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Abstract

We carried out measurements of the excitation function for the reaction $^{45}Sc(p,2n)^{44}Ti$ from 16- to 55 MeV. The results show a discrepancy with the only previous work on the subject. It was also possible to measure the cross-sections for the reactions $(p,pn)^{44}Sc^m$ from 16- to 55 MeV, $(p,pn)^{44}Sc^g$ and $(p,n)^{45}Ti$ from 16- to 22 MeV, and $(p,3pn)^{42}K$ and $(p,3p)^{43}K$ from 40- to 55 MeV.

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The long-lived radioisotope ^{44}Ti has a significant astrophysical interest. The decay chain $^{44}\mathrm{Ti} \overset{(EC)}{\Longrightarrow} {}^{44}\mathrm{Sc} \overset{(EC+\beta^+)}{\Longrightarrow} {}^{44}\mathrm{Ca}$ yields the 1157 keV line that was recently observed by the COMPTEL telescope in the young supernova remnant Cas A [1] and also contributes to the diffuse 511 keV line in the galaxy through β^+ annihilation [2]. ^{44}Ti can also be produced in meteorites through cosmic-ray interactions providing information on solar activity from the cosmic-ray exposure of such objects [3]. Furthermore, the abundance of ^{44}Ca is believed to be determined by the nucleosynthesis of ^{44}Ti and its subsequent decay [4].

One of the important production mechanisms of ^{44}Ti is the ^{45}Sc(p,2n) reaction. There is only one account of the cross-sections for this reaction in the literature [5]. In the present Report, we show the results of our measurements of the excitation function for the reaction ^{45}Sc(p,2n) in the energy range of 16- to 55 MeV. Above 25 MeV, our results are in disagreement with the ones of ref. [5] and lead to a much faster decrease of the excitation function at high energies. We also measured the cross-sections for the following reactions resulting from the bombardment of protons on ^{45}Sc at the corresponding energies: (p,pn)^{44}Sc^m from 16- to 55 MeV, (p,pn)^{44}Sc^g from 16- to 22 MeV, (p,n)^{45}Ti from 16- to 22 MeV, (p,3pn)^{42}K from 40- to 55 MeV and (p,3p)^{43}K from 40- to 55 MeV.

The irradiations were performed in two different cyclotrons. For the lower energies, the cyclotron at IPEN in São Paulo was used. The targets consisted of about 50 mg of Sc^2O_3 enclosed in a 1.2 x 1.2 cm^2 holder of Al foil. They were then fixed to a water-cooled target holder. Irradiations at the energies 16-, 18-, 20- and 22 MeV at the target were performed with duration of 10 min. and at a current of 0.8 μA. The irradiated material was then placed inside a lucite ampoule which was put in front of a HPGe detector for activity measurement. The distance between the source and the detector was kept constant at 8 cm for the longer-lived isotope measurements and 13 cm for the shorter-lived ones. The detector efficiencies were measured in the experimental geometry with standard calibrated sources. We verified that corrections due to the fact that the material under investigation was not as point-like as the calibration sources and due to self-absorption and absorption in the lucite were negligible [6].

At higher energies, the 88" cyclotron at the Lawrence Berkeley National Laboratory (LBNL) was used. There were two different runs at proton energies of 55 MeV and 36 MeV. For each irradiation, a stack of metallic Sc foils with Al degraders in between was used. The scandium targets were each 37.8mg/cm^2 99.9% pure foils obtained from *Alfa Products.* The iron foils were each 78.6 mg/cm^2 99.9975% pure and also obtained from *Alfa Products.* The Al degraders ranged from 250-500 mg/cm^2. Energy losses in the targets and degrader were calculated using the parametrization of Andersen and Ziegler [7]. Also, two Fe foils were put in each of the stacks to act as a beam monitor through the reaction ^{56}Fe(p,n) [8]. The two irradiations were made in such a way that there was an overlap of at least one data point between the 36 MeV run and the São Paulo data and between the 36- and 55 MeV runs at LBNL. The energy of the beam at each target was: 20-, 25-, 30- and 35 MeV for the 36 MeV run and 30-, 35-, 40-, 45-, 50- and 55 MeV for the 55 MeV run. The irradiations lasted 1-2 hours at a current of 1 μA. The beam current was integrated using a BIC current integrator. The Sc foils were later allowed to cool off and then gamma counted off-line in a similar way as above.

Examples of the spectra obtained are shown in figs. 1 and 2 along with the corresponding fits to the 1157 keV line which was chosen for the determination of the residual activities of ^{44}Ti, ^{44}Sc^m, ^{44}Sc^g. In the case of fig. 1, the spectrum was measured one day after irradiation, whereas fig. 2 was obtained approximately two months after the irradiation. The iron monitor foils were also γ-ray counted offline. The observed yields of ^{56}Co from the ^{56}Fe(p,n) reaction were used to calculate the proton fluence through the target stack. In each case, the number derived from the iron monitors and current integrator agreed to within 5%.

The results of the cross-sections of this work are shown in table 1 and figs. 3a-f along with the results of ref. [5] for comparison. The uncertainties assigned to the cross-sections were 15% for the São Paulo data set, obtained from standard propagation of uncertainties (mainly due to detection efficiency and number of counts), which was confirmed by the distribution of results in 4 runs at 20 MeV. For the LBNL data, an uncertainty of 10%

was ascribed by considering uncertainties in efficiency calibration and peak areas. For the points that had an overlap of different runs, an average weighed by the uncertainties was used. The uncertainty in the beam energy was 1 MeV for the IPEN cyclotron due to the degradation at the target holder and inside the target. At LBNL, an uncertainty of 0.25 MeV was ascribed for the degraded energies in the stacked foil runs.

