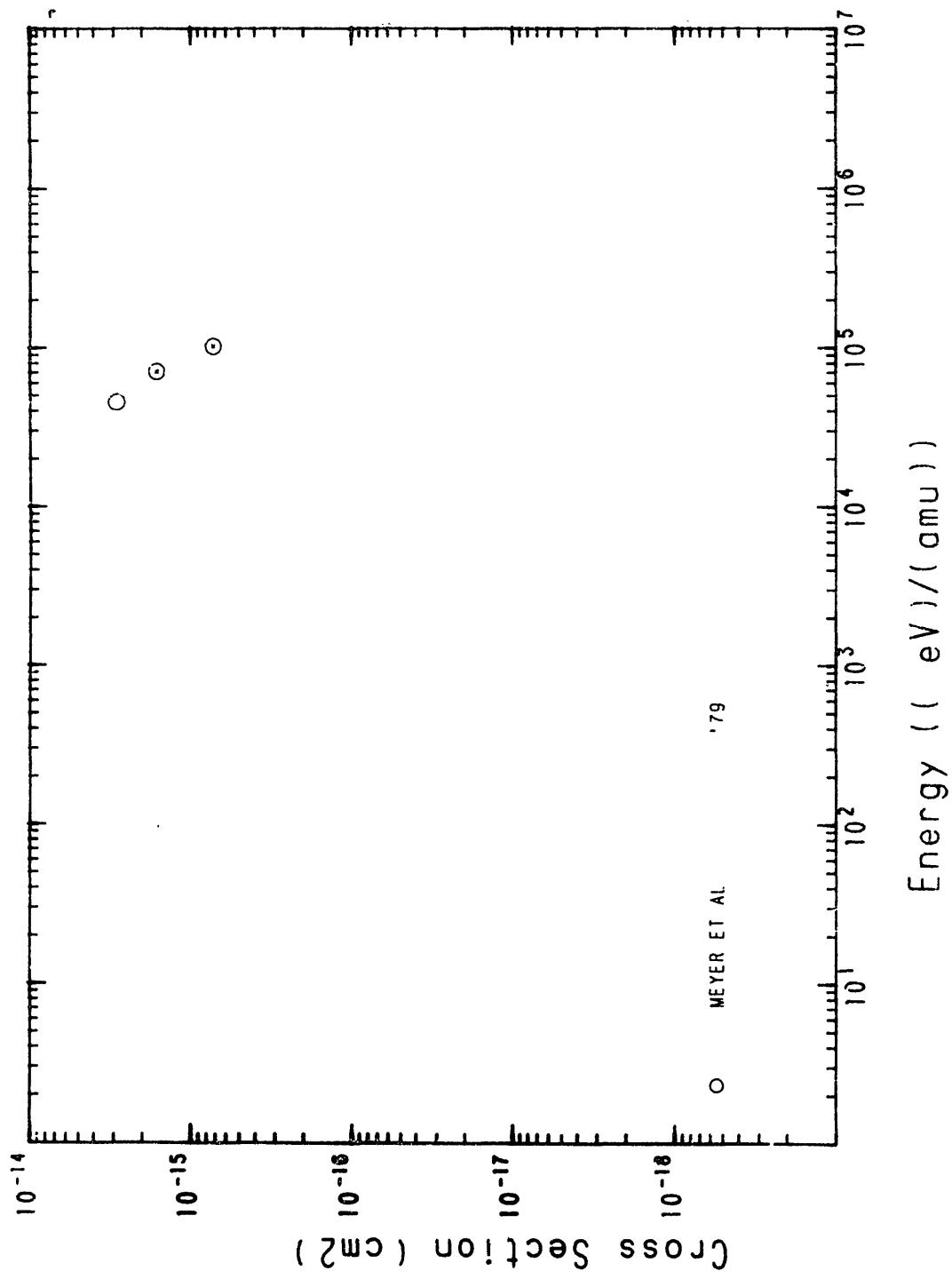


Fig.102 $\text{Ta}^{10+} + \text{H} \longrightarrow \text{Ta}^{9+}$

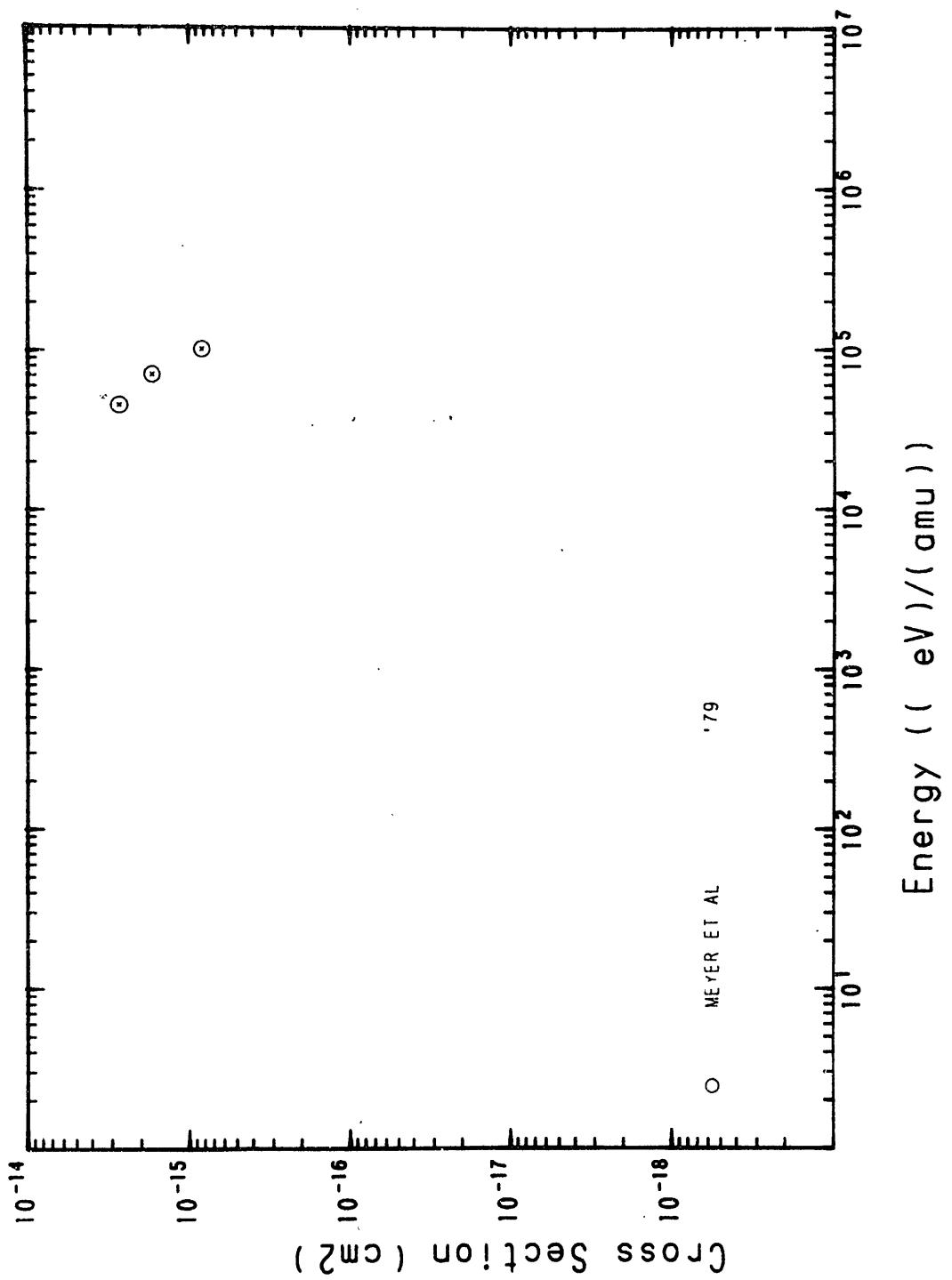


Fig.103 $\text{Ta}^{11+} + \text{H} \longrightarrow \text{Ta}^{10+}$

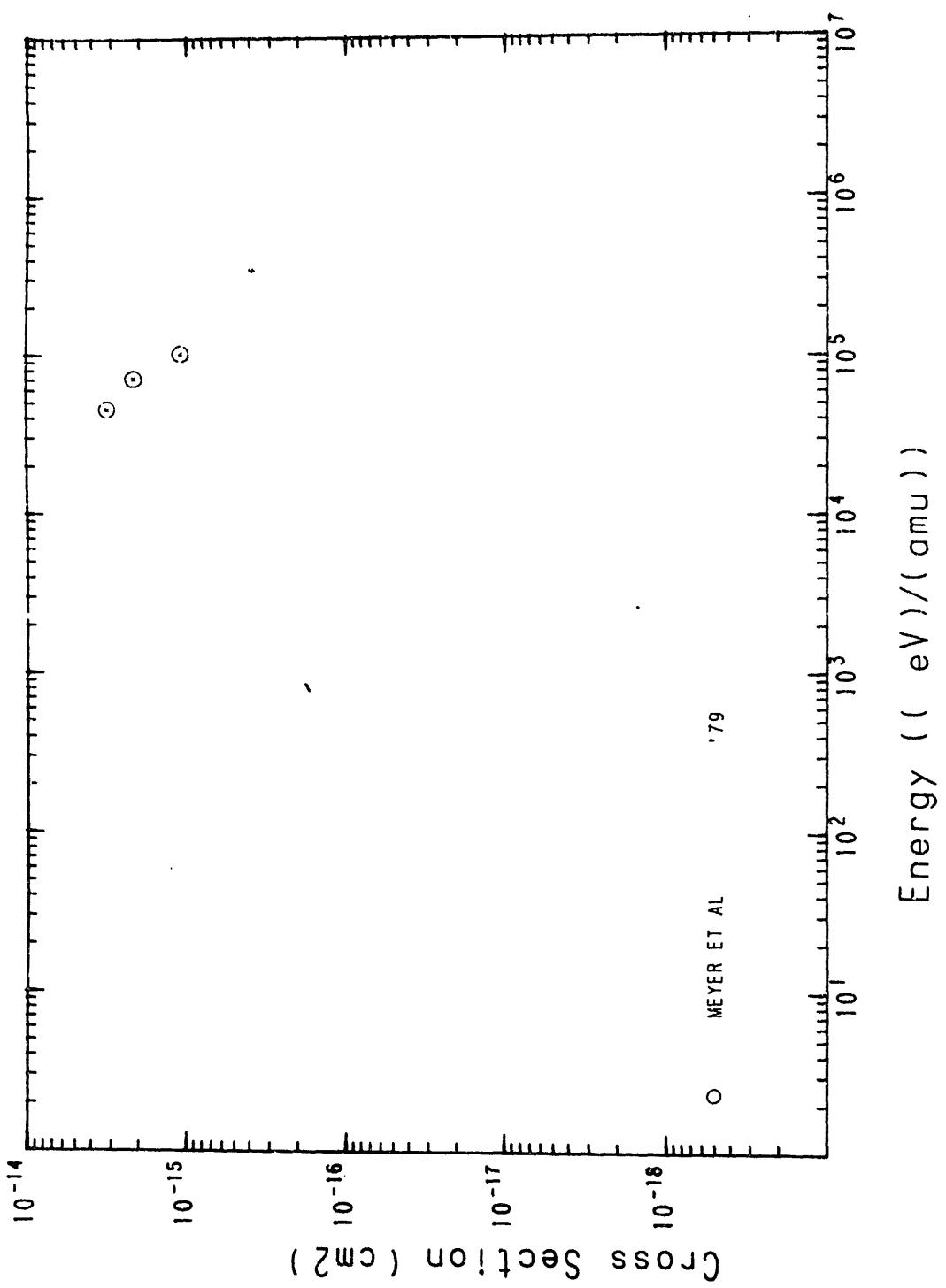


Fig.104 $\text{Ta}^{12+} + \text{H} \rightarrow \text{Ta}^{11+}$

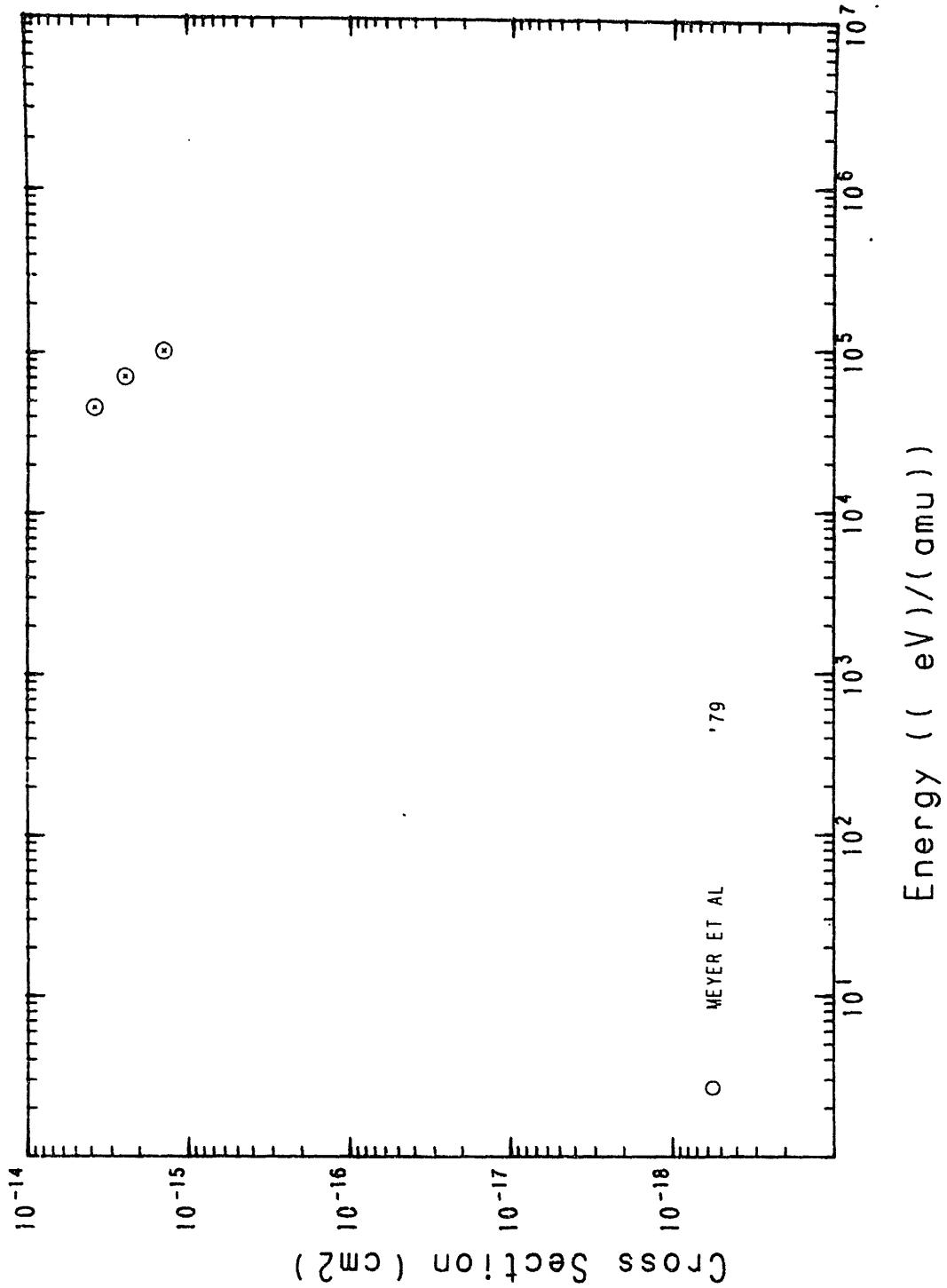


Fig.105 $\text{Ta}^{13+} + \text{H} \rightarrow \text{Ta}^{12+}$

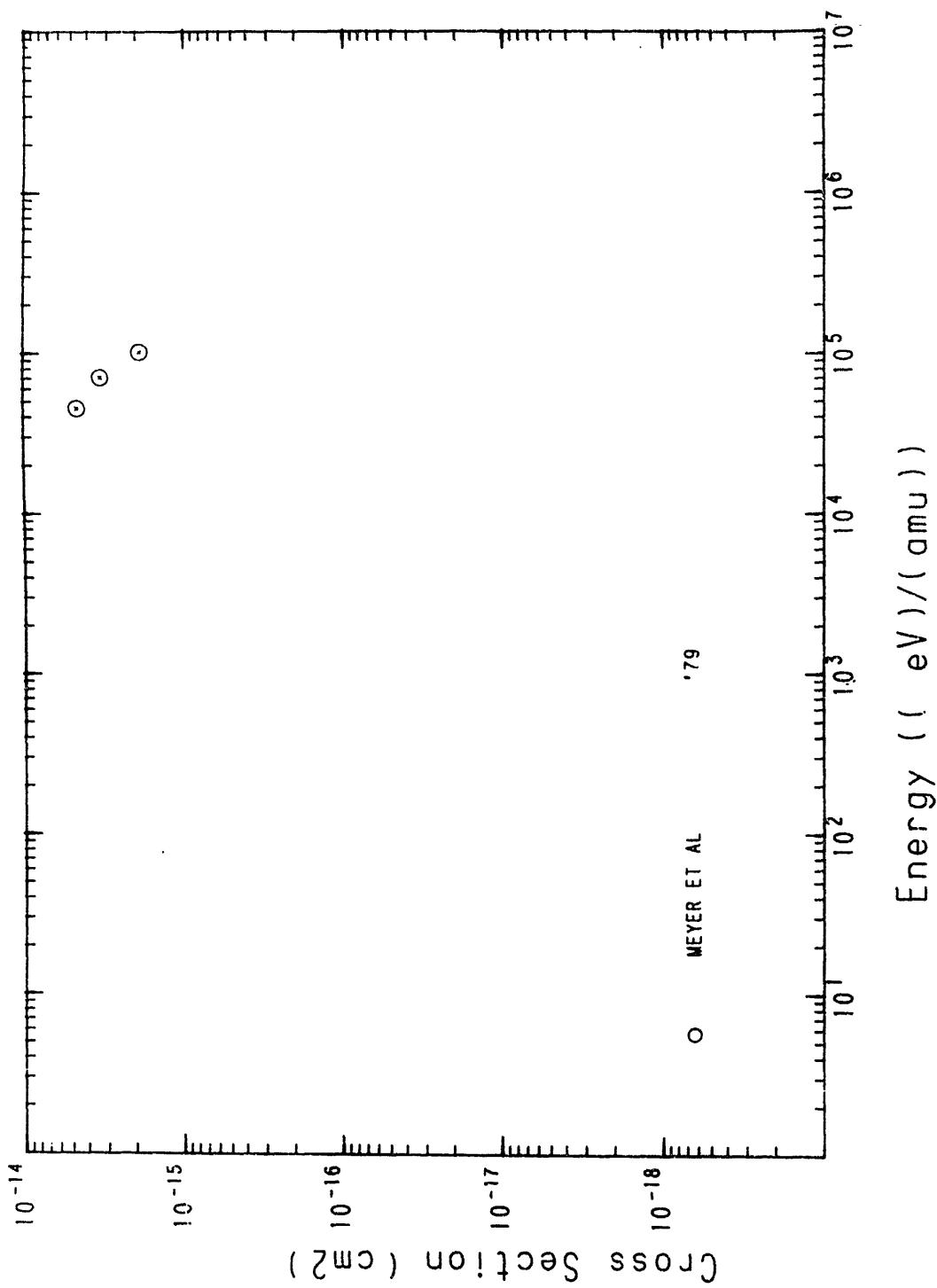


Fig.106 $\text{Ta}^{14+} + \text{H} \rightarrow \text{Ta}^{13+}$

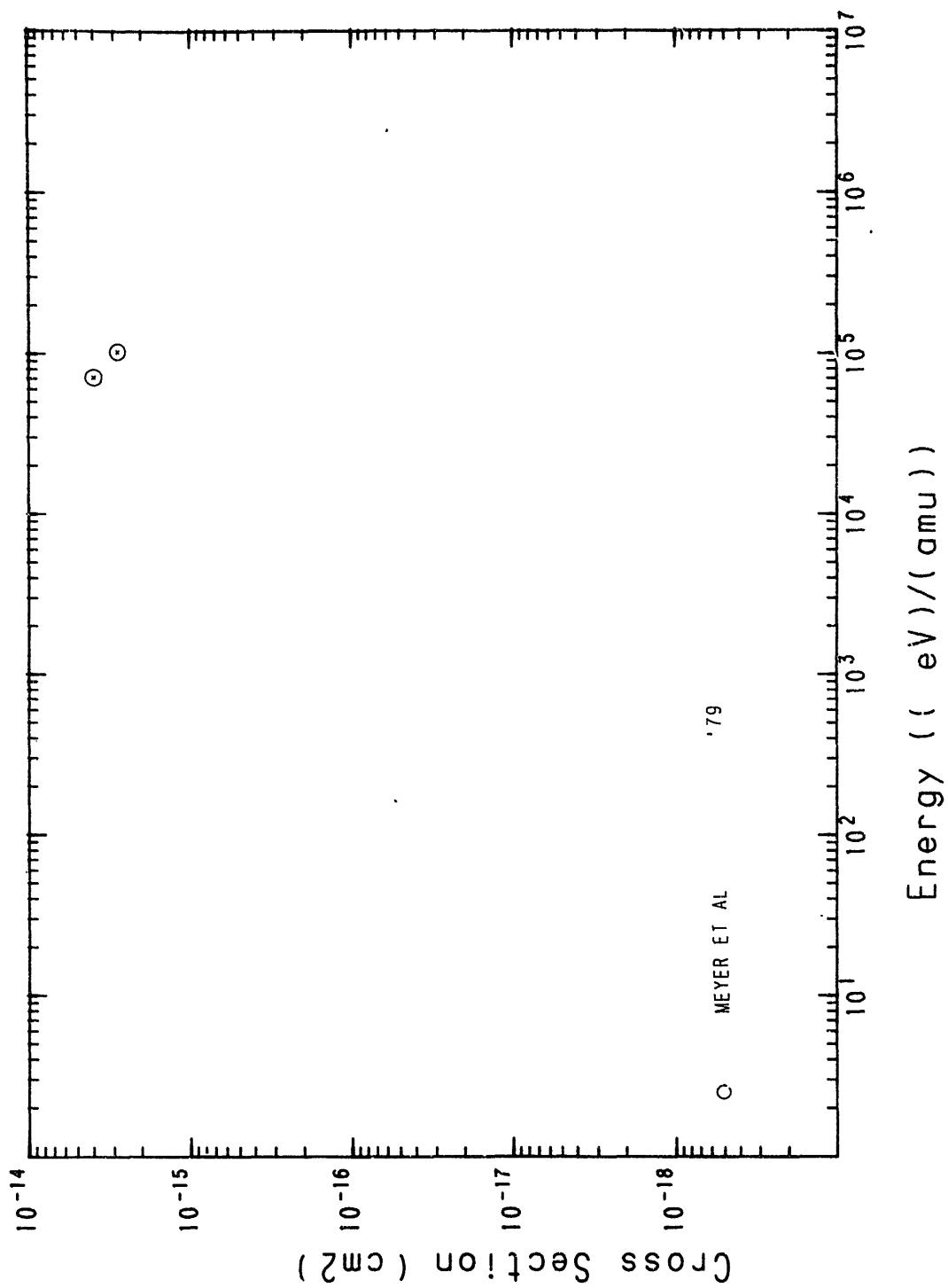


