Title
EXCITATION FUNCTIONS FOR THE 48Ti(p,2p)47Tsc AND 74Ge(p,2p)73Ga REACTIONS ABOVE 0.3 GeV

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DISCLAIMER

CROSS SECTIONS ABOVE 0.3 GeV FOR (p,2p) REACTIONS OF ^{48}Ti AND ^{74}Ge†

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ABSTRACT

Cross sections for the ^{48}Ti(p,2p)^{47}Sc and the ^{74}Ge(p,2p)^{73}Ga reactions were measured from 0.3 GeV to 4.6 GeV incident proton energy. A rise in cross section of about 20% is observed for each reaction in the energy region from 0.3 GeV to 1.0 GeV. Comparisons with four prior cases are made. The present results are compared to (p,2p) cross section calculations up to 1.0 GeV based on a Monte Carlo intranuclear cascade-evaporation model. While the model yields cross sections a factor of 2 greater than the measured experimental values, fair to good agreement is obtained for predicting relative (p,2p) cross section increases.

[NUCLEAR REACTIONS: ^{48}Ti(p,2p)^{47}Sc, ^{74}Ge(p,2p)^{73}Ga
E = 0.3 - 4.6 GeV, measured and calculated σ(E)]

I. INTRODUCTION

Excitation functions for (p,2p) reactions in the GeV energy region on various target nuclei have been studied over several years.[1-3] Since the predominant mechanism for such a reaction involves a "quasi-free" knockout[4] of a target proton, it has been used to illustrate free-pp scattering structure[5,6] in the (p,2p) excitation functions determined by activation.

This work reports the results for (p,2p) excitation functions of ^{48}Ti and ^{74}Ge, both medium mass nuclei amenable to analysis without chemical separation. The purpose of this particular study was to supplement the several prior excitation function studies and gain a more complete notion of the systematic variation of free-particle structure in such reactions. The present results are compared to excitation functions calculated with a Monte-Carlo intra-nuclear cascade-statistical evaporation model, using a code by Harp, et. al.[7] for incident proton energies up to 1.0 GeV.

II. EXPERIMENT

All targets were activated in the internal proton beams of the Lawrence Berkeley Laboratory 184-inch synchro-cyclotron for energies from 0.3 GeV to 0.73 GeV, and the Bevatron for energies from 1.0 GeV to 4.6 GeV. The beam energies at the 184-inch synchro-cyclotron were known to ± 4%, corresponding to a one-inch error in radial placement of the targets and ± 1% at the Bevatron. The targets were prepared by vacuum evaporation of enriched $^{46}TiO_2$[8] (99.13%) and $^{74}GeO_2$[8] (94.5%) to thicknesses of 0.7 - 1.5 mg/cm^2 on 0.0013 cm aluminum foil.

The target stacks as traversed by the proton beam consisted of a 0.005 cm aluminum foil, 3 separate 0.0008 cm aluminum foils, the enriched target layer on the thin aluminum backings and a final 0.005 cm aluminum foil. The first and last thick 0.005 cm aluminum foils held the thinner intermediate foils together. The central 0.0008 cm aluminum foil was used as a beam flux monitor via the $^{27}Al(p,3pn)^{24}Na$ reaction,[9] while the forward and backward 0.0008 aluminum foils acted as guards and compensated for ^{24}Na recoil loss in the monitor foil. When targets of $^{48}TiO_2$ and $^{74}GeO_2$ were run simultaneously, an extra guard and target foil were included in the stack. Typical total stack thicknesses were about 35-40 mg/cm^2.

Irradiation times were for periods of 10-20 minutes. After each run, a 1.25 cm diameter circle was punched from the stack just back of the leading edge. This insured foil alignment. As a check on this alignment, the thick 0.005 cm front and back aluminum foils were counted after each run in an end-window-beta proportional counter. After correcting for recoil losses, the difference in decay rate between the foils was invariably less than 2%. Alignment error was thus ignored.