The cross-sections for the (p,2n)^{44}Ti reaction can be seen in fig. 3a. The 1157 keV transition from the decay in equilibrium ^{44}Ti $\Rightarrow$ ^{44}Sc $\Rightarrow$ ^{44}Ca was used for the measurements. It is important to notice that the results for the (p,2n) reaction in fig. 3a and table 1 are based on a value of 46 yr for the half-life of ^{44}Ti, as used by McGee et al. More recent experiments suggest a longer half-life, but to date the correct value of the half-live of ^{44}Ti is still an open question [9].

It can be seen that the present values for (p,2n) are lower than the ones of ref. [5] at the peak and that the peak is shifted by about 5 MeV. There is a good agreement at low energies, which is also consistent with the results obtained by Dmitriev and collaborators [10]. However, we find a much faster decrease of the excitation function at higher energies.

A possible explanation for the high cross-sections obtained by McGee et al is that to determine the ^{44}Ti production cross-sections, they counted only the 511 keV line using NaI detectors and attributed all of the yield to ^{44}Ti decay. Hence, the presence of the other long-lived β^+ emitters could have produced part of the 511 keV line attributed to ^{44}Ti. The fact that they had irradiated a mixture of Cu, Zn and Sc which was chemically separated after the irradiation supports this hypothesis since it increases the possibilities of contamination. In our case, the use of HPGe detectors and the 1157 keV line (fig. 2) circumvents such problems. Furthermore, systematics shows that the full width at half maximum for the excitation functions of (p,2n) reactions is of about 12 MeV [11]. This is consistent with what we observed, $\sim$10 MeV, but is discrepant with the results of ref. [5], $\sim$ 20 MeV.

The reaction (p,pn)^{44}Sc^m was investigated by using both the 1157- and 271 keV lines. The results are presented in fig. 3b and show reasonable agreement between the data obtained in this work and in ref. [5]. The reaction (p,pn)^{44}Sc^g was studied for a small energy interval (fig. 3c). It is also in good agreement with the experimental results of previous works [5,12]. The isomer formation ratio $\sigma(^{44}Sc^m)/\sigma(^{44}Sc^g)$ was close to 0.6 as observed before [5,12,13].

For the reactions $(p,n)^{45}Ti$, $(p,3pn)^{42}K$ and $(p,3p)^{43}K$ (figs. 3d-f respectively) it was not possible to obtain the whole excitation function which complicates comparisons. We notice however a good agreement between our results and the ones reported by McGee et al, with a possible exception for the (p,3p) reaction.

In conclusion, we measured the excitation function for the $^{45}Sc(p,2n)^{44}Ti$ reaction. We observed that its cross-sections are in contrast with a previous work at high energies. We also investigated other reactions that occur through the bombardment of protons in Sc and have seen a reasonable qualitative agreement with previous works.

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TABLE CAPTION

Table 1 - Cross-sections (in millibarns) obtained in this work. The numbers in parentheses are the uncertainties in the present results.