Fig.107 $\text{Ta}^{15+} + \text{H} \rightarrow \text{Ta}^{14+}$

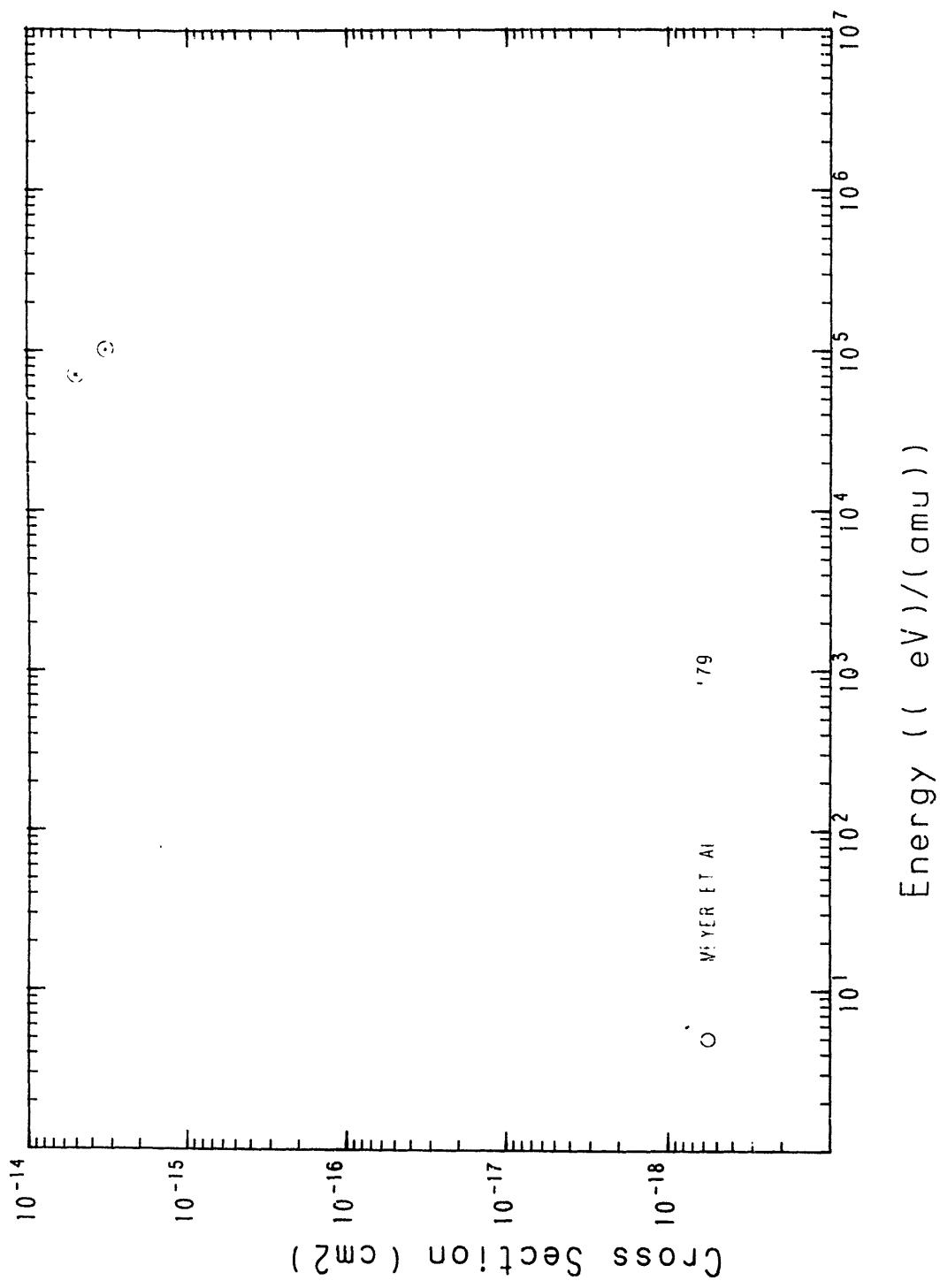


Fig.108 $\text{Ta}^{16+} + \text{H} \rightarrow \text{Ta}^{15+}$

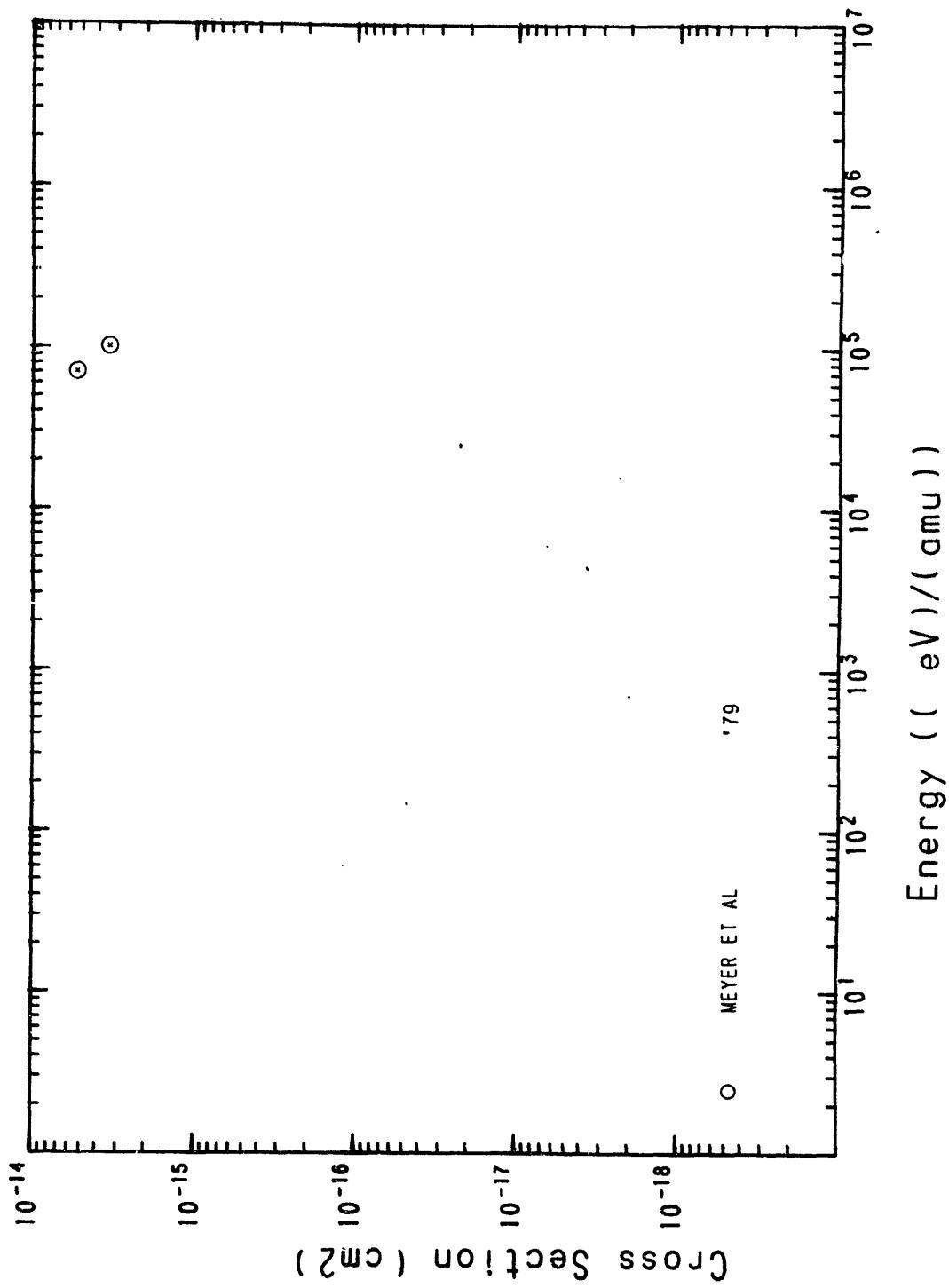


Fig.109 $\text{Ta}^{17+} + \text{H} \longrightarrow \text{Ta}^{16+}$

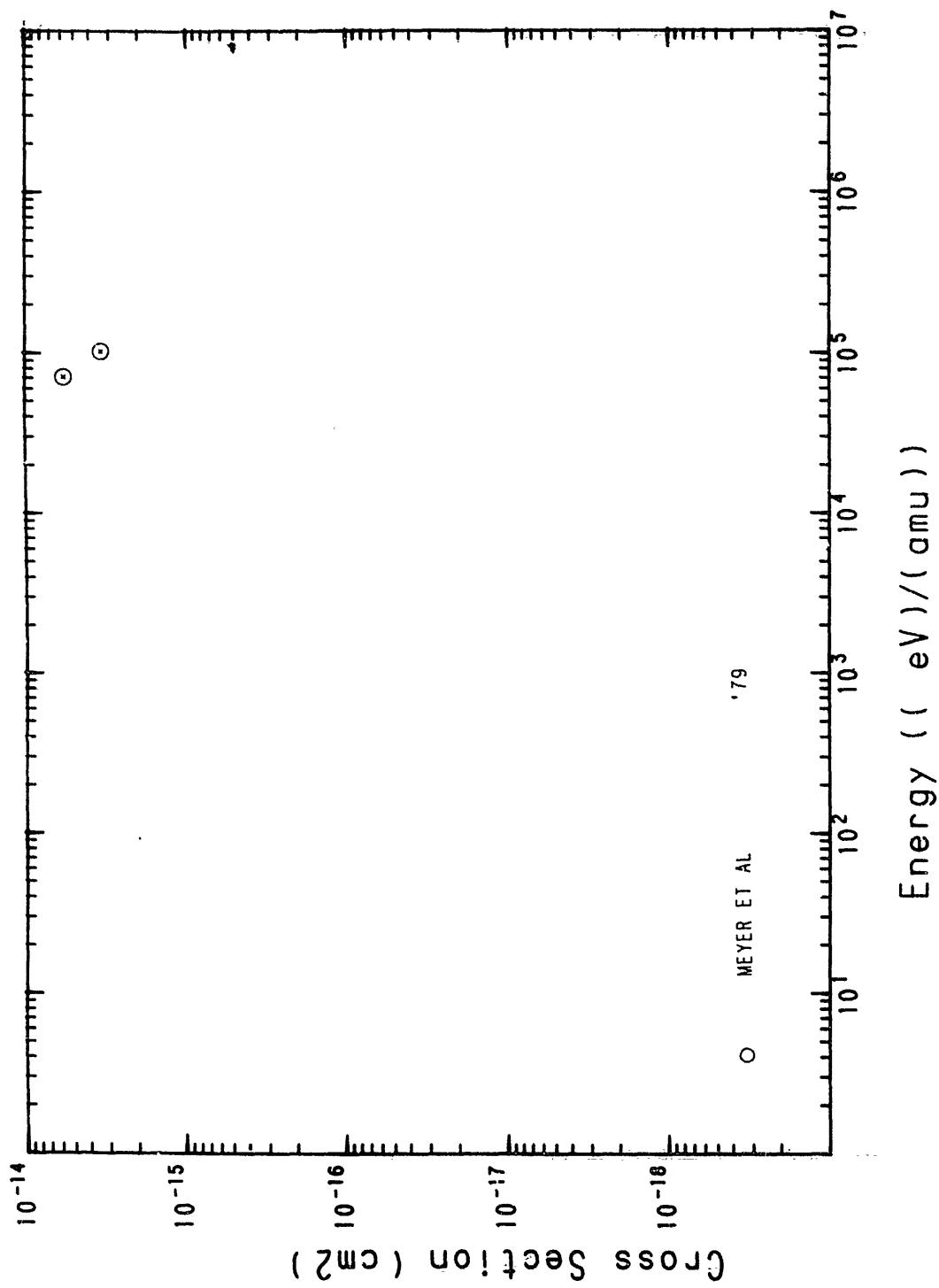


Fig.110 $Ta^{18+} + H \longrightarrow Ta^{17+}$

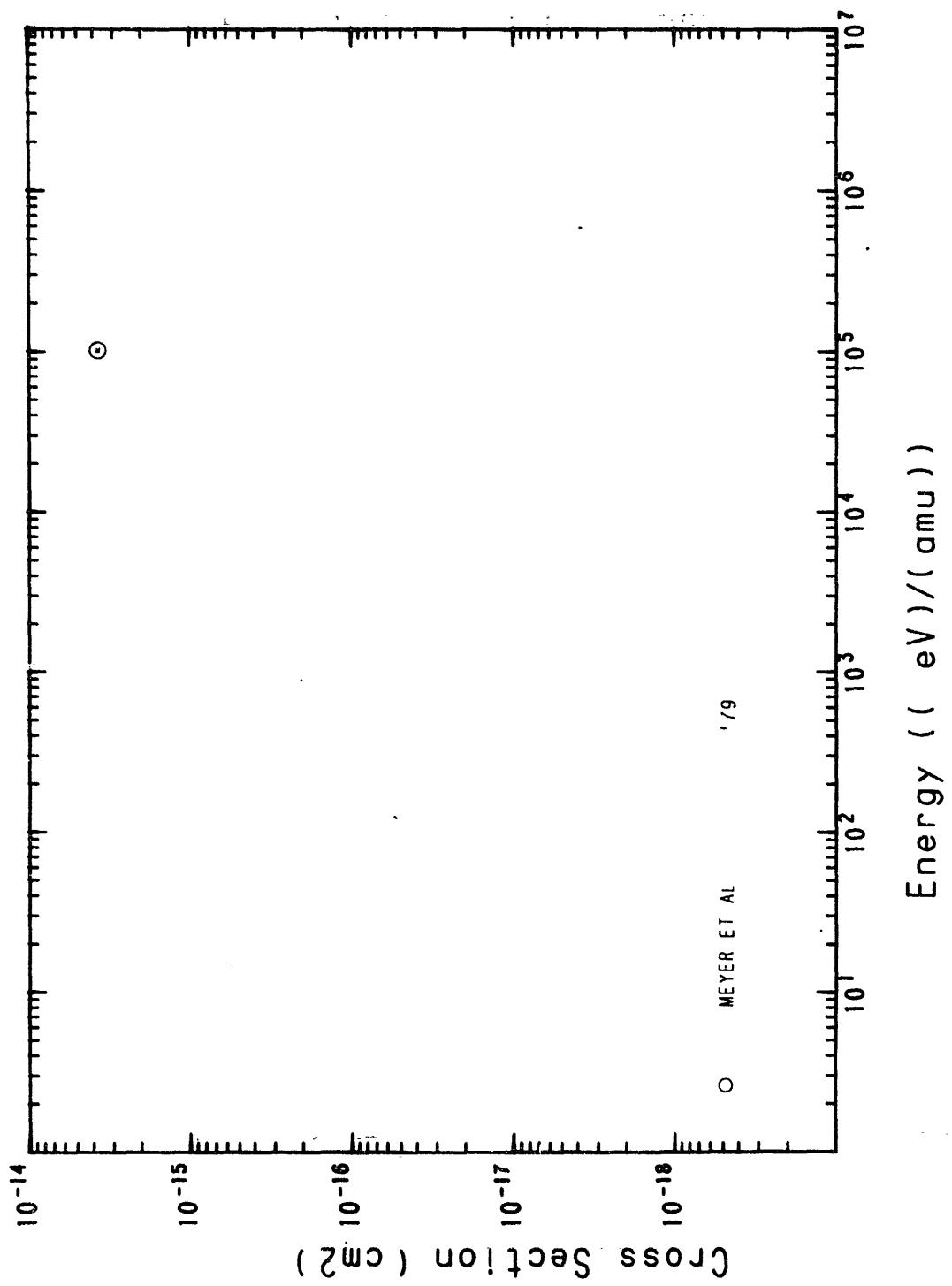


Fig.111 $Ta^{19+} + H \rightarrow Ta^{18+}$

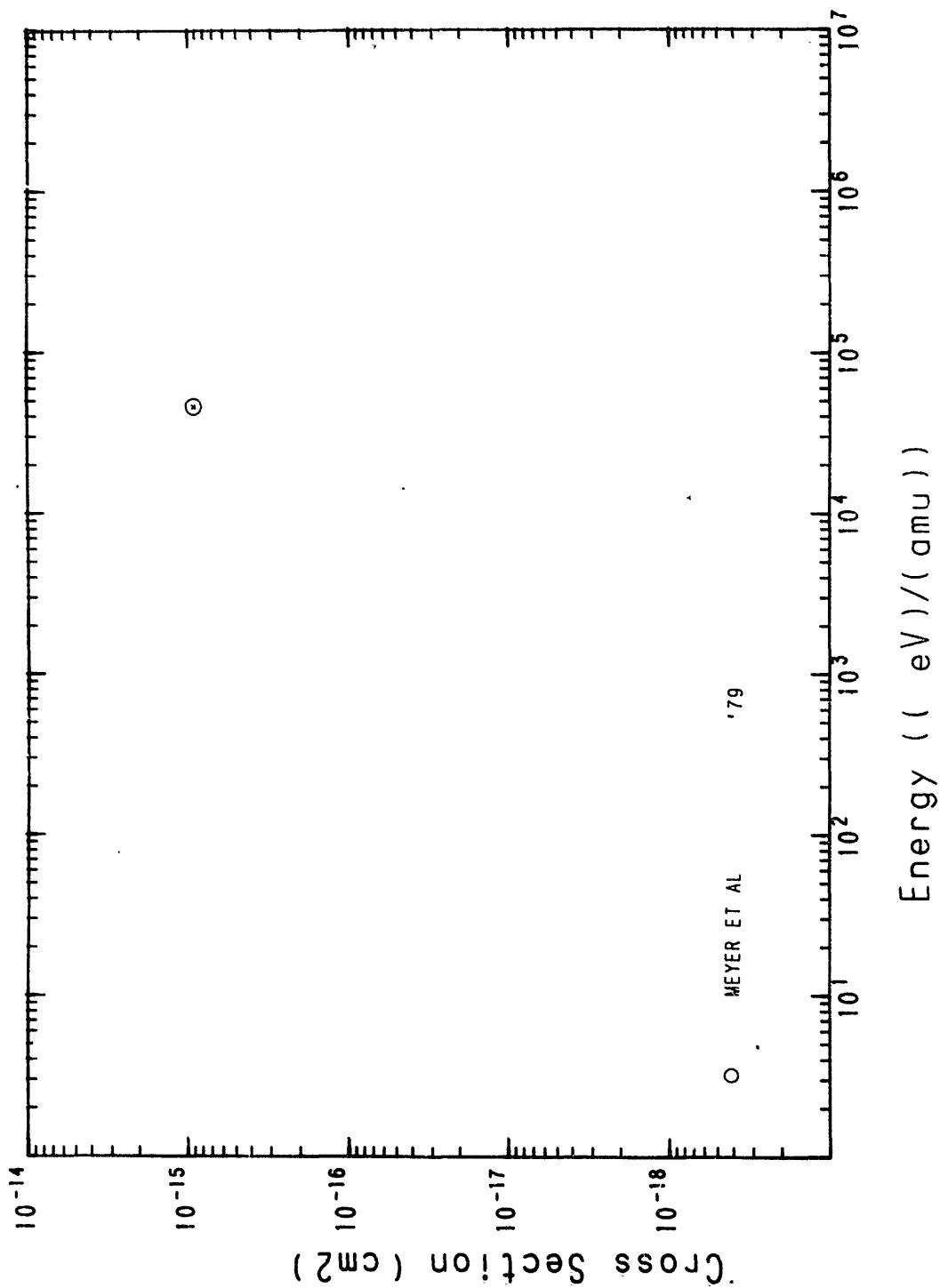


Fig.112 $W^{4+} + H \longrightarrow W^{3+}$

