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Cross Section Measurements in the $^{54}Cr(p,\gamma)^{55}Mn$ Reaction

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ABSTRACT

Cross sections for production of individual γ-rays in the $^{54}Cr(p,\gamma)^{55}Mn$ reaction have been measured over the proton energy range 1.0 to 3.8 MeV. Gamma ray yields are observed to fall by factors of between 5 and 10 at the crossing of the neutron threshold at a proton bombarding energy of 2.2 MeV. Statistical model calculations with global parameter sets successfully account for the dramatic effect of neutron competition on the (p,γ) cross section, and at the same time correctly predict the $^{54}Cr(p,n)^{54}Mn$ reaction cross section.

1. INTRODUCTION

As part of a continuing program in this laboratory of (p,γ) cross section measurements for intermediate mass nuclei (Switkowski et al 1978a, 1978b; Kennett et al 1979; Solomon and Sargood 1979) we have studied the $^{54}Cr(p,\gamma)^{55}Mn$ reaction. The yields of individual γ-rays de-exciting low-lying bound states of ^{55}Mn have been measured for proton energies around the (p,n) threshold. Measurements such as these have provoked considerable interest in recent years especially in those cases where the opening of a new and strongly competing reaction channel introduces an abrupt change in the energy dependence of already open reaction channels. The original report of a spectacular cusp in the energy dependence of the $^{64}Ni(p,\gamma)^{65}Cu$ reaction (Mann et al 1975) has led to further work at Caltech (Zyskind et al 1977, 1978, 1979; Fowler 1976, 1978) in parallel with the present program.

The change in cross section for a nuclear reaction when a competing channel opens can show up as gross structure in an otherwise smooth yield curve which may provide a stringent test for Hauser-Feshbach statistical model codes. Switkowski et al (1978b), and references therein, discuss the importance of such models in current theoretical and technological problems. The most spectacular competition effects occur at the crossing of neutron thresholds for those cases where the daughter nucleus can be readily produced by s-wave neutrons and the total number of open channels is small. Fig. 1. shows a partial energy level scheme for ^{54}Cr + p reactions. Although s-wave neutron emission to the two lowest ^{54}Mn states follows only d-wave proton capture, preliminary calculations by Woosley et al (1975) exhibited a deep cusp in the computed (p,γ) cross section at the opening of the neutron channels. We therefore undertook a study of the $^{54}Cr(p,\gamma)^{55}Mn$ reaction with the aim of comparing the experimental results with the predictions of statistical model calculations using global optical model and level density parameter sets.

At a time near the completion of this work, the results of a similar investigation at Caltech were published (Zyskind et al 1978). The results of the present investigation are compared with these published Caltech data in the text.

2. EXPERIMENTAL DETAILS

2.1 Targets

Targets of chromium metal, approximately 1 mg/cm^2 thick, were prepared, using a technique similar to that of Kuehn et al (1972), by electroplating from a solution containing Cr_2O_3 on to clean surgical grade 0.25mm thick tantalum. The Cr_2O_3 was isotopically enriched in ^{54}Cr to 94.1% (also ^{50}Cr - 0.11%, ^{52}Cr - 4.01% and ^{53}Cr - 1.79%). The target thickness, which was determined by direct weighing of the deposited Cr and was ~ 85 keV at the bombarding energy of the neutron-threshold, was chosen to be thick enough to average over hundreds of compound nucleus resonances (Kailas et al 1975) and yet be thin enough to allow observation of the gross structure of the yield curve, namely the cusp.

The target thickness was shown to be macroscopically uniform to 3% from observations of the 1529 keV γ-ray yield from the ^{54}Cr(p,γ)^{55}Mn reaction during a scan of the target with a 2 MeV proton beam collimated to 2mm diameter. However, inspection of the target surface with an optical microscope suggested a non-uniform grainy topology of characteristic linear dimension near 100μm. This microscopic roughness was attributed to the pretreatment of the Ta substrate by sandblasting which had been found essential in order to ensure good adhesion of the electroplated Cr.