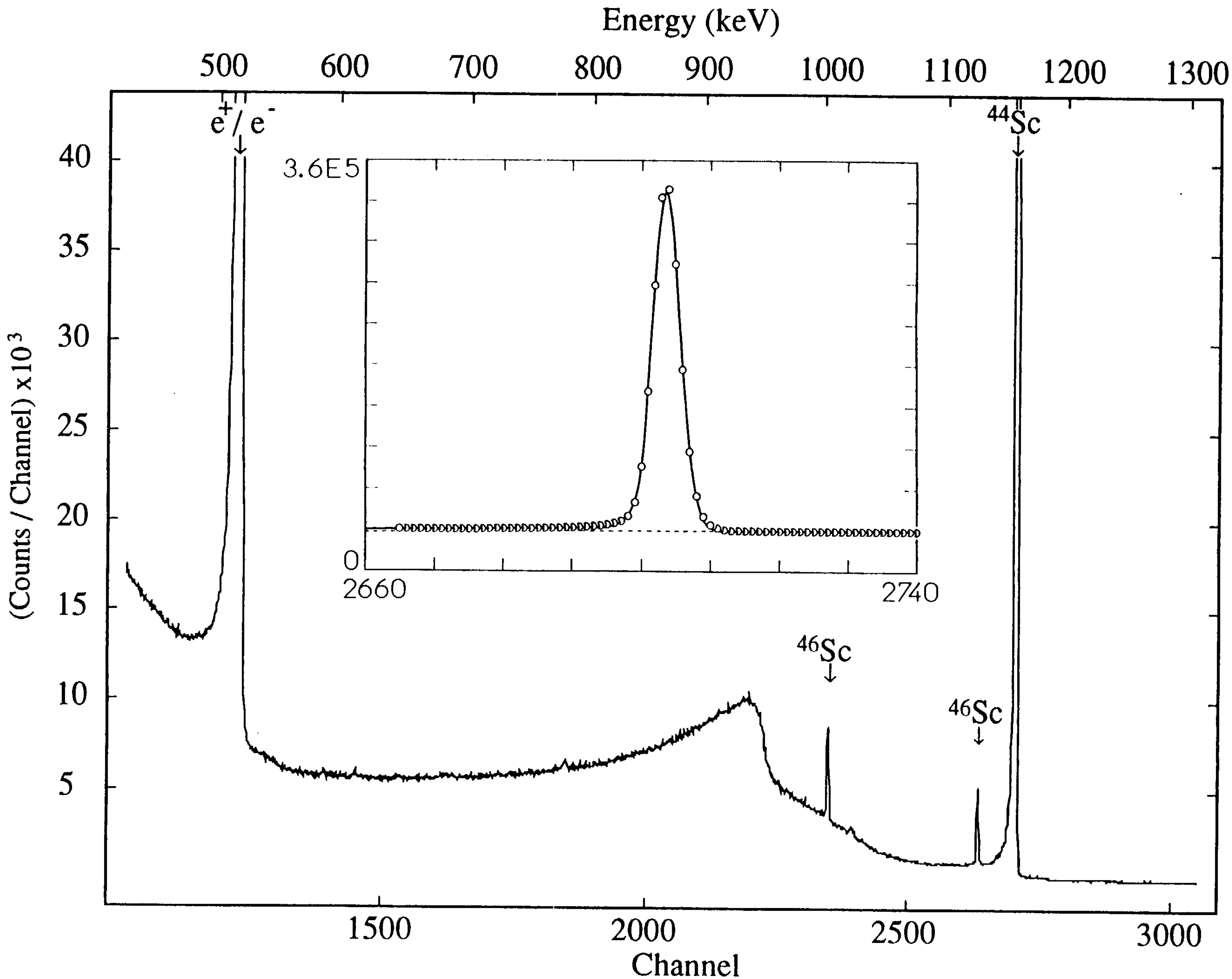
FIGURE CAPTIONS

Figure 1: Gamma-ray spectrum obtained one day after the irradiation with protons of 20 MeV. The most intense lines are identified in the figure. In the inset, a fit to the 1157 keV peak is shown for appreciation.

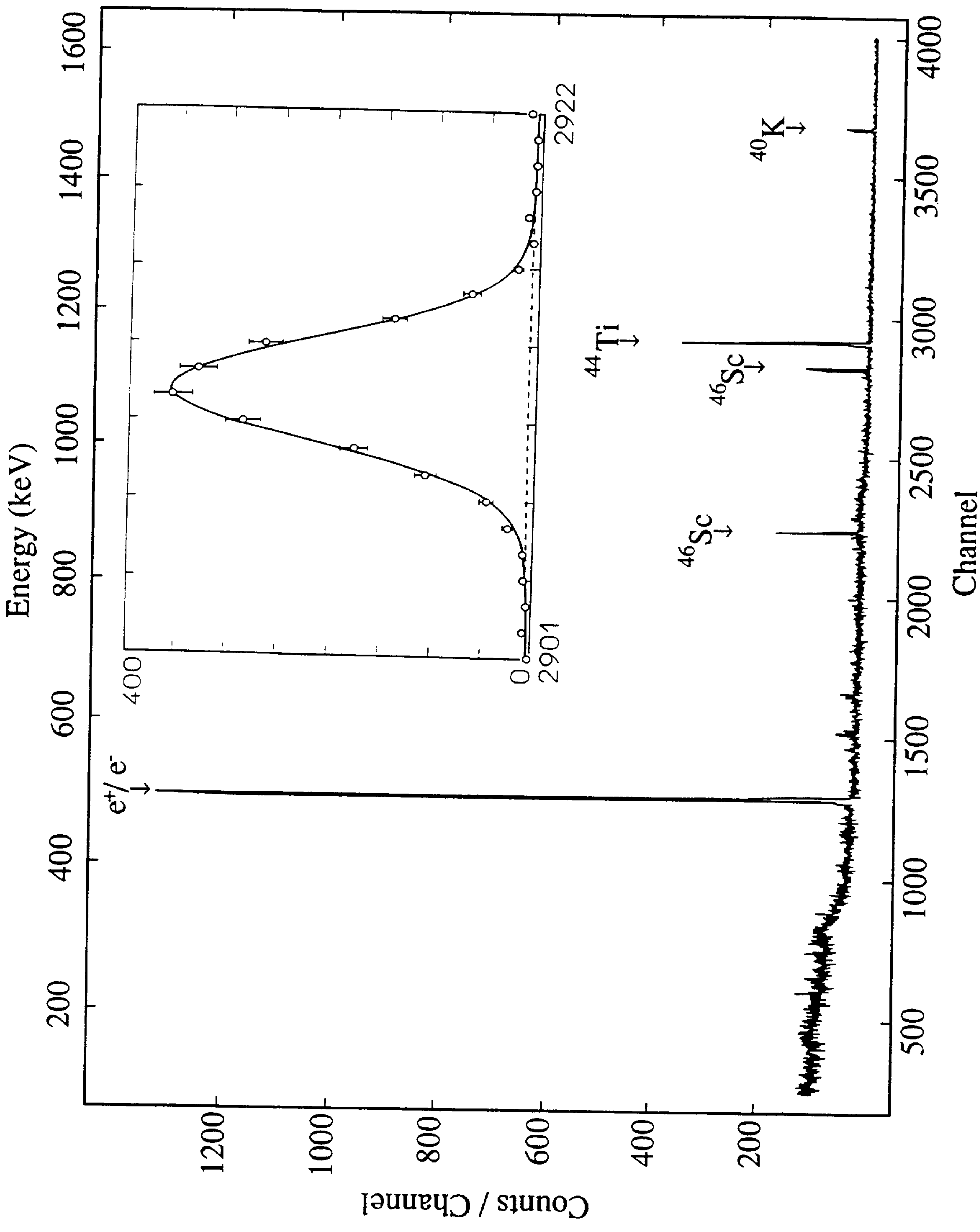
Figure 2: Gamma-ray spectrum obtained approximately two months after the irradiation with protons of 22 MeV. The most intense lines are identified in the figure. In the inset, a fit to the 1157 keV peak is shown for appreciation.