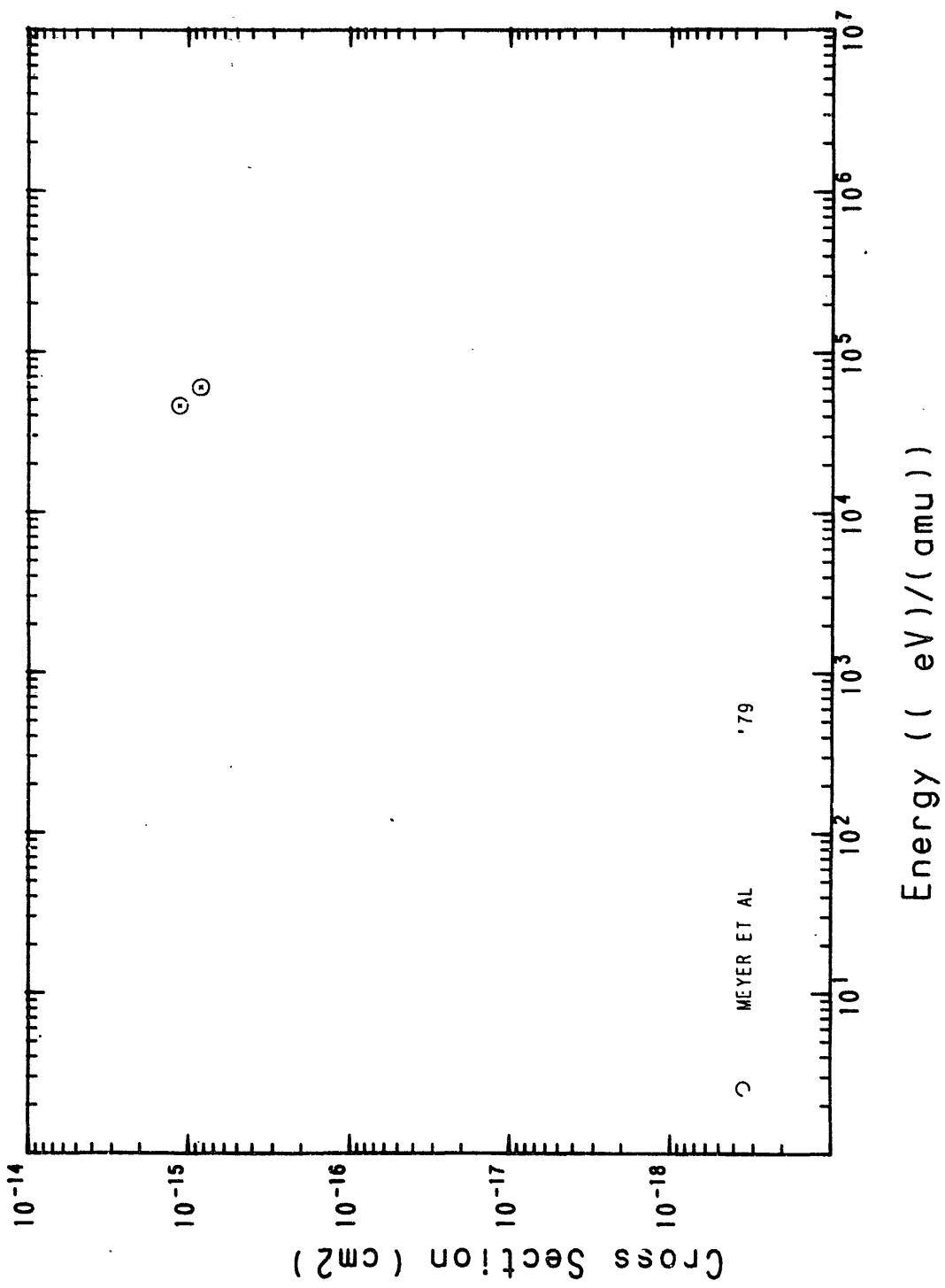


Fig.113 $\text{W}^{5+} + \text{H} \rightarrow \text{W}^{4+}$

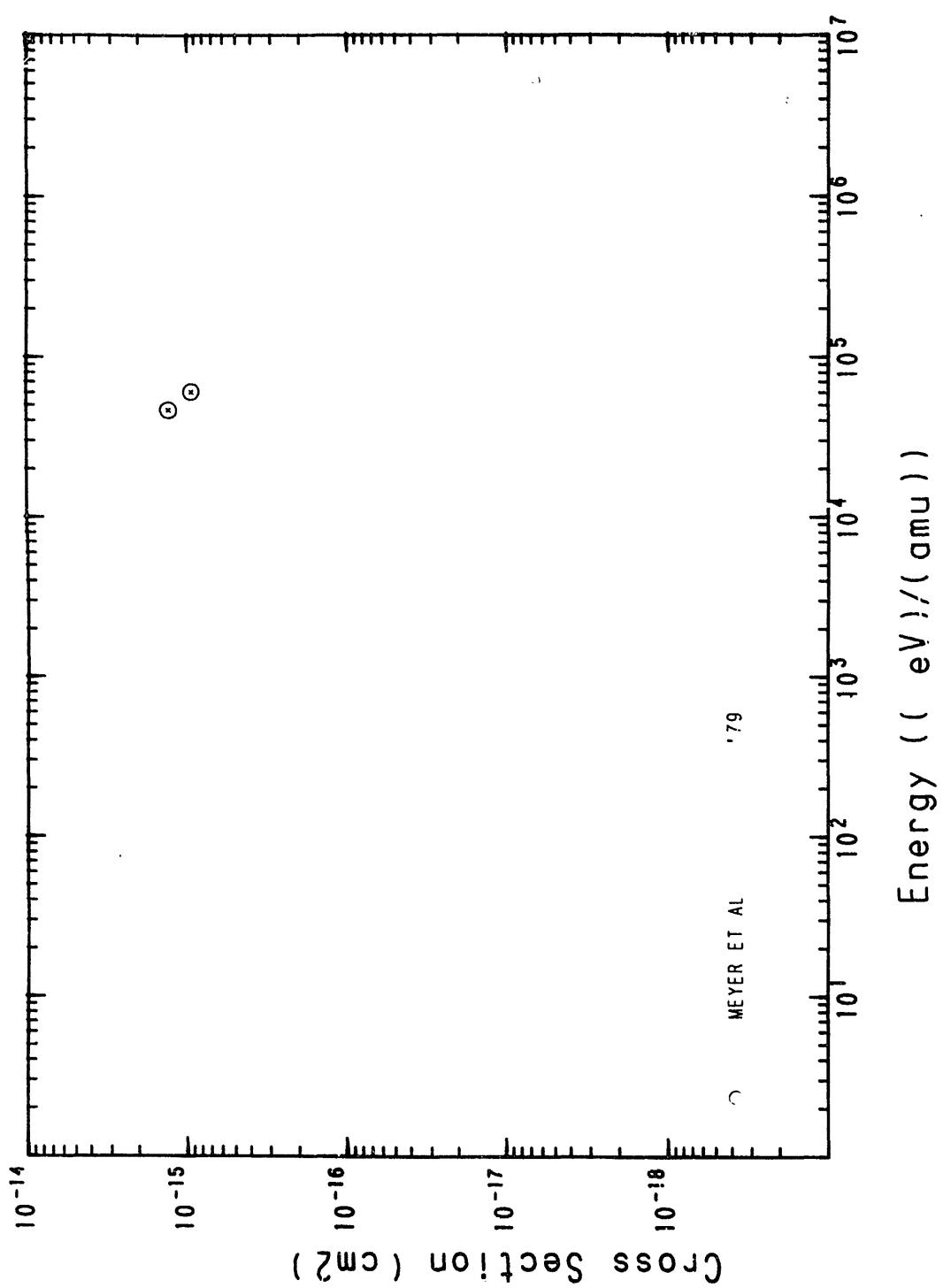


Fig.114 $\text{W}^{6+} + \text{H} \longrightarrow \text{W}^{5+}$

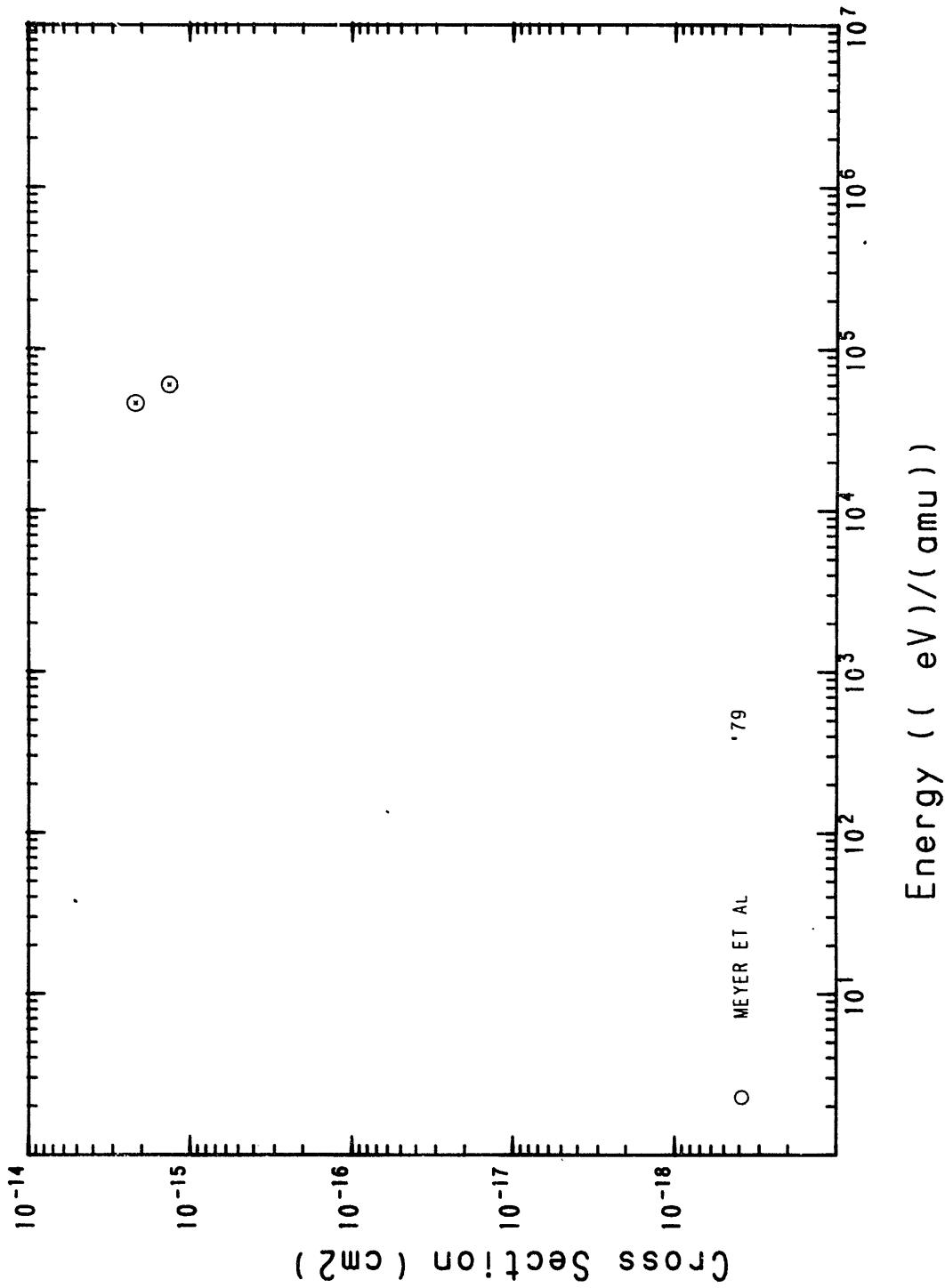


Fig.115 $\text{W}^{7+} + \text{H} \longrightarrow \text{W}^{6+}$

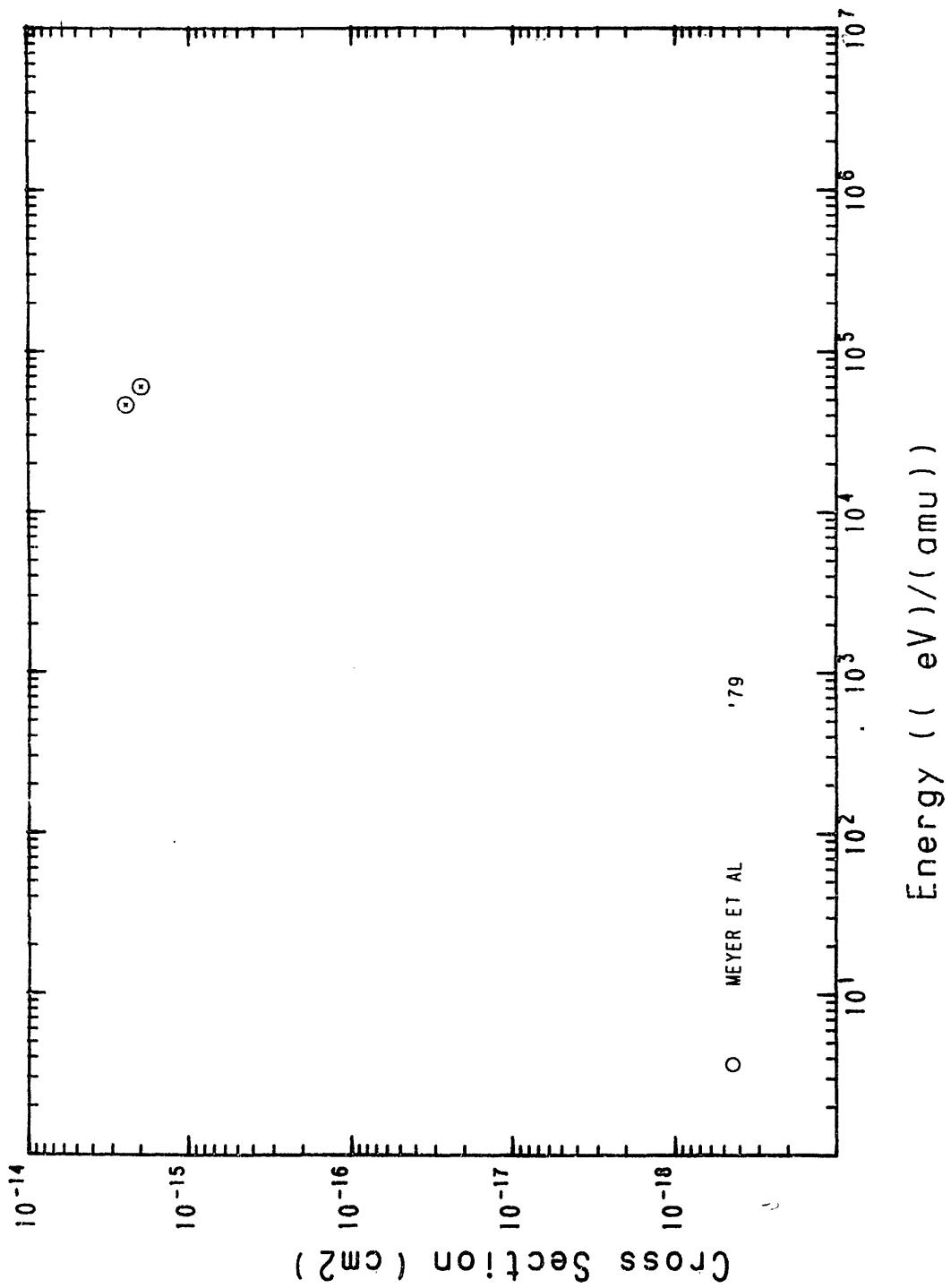


Fig.116 $W^{8+} + H \rightarrow W^{7+}$

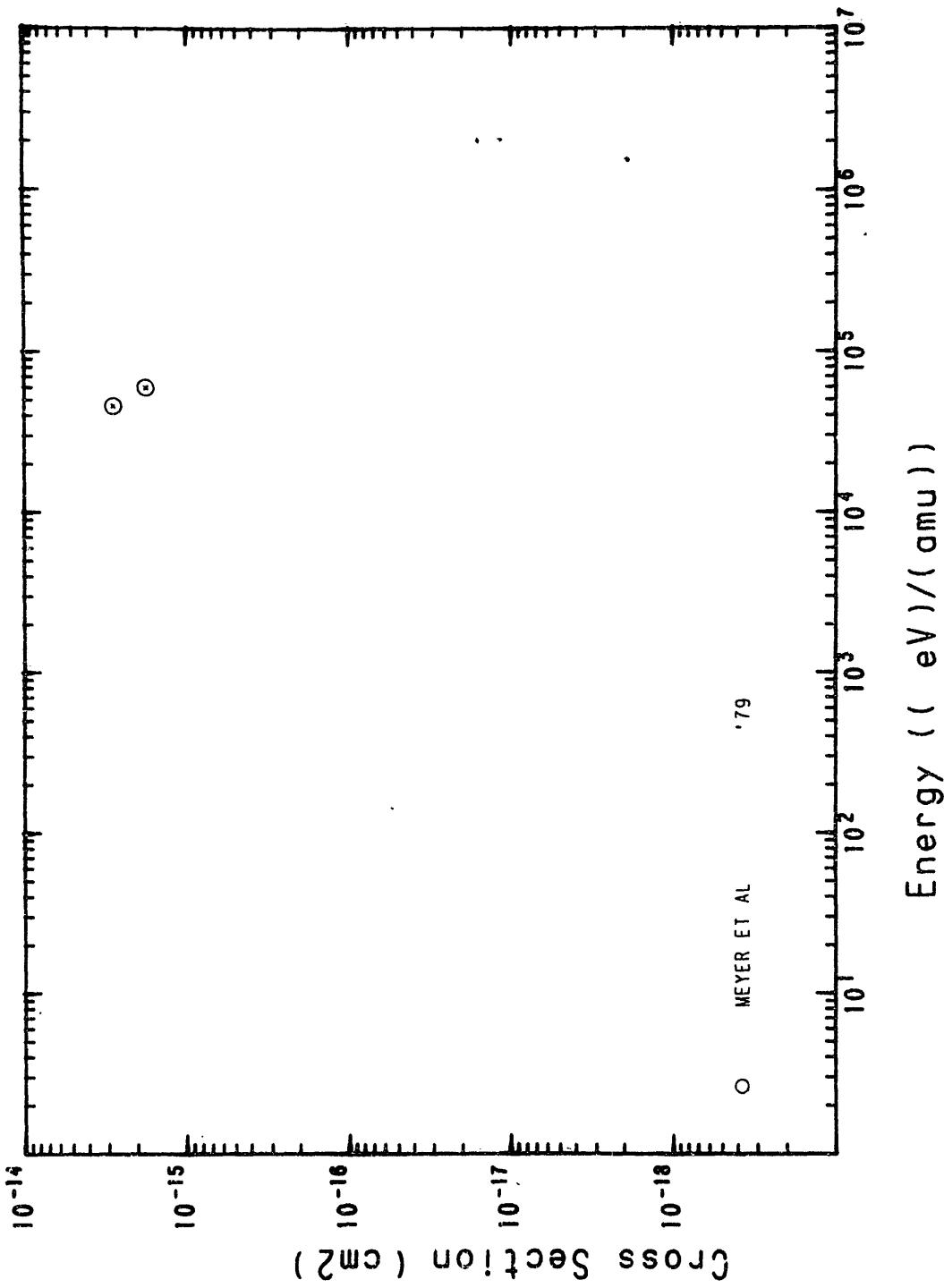


Fig.117 $\text{W}^{9+} + \text{H} \rightarrow \text{W}^{8+}$

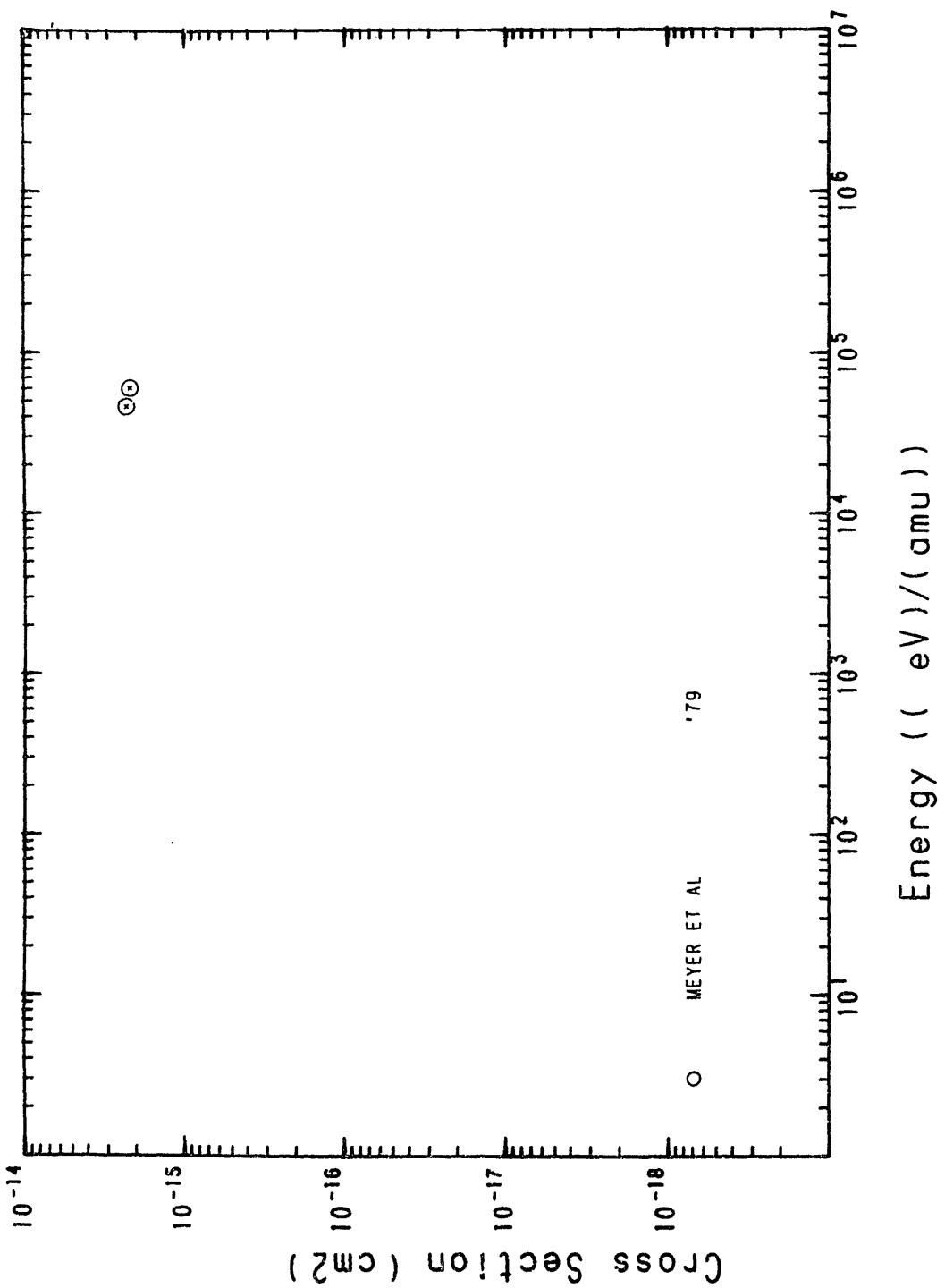
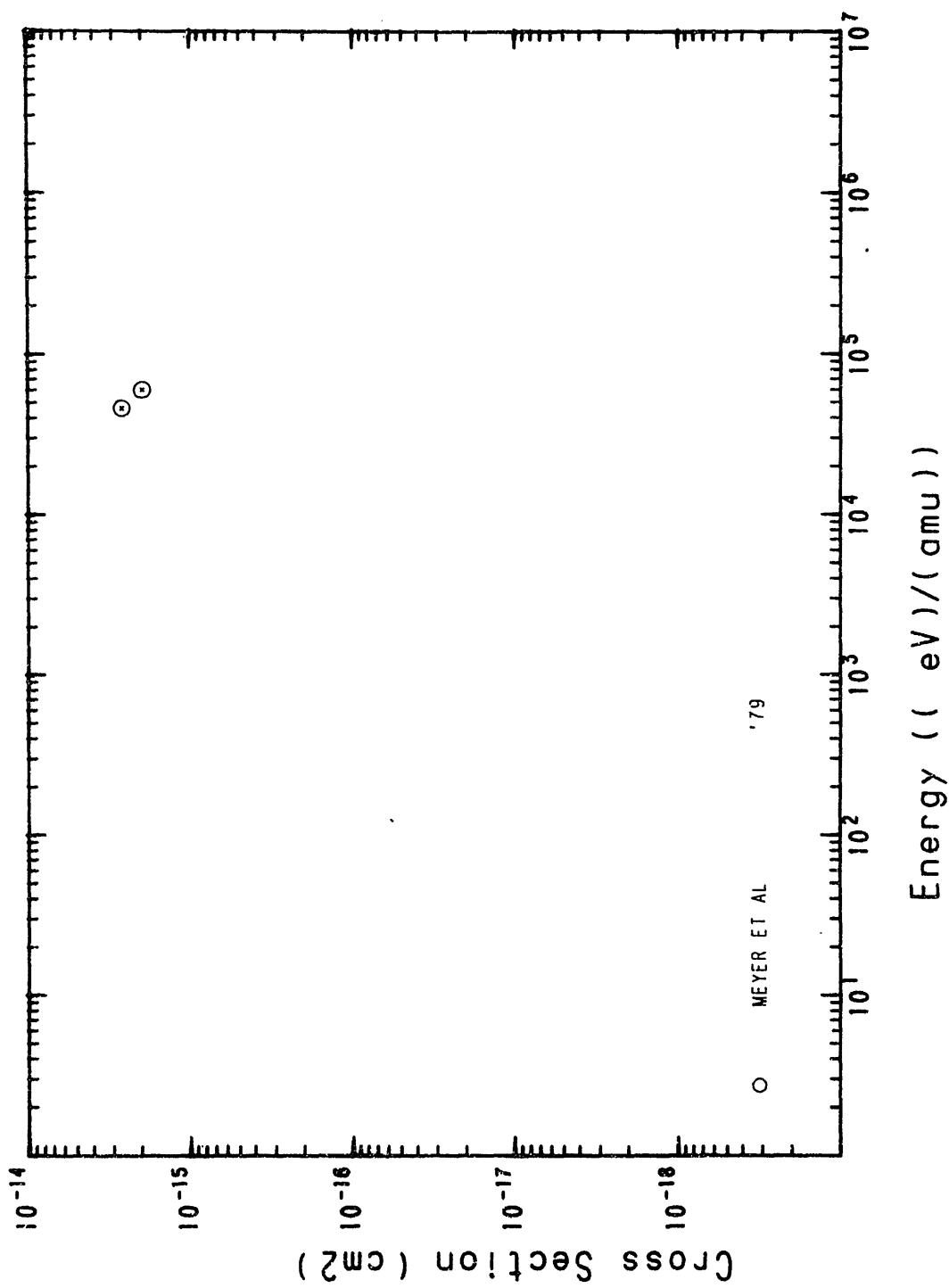