As it was considered prudent to perform several independent analyses of target thickness including use of Rutherford backscattering, an alternative target making scheme, suitable for the fabrication of uniform thin Cr films on flat substrates was used.

To this end, spectroscopic grade elemental Cr of natural isotopic composition (and ^{54}Cr constitutes 2.36%) was evaporated from a tungsten boat on to a cleaned smooth Ta substrate. The thickness of this target, which was verified to be optically smooth, was determined from the mass difference before and after evaporation to be $1070 \pm 70 \mu g/cm^2$. This target was then bombarded by 3 MeV protons and the thickness inferred from the backscattered ($\theta = 140^\circ$) spectrum by analyzing the backscattered proton peak area and also the shift in the Ta edge when compared with a standard Ta target. From those analyses, the Cr thickness was found to be $950 \pm 100 \mu g/cm^2$, in good agreement with the more precise mass difference value which was then adopted. It should be noted that investigation of the target composition by backscattering of protons as well as of 4 MeV α-particles indicated no evidence of oxygen, or other light elements, at levels sufficient to invalidate this analysis procedure.

This natural Cr target was used to obtain absolute $^{54}Cr(p,\gamma)$ cross sections as will be described subsequently.

2.2 Yield Curve Measurement

The ^{54}Cr - enriched target and a quartz disk for beam inspection were mounted on a linear motion drive and contained within a stainless steel chamber which was maintained at a pressure near 10^{-8} Torr by ion pumping. Proton beams were delivered by the University of Melbourne

5U Pelletron accelerator and impinged on the target at normal incidence. The proton beam spot was collimated to a diameter of 2mm and the beam current was typically 100nA. An open-meshed earthed grid was mounted between the last aperture of the collimator and the target and any secondary electrons were suppressed by voltages of 600V and 630V on the aperture and target respectively.

Gamma rays resulting from the target bombardment were viewed with a 60 cm^3 Ge(Li) detector, 2 cm from the beam spot in the 90° direction. Low energy γ-rays resulting from the Coulomb excitation of the Ta backing were attenuated by 4 mm of lead mounted on the face of the detector. The (p,γ) excitation function was measured over the energy range 1.0 to 3.8 MeV in 50 keV steps. At each bombarding energy, spectra were recorded, for 100μC of incident charge, with a 4096 channel ADC and PDP 11/40 computer and were stored on magnetic tape for off line analysis.

In a separate series of runs on the natural Cr target of calibrated thickness, γ-ray spectra were acquired for the same target-detector configuration at proton energies of 1.9, 2.0, 2.1 and 2.2 MeV for an incident charge of 1300μC per point. Although the γ-ray spectrum was complex owing to reactions with other, more abundant, Cr isotopes, the 1529 keV photopeak, characteristic of $^{54}Cr(p,\gamma)$ reactions, was unambiguously resolved and its area could be determined to a statistical precision of ± 6%. Following a measurement of Ge(Li) detector efficiency using calibrated sources, the absolute 1529 keV γ-ray production cross section was readily determined as the target thickness was known. The relative yield measurements with the enriched ^{54}Cr target were then normalised to the absolute 1529 keV γ-ray production cross section.

