Channel cross correlation and intermediate resonance in the ^{55}Mn(p,p)^{55}Mn and ^{55}Mn(p,α)^{52}Cr reactions

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The excitation functions for the α particles and protons from the reactions ^{55}Mn(p,p)^{55}Mn and ^{55}Mn(p,α)^{52}Cr were measured from $E_p=5.8$ to 7.0 MeV at $\theta_{\rm lab}=90°$, 125°, and 160°. The cross sections were analyzed by the channel cross correlation function, the autocorrelation function, and the statistical compound nuclear theory of Feshbach to determine the number of correlating channels n_d, the average total level width $\langle\Gamma_\mu\rangle$, and the ratio $\langle\Gamma_\mu\rangle/D$. With these values, the theoretical intermediate width $\langle\Gamma_d\uparrow\rangle$ was calculated to be 27 ± 11.7 keV, which was consistent with the experimental result 36 ± 8 keV within the errors. The ratio $n_d(n_d-1)/n^2$ was determined to be 0.63 ± 0.16, which was also in agreement with the theoretical prediction $(2D/\pi\langle\Gamma_\mu\rangle)^{1/2}=0.40\pm0.09$, within the error.

I. INTRODUCTION

The relationship between the channel cross correlation and the intermediate resonance in the compound nuclear reaction has been studied by many authors.[1-4] The relationships given by Hsu[5-7] are

$$\langle\Gamma_d\uparrow\rangle=\frac{n_d(n_d-1)}{n^2}\frac{\pi\langle\Gamma_\mu\rangle}{2D}\langle\Gamma_\mu\rangle \quad \text{for small } n$$
$$\approx\left[\frac{n_d}{n}\right]^2\frac{\pi\langle\Gamma_\mu\rangle}{2D}\langle\Gamma_\mu\rangle \quad \text{for large } n\ , \tag{1}$$

and

$$\frac{n_d(n_d-1)}{n^2}=\left[\frac{2D}{\pi\langle\Gamma_\mu\rangle}\right]^{1/2} \quad \text{for small } n\ ,$$
$$\left[\frac{n_d}{n}\right]^2=\left[\frac{2D}{\pi\langle\Gamma_\mu\rangle}\right]^{1/2} \quad \text{for large } n\ , \tag{2}$$

where $\langle\Gamma_\mu\rangle$ is the average total level width; D is the average level spacing of spin zero states; n_d and n are, respectively, the numbers of correlating and open channels; and $\langle\Gamma_d\uparrow\rangle$ is the escape width of the intermediate resonance. Equations (1) and (2) have been confirmed by Hsu *et al.*,[1] Huang *et al.*,[2] and Yeh *et al.*,[3,4] with the reactions in-

TABLE I. The values of $\langle\Gamma_\mu\rangle$ determined by the autocorrelation function. The total average value is 6.8 ± 2.0 keV. The error is the standard deviation.

Emitted particle		α_0	α_1	p_0	p_1	p_2	$p_{3\text{-}4}$	p_5	p_6	$p_{7\text{-}8}$	$p_{9\text{-}11}$	p_{12}
$\langle\Gamma_\mu\rangle$ (keV)	$\theta_{\rm lab}=90°$	6.0	6.5	10.0	7.5	7.5	6.0	7.0	7.5	6.0	6.5	5.5
	$\theta_{\rm lab}=125°$	6.5	5.5	8.0	8.0				6.5	6.5	6.5	
	$\theta_{\rm lab}=160°$	6.0	6.0	10.0	8.5				6.5	7.5	6.0	7.0

Emitted particle		$p_{13\text{-}15}$	$p_{12\text{-}15}$	$p_{16\text{-}17}$	$p_{18\text{-}19}$	$p_{20\text{-}22}$	p_{23}	$p_{24\text{-}34}$	p_+	p_{++}	p_{+++}	p_{++++}
$\langle\Gamma_\mu\rangle$ (keV)	$\theta_{\rm lab}=90°$	8.0		7.0	6.0	6.5	6.0	9.0	6.5	6.5	9.5	5.0
	$\theta_{\rm lab}=125°$		5.0	6.0	5.5	6.0	6.5	9.0	6.5	6.5	6.5	6.0
	$\theta_{\rm lab}=160°$		6.0	6.0	6.5	6.5	6.0	8.0	6.5	6.0	7.5	6.5