Fig.118 $\text{W}^{10+} + \text{H} \rightarrow \text{W}^{9+}$

Fig.119 $W^{11+} + H \rightarrow W^{10+}$



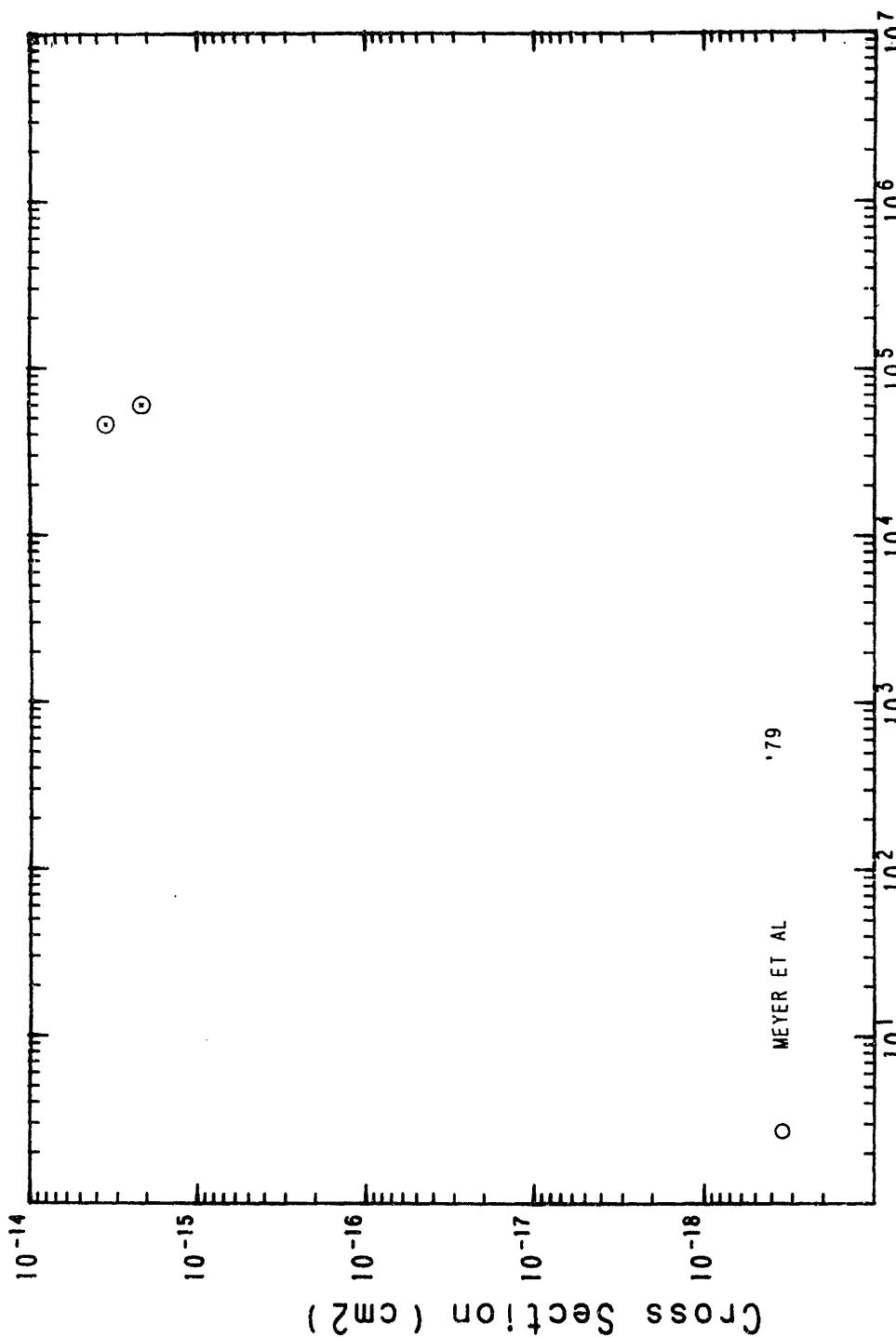


Fig.120 $\text{W}^{12+} + \text{H} \rightarrow \text{W}^{11+}$

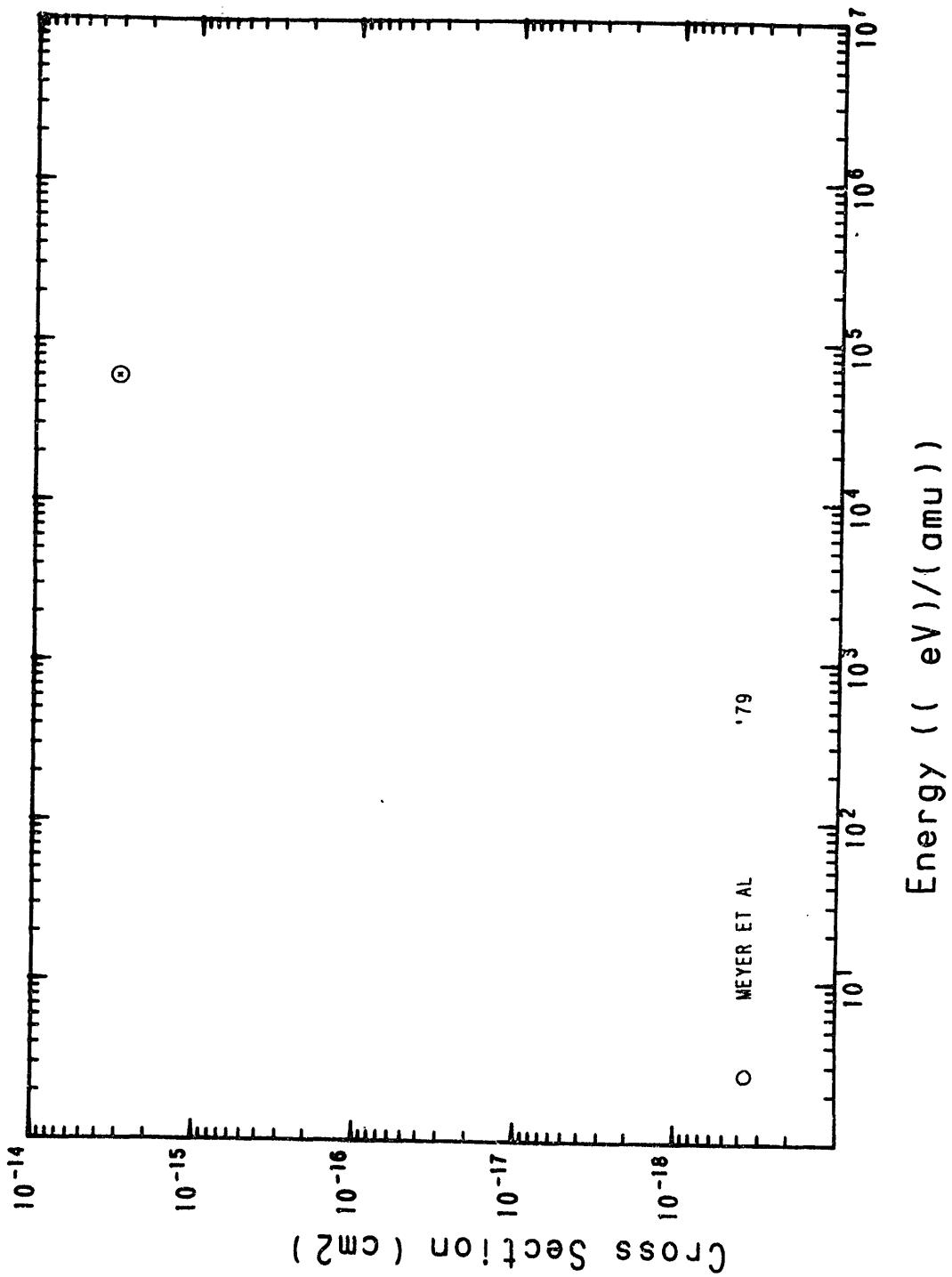


Fig.121 $\text{W}^{13+} + \text{H} \rightarrow \text{W}^{12+}$

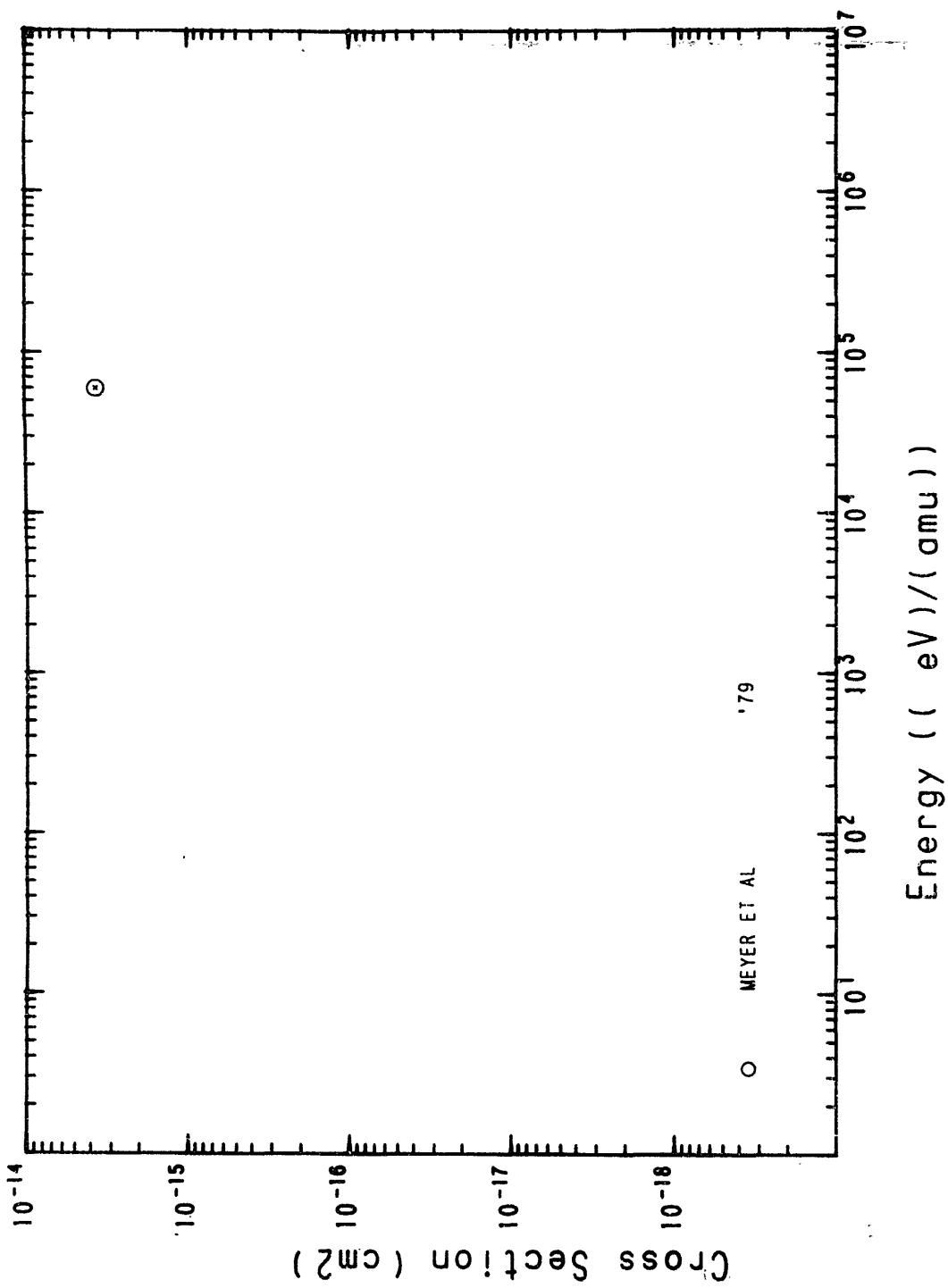


Fig.122 $\text{W}^{14+} + \text{H} \longrightarrow \text{W}^{13+}$

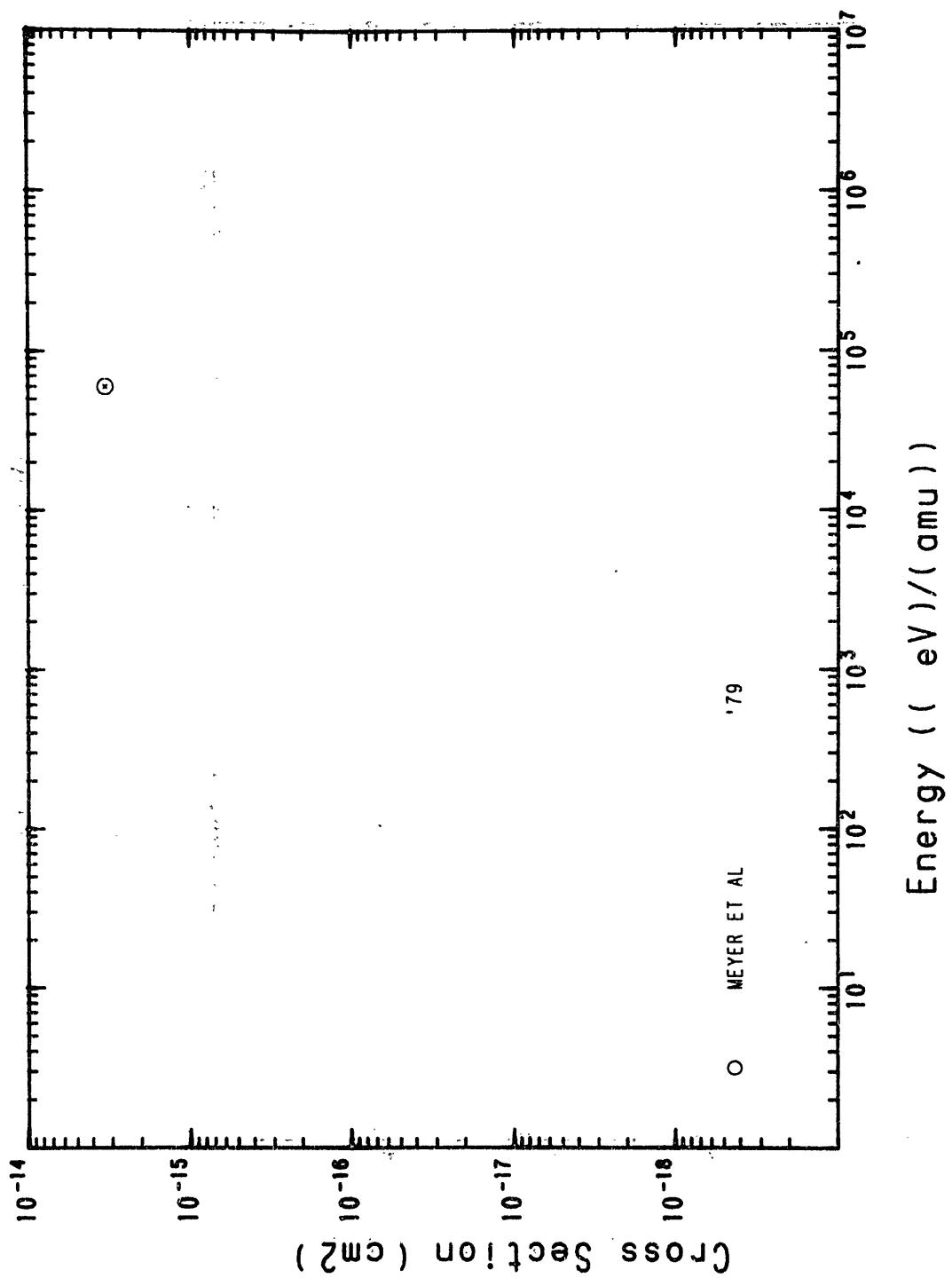


Fig.123 $W^{15+} + H \rightarrow W^{14+}$

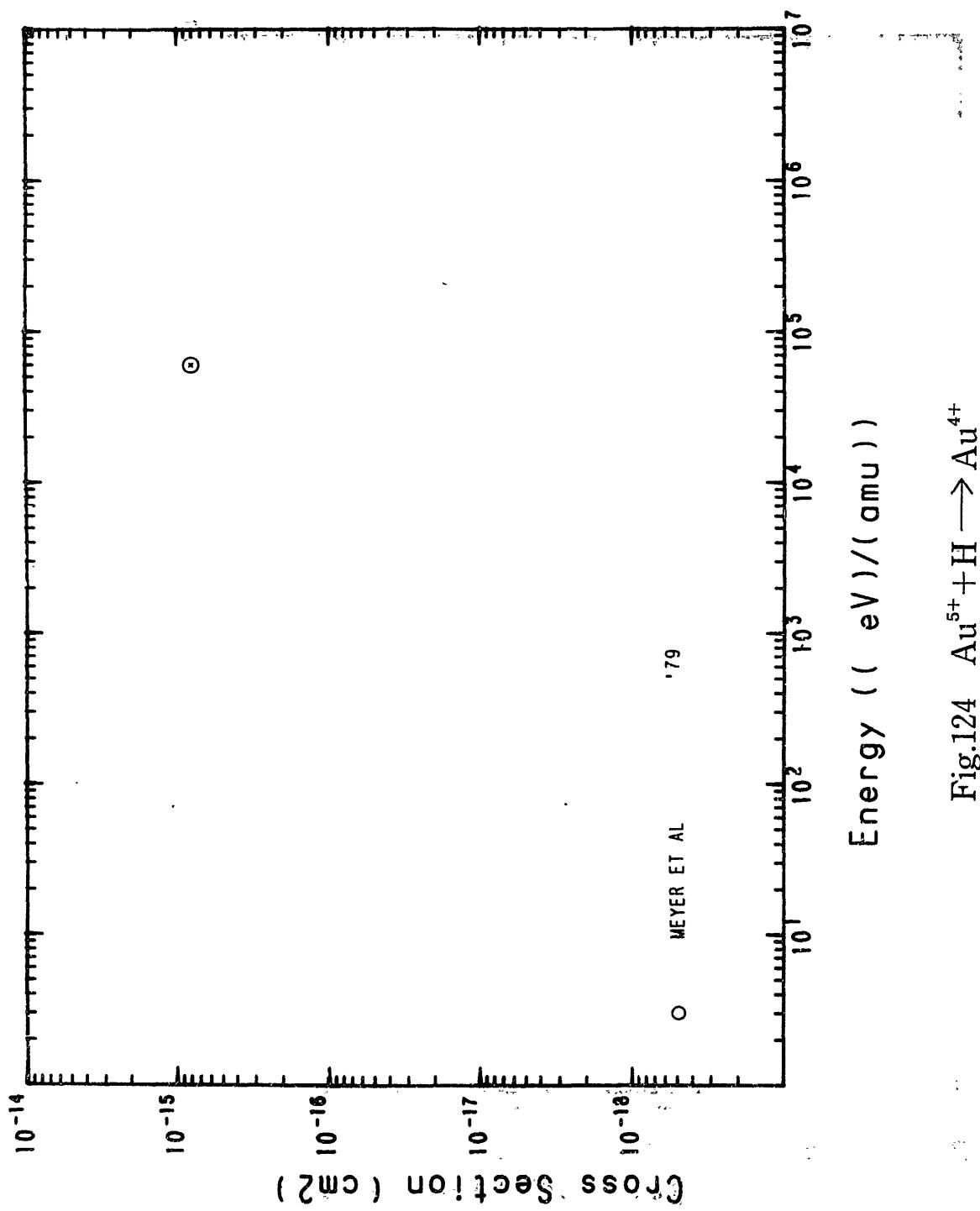


Fig.124 $\text{Au}^{5+} + \text{H} \rightarrow \text{Au}^{4+}$

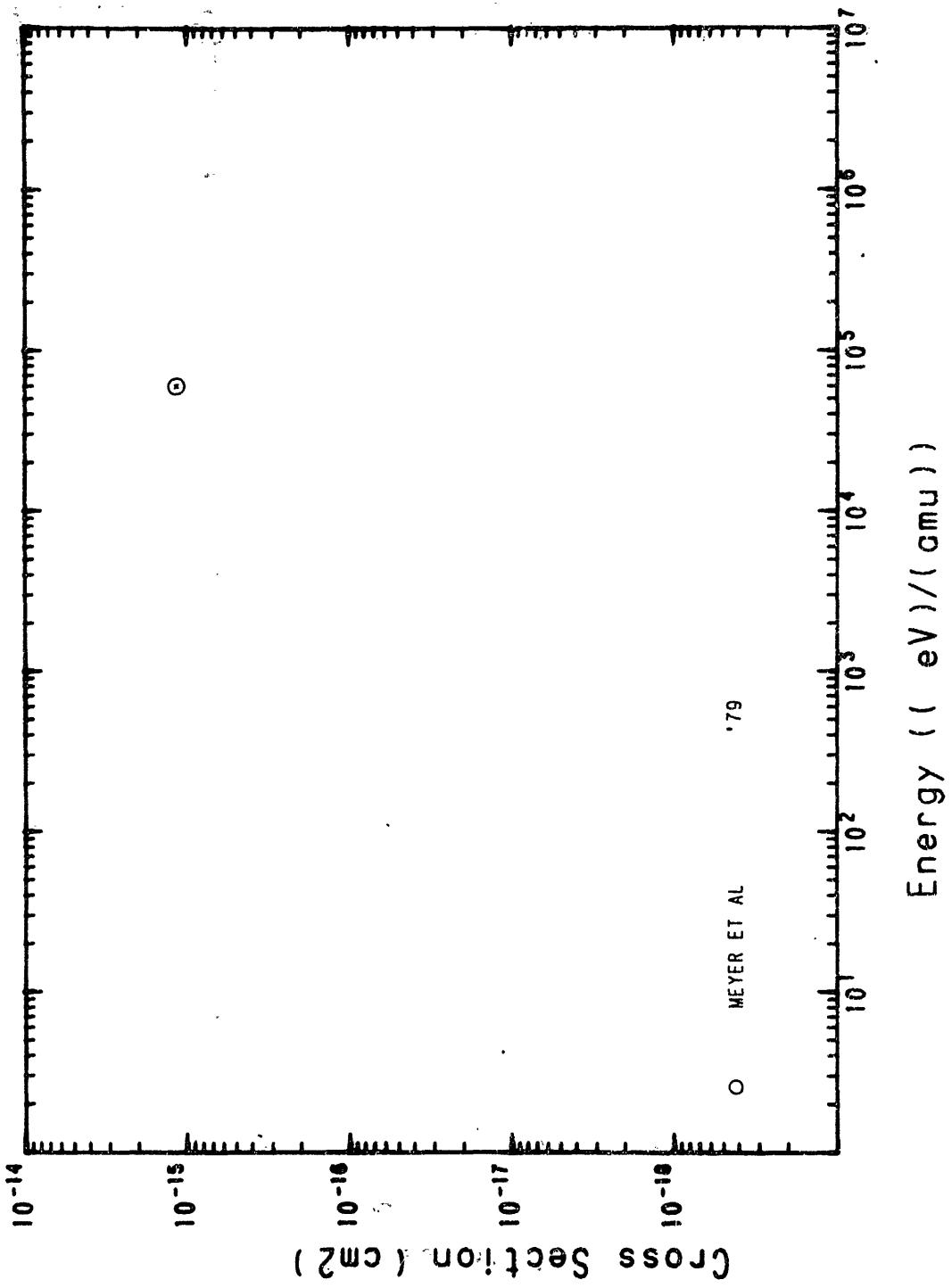


Fig.125 $\text{Au}^{6+} + \text{H} \rightarrow \text{Au}^{5+}$

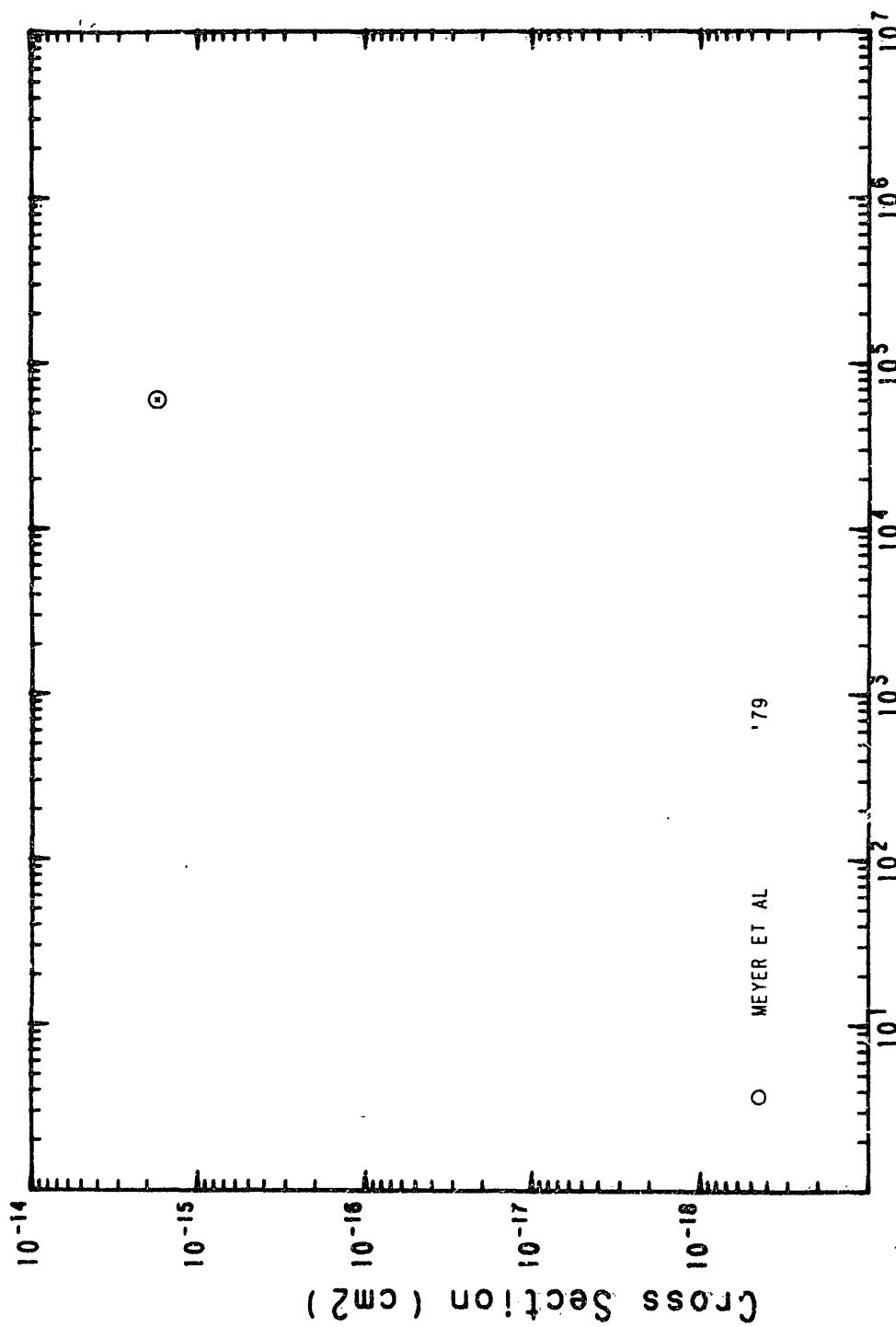


Fig.126 $\text{Au}^{7+} + \text{H} \longrightarrow \text{Au}^{6+}$