Figure 3: (a) Excitation curve for ^{45}Sc(p,2n)^{44}Ti reaction. (b) Excitation curve for ^{45}Sc(p,pn)^{44}Sc^{m} reaction. (c) Excitation curve for ^{45}Sc(p,pn)^{44}Sc^{g} reaction. (d) Excitation curve for ^{45}Sc(p,n)^{45}Ti reaction. (e) Excitation curve for ^{45}Sc(p,3pn)^{42}K reaction. (f)Excitation curve for ^{45}Sc(p,3p)^{43}K reaction. Our results are represented by solid squares and are compared to the data of ref. [5] (open circles).

E(MeV)	(p,2n)^{44}Ti	(p,pn)^{44}Sc^{m}	(p,pn)^{44}Sc^{g}	(p,n)^{45}Ti	(p,3pn)^{42}K	(p,3p)^{43}K
16	5(1)	9(1)	9(1)	265(40)	-	-
18	17(3)	60(9)	90(14)	191(29)	-	-
20	27(3)	146(12)	190(29)	111(17)	-	-
22	32(5)	131(20)	311(47)	89(13)	-	-
25	19(2)	138(14)	-	-	-	-
30	14(1)	131(9)	-	-	-	-
35	6.7(5)	84(6)	-	-	-	-
40	3.5(3)	60(6)	-	-	0.7(1)	0.14(1)
45	3.7(4)	53(5)	-	-	1.1(1)	0.76(8)
50	2.7(3)	47(5)	-	-	4.8(5)	1.5(2)
55	3.0(3)	44(4)	-	-	8.7(9)	1.6(2)