The desired product nuclei, whose pertinent decay schematics are summarized in Table I, were assayed by γ-counting the target and monitor foils with a 20 cm^2 or 30 cm^3 Ge(Li) detector, coupled to a Victoreen 400 on Northern 1024 channel analyzer. For each detector, the resolution was very nearly 2 keV full width at half-maximum (FWHM) for the 122 keV gamma ray of ^{57}Co. The targets were cooled before counting to allow short-lived interfering activities to decay.

The decay of all photopeaks was followed to two or more half lives of the product ^{47}Sc and ^{73}Ga nuclei. All photopeaks were analyzed by the computer code SAMPO.[10] The resulting decay curves were analyzed by the standard least squares program CLSQ.[11] For all fits, a fixed half life, taken from Table I, was used in obtaining the initial activity of a product at the end of bombardment.

For ^{73}Ga, the 297 keV peak (87%)[13] was chosen for analysis rather than the 326 keV (13%)[13] because of its larger abundance. Often, the smaller 326 keV peak was washed almost completely out, resulting in larger errors in area analysis. Also noteworthy is that ^{67}Ga ($t_{1/2}$ = 78.0h) produced in the reaction on ^{74}Ge emits a γ of 300 keV energy (16%).[12] This was difficult to resolve from the more abundant 297 keV photopeaks, even with the assistance of the computer code. By comparison, however, it comprised about 2% of the area of the larger peak, and its presence was ignored in the early counting.

Because decomposition of the enriched target isotopes during the high temperature vacuum preparation was possible, all targets were spectrophotometrically analyzed. Since this method of determining the content of the target was more accurate than the weighing procedure used in preparing the targets, the values obtained from the analysis were used in calculating the cross sections. Generally, the weighing of the prepared targets agreed to within 10% when compared to the spectrophotometric analysis.

III. RESULTS

The cross sections for the monitor reaction ^{27}Al(p,3pn)^{24}Na used to calculate the reaction cross sections were taken from the review article by Cumming.[9] These cross sections and the reaction cross sections determined in this work are summarized in Table II. The free-particle cross sections are also tabulated for comparison. For the (p,2p) cross section determinations, random errors include 1-2% for photopeak analysis, and about 3% for the spectrophotometric analysis for Ti and Ge. A root-mean-square value of about 3-4% for random errors is in good agreement with the standard deviations of the individual cross sections listed in Table II. Estimates of important systematic errors are 7% for the monitor cross sections, 3-5% for γ - ray detection efficiency, and 1-3% for decay schematics. This brings the combined error in cross section determination to 8-9%. In subsequent discussions, only the random errors are recognized in considering relative cross section changes for a particular target.

The excitation functions for the ^{48}Ti(p,2p)^{47}Sc and the ^{74}Ge(p,2p)^{73}Ga reactions shown are in Figure 1. The datum at 0.16 GeV is taken from Cohen <u>et al</u>.[14] Also plotted for comparison is the total free-pp scattering cross section versus energy.

As seen from Fig. 1 and Table II, quasi-free pp scattering is also observed for these medium mass nuclei. Each (p,2p) excitation function exhibits a slight but significant rise between 0.3 GeV and 1.0 GeV. Because the onset of meson production from inelastic pp collisions is the cause of the marked rise in pp cross sections, such collisions also contribute to the (p,2p) cross sections. Figure 2 illustrates that these collisions are less efficient in producing (p,2p) products by a decrease in the ratio σ(p,2p)/σ(pp) between 0.3 GeV and 1.0 GeV and constant behavior at higher energies.

IV. DISCUSSION

A. Comparison to Other (p,2p) Results

Previously determined (p,2p) excitation functions in the GeV energy region have reflected corresponding changes in free pp scattering cross sections.[1-3] In addition to these studies, we note that the ^{18}O(p,2p)^{17}N reactions has cross sections of 14.5, 30.4, and 25.1 mb at 0.16, 1.0, and 2.8 GeV respectively.[15,16]

In Table III, the ratios of the cross section at 1.0 GeV to those at or near 0.4 GeV for prior and present work are summarized. The increases in relative cross section observed in the present study are in good agreement with those determined by Reeder for the $^{25}Mg(p,2p)^{24}Na$ reaction.[3] We note, however, that although no trend appears obvious, the cross section or "reduced free-pp" ratio has a roughly constant weighted value of 1.39 ± 0.14 for each reaction. This fact may imply that an increasing nuclear surface area, where simple knockout reactions are thought to occur, may nearly compensate for particle attenuation scattering, which would also increase with mass number. Further work on (p,2p) reactions on target nuclei heavier than ^{142}Ce would test this idea.