3. RESULTS AND DISCUSSION

A γ-ray spectrum typical for bombarding energies below the (p,n) threshold for ^{54}Cr is shown in Fig. 2. The spectrum is characterised by a multiplicity of photopeaks most of which may be positively identified with ^{54}Cr(p,γ)^{55}Mn reactions. Strong lines are also evident for proton induced reactions on the 4% ^{52}Cr and the ubiquitous ^{23}Na(p,p'γ)^{23}Na reaction arising from Na contamination in the electrodeposited target. Cross section as a function of energy is plotted in fig. 3 for four of the stronger ^{54}Cr(p,γ) reaction γ-rays. These γ-rays correspond to transitions between low-lying bound states of ^{55}Mn (see Fig. 1). The 1529, 1885 and 2565 keV γ-rays are the final stages of cascades from ^{55}Mn resonances populated by proton capture; the 900 keV γ-ray is the transition between the 2429 and 1529 keV states. It is anticipated that these γ-rays will have highly damped angular distributions arising from the summation over many resonances, each of different J^{π} and cascade structure, and that these angular distributions will be further attenuated by the large solid angle subtended by the Ge(Li) detector. The uncertainty in the present data is estimated to be ±15%.

The excitation functions for the individual γ-rays exhibit similar features. As the proton energy is increased up the Coulomb barrier, the cross sections increase rapidly until the first (p,n) threshold is reached near E_p = 2.2 MeV. Thereafter the cross sections plummet, falling by factors of up to 10 for an increase of proton energy of only several hundred keV. Such dramatic threshold phenomena have been seen in some other (p,γ) reactions, particularly ^{64}Ni(p,γ)^{65}Cu (Mann et al 1975) and have been somewhat inaccurately labelled "Wigner cusps" as a result of Wigner's pioneering calculations (Wigner 1948) which, however, addressed phenomena involving only isolated resonances, (W.A. Fowler, private communication).

An interesting feature of the experimental data is the structure in the form of three peaks near E_p = 2.0, 2.3 and 2.6 MeV. The experimental widths of these peaks appear to reflect only the energy thickness of the target. These peaks are attributed to the influence of the lowest $T = \frac{7}{2}$ states in ^{55}Mn which carry the isobaric analogue strength of the ground state, first excited state and third excited state of ^{55}Cr, with J^{π} values of $\frac{3}{2}^-$, $\frac{1}{2}^-$ and $\frac{3}{2}^-$ respectively. The $T = \frac{7}{2}$ states in ^{55}Mn would be expected to have much larger proton widths to the ground state of ^{54}Cr than would the $T = \frac{5}{2}$ states in which they are embedded. Consequently these isobaric analogue resonances (IAR), previously identified by Moses et al (1971), should be conspicuously superimposed upon a smoothly varying (p,γ) compound statistical yield. The analogue of the second excited state of ^{55}Cr would also be expected to have a large proton reduced width but, since it has $J^{\pi} = \frac{5}{2}^-$ or $\frac{7}{2}^-$ (Bock et al 1965), f-wave proton capture would be needed to populate it, whereas the other three states are populated by p-wave proton capture. Accordingly, no structure is seen corresponding to this state. The decays of the two IAR's at energies above the neutron threshold differ from the decay of the sub-threshold resonance because, in the absence of isospin mixing, neutron emission from the $T = \frac{7}{2}$ states to the ground and low-lying states of ^{54}Mn, which have T = 2, is isospin forbidden. The γ-ray yield from the $T = \frac{5}{2}$ states is therefore depleted much more by the opening of the neutron channels than is that from the $T = \frac{7}{2}$ states. Hence a $T = \frac{7}{2}$ state may provide a larger fraction of the total γ-ray yield just above the neutron threshold than does one just below. In the statistical model calculations, such as described in the following section, it is customary to assume complete isospin mixing, thereby making no distinction between $T = \frac{5}{2}$ and $T = \frac{7}{2}$ states.

Zyskind et al (1978) have published an excitation function for the 1529 keV and 2565 keV γ-rays in addition to a total (p,γ) cross section curve, over an energy range similar to that covered by the present experiment. A comparison of the respective yield curves shows excellent agreement in absolute magnitude and correspondence between fine and gross structure.