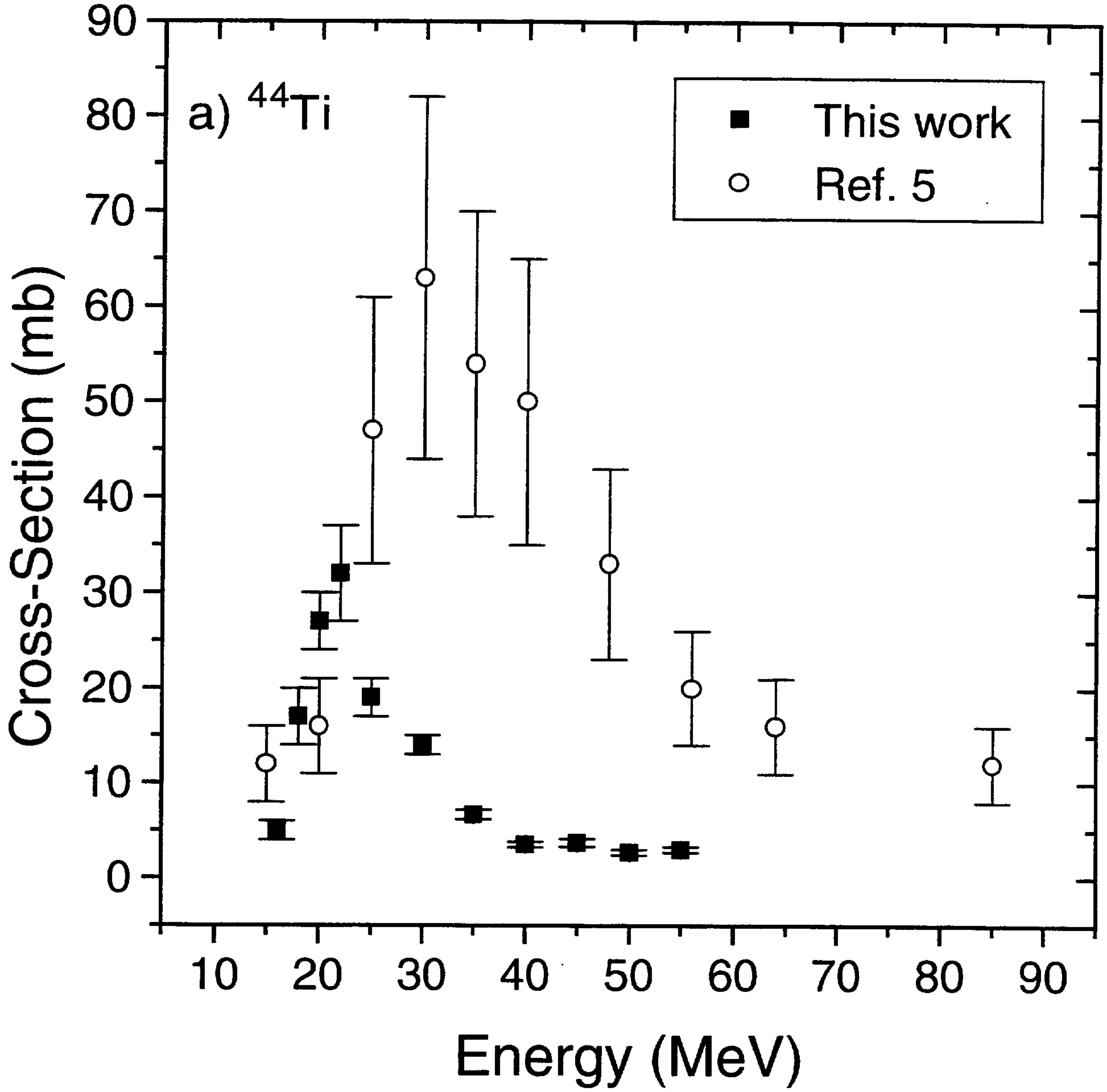


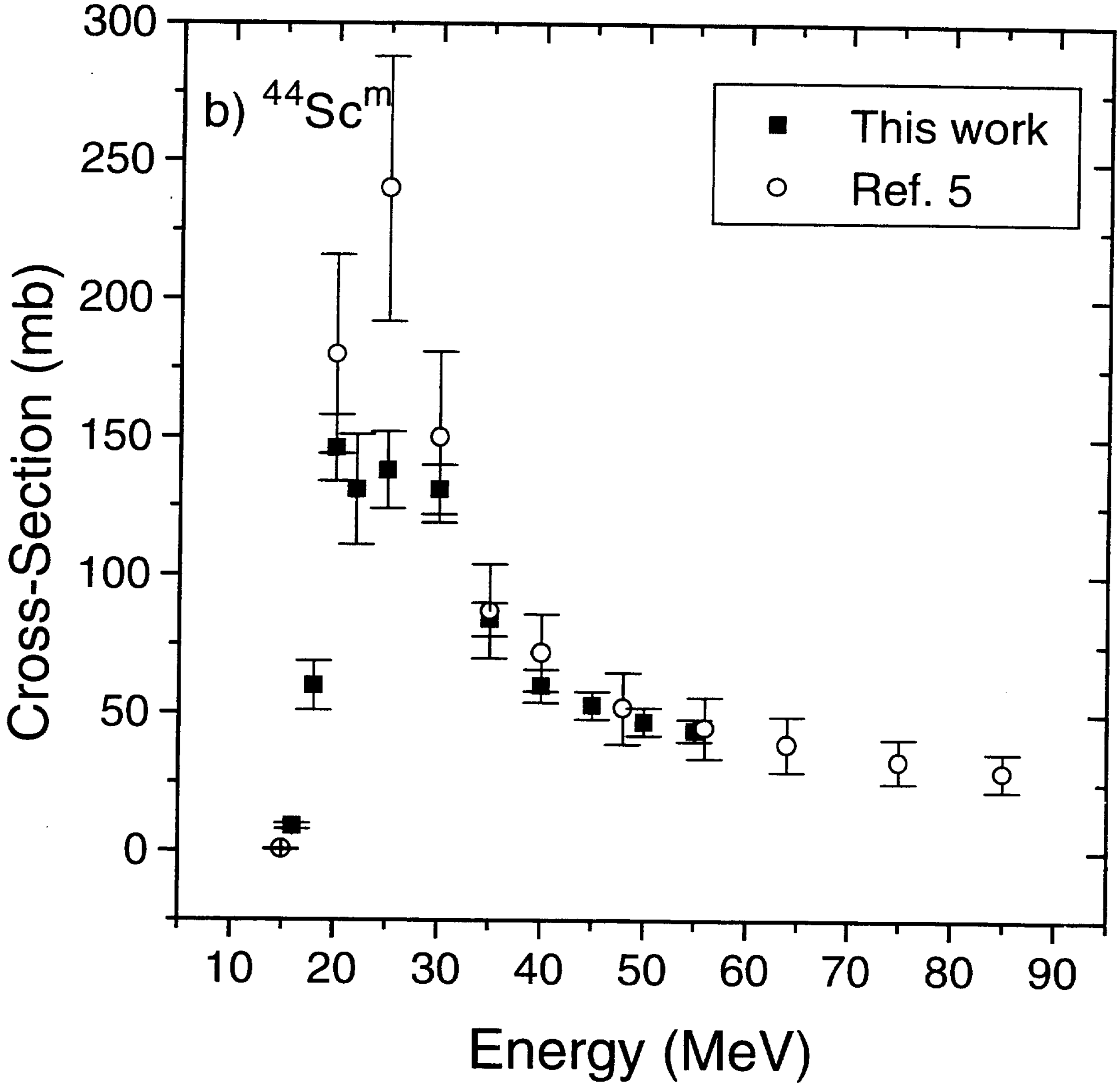
Energy (keV)
500
600
700
800
900
1000
1100
1200
1300
e+/e-
44Sc
46Sc
46Sc
3.6E5
0
2660
2740
40
35
30
25
20
15
10
5
(Counts / Channel) x10^3
1500
2000
2500
3000
Channel



