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The $^{55}Mn(p,\gamma)^{56}Fe$ and $^{55}Mn(p,n)^{55}Fe$ Cross Sections

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Abstract

The cross section of the reaction $^{55}Mn(p,\gamma)^{56}Fe$ has been measured in the energy range $0\cdot80$–$2\cdot04$ MeV and of the reaction $^{55}Mn(p,n)^{55}Fe$ from threshold to $2\cdot04$ MeV. Statistical model calculations reproduce the (p, n) cross section to within a factor of $1\cdot4$, but with the (p, γ) reaction they fail by a factor $\geqslant 2$ over a significant part of the energy range. Thermonuclear reaction rates are calculated from the data for temperatures in the range $(1$–$5)\times 10^9$ K.

1. Introduction

The theory of nucleosynthesis in evolving and exploding stars depends ultimately on the availability of reliable nuclear-reaction cross sections. Many of the reactions appearing in the network calculations of the late burning stages of stars involve stable target nuclei and the cross sections of significant numbers of these have now been measured. However, most of the reactions of interest in these calculations involve short-lived radioactive targets and one must rely on theoretical cross sections for these. The theoretical cross sections are derived from statistical model calculations with global optical model parameters and it is only by comparing large numbers of calculated cross sections with experimental values that one may assess the reliability of the global parameters. As part of an on-going program of cross-section measurements directed towards the testing of the statistical model codes of Mann (1976) and Woosley *et al.* (1975), we report here experimental determinations of cross sections of the reactions $^{55}Mn(p,\gamma)^{56}Fe$ and $^{55}Mn(p,n)^{55}Fe$. For a large body of reactions, agreement between the predictions of these codes and the results of experimental measurements has been better than to within a factor of 2. However, most of the comparisons have involved reactions on even-A targets and, with the exception of target nuclei with a closed shell of 28 neutrons, which have been discussed separately by Kennett *et al.* (1981*a*), disagreements of the order of, or greater than, a factor of 2 have been associated disproportionately with odd-A target nuclei. These have included ^{41}K (Sevior *et al.* 1982), ^{45}Sc (Solomon and Sargood 1978; Mitchell *et al.* 1982) and ^{47}Ti (Kennett *et al.* 1981*b*). On the other hand, agreement for reactions on ^{49}Ti (Kennett *et al.* 1980) and ^{53}Cr (Gardner *et al.* 1981) has been very good. It therefore appears that, if the shortcomings of the codes are to be understood and rectified, it will be necessary to study as many odd-A target reactions as possible. This was the prime motivation for choosing ^{55}Mn as the target for the present work.

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Early experiments carried out as tests of statistical model codes were directed at situations for which the codes of Woosley *et al.* (1975) (referred to hereafter as the OAP-422 code) predicted dramatic competition effects as the neutron threshold was crossed (Mann *et al.* 1975; Switkowski *et al.* 1978; Zyskind *et al.* 1978; Anderson *et al.* 1979; Wilkinson *et al.* 1979; Kennett *et al.* 1980; Zyskind *et al.* 1979; Zyskind *et al.* 1980; Kennett *et al.* 1980; Esat *et al.* 1981). The reaction $^{55}Mn(p,\gamma)^{56}Fe$ reported here provides an interesting complementary study because the neutron channel opens up very low on the Coulomb barrier, with the result that the shape of the predicted competition cusp in the excitation function is very different from those of the reactions described in the papers cited. This provided a second motivation for selecting ^{55}Mn as the target for the present work.

2. Experimental Details

The target was prepared by evaporation of elemental Mn from a tungsten boat onto a 0·13 mm thick etched gold backing. The target thickness was determined by weighing the backing before and after the evaporation and by back-scattering 4·0 and 4·5 MeV α particles at a scattering angle of 145°. The shift in the position of the thick-target step in the pulse-height spectrum, attributable to scattering from the gold backing when α particles were scattered from the front and the back of the target, gave the target thickness in energy units. This was converted to target nuclei per cm^2 by means of the energy-loss tables of Ziegler (1977): the number of counts in the peak attributable to ^{55}Mn, when divided by the number of incident α particles, the solid angle subtended by the detector, and the Rutherford differential-scattering cross section, gave the number of target nuclei per unit area, as did the ratio of the number of counts in the ^{55}Mn peak to the height of the Au thick-target step when analysed by the method of Foti *et al.* (1977). The four target thickness determinations were in agreement at the 7% level.

The target was bombarded with a beam of protons delivered by the University of Melbourne 5U Pelletron accelerator. Beam currents were typically 1 μA and the energy was varied over the range 0·80–2·04 MeV in 40 keV steps, this step size corresponding to the thickness of the target to 1 MeV protons. The beam collimating apertures were 4 mm in diameter and were followed by an electron suppression ring held at -600 V. The target chamber was insulated and used as a Faraday cup.