B. Monte Carlo Calculations

Previous calculations of absolute (p,2p) cross sections for selected target nuclei have employed a Monte Carlo intranuclear cascade-evaporation model.[3,17] To date, the few calculations performed for these reactions have been confined to incident energies less than the meson threshold of about 400 MeV.

As part of this study, (p,2p) cross sections were calculated for ^{48}Ti and ^{74}Ge up to 1.0 GeV incident proton energy using the intranuclear cascade model of Harp, et al,[7] coupled to the evaporation code of Dostrovsky et. al.[18] Because this particular cascade model assumes single (3,3) isobar production and interaction, cross section values above 1.0 GeV, where double isobar formation becomes a possibility, were not calculated. For all calculations in this work, a constant attractive pion-nucleus potential of 25 MeV was assumed, while the process of isobar-nucleon exchange scattering was ignored.

A comparison of the experimental and calculated values is presented in Figures 3 and 4. Included in the plots for contrast are calculated (p,pn) cross sections, which display little change above 0.4 GeV for ^{74}Ge and a marked decrease above 0.3 GeV for ^{48}Ti. Generally, the cascade-evaporation model predicts (p,2p) cross sections that are factors of 1 1/2 and 2 higher than the experimental values for ^{48}Ti and ^{74}Ge, respectively. In spite of this large discrepancy, fair to good agreement is obtained for predicting (p,2p) cross section increases. These calculated cross section increases for ^{48}Ti and ^{74}Ge over the energy region illustrated for each in Figures 3 and 4 are (51 ± 19)% and (21 ± 15)% respectively.

These values compare to experimentally measured increases of (25 ± 4)% for ^{48}Ti and (16 ± 5)% for ^{74}Ge.

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FOOTNOTES AND REFERENCES

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Table I. Decay schematics used in this work for the product nuclei studied.

Nucleus	Half-Life	γ-Energy (MeV)	Fraction of decays leading to γ-emission	Reference
^{24}Na	15.0 h	1.37	1.0	12,13
^{47}Sc	3.43 d	0.160	0.73	12
^{73}Ga	4.9 h	0.297	0.87	12
		0.326	0.13	12

Table II. Reaction cross sections. All free pp cross sections are obtained from Ref. 6, unless indicated otherwise.

Energy (GeV)	$^{48}Ti(p,2p)^{47}Sc$ Individual Cross Sections (mb)	$^{48}Ti(p,2p)^{47}Sc$ Average±s.d. (mb)	$^{74}Ge(p,2p)^{73}Ga$ Individual Cross Sections (mb)	$^{74}Ge(p,2p)^{73}Ga$ Average±s.d. (mb)	Free pp (mb)	Monitor Cross Sections (mb)[b]
0.300±0.012	23.3,22.9,22.8, 22.9,24.5	23.3±0.7			22.5±1.5[a]	10.1±7%
0.400±0.016			19.4,20.2	19.8±0.6	24.0±1.0[a]	10.5
0.520±0.022	27.3,25.5,27.8, 26.9	26.9±1.0			34.0±0.2	10.7
0.730±0.029	27.9,28.4,28.1, 29.5	28.5±0.7	23.9,21.2	22.6±1.9	46.0±0.1	10.8
1.00±0.01	29.4,28.8	29.1±0.4	23.5,22.3	22.9±0.8	47.5±0.1	10.5
1.60±0.02	28.8,28.1	28.5±0.5	21.9,20.7	21.3±0.8	46.4±0.1	10.0
2.80±0.03	26.5,23.9	25.2±1.8	18.8,20.0	19.4±0.8	43.0±0.1	9.2
4.62±0.05	25.4,26.6	26.0±0.8	18.5,16.1	17.3±1.7	40.9±0.1	8.8

[a]Ref. 5.