4. STATISTICAL MODEL

The aim of the present study has been to compare the predictions of Hauser-Feshbach statistical model calculations with experimental data for a reaction characterized by a large threshold effect. Full details of the calculations performed in this laboratory with the computer code Hauser *4 are given in Mann (1976), Switkowski et al (1978b) and Christensen et al (1977). The parameters which enter into such a calculation include optical potentials and level densities. As described in Switkowski et al (1978b), only global parameter sets are used and no adjustments are performed in order to optimize fits. Such an approach is motivated by the realisation that extensive statistical model calculations often need to be performed in stellar nucleosynthesis networks where it is sensible to rely on only a single global set of parameters.

Inspection of the level scheme of Fig. 1 also shows that the data available for discrete levels are sufficient for the calculated results to be insensitive to the details of the level density parametrisation which is turned on in the code once discrete level information is exhausted. All calculations include width fluctuation corrections (Tepel et al 1974, Fowler 1978).

A distinctive feature of Hauser *4 is its ability to compute the cross sections for the production by the (p,γ) reaction of individual γ-rays once branching ratio data are included (Mann and Schenter 1977, Mann 1976). The results of such statistical model calculations with global parameter sets are shown by the solid curves in Fig. 3. The agreement between theory and experiment is impressive with the theory following the experimental data over the cross section range 2-300μb to within a factor of 2. Similar correspondence for the total (p,γ) cross section has also been noted (Zyskind et al 1978).

In view of the success of the model in predicting the effects of neutron competition on the (p,γ) yield, it is interesting to compare the predicted (p,n) cross section with the results of experiment. A detailed (p,n) excitation function has been reported by Kailas et al (1975) and their data, which have been smoothed for convenience of presentation, are represented by the dashed curve in Fig. 4. The statistical model predictions, shown by the solid curve, reproduce the data rather well.

In summary, the Hauser Feshbach statistical model code Hauser *4, using global parameters, successfully describes (p,γ) and (p,n) reactions for ^{54}Cr at proton energies around the (p,n) threshold. There are now emerging systematics which attest to the accuracy of such model calculations for proton induced reactions on intermediate mass nuclei. (Fowler 1978). Further experimental tests of the statistical model may now begin to address the hitherto neglected group of reactions including an α-particle in either entrance or exit channel.

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FIGURE CAPTIONS

Fig. 1 Partial energy level scheme for the ^{54}Cr + p system. The reaction Q-values (in MeV) relative to the entrance channel are shown in parentheses. All other energies are in keV. Cross hatching indicates energy regions of high level density.

Fig. 2 Portion of a γ-ray spectrum taken at a proton bombarding energy of 2 MeV. The spectrum was acquired for a integrated current of 100μC. Every eighth channel is plotted except near the peaks where the channel with maximum counts is also shown. Gamma-ray peaks at 378, 835, 1440 and 1619 keV arise from p-induced reactions on the 4% ^{52}Cr in the target. The 440 keV line is produced by the contaminant $^{23}Na(p,p'\gamma)$ reaction. All other photopeaks labelled by their energies in keV are attributed to the $^{54}Cr(p,\gamma)$ reaction. Excitation functions for the shaded peaks are shown in Fig. 3.

Fig. 3. Energy dependence of the cross section for some γ-rays from $^{54}Cr(p,\gamma)^{55}Mn$. Each excitation function is labelled by the relevant γ-ray energy. Where shown, error bars reflect statistical uncertainties. Curves are the results of statistical model calculations described in the text. The first (p,n) threshold occurs at E_p = 2.20 MeV.

Fig. 4. Cross section of the $^{54}Cr(p,n)^{54}Mn$ reaction. The dashed curve represents the trend of the experimental data of Kailas et al (1975). The solid curve is a statistical model calculation as described in the text.