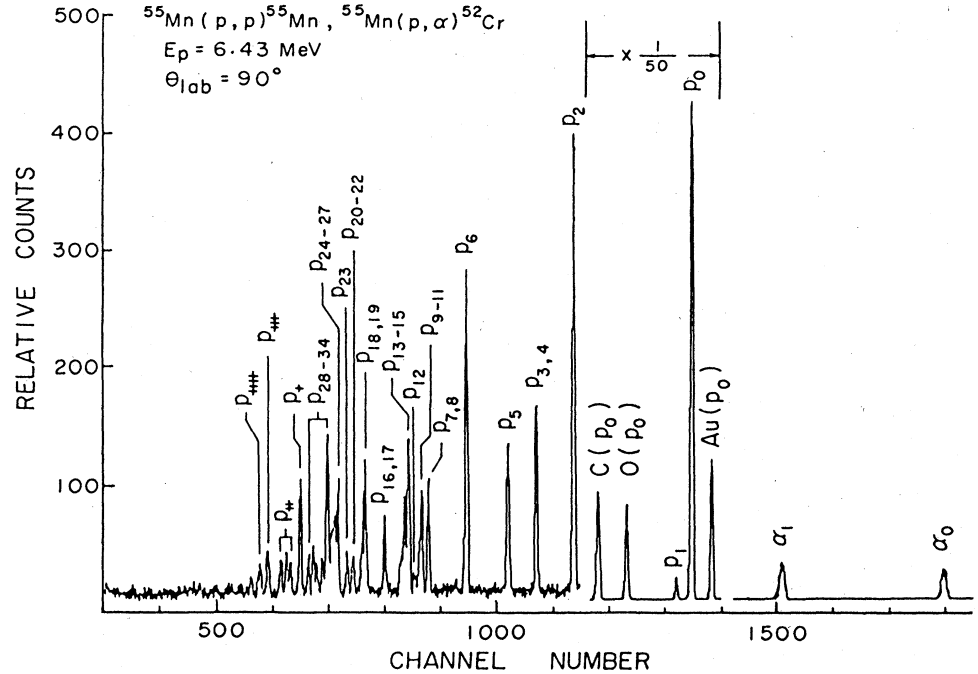

FIG. 1. Typical energy spectrum of the ^{55}Mn(p,p)^{55}Mn and ^{55}Mn(p,α)^{52}Cr reactions at $E_p=6.43$ MeV and $\theta_{lab}=90°$.

duced by deuterons at a high excitation energy of a compound nuclear formation, where $\langle \Gamma_\mu \rangle / D$ is around 8. So far, the preceding relationships have not been investigated in the energy region where the value of $\langle \Gamma_\mu \rangle / D$ is smaller than 8, and the ratio $n_d(n_d-1)/n^2$ will be larger if Eq. (2) is held. In order to achieve such an energy region, the experiments of elastic and inelastic scattering in low energy are favorable. The reaction ^{55}Mn(p,p)^{55}Mn has been studied by Maki[8] from $E_p=4.24$ to 6.07 MeV. He analyzed the cross sections by fluctuation theory and did not discuss Eqs. (1) and (2). In the present studies, we have carried out the reactions ^{55}Mn(p,p)^{55}Mn and ^{55}Mn(p,α)^{52}Cr from $E_p=5.8$ to 7.0 MeV, and the main discussion is the channel cross correlation and the relationships of Eqs. (1) and (2).

II. EXPERIMENTAL METHOD AND RESULTS

The experiments were carried out with the 7 MV Van de Graaff accelerator at the Institute of Nuclear Energy Research. The protons were accelerated and deflected by a 90° analyzing magnet into a 55 cm diameter scattering chamber. The beam energy resolution was estimated to be 0.2%. The ^{55}Mn targets were prepared by vacuum evaporation on a 10 μg/cm^2 carbon backing, and their thicknesses were about 100 μg/cm^2. In addition, the gold was slightly evaporated on the surface of the target, and the total energy loss in the target was about 6 keV for 6 MeV protons. The scattered protons and α particles were simultaneously detected by four surface barrier detectors which were fixed at $\theta_{lab}=40°$, 90°, 125°, and 160°, with respect to the beam direction. In front of every detector there was a 4.83 cm long brass cylindrical collimator, where the diameter of the aperture near the target was 3 mm, and the diameter of another aperture far from the target was 4 mm.

The detector fixed at $\theta_{lab}=40°$ was used as a monitor to see the Rutherford scattering protons of the gold. The signals from the four detectors were fed via a preamplifier, an amplifier, and an Ortec 6260 computer-based multichannel analyzer system, respectively. The beam was focused on a target as small as a point and the beam current was kept at 300 nA. Thus, the dead times were negligibly small. Figure 1 shows the typical energy spectrum of the ^{55}Mn(p,p) ^{55}Mn and ^{55}Mn(p,α)^{52}Cr reactions. The energy resolution estimated from the spectrum is about 22 keV; thus, as many of the particles of different channels as could be resolved were measured in this experiment. The data of up to $n=21$, 18, and 17 open channels at $\theta_{lab}=90°$, 125°, and 160°, respectively, were measured in this study. The excitation function was carried out from $E_p=5.8$ to 7.0 MeV in steps of 10 keV. Figure 2 shows the typical excitation functions of $\theta_{lab}=90°$. The absolute cross sections were estimated by comparing them with the cross sections of back scattered α particles by the

TABLE II. Comparisons between the C_{cc} and N^{-1} for α particles.