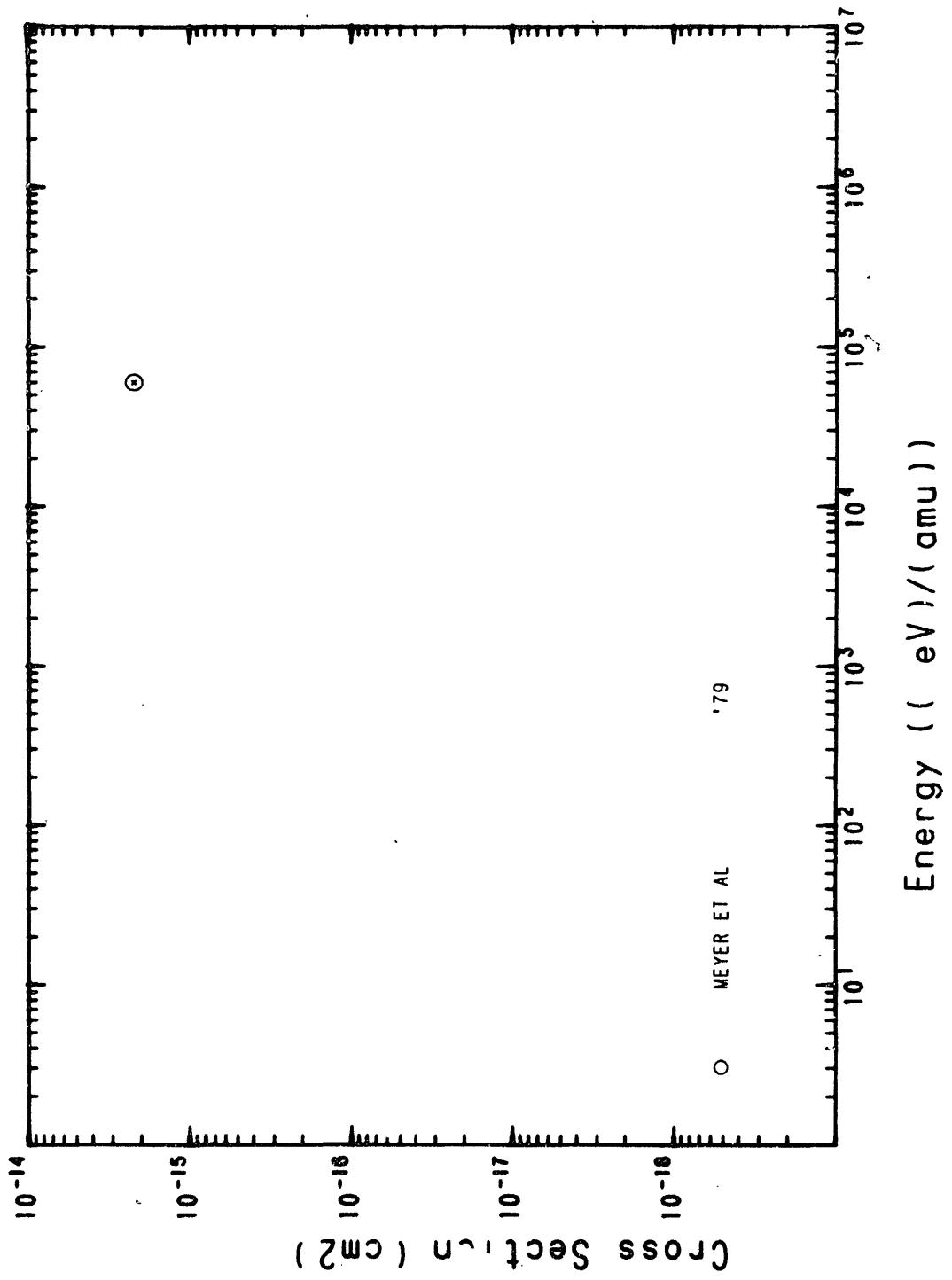


Fig.127 Au⁸⁺ + H → Au⁷⁺

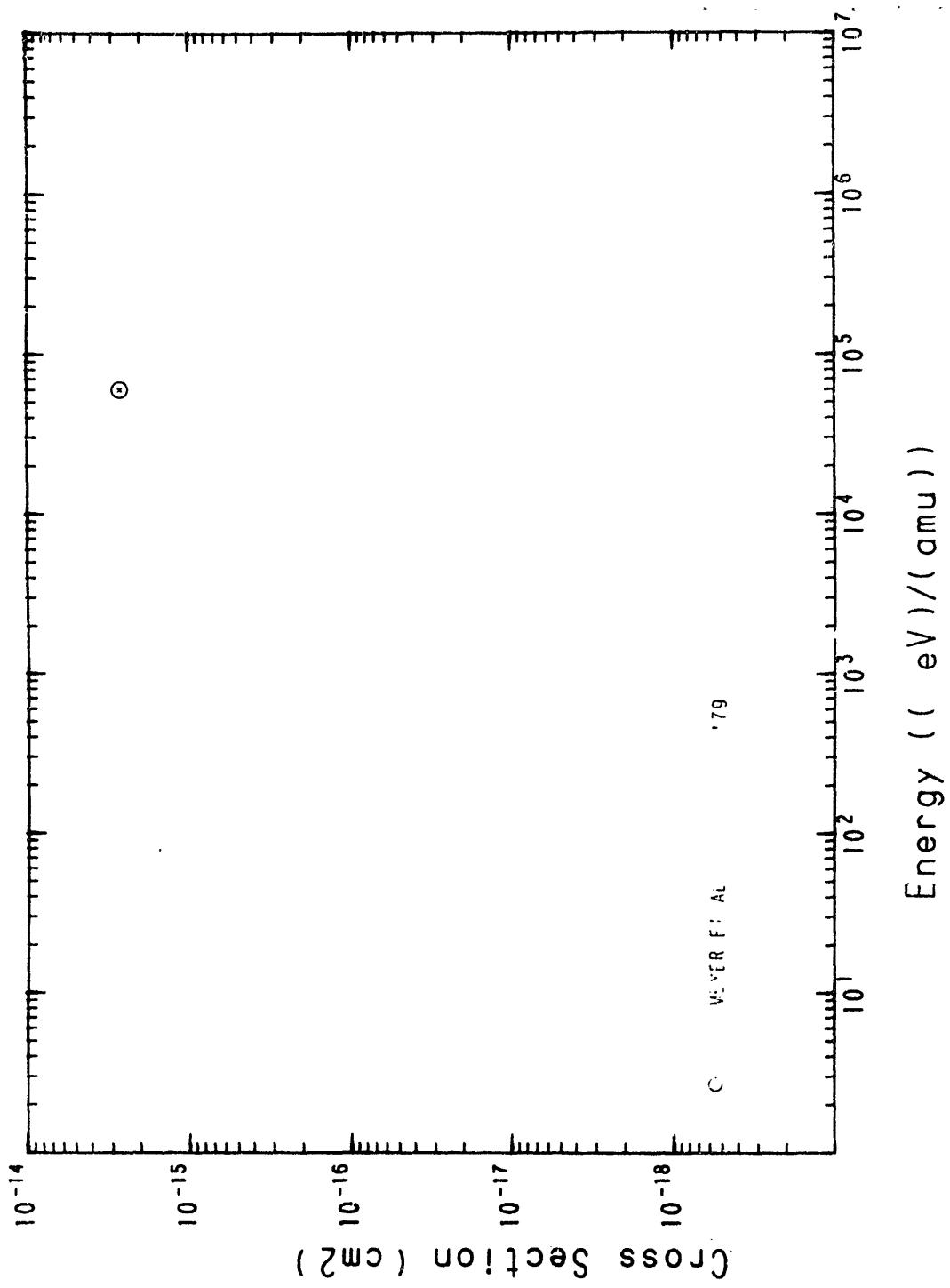


Fig.128 $\text{Au}^{9+} + \text{H} \longrightarrow \text{Au}^{8+}$

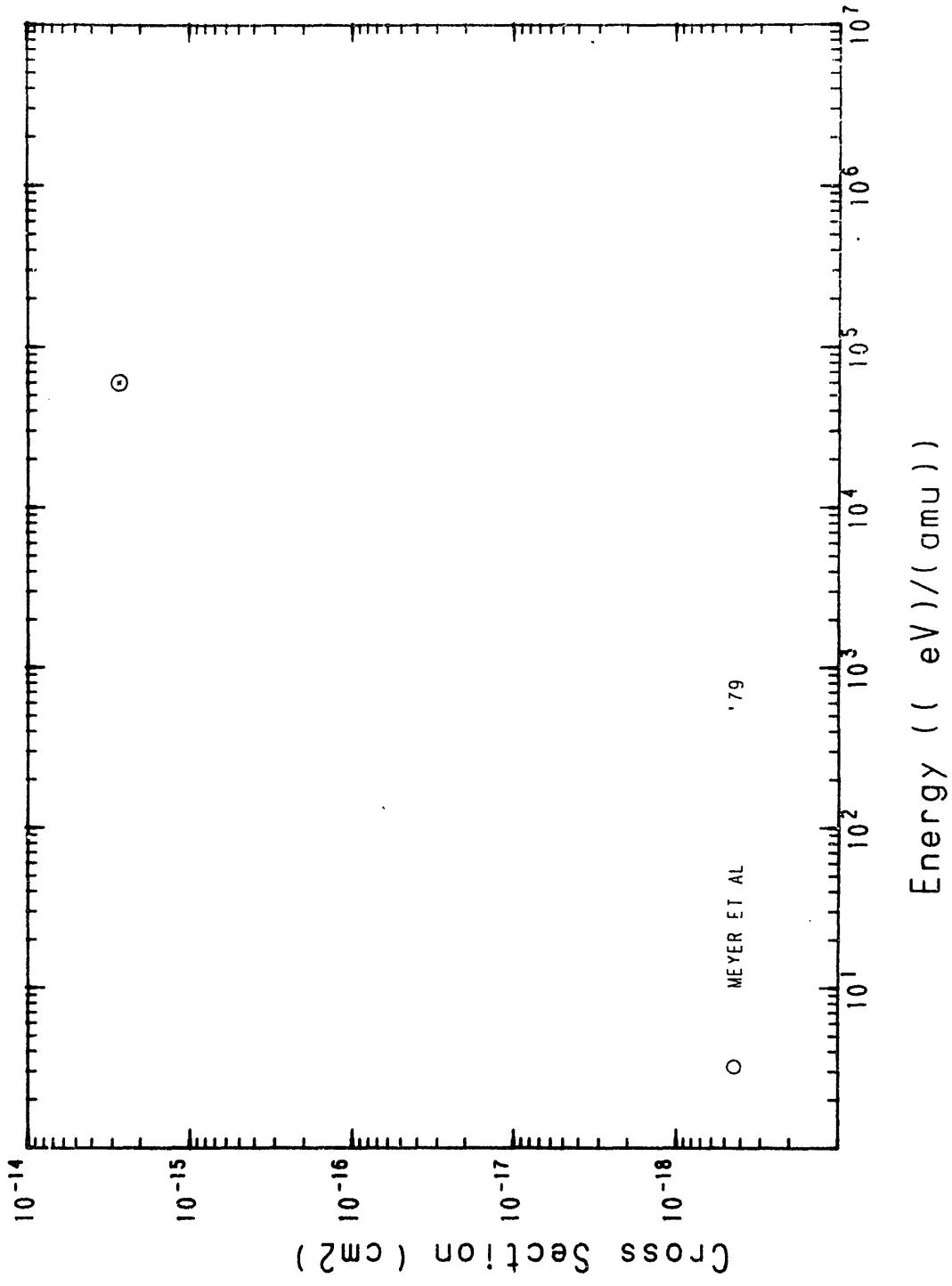


Fig.129 Au¹⁰⁺+H → Au⁹⁺

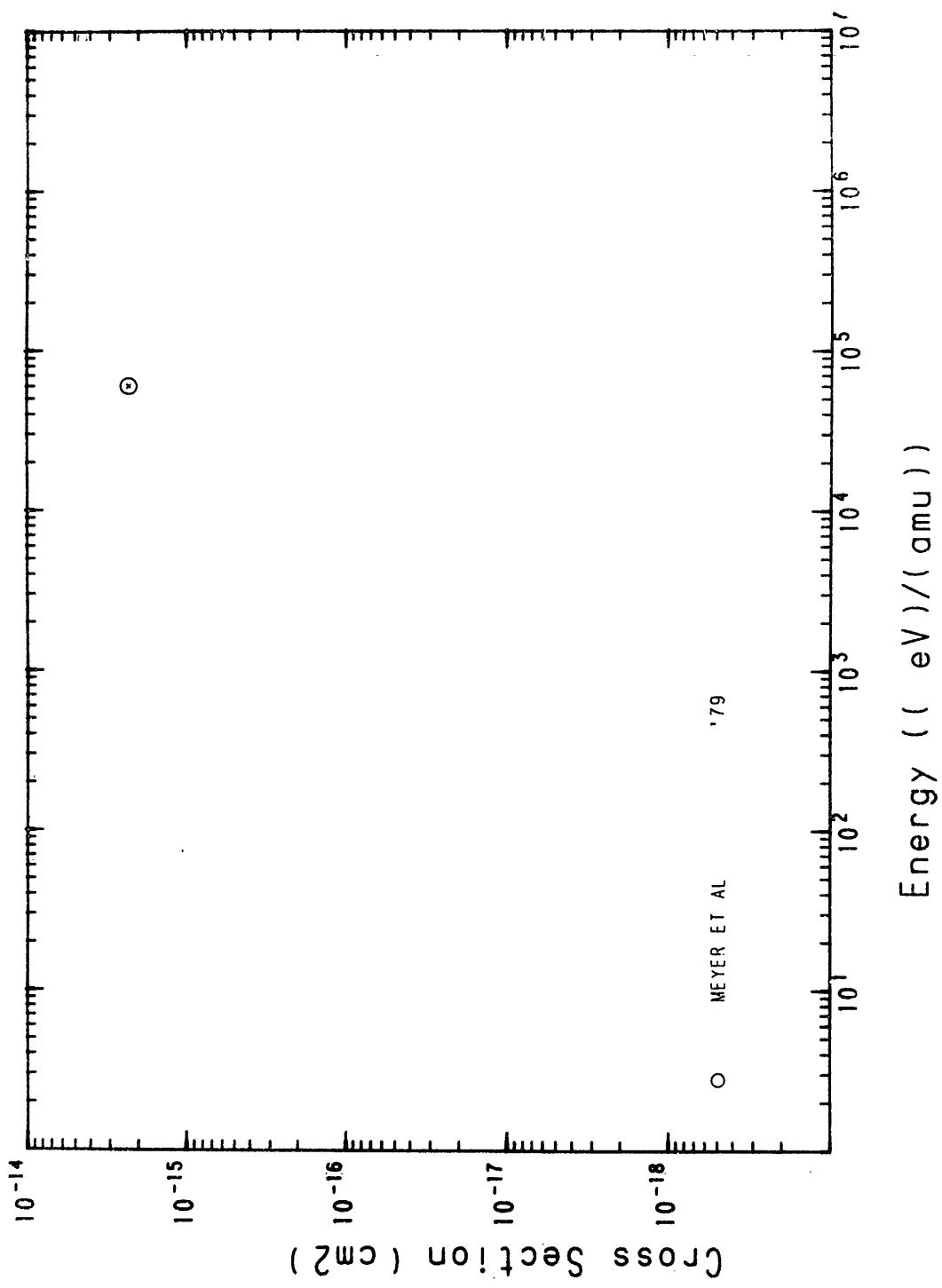


Fig.130 $\text{Au}^{11+} + \text{H} \longrightarrow \text{Au}^{10+}$

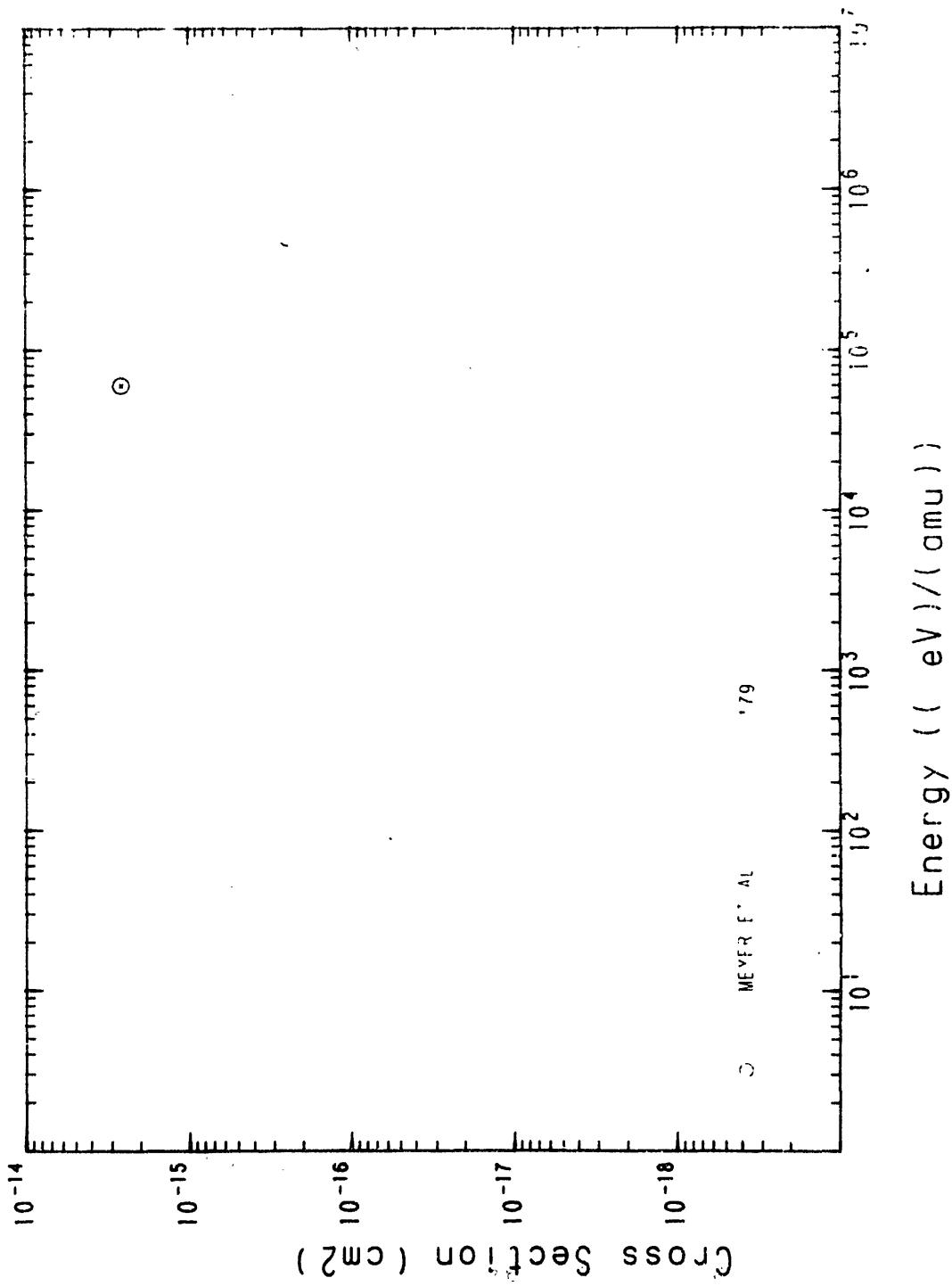


Fig.131 $\text{Au}^{12+} + \text{H} \longrightarrow \text{Au}^{11+}$

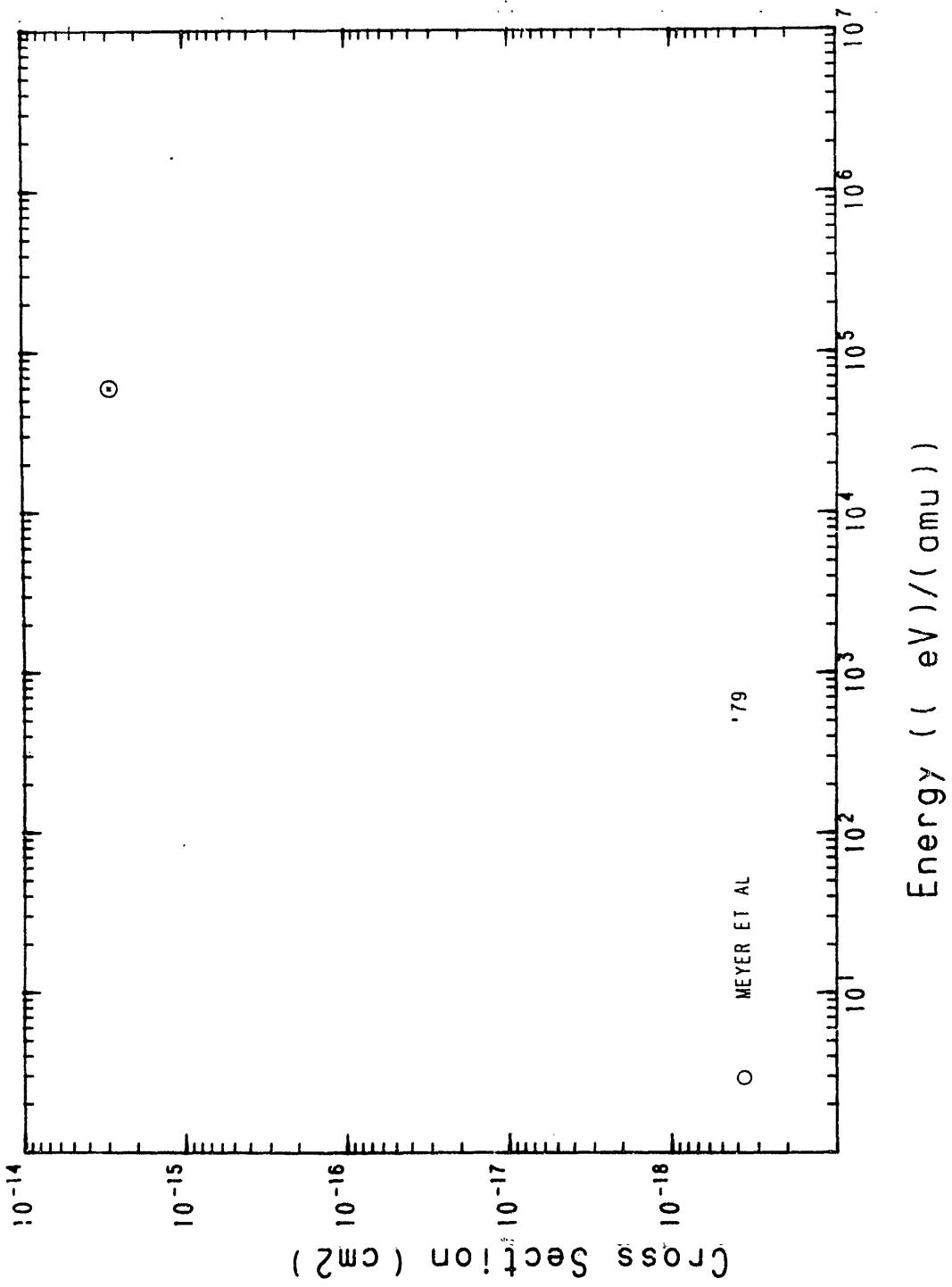


Fig.132 $\text{Au}^{13+} + \text{H}^- \rightarrow \text{Au}^{12+}$

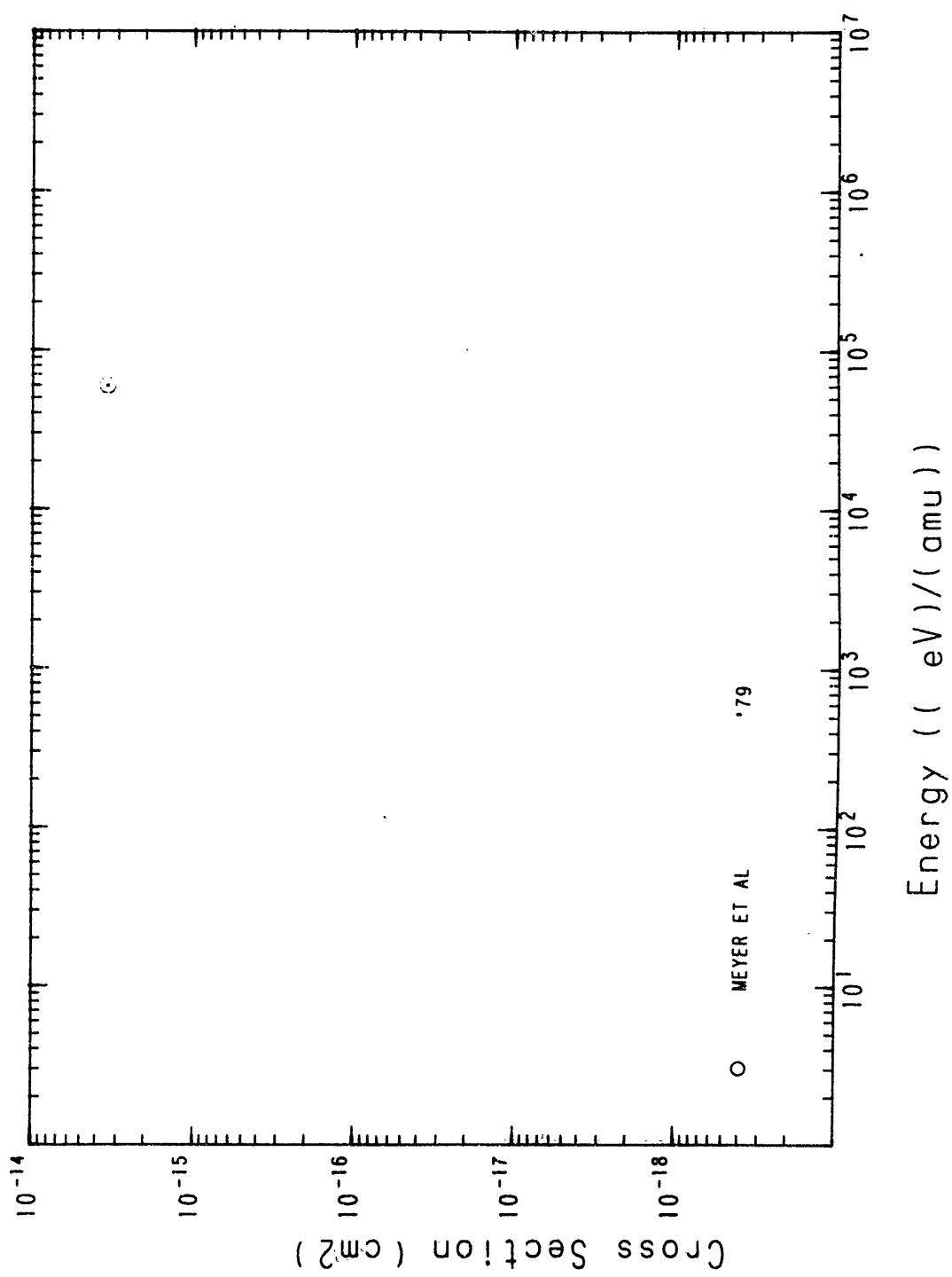


Fig.133 $\text{Au}^{14+} + \text{H} \rightarrow \text{Au}^{13+}$

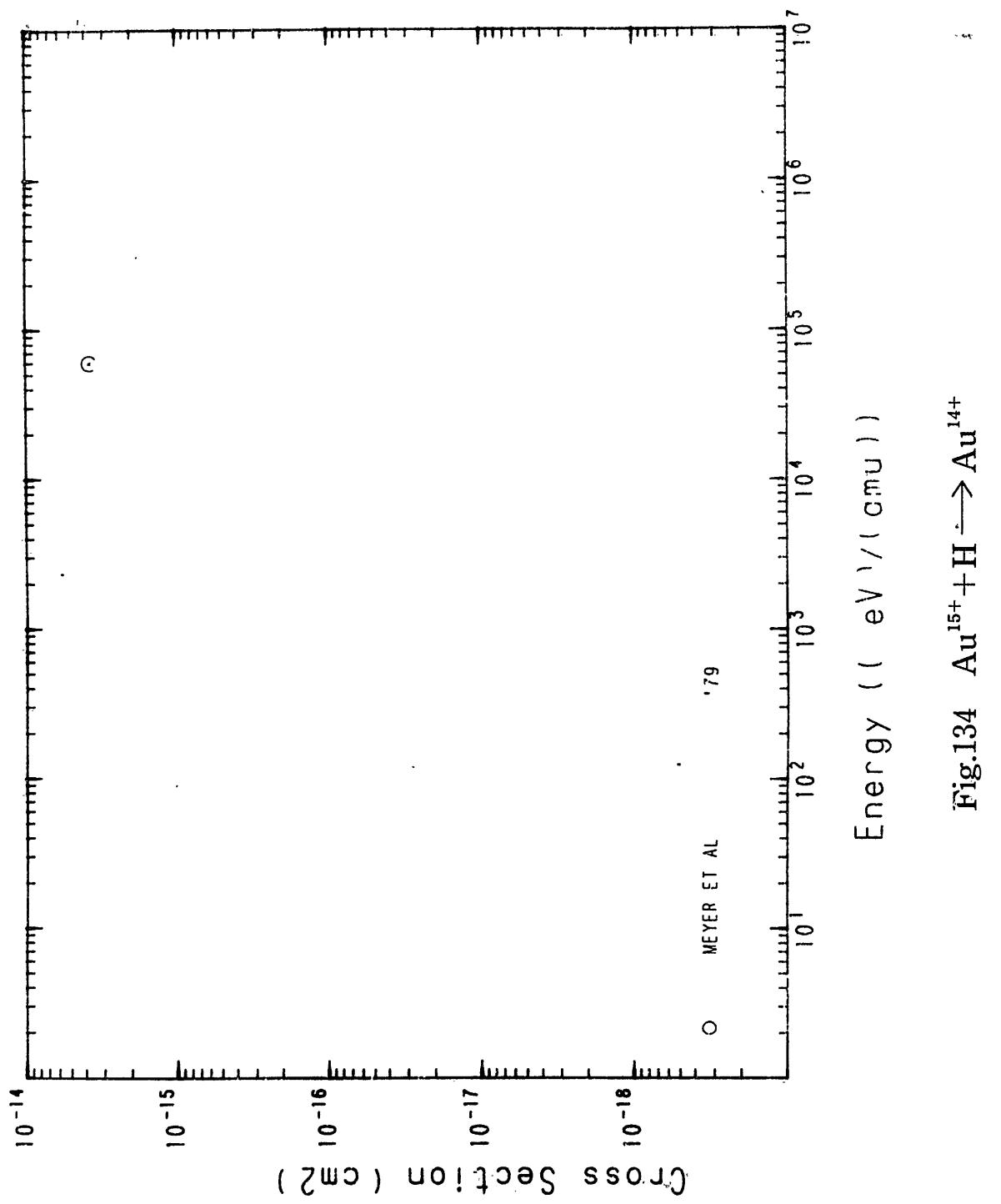


Fig.134 $\text{Au}^{15+} + \text{H} \rightarrow \text{Au}^{14+}$

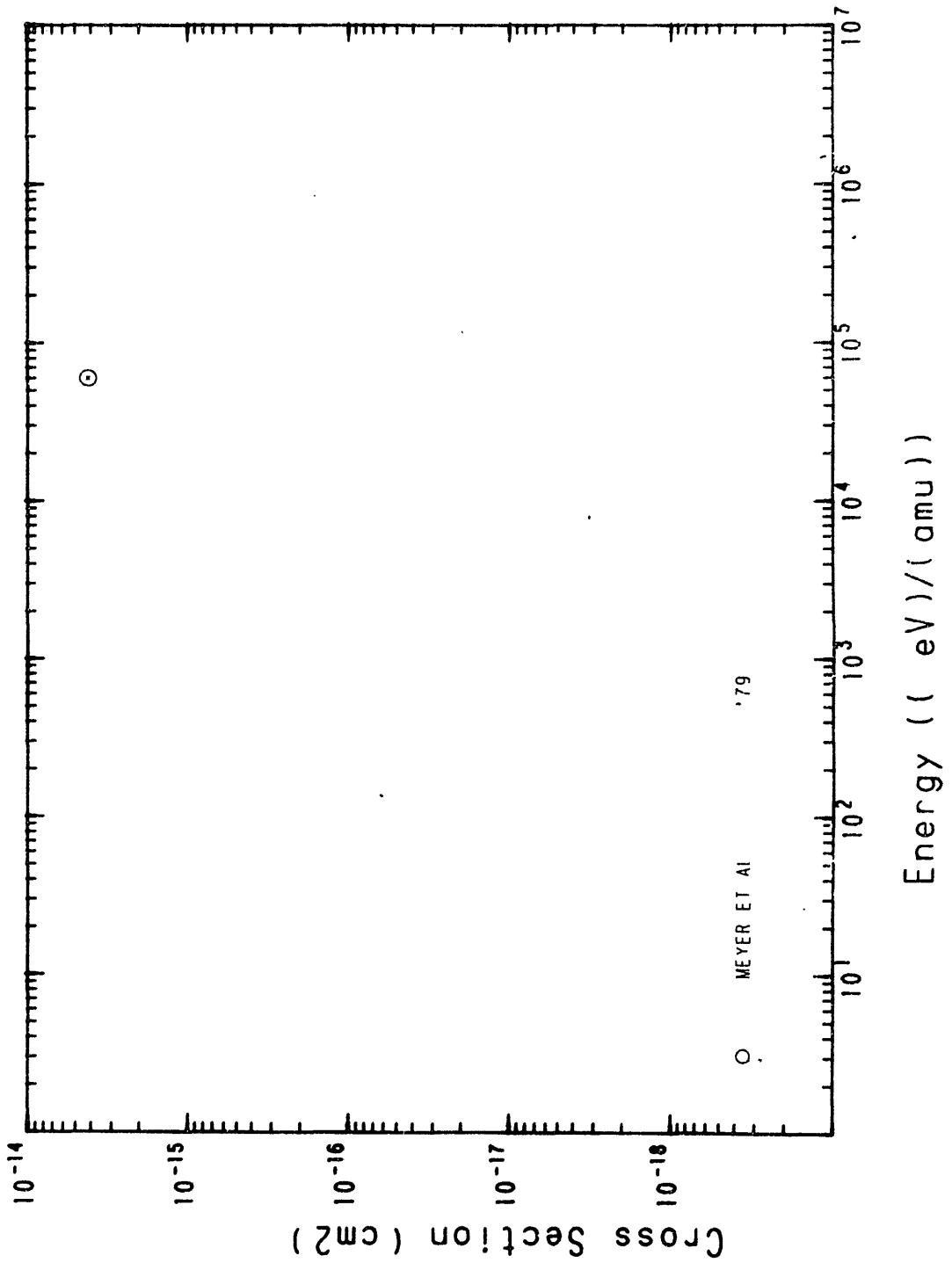