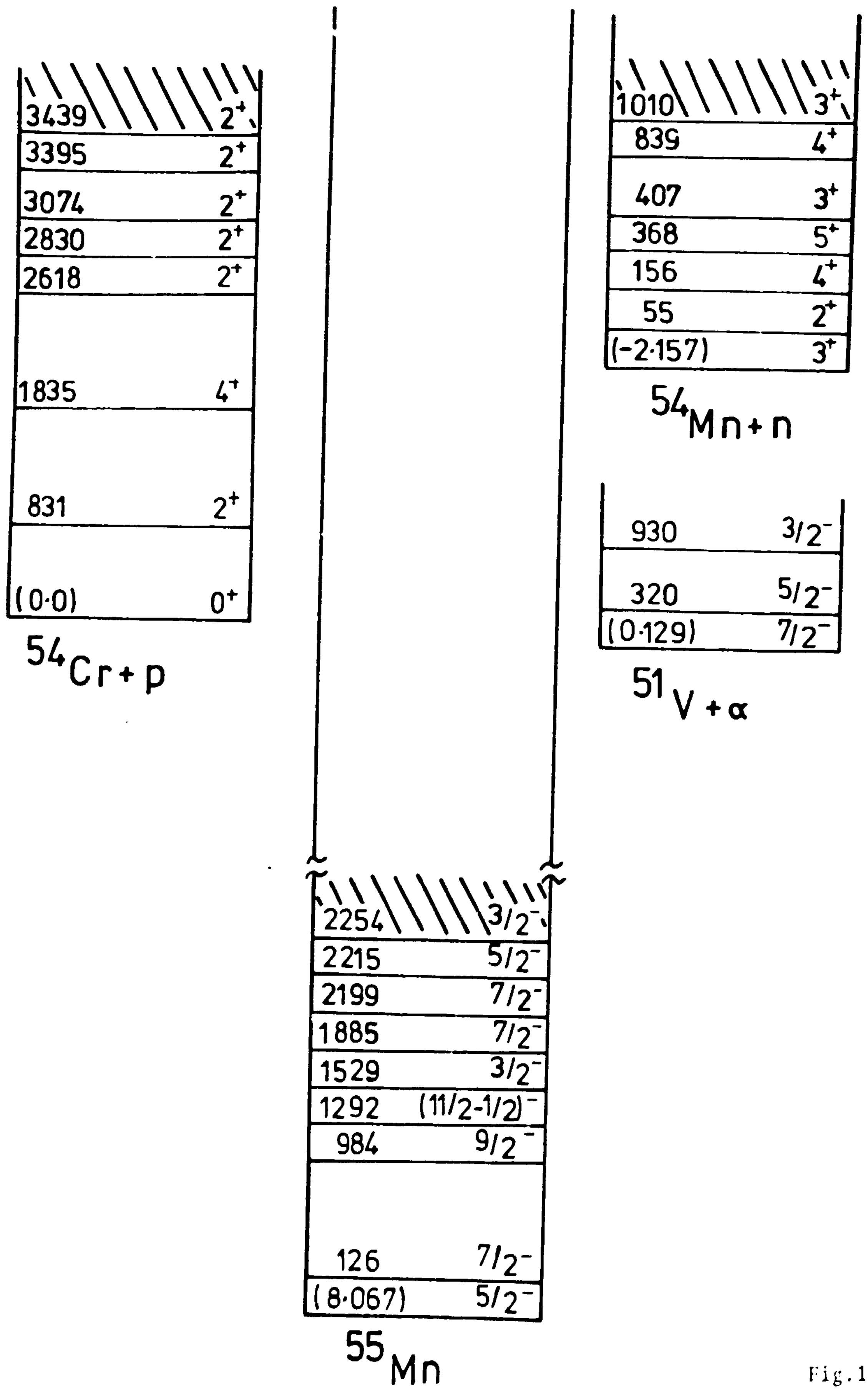

Fig.1.