	N^{-1}	$C_{cc} \pm \Delta C_{cc}$ ($\theta=90°$)	$C_{cc} \pm \Delta C_{cc}$ ($\theta=125°$)
α_0	0.167	0.146±0.005	0.190±0.028
α_1	0.033	0.056±0.008	0.057±0.008

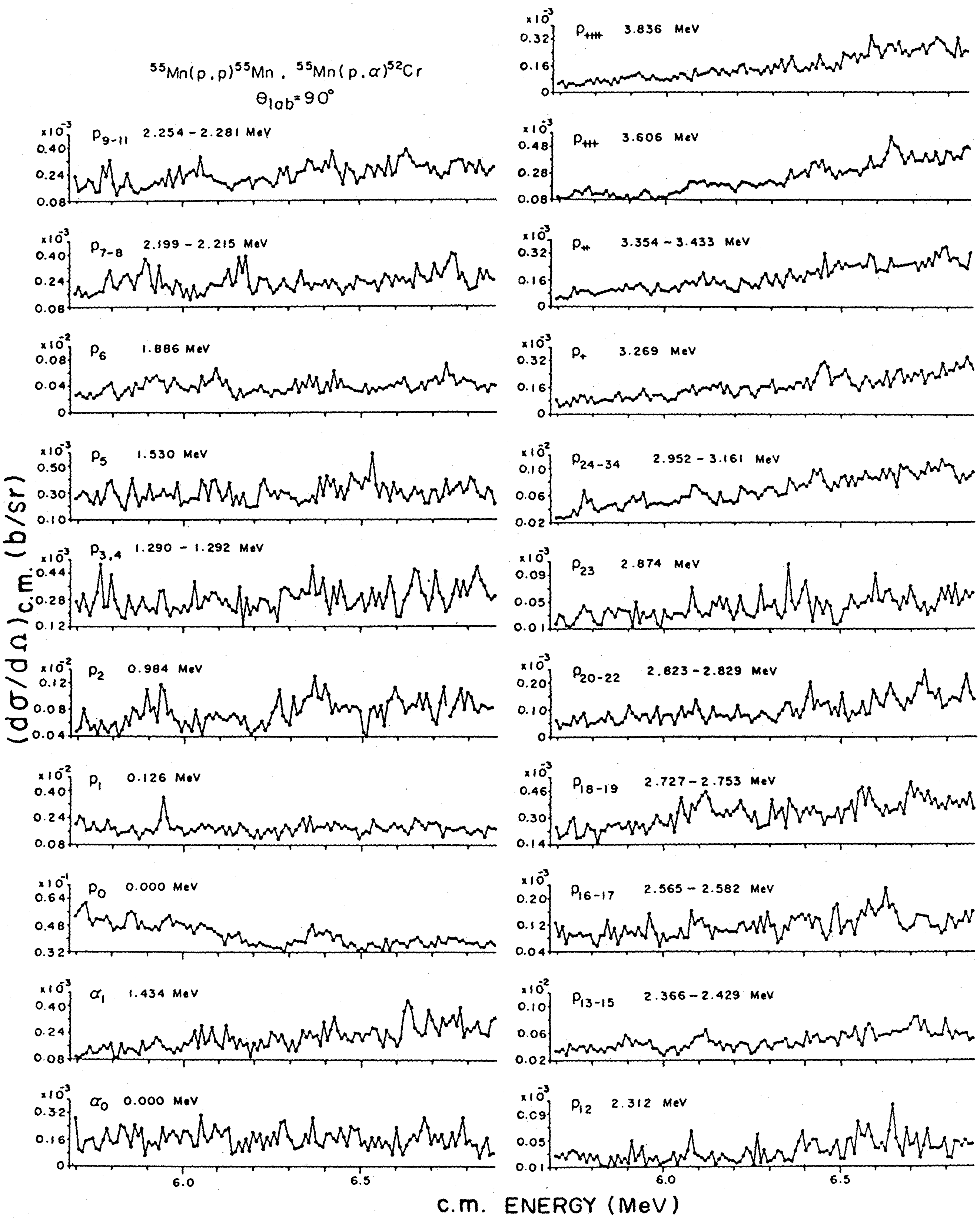

FIG. 2. Typical excitation functions for ^{55}Mn(p,p)^{55}Mn and ^{55}Mn(p,α)^{52}Cr reactions at $\theta_{lab}=90°$.