Gamma rays were detected with a 60 cm^3 Ge(Li) detector located 2 cm from the target in the 55° direction. This detector was calibrated up to an energy of 3·5 MeV by means of calibrated radioactive sources mounted in the same geometry as was the target during the experiment. The calibration was extended to 8·94 MeV by means of the 2046 keV resonance in $^{27}Al(p,\gamma)^{28}Si$ (Kennedy *et al.* 1977). The overall calibration was considered reliable to 8%. The neutron detector consisted of a cylinder of polythene 21·6 cm in diameter and 25·4 cm long with a BF_3 tube embedded along its axis, and was located 4 cm from the target in the 35° direction. Because $^{55}Mn(p,n)^{55}Fe$ can proceed to the ground state of ^{55}Fe with s-wave protons and neutrons, it was anticipated that the neutron yield would be dominated by this particular exit channel, in which case the neutron angular distribution would be isotropic and the angular location of the neutron detector unimportant. The direction chosen was that which allowed the placement of the detector as close to the target as possible. The absence of γ rays attributable to the $(p,n_1\gamma)$ and $(p,n_2\gamma)$ channels vindicated this choice of geometry. The detection efficiency was a function of neutron energy, and this energy dependence had been measured previously (Kennett *et al.* 1980). The absolute detection efficiency was determined from an activation measurement on the reaction $^{48}Ca(p, n)^{48}Sc$, as described by Kennett *et al.* (1980), and was considered reliable to 10%.

The $^{55}Mn(p, \gamma)^{56}Fe$ excitation function was determined from measurement of the yield of the 847 keV first excited state to ground state transition in ^{56}Fe. To determine the fraction of the total γ-ray yield represented by this transition we summed the Ge(Li) spectra collected at all energies in the excitation function measurement, and identified all peaks in the summed spectrum. The total yield is the sum of the yield of all transitions leading to the ground state of ^{56}Fe. The only such transition which appeared in the spectrum was that at 847 keV, and we concluded that all cascades fed the first excited state and that this γ ray constituted a reliable measure of the total yield. To allow for possible weak but unobserved transitions, we attached an uncertainty of 10% to this yield.

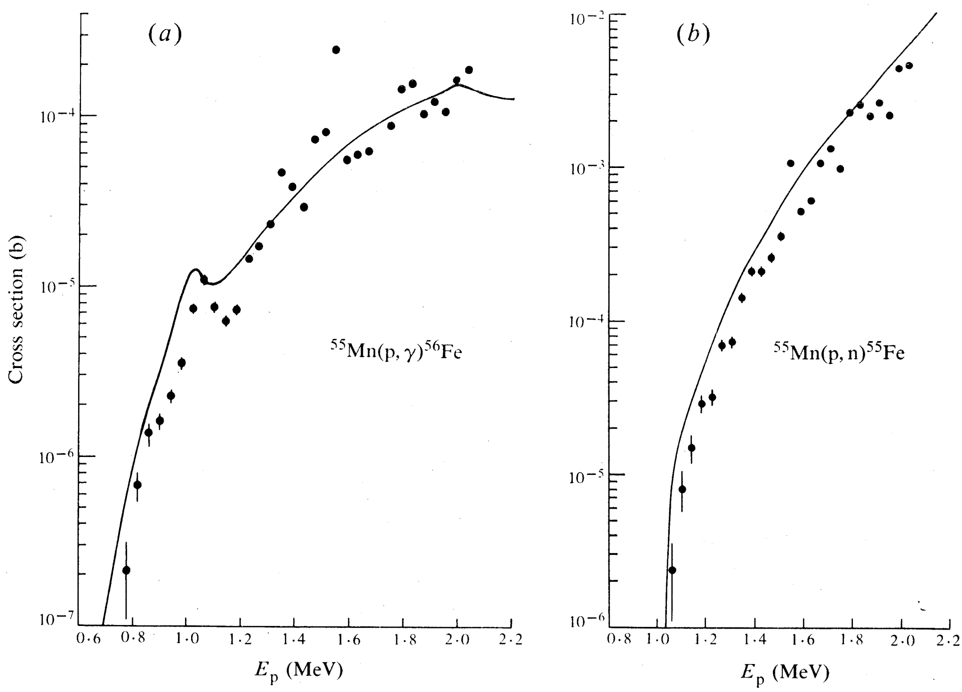

Fig. 1. Comparison between experimental data (points) and statistical model calculations (curves) for the proton energy dependence of the cross section for (*a*) the $^{55}Mn(p, \gamma)^{56}Fe$ reaction and (*b*) the $^{55}Mn(p, n)^{55}Fe$ reaction. Where shown, experimental error bars reflect statistical uncertainties. The errors associated with the absolute cross-section scales are 15% and 14% in (*a*) and (*b*) respectively.

3. Results and Discussion

The excitation function for the 847 keV γ ray from $^{55}Mn(p, \gamma)^{56}Fe$ is shown in Fig. 1*a*. The curve represents the prediction of the code HAUSER*4 for the total (p, γ) cross section, smoothed over an energy interval of 40 keV, the effective thickness of the target. The shape of the excitation function in the vicinity of the neutron threshold, at 1·032 MeV, is satisfactorily reproduced, although the magnitude of the theoretical cross section is high by a factor of 2.