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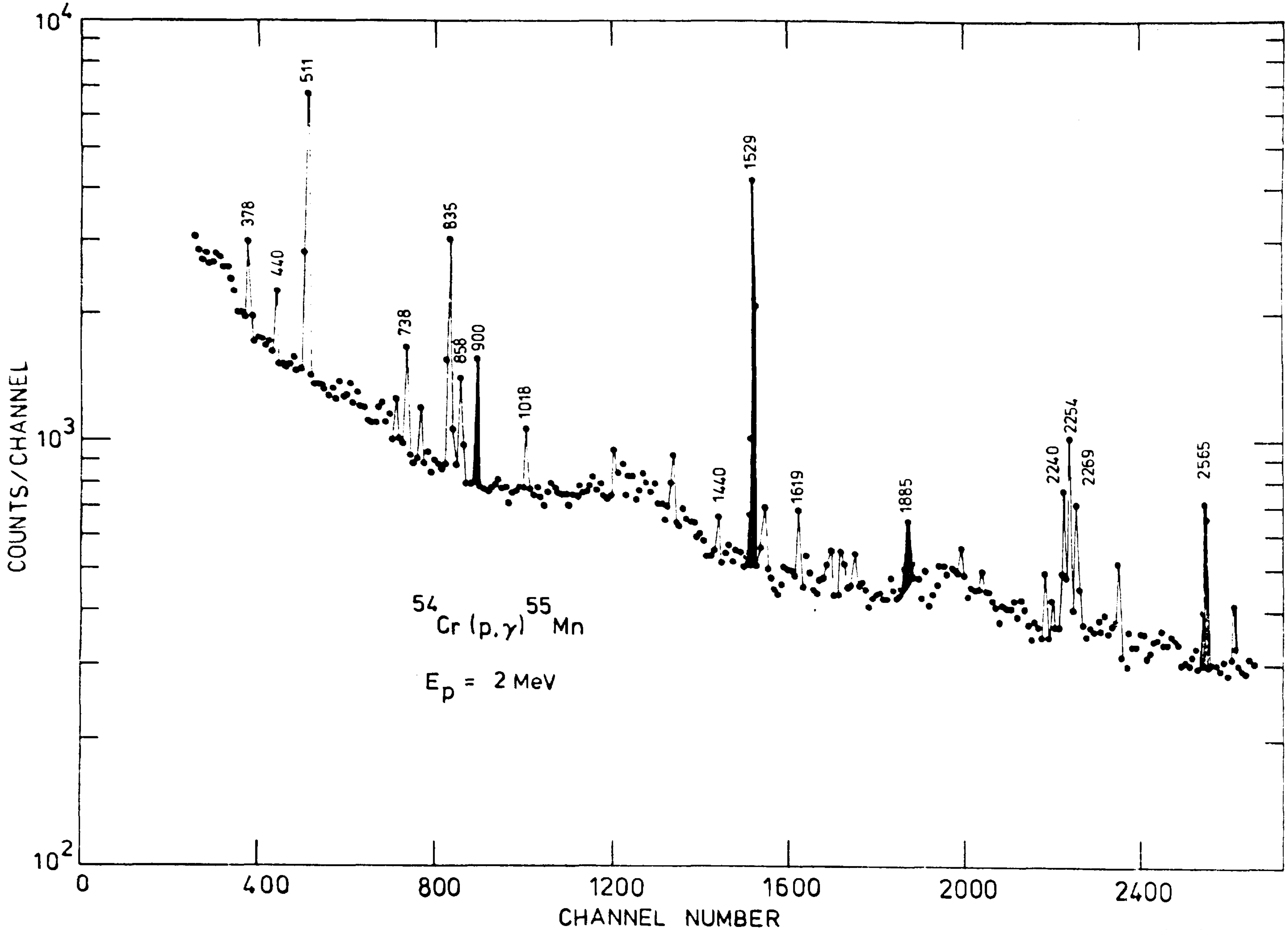