Fig.135 $\text{Au}^{16+} + \text{H} \longrightarrow \text{Au}^{15+}$

V. APPENDIX

- GRAPHS FOR RELATED PROCESSES -

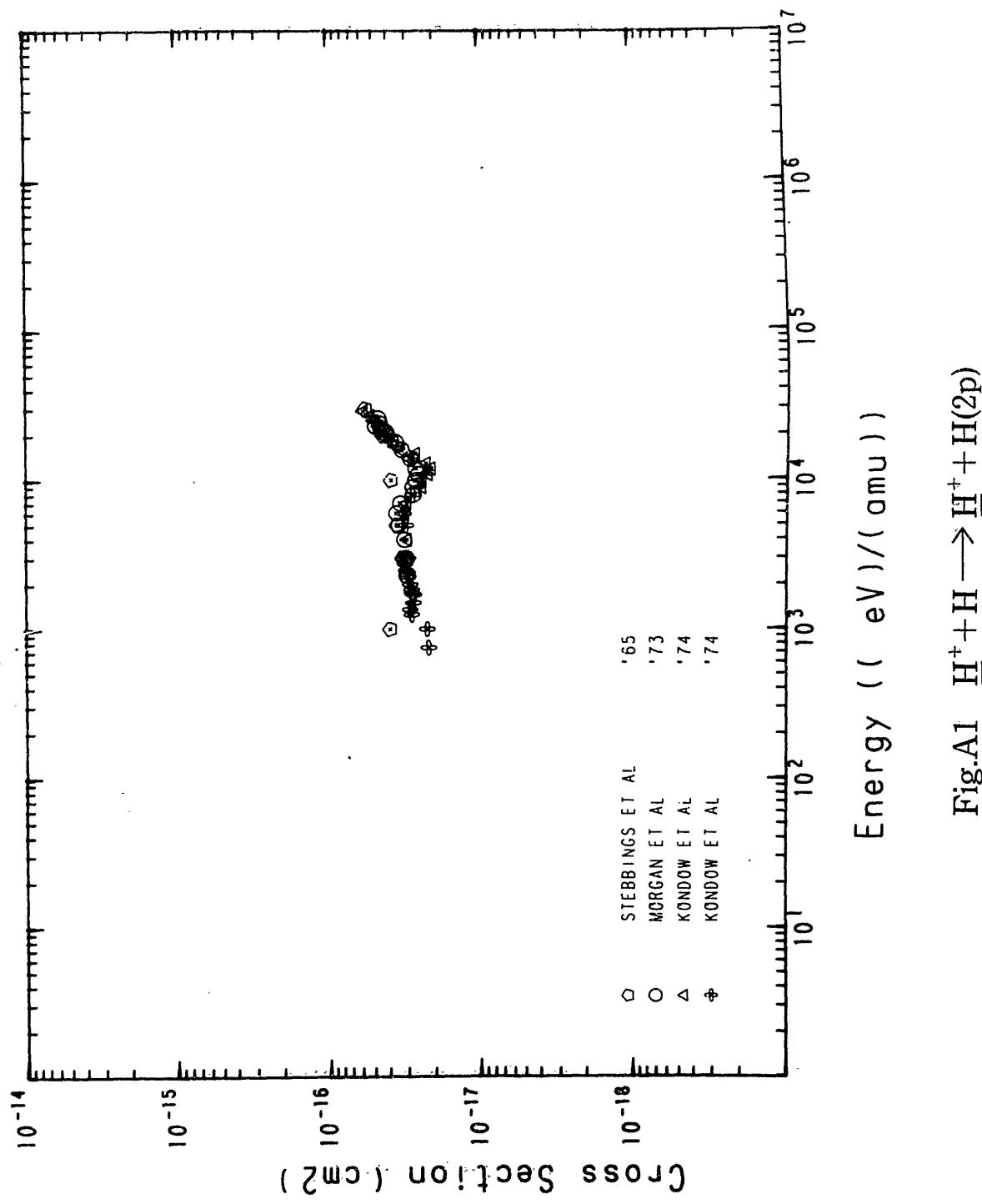


Fig.A1 $\text{H}^+ + \text{H} \rightarrow \text{H}^+ + \text{H}(2\text{p})$

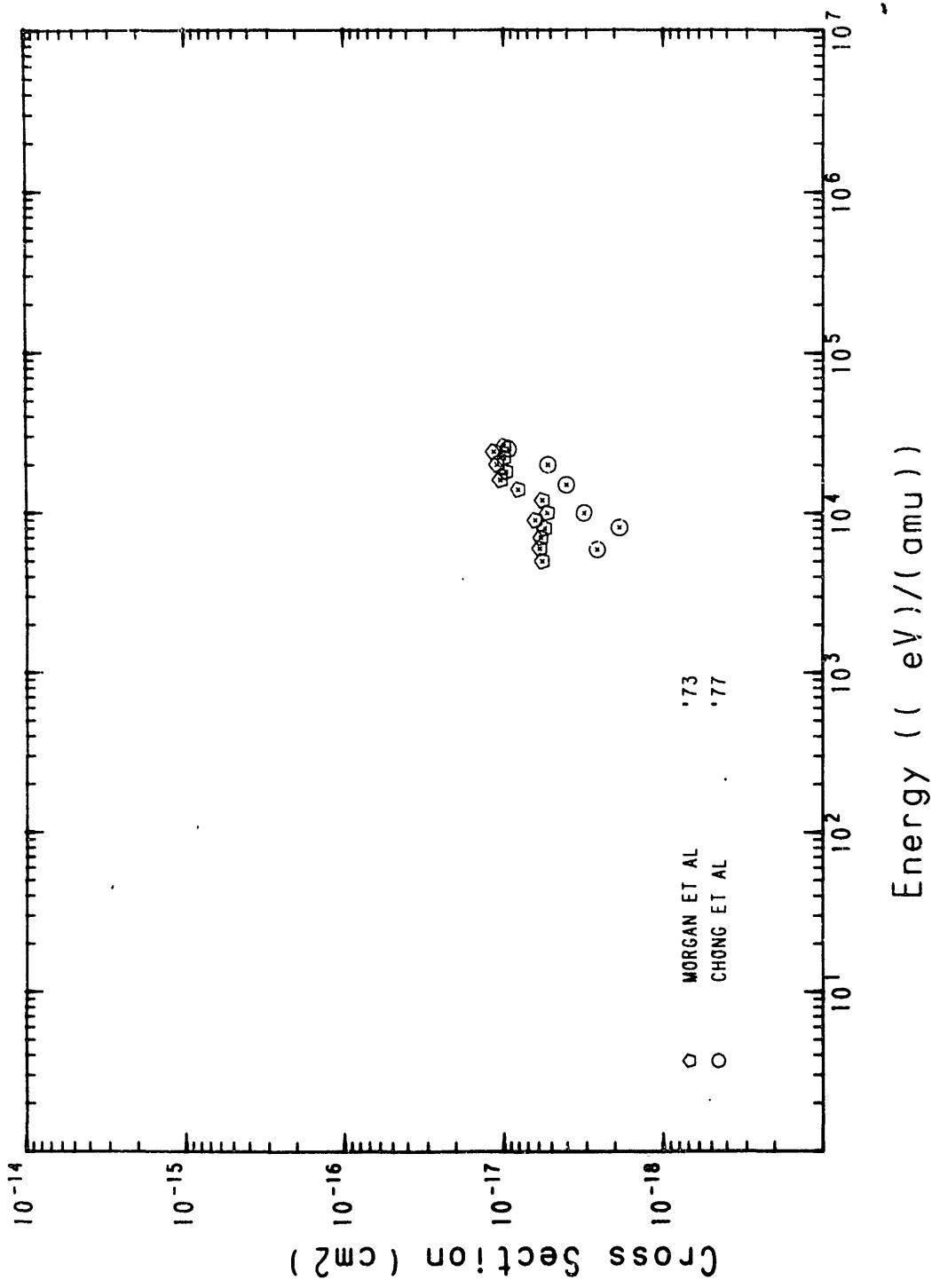


Fig.A2 $\bar{H}^+ + H \rightarrow \bar{H}^+ + H(2s)$

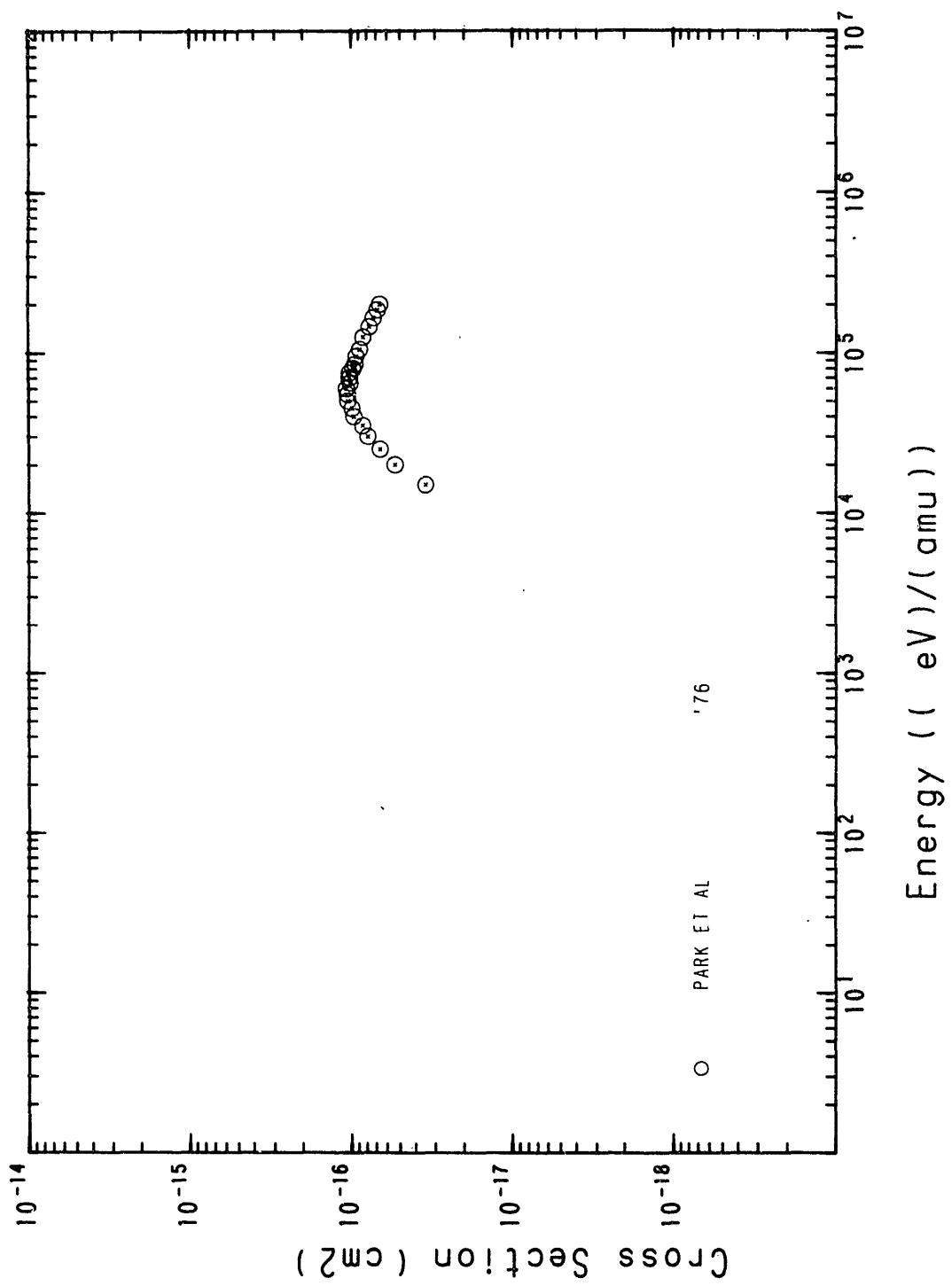


Fig.A3 $\underline{\text{H}}^+ + \text{H} \longrightarrow \underline{\text{H}}^+ + \text{H}(n=2)$

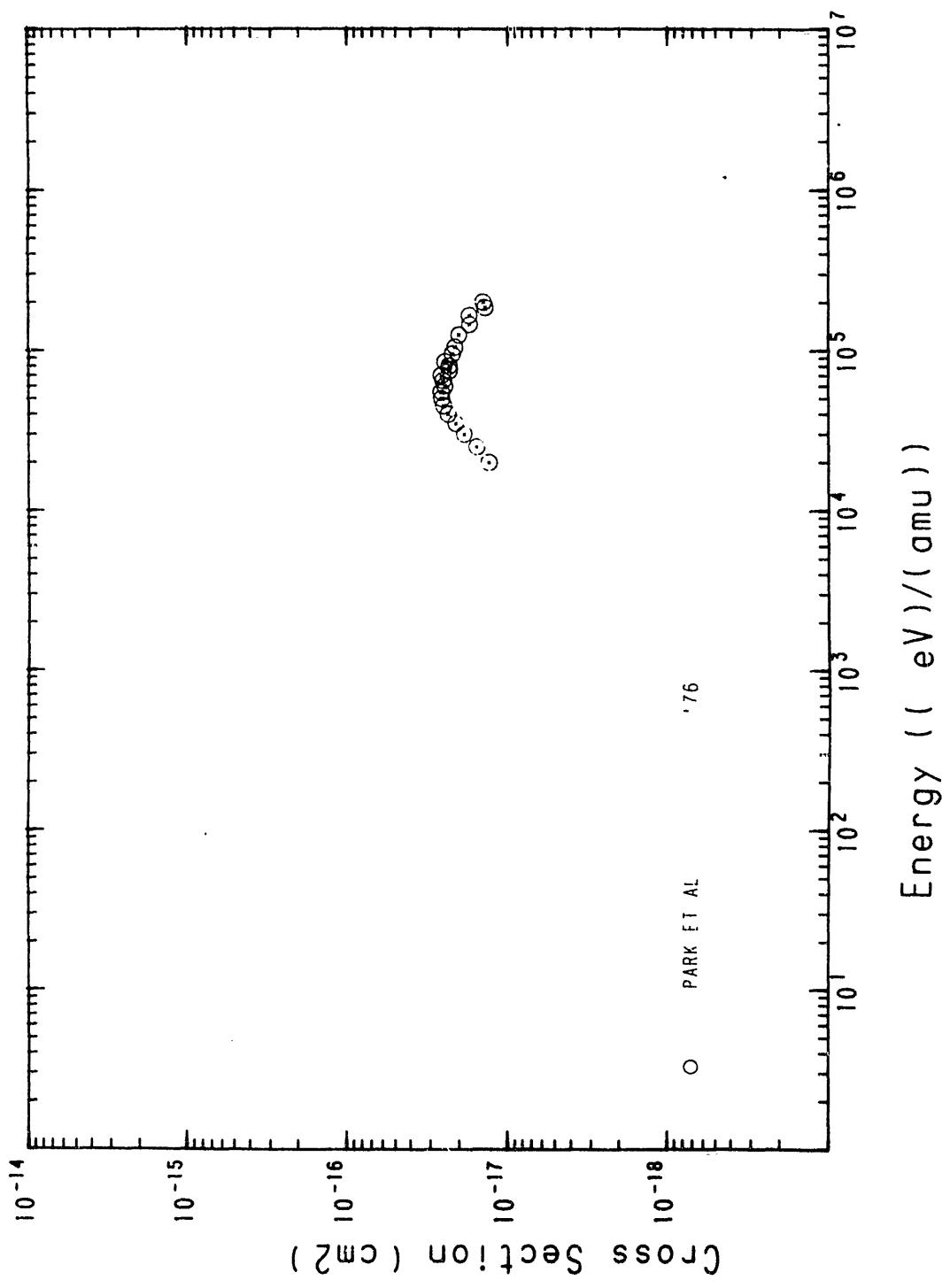


Fig.A4 $\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(n=3)$

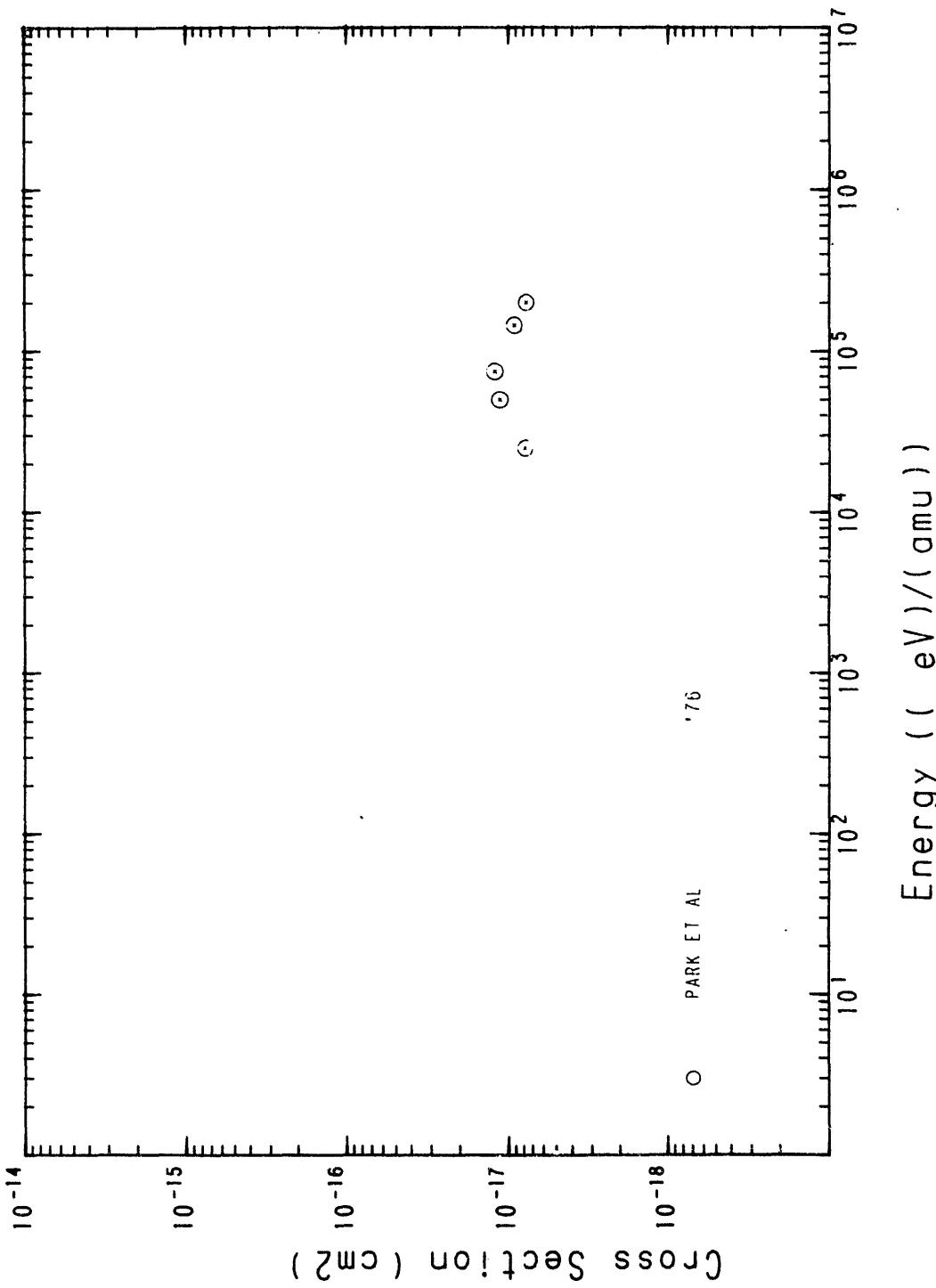


Fig.A5 $\underline{H}^+ + H \longrightarrow \underline{H}^+ + H(n=4)$

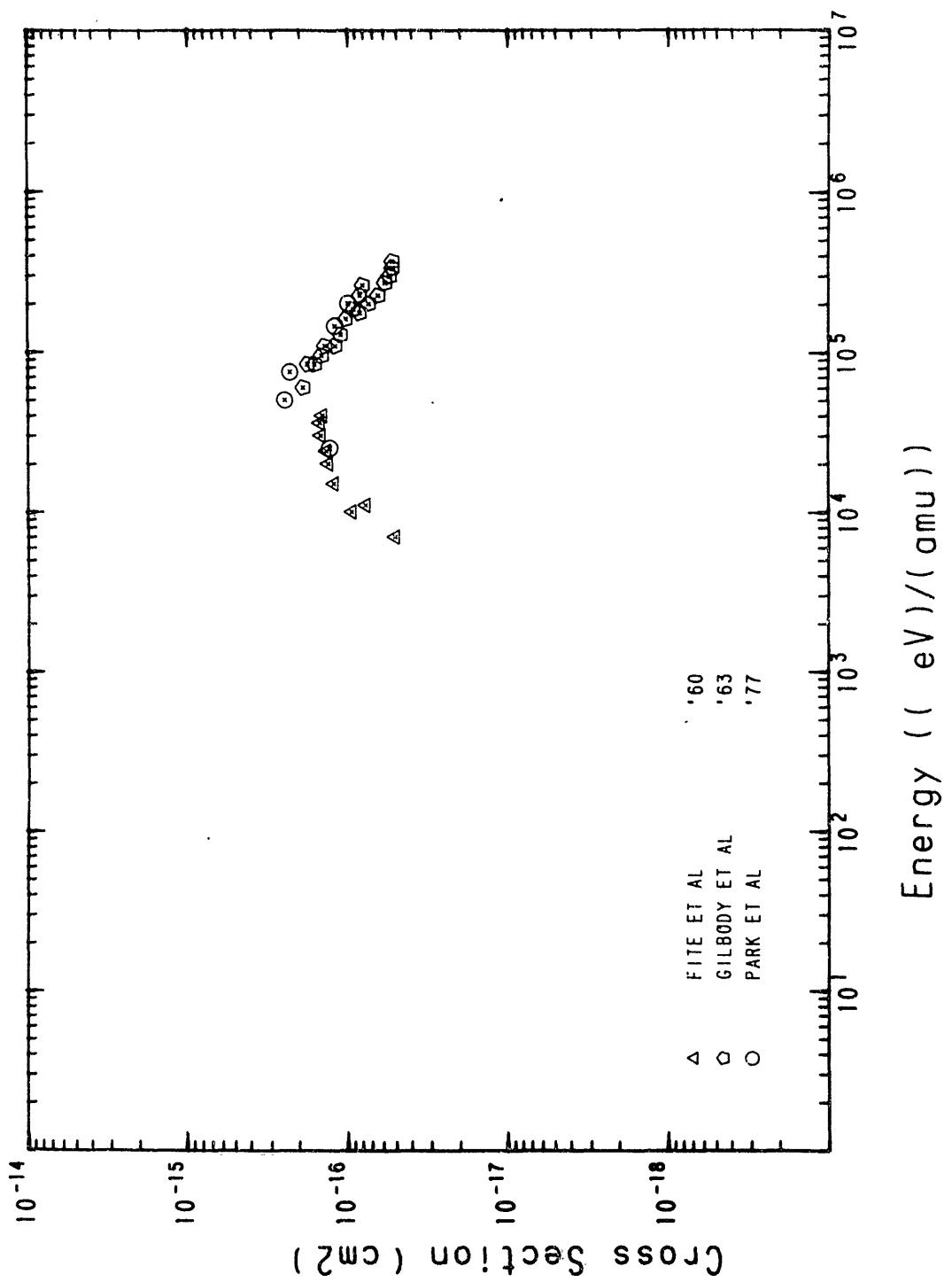


Fig.A6 $\underline{\text{H}}^+ + \text{H} \longrightarrow \underline{\text{H}}^+ + \text{H}^+ + \text{e}$