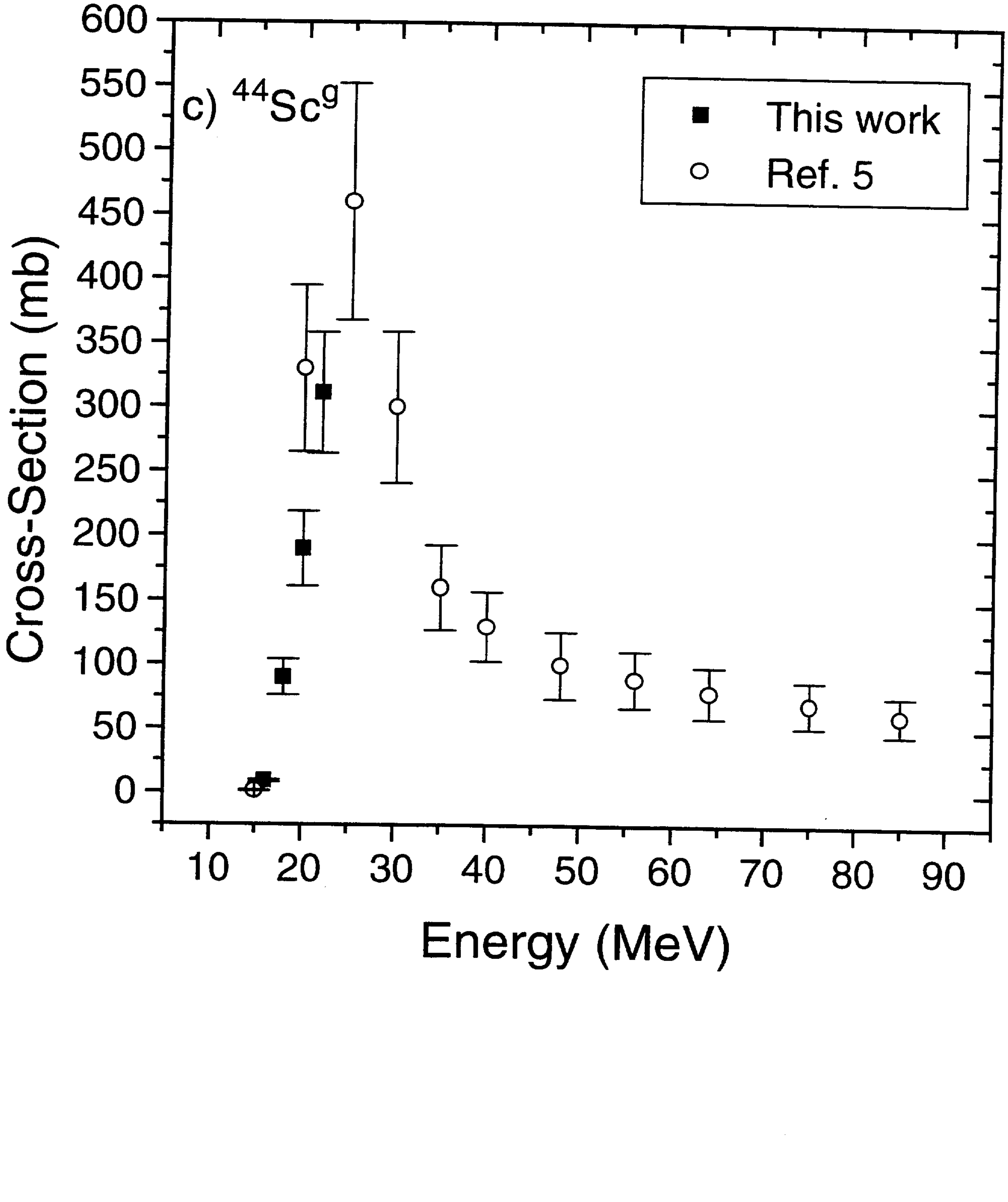
Energy (keV)
200
400
600
800
1000
1200
1400
1600
e+/e-
44Ti
46Sc
46Sc
40K
400
0
2901
2922
Counts / Channel
200
400
600
800
1000
1200
Channel
500
1000
1500
2000
2500
3000
3500
4000