To correct the neutron cross-section data for an energy dependence in detection efficiency, we used the HAUSER*4 prediction for the splitting of the yield between (p, n_0) and (p, n_1) and applied mono-energetic corrections to the two parts of the yield. The (p, n_2) threshold is at 1·980 MeV, so this neutron group affected only the last two points in the energy range of the experiment. These last two points aside, the predicted fraction of the neutron yield to the first excited state of ^{55}Fe was always less than 18% and was consistent with our failure to observe any γ rays attributable to ^{55}Mn(p, nγ)^{55}Fe in our Ge(Li) spectra. The reliance on HAUSER*4 in correcting the raw data led to a contribution of at most 6% in the final result. The first point above threshold was corrected to allow for the fact that it constituted a thick yield, and the first two points were also corrected for the effects of a rapidly changing cross section, by the method of Kennett *et al.* (1980). The corrected data are plotted in Fig. 1*b*. The curve represents the prediction of HAUSER*4 and is consistently high, but by a factor of only 1·4, over the energy range studied. What little structure there is in the (p, n) excitation function corresponds, peak for peak, with that in the (p, γ) excitation function over the same energy range. All the peaks (at $E_p = 1\cdot35$, 1·54 and 1·81 MeV) occur at or near the predicted energies for isobaric analogue resonances corresponding to the ground state, 0·21 MeV doublet and 0·47 MeV doublet in ^{56}Mn. Such low-lying states may be expected to have significant single particle widths, and it is to the corresponding proton widths in the isobaric analogue states that we attribute the structure observed in our excitation functions.

Table 1. Thermonuclear reaction rates (cm^3 s^{-1} mole^{-1})

T (10^9 K)	^{55}Mn(p, γ)^{56}Fe This work	^{55}Mn(p, γ)^{56}Fe OAP-422	^{55}Mn(p, n)^{55}Fe This work	^{55}Mn(p, n)^{55}Fe OAP-422
1·0	$9\cdot46\times10^{-1}$	$8\cdot50\times10^{-1}$	$7\cdot46\times10^{-1}$	$7\cdot58\times10^{-1}$
1·5	$3\cdot13\times10$	$2\cdot21\times10$	$9\cdot79\times10$	$8\cdot55\times10$
2·0	$2\cdot34\times10^{2}$	$1\cdot34\times10^{2}$	$1\cdot52\times10^{3}$	$1\cdot32\times10^{3}$
2·5	$8\cdot58\times10^{2}$	$4\cdot40\times10^{2}$	$9\cdot47\times10^{3}$	$8\cdot53\times10^{3}$
3·0	$2\cdot11\times10^{3}$	$1\cdot02\times10^{3}$		
4·0	$6\cdot80\times10^{3}$	$3\cdot14\times10^{3}$		
5·0	$1\cdot42\times10^{4}$	$6\cdot43\times10^{3}$		

For comparison of our data with the predictions of the OAP-422 code, we have first used our data to calculate thermonuclear reaction rates according to the procedure of Fowler *et al.* (1967) using HAUSER*4, normalized to the experimental data, to provide cross sections outside the experimental energy range. Since Woosley *et al.* (1975) presented tables of thermonuclear reaction rates calculated from their statistical model cross sections, this constitutes the most convenient means of comparison of the experimental data and the results of their OAP-422 code calculations. The comparison is given in Table 1. No (p, n) comparison is listed for $T > 2\cdot5\times10^9$ K because the HAUSER*4 contribution to the experimental rate would have exceeded 50%. In such cases, any comparison would have been essentially one of the OAP-422 code with HAUSER*4 normalized to lower energy experimental data. The HAUSER*4 contribution to the experimental (p, γ) rate was 33% at 5×10^9 K, 22% at 4×10^9 K, and <15% at all the temperatures listed below 4×10^9 K. Clearly the code is very successful in its prediction of the ^{55}Mn(p, n)^{55}Fe cross section but, except at the low energies which correspond to the low temperatures in Table 1, it underestimates the $^{55}Mn(p, \gamma)^{56}Fe$ cross section by a factor slightly in excess of 2. Underestimation of a (p, γ) cross section above the neutron threshold, relative to its value below the neutron threshold, is a feature of codes, such as the OAP-422, which neglect width-fluctuation corrections (Tepel *et al.* 1974). For the reaction $^{55}Mn(p, \gamma)^{56}Fe$, cross sections for energies below the neutron threshold contribute $\sim 50\%$ of the thermonuclear reaction rate at a temperature of 10^9 K but $\lesssim 10\%$ at temperatures $\geqslant 3 \times 10^9$ K. The neglect of width-fluctuation corrections therefore appears to be a significant contributor to the rather disappointing performance of the OAP-422 code for this reaction. However, HAUSER*4, which does include width-fluctuation corrections, does little better. There is a factor of approximately 2 between the (p, γ) cross sections of the two codes, with the OAP-422 code performing well below the neutron threshold and HAUSER*4 performing well above the neutron threshold.

The rather mixed degree of agreement between the predictions of the codes and experiment, for the pair of reactions reported here, reinforces our belief that reactions on odd-A targets are very important for identifying the weakness in the currently used sets of global optical model parameters. More data such as these will be required to establish the nuclear systematics on which more reliable sets of global parameters may eventually be based.

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