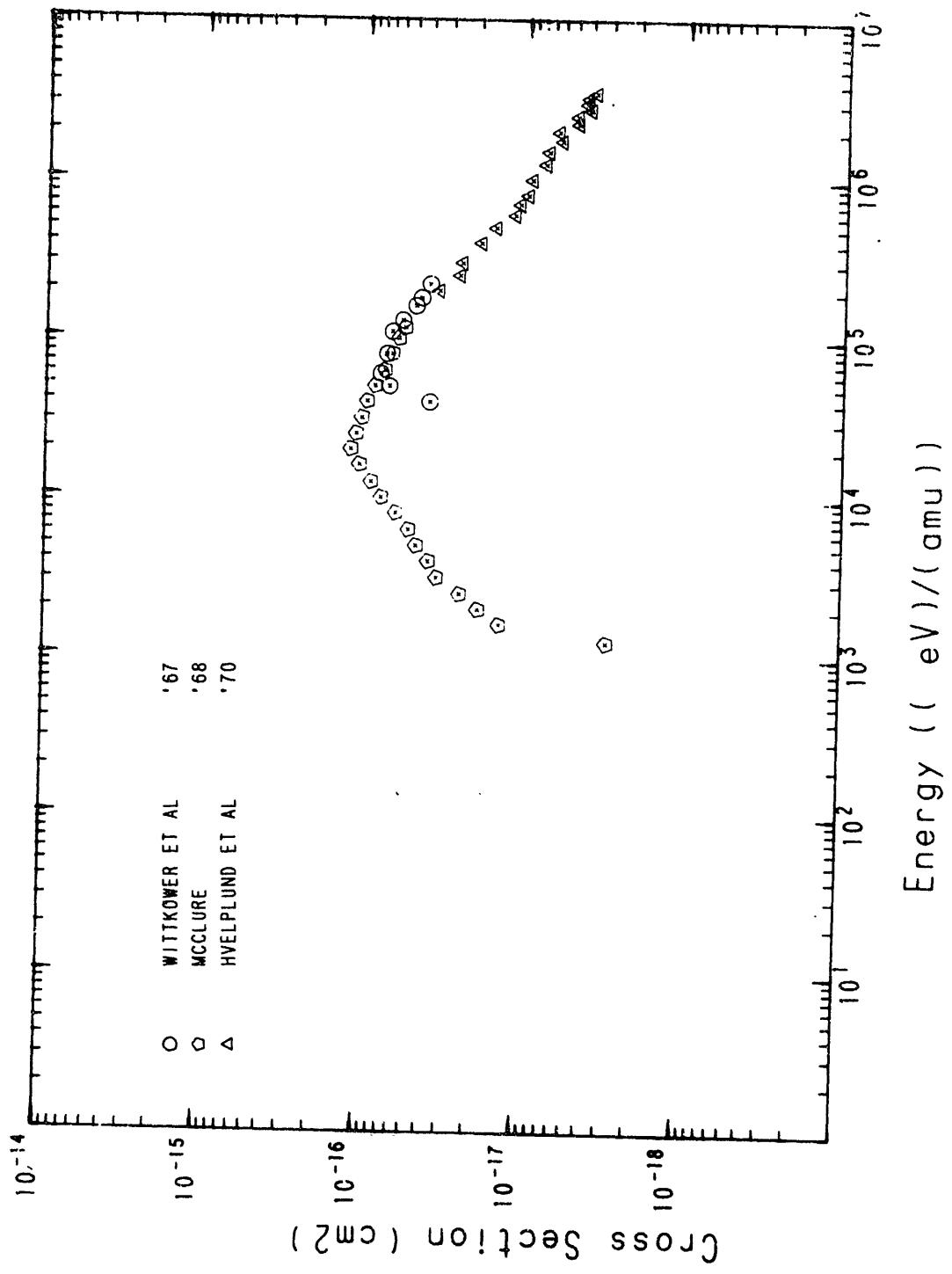


Fig.A7 $\underline{\text{H}} + \text{H} \rightarrow \underline{\text{H}}^+$

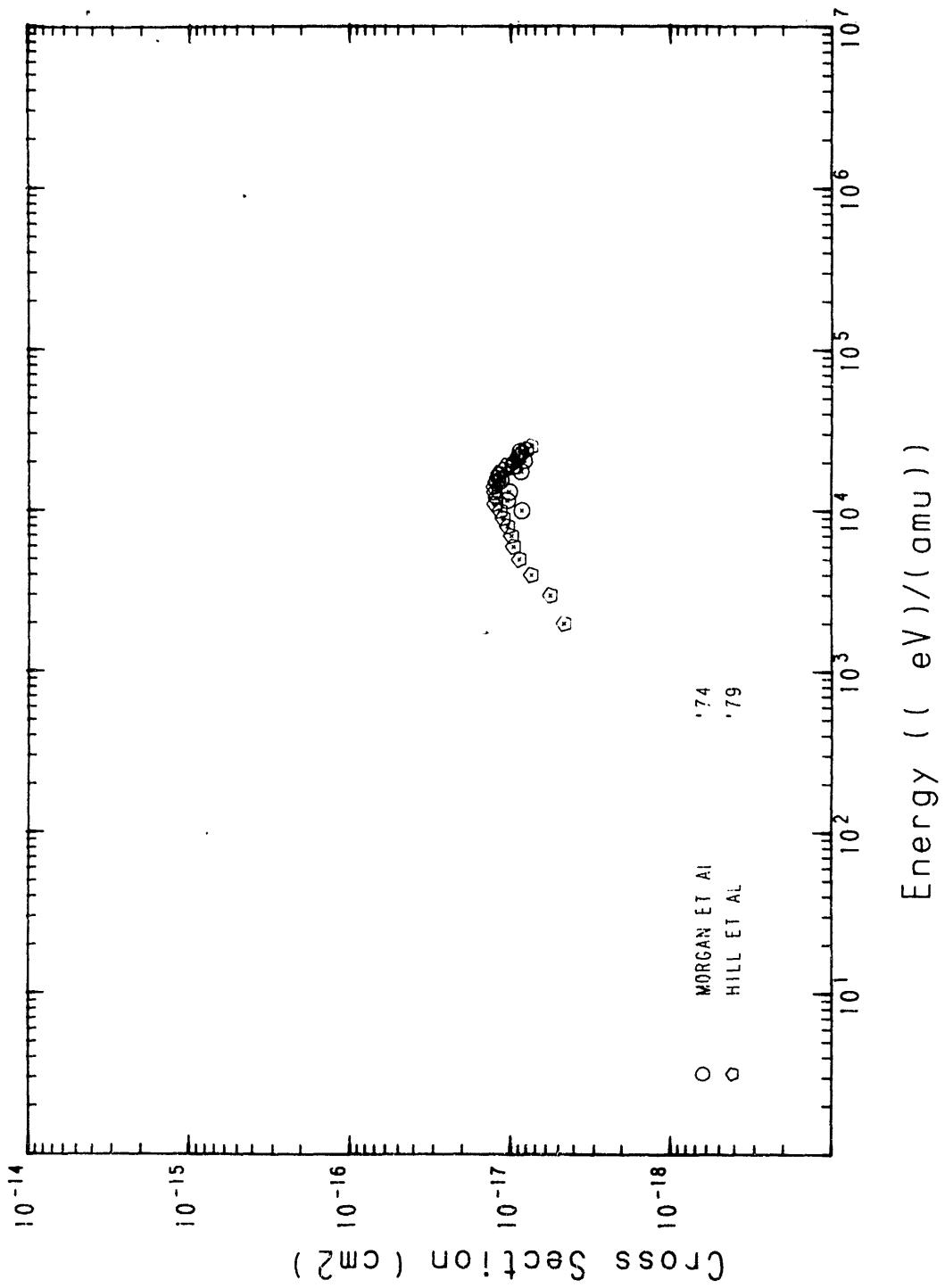


Fig.A8 $\underline{\text{H}} + \text{H} \longrightarrow \underline{\text{H}}(2\text{s})$

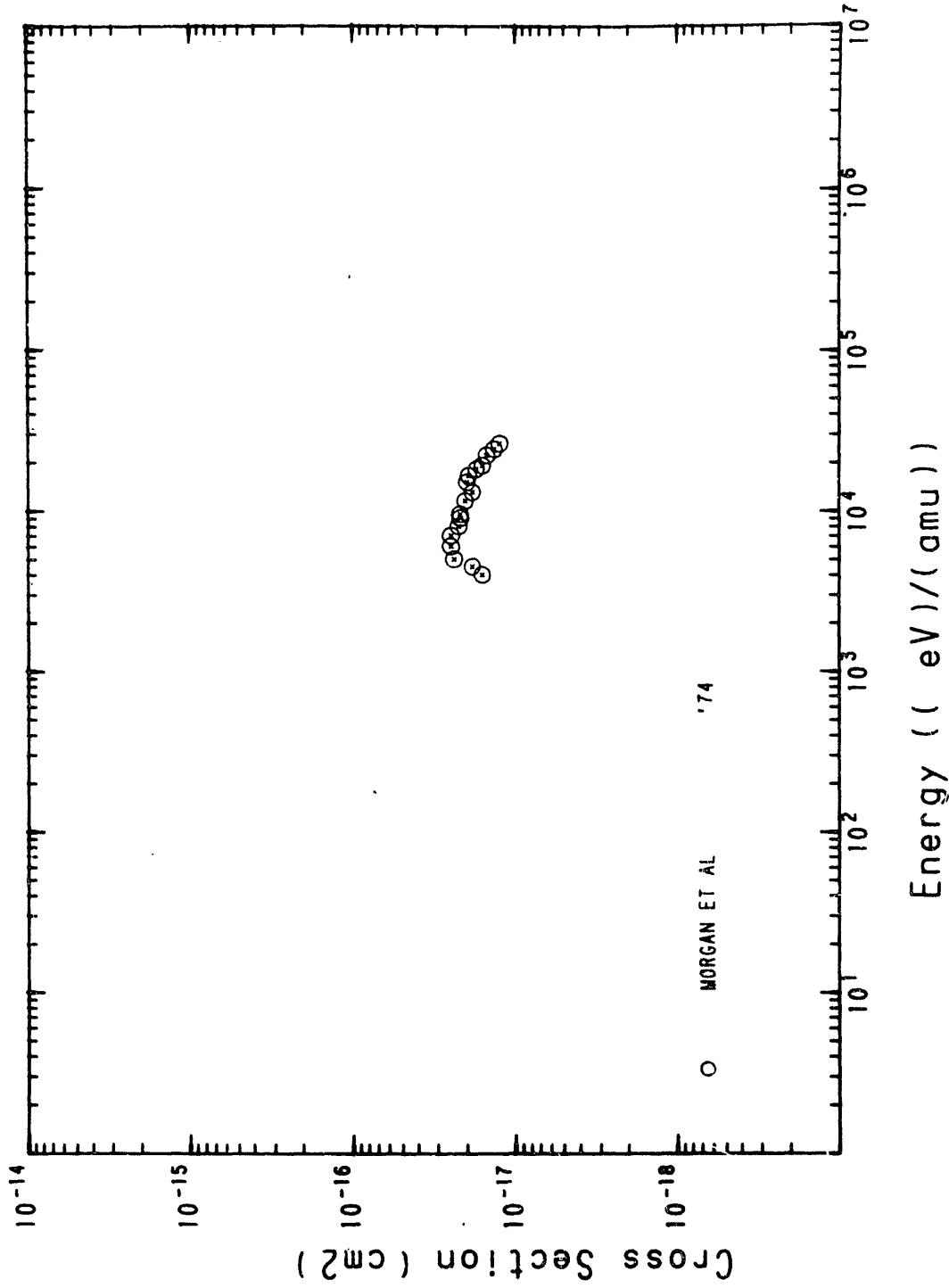


Fig.A9 $\bar{H} + H \rightarrow H(2p)$

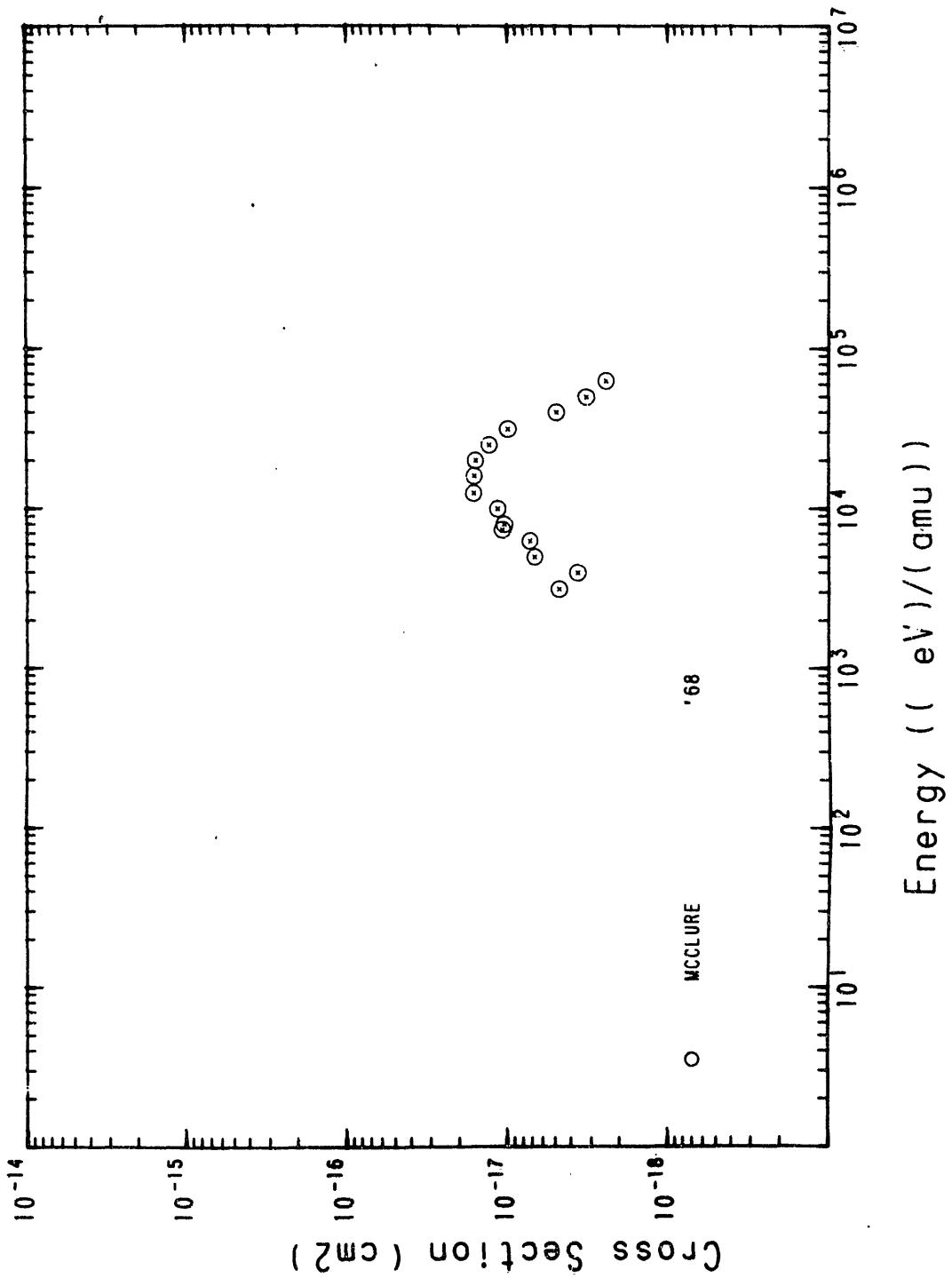


Fig.A10 $\underline{\text{H}} + \text{H} \rightarrow \underline{\text{H}}^- + \text{H}^+$