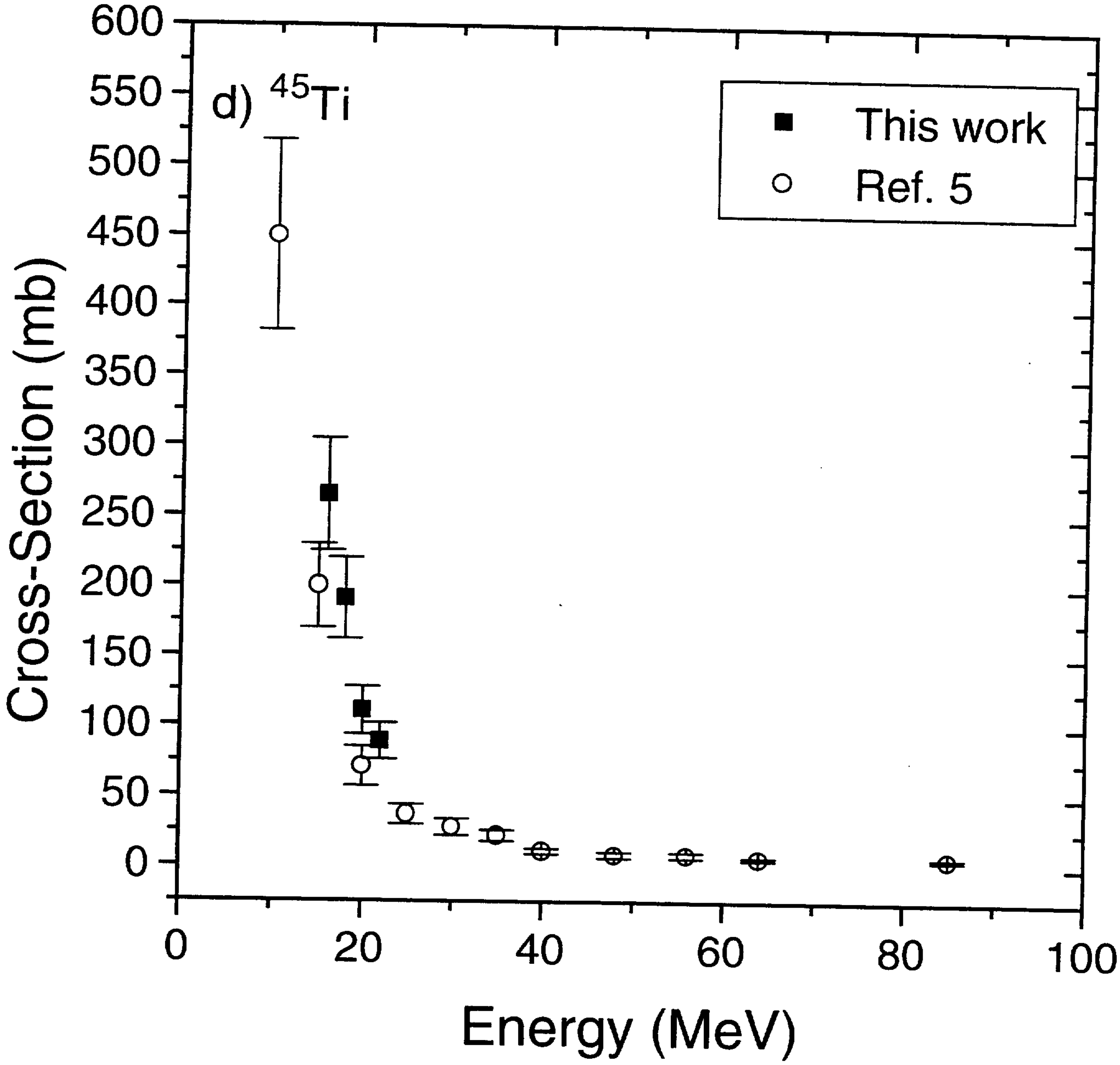
fig. 2


a) 44Ti
This work
Ref. 5
Cross-Section (mb)
Energy (MeV)
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90