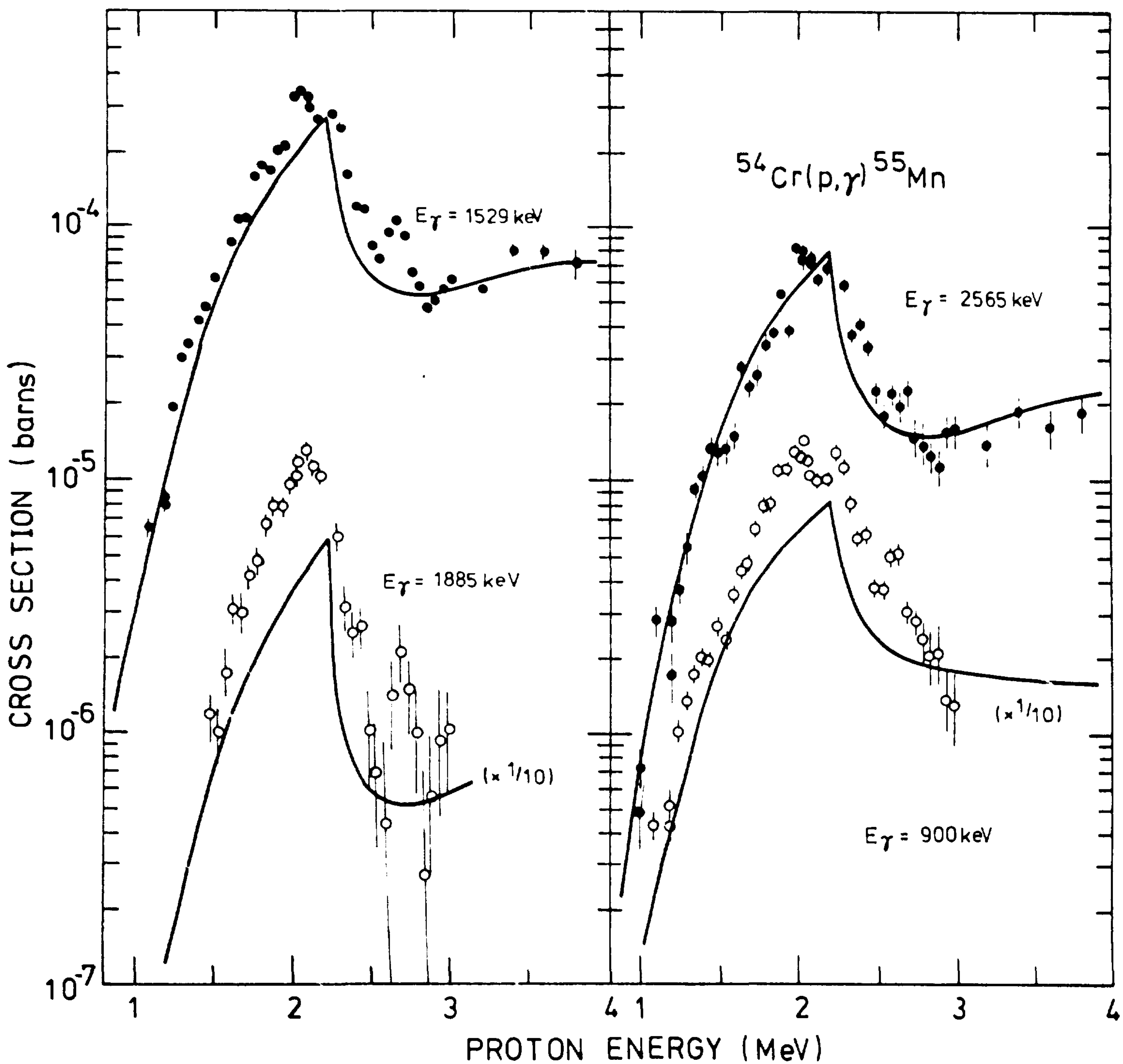