[b]Ref. 9.

Table III. Ratio of (p,2p) cross section at 1.0 GeV to the cross section at 0.4 GeV for various targets.

Reaction	$\sigma_{1.0}/\sigma_{0.4}$	Reference
free pp	1.98±0.08	5,6
$^{25}Mg(p,2p)^{24}Na$	1.19±0.05	3
$^{48}Ti(p,2p)^{47}Sc$	1.17±0.04	Present Work[a]
$^{57}Fe(p,2p)^{56}Mn$	1.40±0.31	1[b]
$^{68}Zn(p,2p)^{67}Cu$	1.46±0.22	1[b]
$^{74}Ge(p,2p)^{73}Ga$	1.16±0.05	Present Work
$^{142}Ce(p,2p)^{141}La$	1.47±0.13	2

[a] Cross section at 0.4 GeV is interpolated from excitation function.

[b] This ratio represents $\sigma_{0.72}/\sigma_{0.42}$.

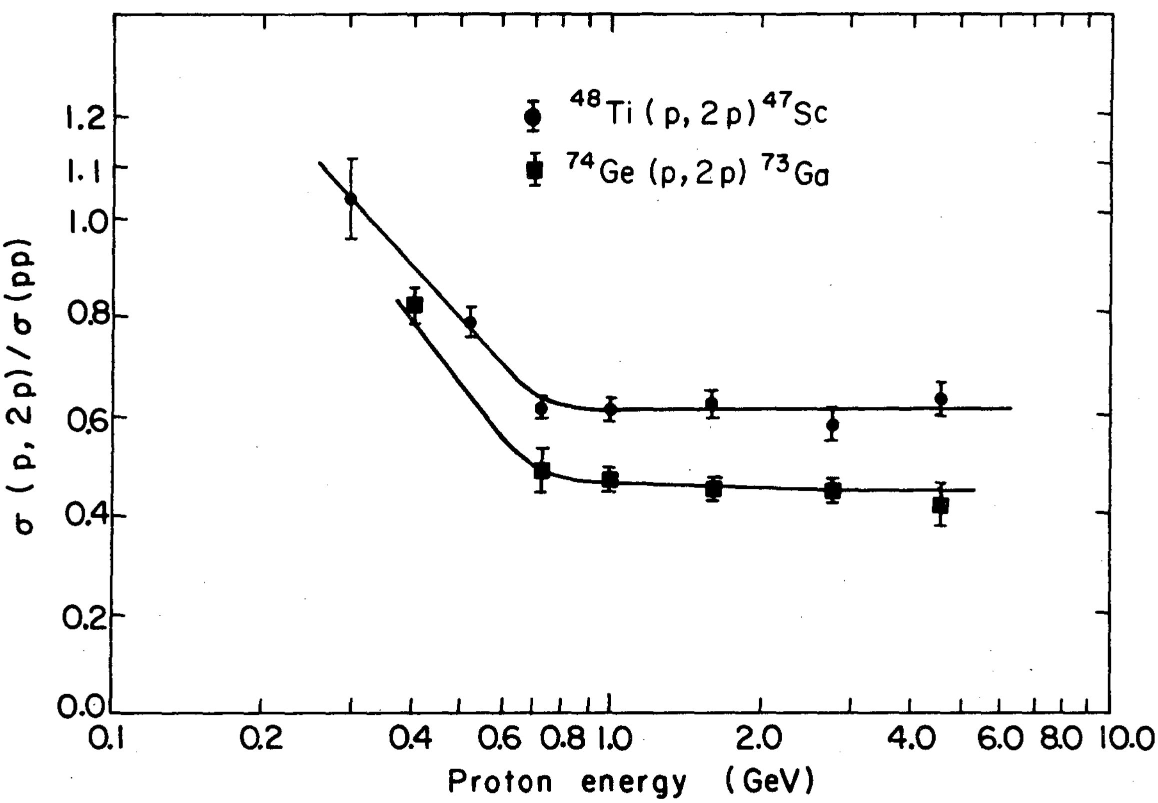
FIGURE CAPTIONS

Fig. 1. Excitation functions for the $^{48}Ti(p,2p)^{47}Sc$ and $^{74}Ge(p,2p)^{73}Ga$ reactions. The open circle at 0.155 GeV is taken from Ref. 14. The total cross section for pp scattering is also plotted for comparison. Below 0.5 GeV, the free-particle curve was taken from Ref. 5, and above 0.5 GeV, the data from Ref. 6 were used.