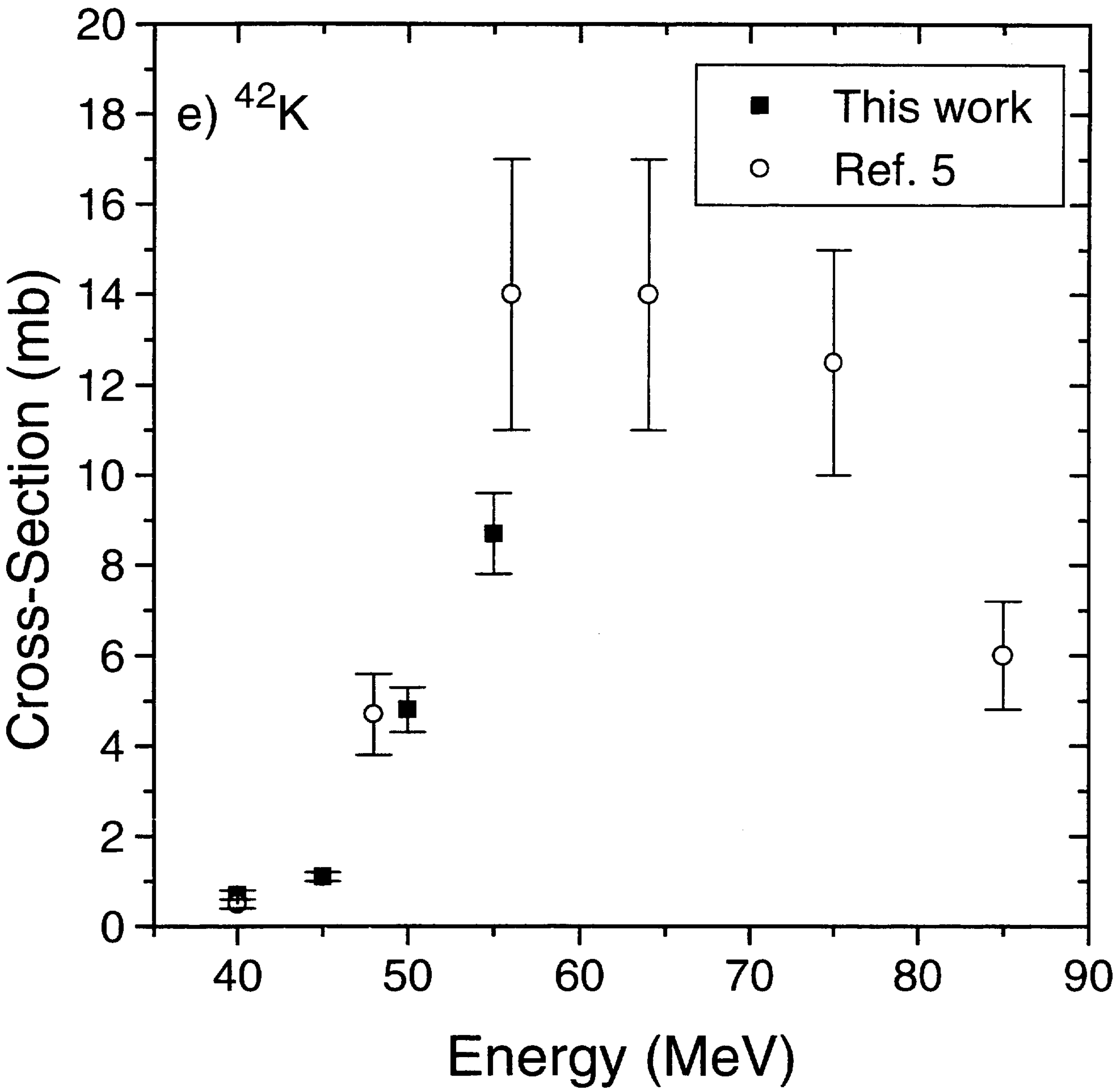


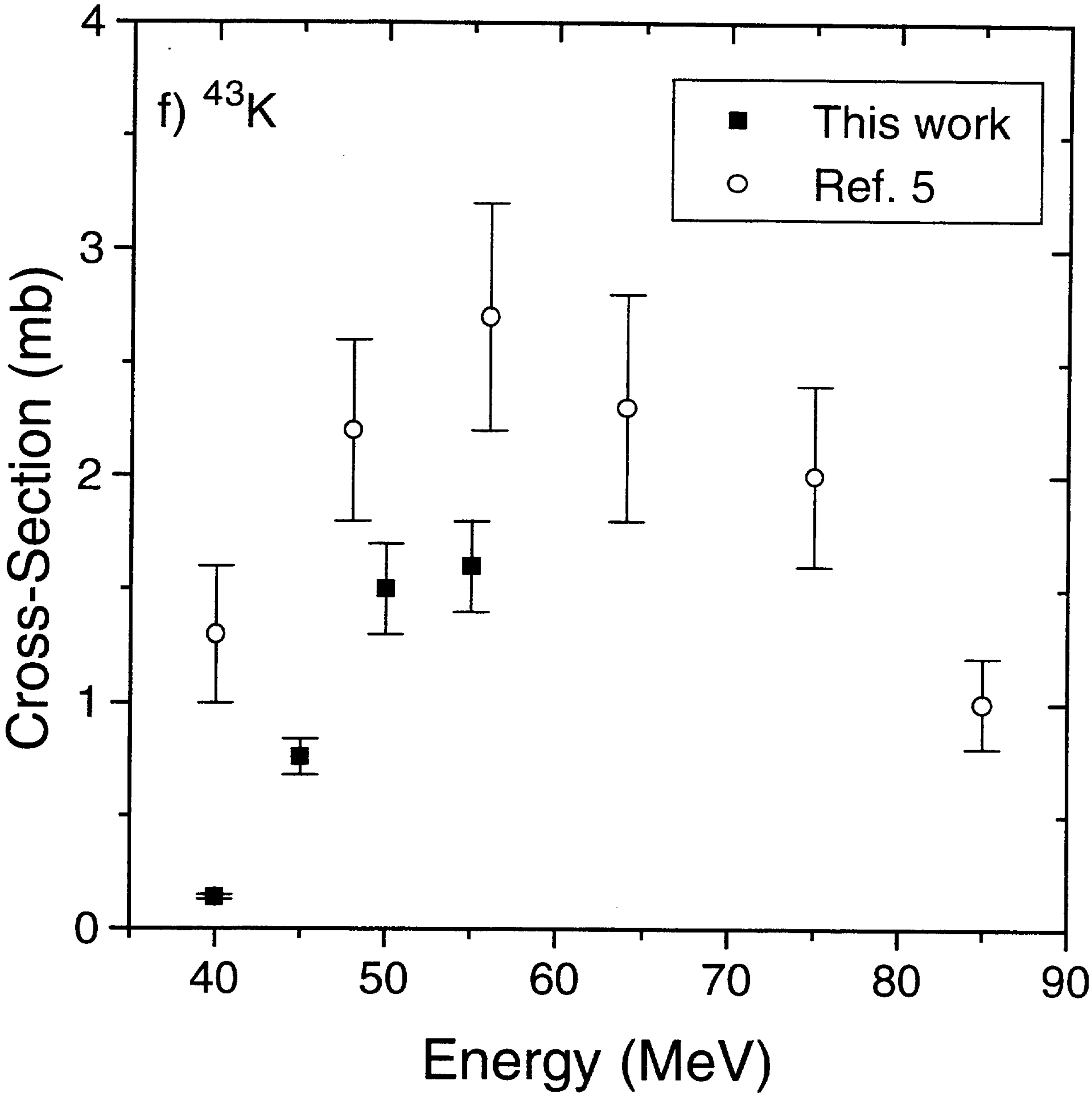
b) $^{44}Sc^{m}$
This work
Ref. 5
Cross-Section (mb)
Energy (MeV)
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90


c) 44Scg
This work
Ref. 5
Cross-Section (mb)
Energy (MeV)
600
550
500
450
400
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90



d) ^{45}Ti
This work
Ref. 5
Cross-Section (mb)
Energy (MeV)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
20
40
60
80
100


20
18
16
14
12
10
8
6
4
2
0
Cross-Section (mb)
e) ^{42}K
This work
Ref. 5
40
50
60
70
80
90
Energy (MeV)



f) ^{43}K
This work
Ref. 5
Cross-Section (mb)
Energy (MeV)
0
1
2
3
4
40
50
60
70
80
90