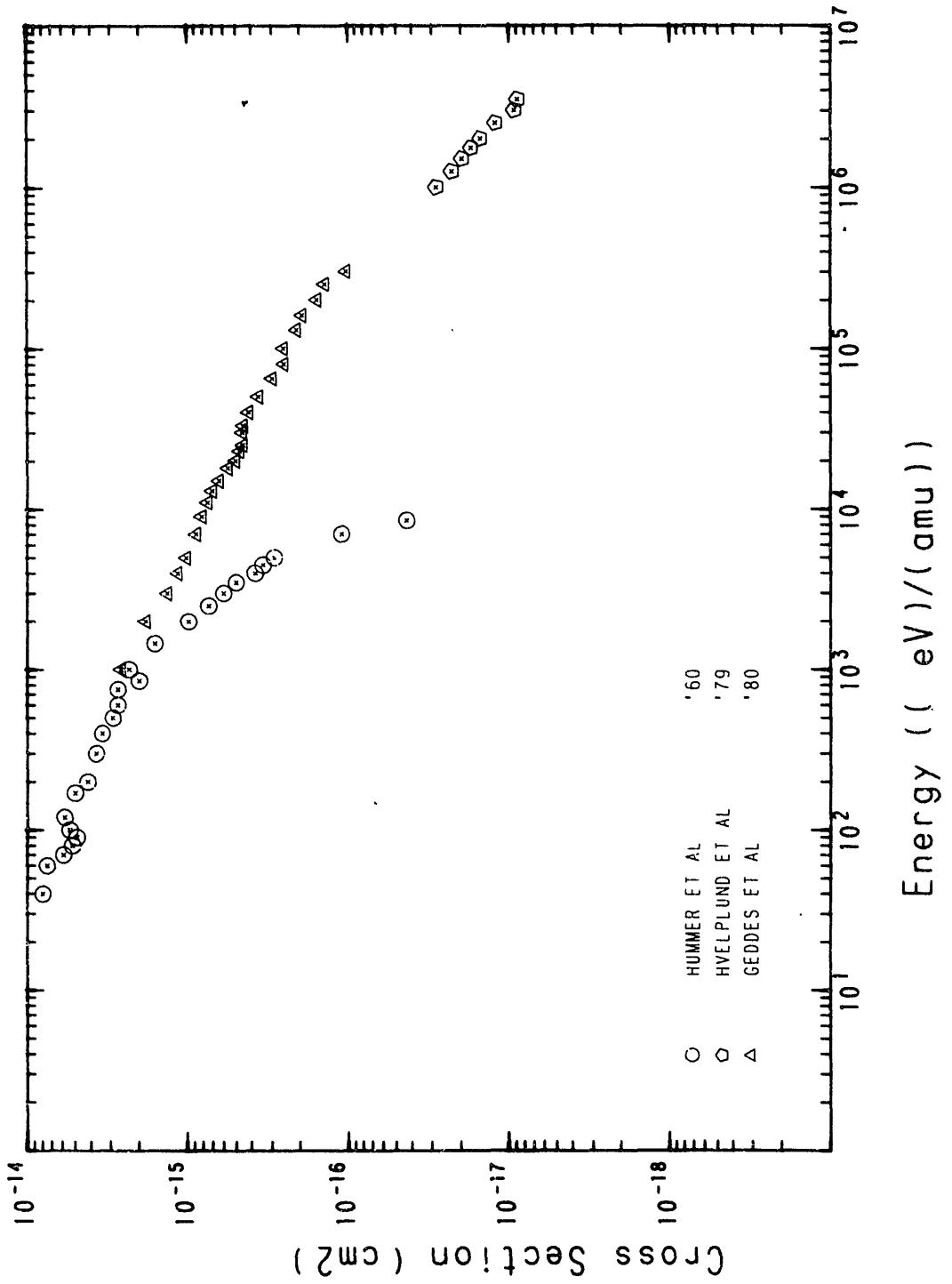


Fig.A11 $\underline{\text{H}}^- + \text{H} \rightarrow \underline{\text{H}}$

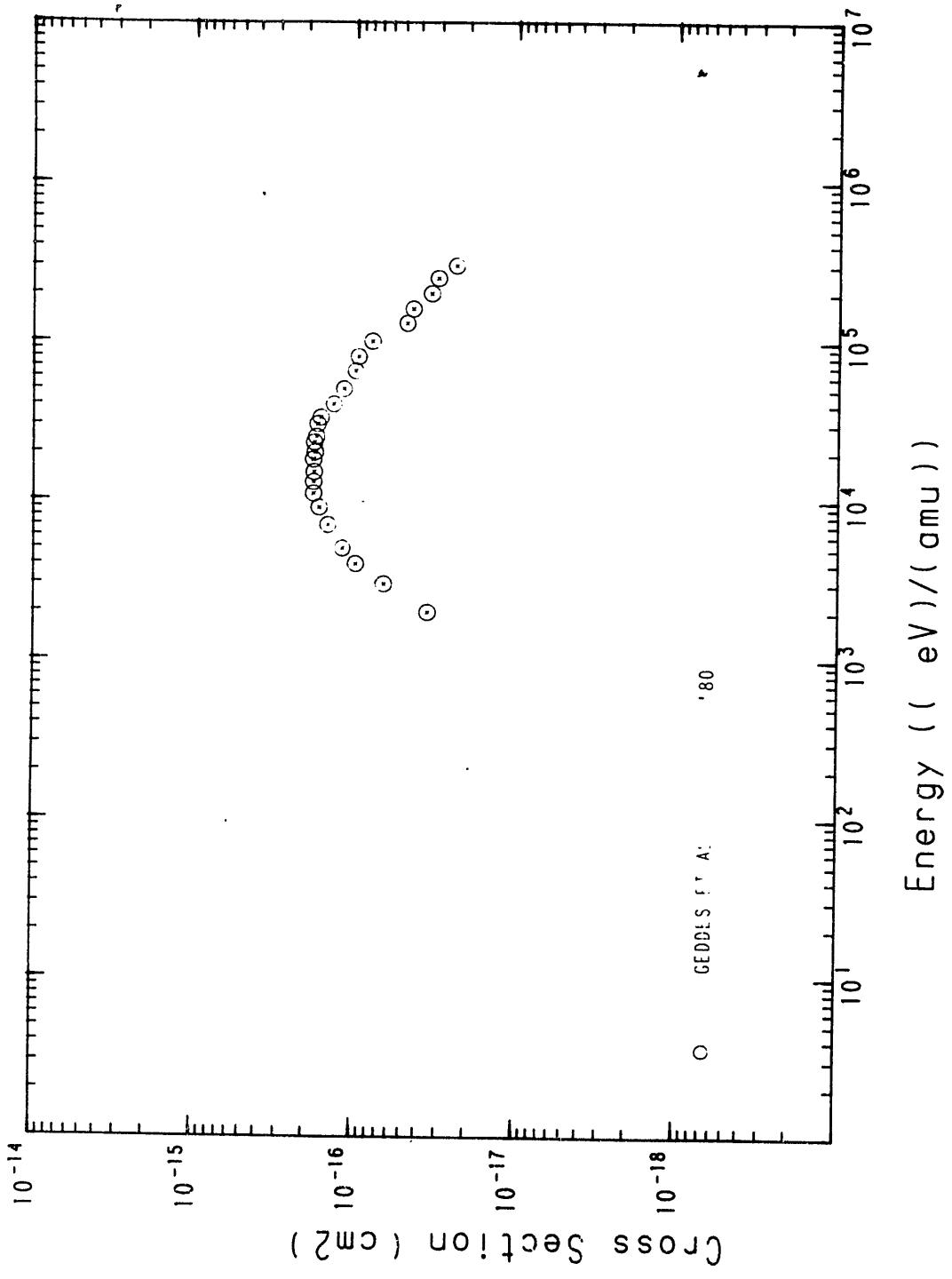


Fig.A12 $\underline{H}^- + H \longrightarrow \underline{H}^+$

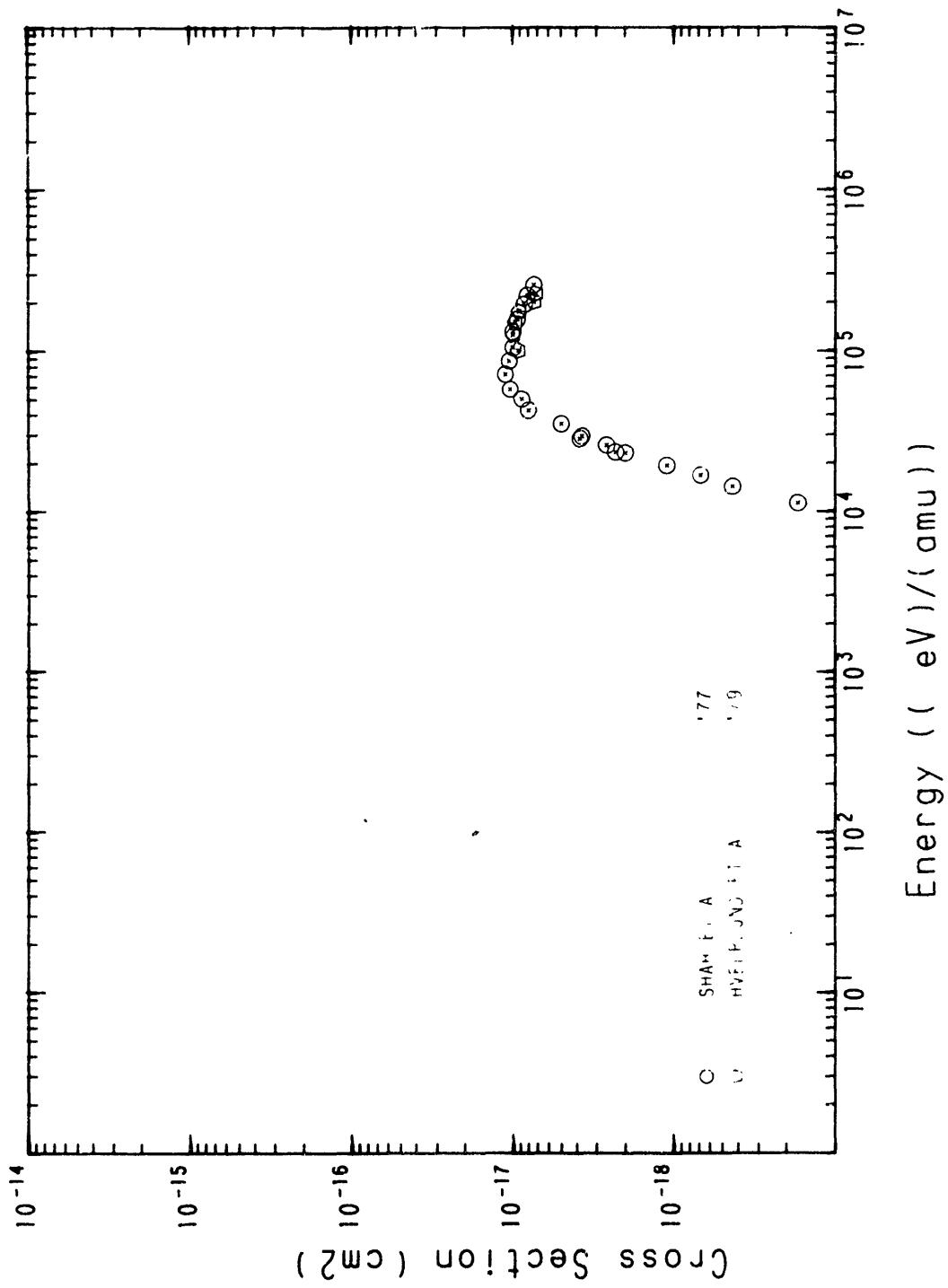


Fig.A13 $\text{He}^+ + \text{H} \rightarrow \text{He}^{2+}$

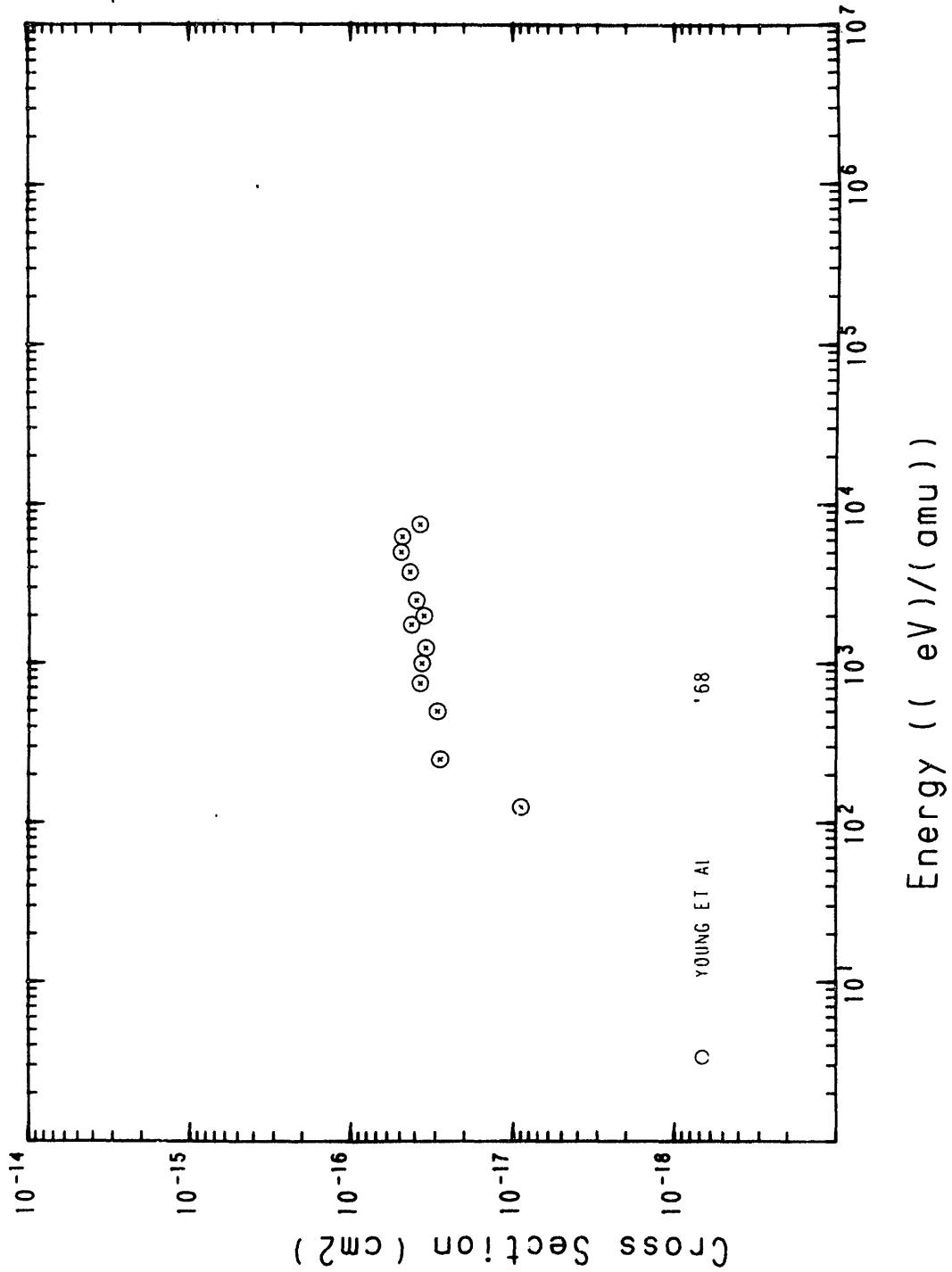


Fig.A14 $\text{He}^+ + \text{H} \rightarrow \text{He}^+ + \text{H}(2\text{p})$

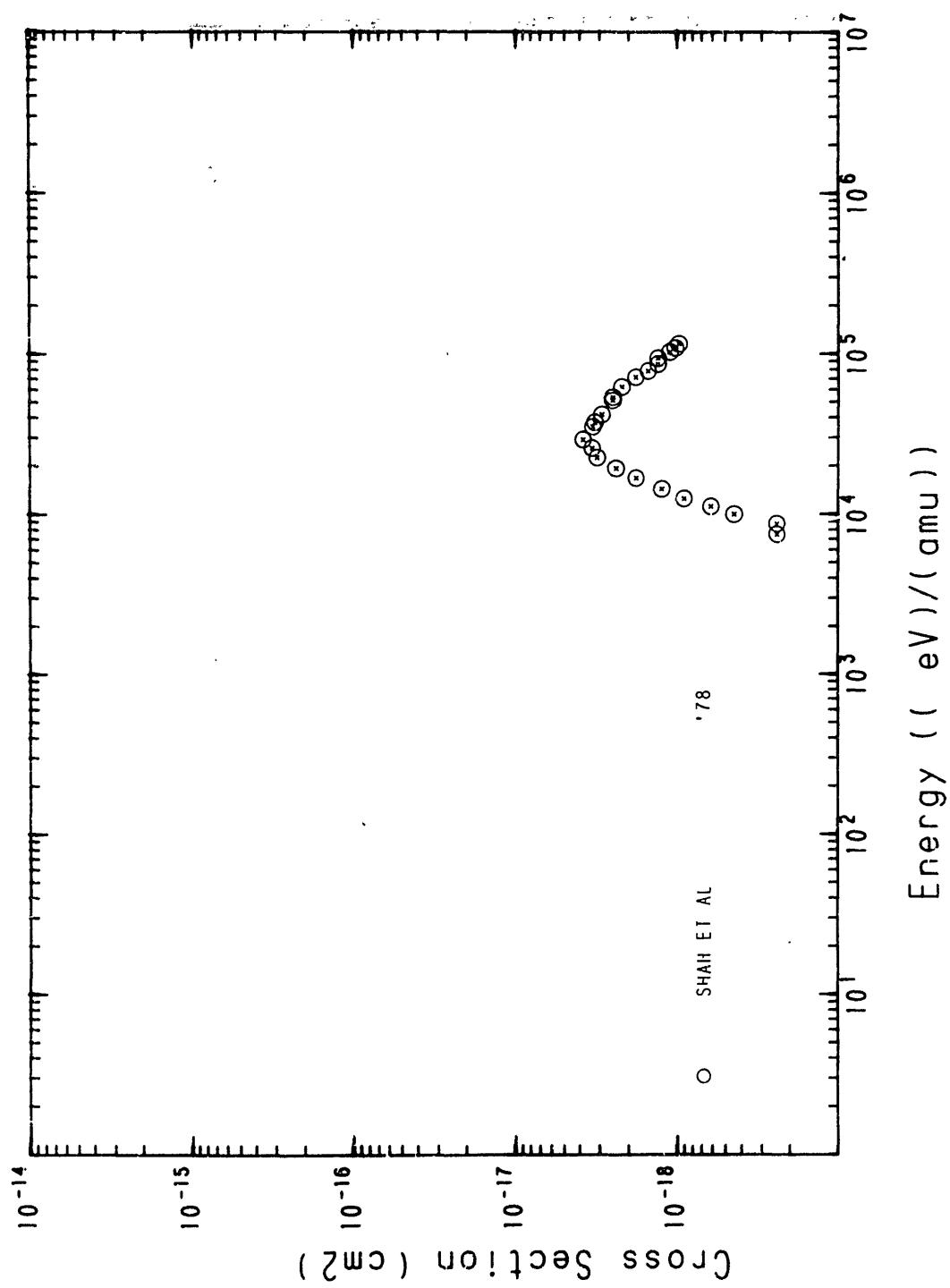


Fig.A15 $\text{He}^+ + \text{H} \rightarrow \text{He}^+(2s)$

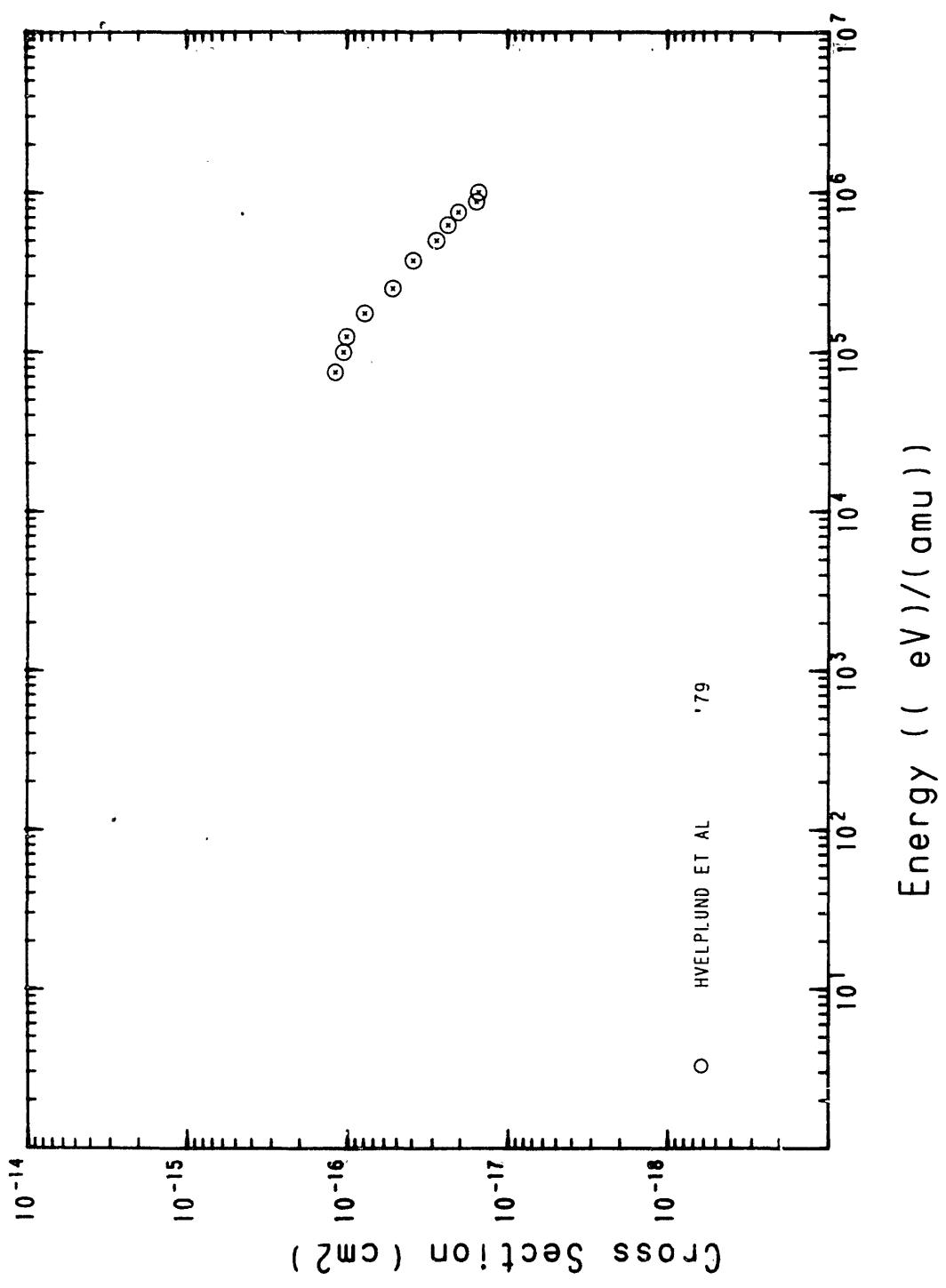


Fig.A16 $\text{He} + \text{H} \rightarrow \text{He}^+$

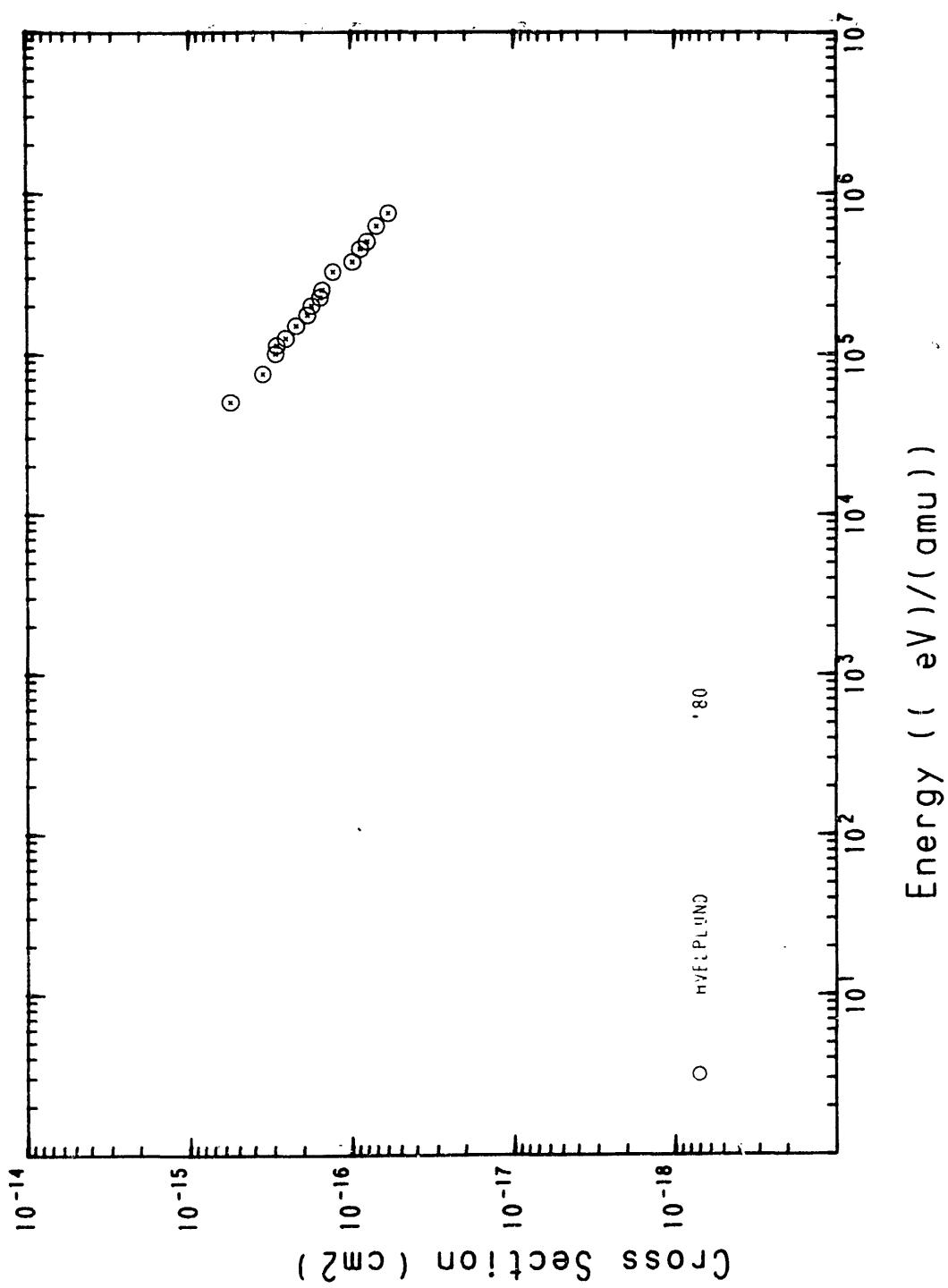


Fig.A17 $\text{He}^- + \text{H} \longrightarrow \text{He}$

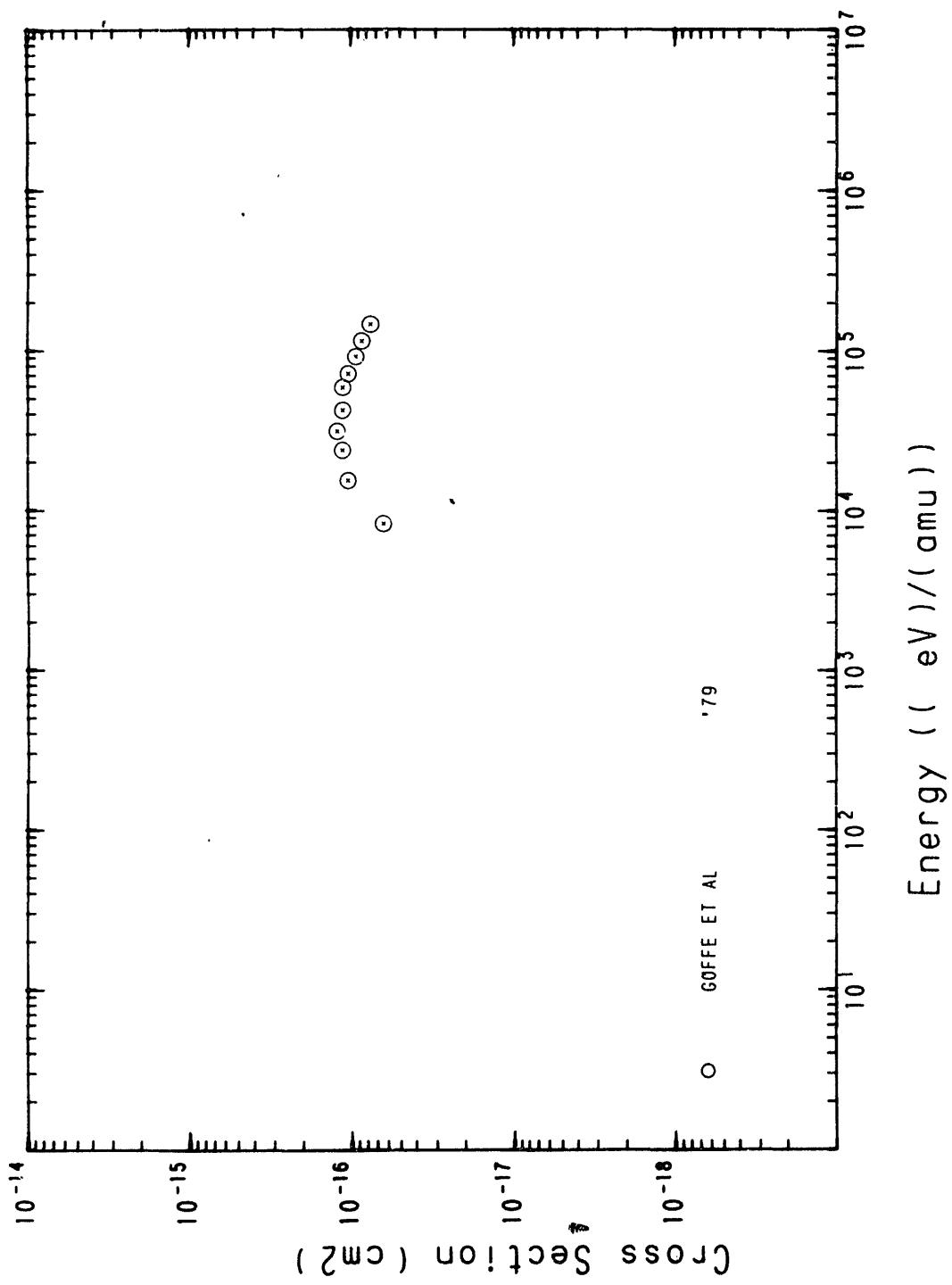


Fig.A18 $\text{C}^+ + \text{H} \rightarrow \text{C}^{2+}$

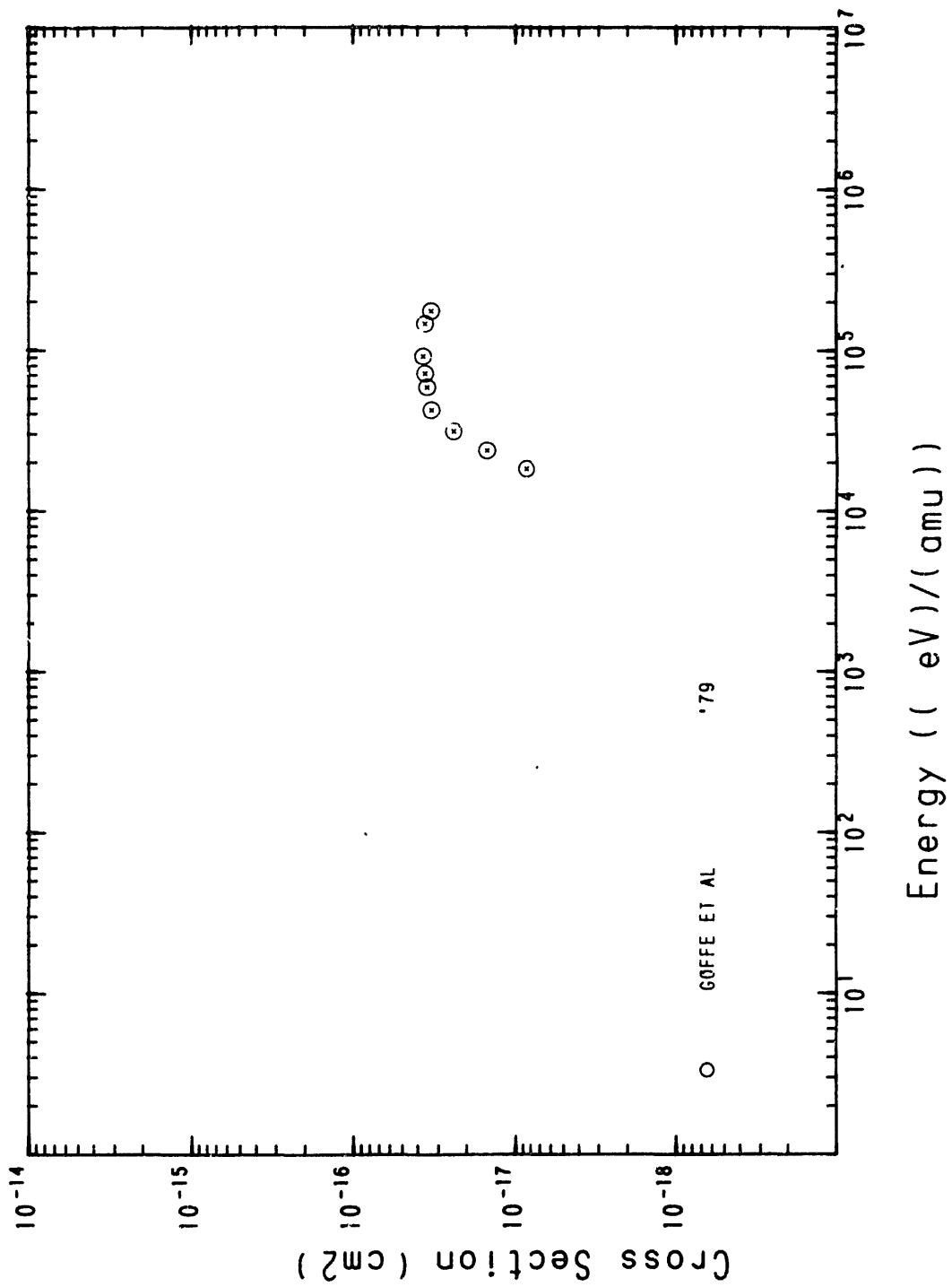


Fig.A19 $\text{C}^{2+} + \text{H} \longrightarrow \text{C}^{3+}$

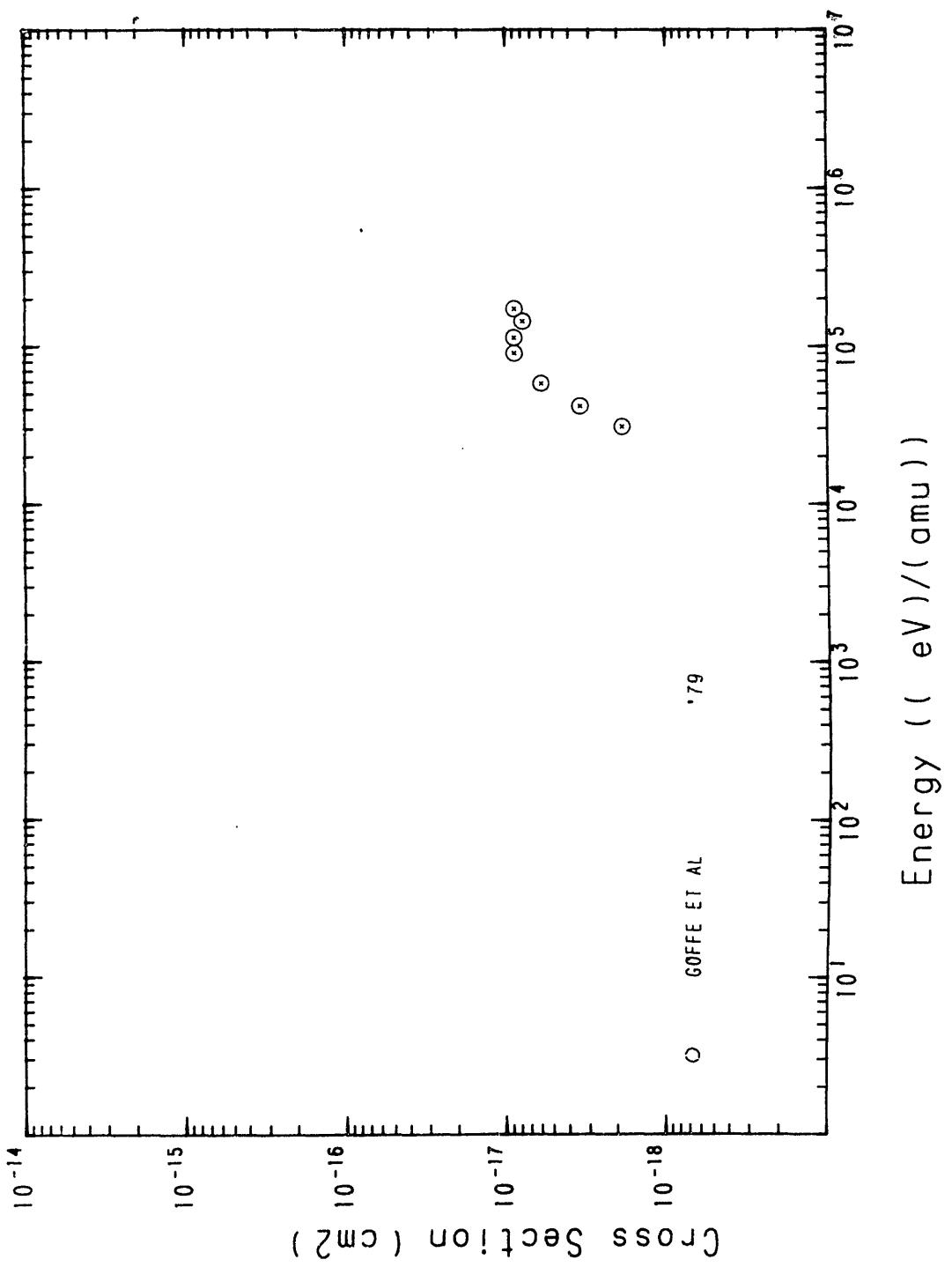


Fig.A20 $\text{C}^{3+} + \text{H} \longrightarrow \text{C}^{4+}$