Fig. 2. Cross section ratios for the $^{48}Ti(p,2p)^{47}Sc$ and $^{74}Ge(p,2p)^{73}Ga$ reactions.

Fig. 3. Calculated and experimental (p,2p) cross sections for the $^{48}Ti(p,2p)^{47}Sc$ reaction. The $^{48}Ti(p,pn)^{47}Ti$ cross sections, calculated using the same model (ref. 7) are also added to the plot for comparison.

Fig. 4. Calculated and experimental (p,2p) cross sections for the $^{74}Ge(p,2p)^{73}Ga$ reaction. The $^{74}Ge(p,pn)^{73}Ge$ cross sections, calculated using the same model (ref. 7), are also added to the plot for comparison.



XBL7312-6999

Fig. 1

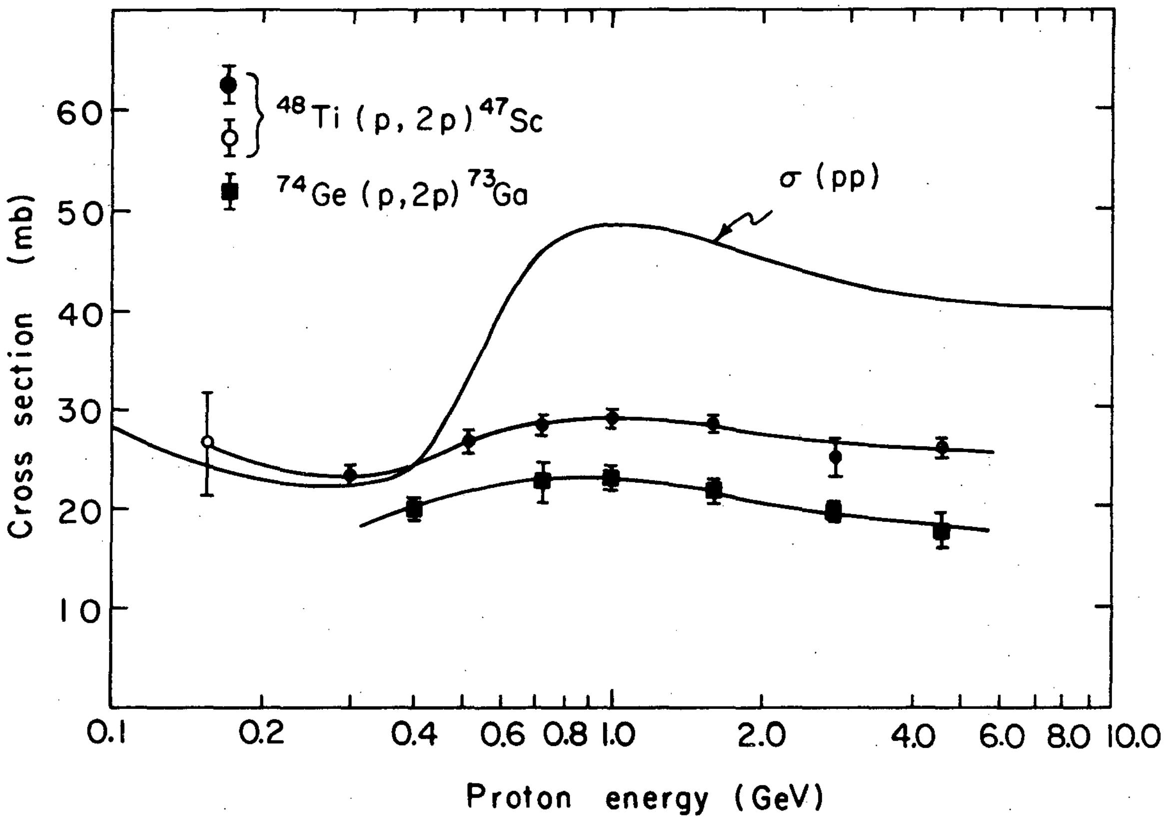