Fig.2.
Wilkinson et al



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Wilkinson et al

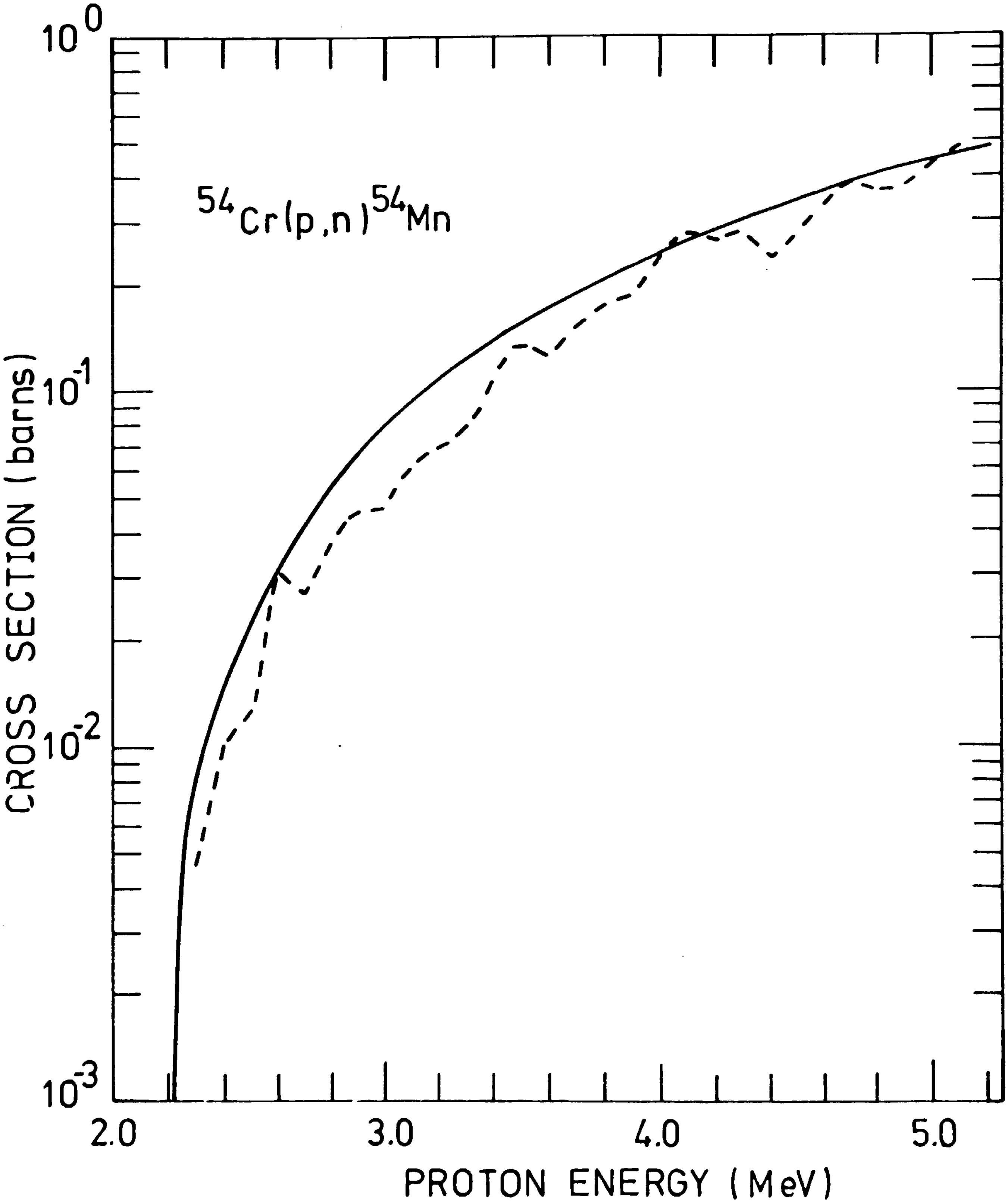

Fig.4.
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