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Fig. 2

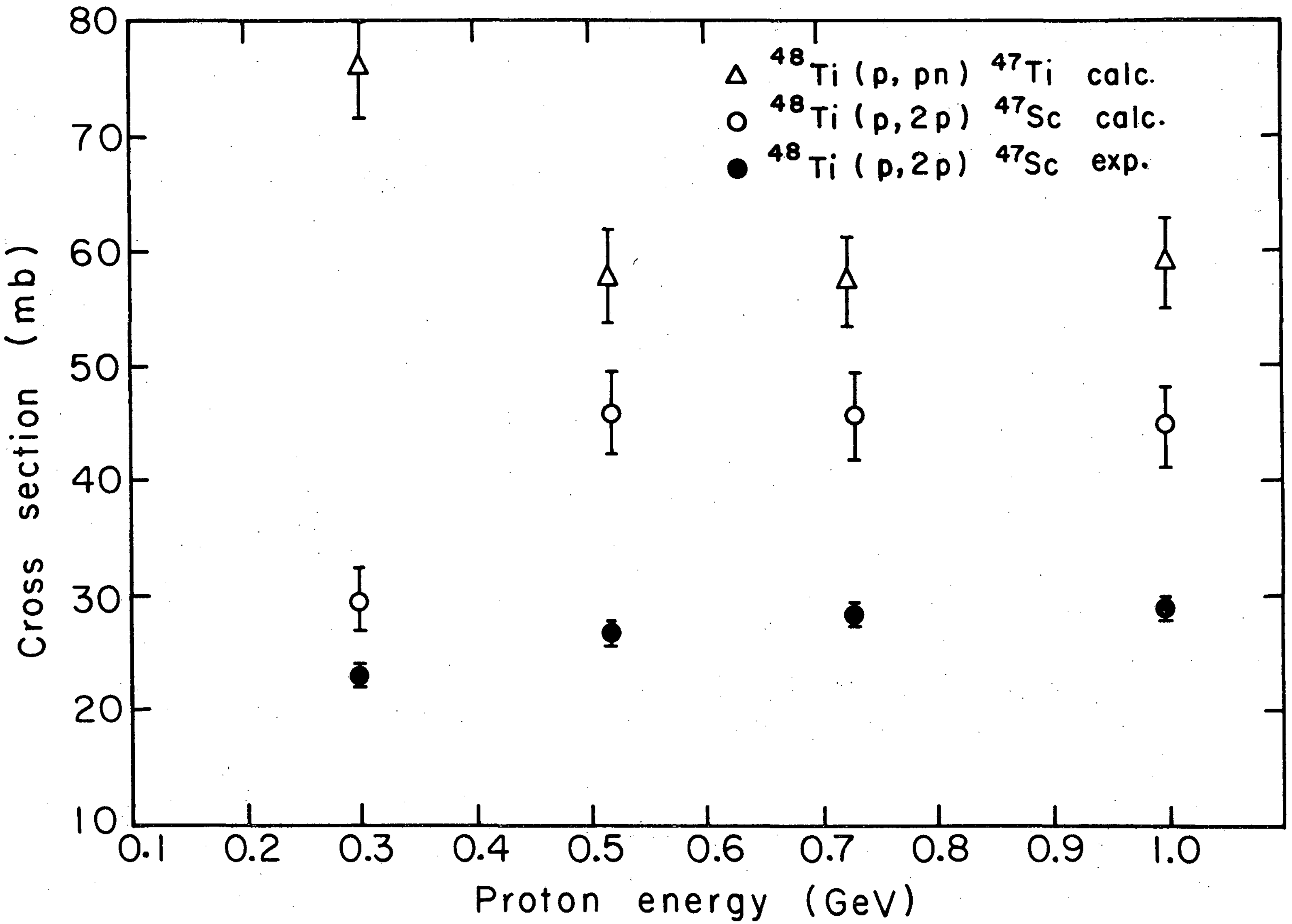

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Fig. 3

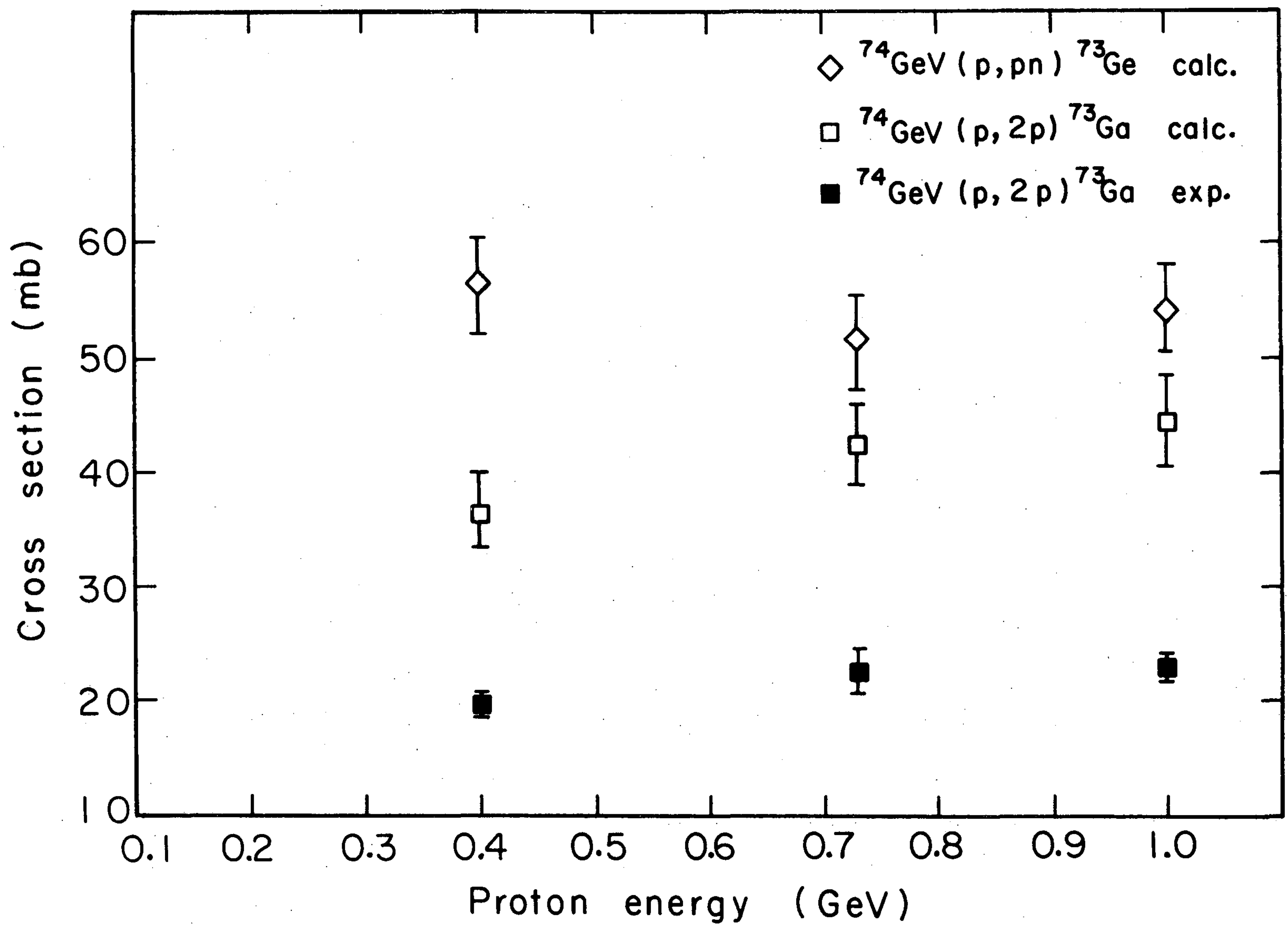

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Fig. 4

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