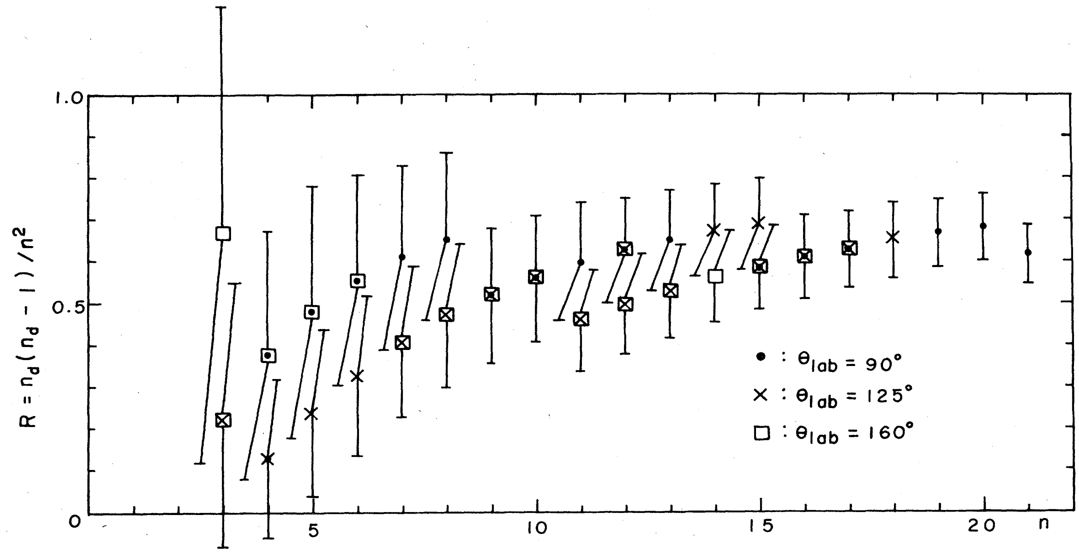

FIG. 3. The ratio $n_d(n_d-1)/n^2$ as a function of n. The error is calculated by $\Delta R=(2n_d-1)/n_d(n_d-1)\%$.

gold on the target. The errors were estimated to be about $\pm 15\%$.

III. ANALYSIS AND DISCUSSION

Channel cross correlations and channel correlations[9–11] for all combinations of measured protons and α particles were calculated by the same procedures as those described by Lee *et al.*[12] and Hsu *et al.*[13] N_d (Refs. 1–4) is obtained from the number of channels from which the cross correlation is larger than its error, and the results were 143, 101, and 88 for $\theta_{lab}=90°$, 125°, and 160°, respectively, with the following relationships:

$$N_d=\tfrac{1}{2}[n_d(n_d-1)]_{expt} \text{ for small } n$$
$$=\tfrac{1}{2}(n_d)^2_{expt} \text{ for large } n\ . \qquad (3)$$

The number of correlating channels n_d was then deduced to be 17, 15, and 14 with respect to $\theta_{lab}=90°$, 125°, and 160°, respectively. The value of $n_d(n_d-1)/n^2$ and its error $\Delta R=(2n_d-1)/n_d(n_d-1)\%$ for $\theta_{lab}=90°$, 125°, and 160° was then calculated to be 0.62 ± 0.08, 0.65 ± 0.09, and 0.63 ± 0.09, respectively. The average of these values is 0.63 ± 0.16. Figure 3 shows the ratio $n_d(n_d-1)/n^2$ as a function of n, which indicates that the magnitude of the error decreases as n increases. In order to calculate the width $\langle\Gamma_d\uparrow\rangle$ of Eq. (1), the values of the ratio $\langle\Gamma_\mu\rangle/D$ and $\langle\Gamma_\mu\rangle$ are necessary. The autocorrelation[14,16] was applied to deduce the coherence width, i.e., the average level width $\langle\Gamma_\mu\rangle$. The results are shown in Table I. The averaged value is $\langle\Gamma_\mu\rangle=6.8\pm2.0$ keV (the error is the standard deviation), which is reasonable if we compare it to the value of 6 keV studied by Maki in which the excitation energy was slightly lower than that of our present study. For the determination of $\langle\Gamma_\mu\rangle/D$, the statistical compound nuclear theory of Feshbach[17] was used.

Since the autocorrelation coefficient C_{cc} is equal to $(1-Y_D^2)/N$ (Refs. 15 and 18), C_{cc} would be equal to $1/N$ (where N is a constant depending on the spins of the incident particle i, target nucleus I, emitted particle i', residual nucleus I', and the angle of scattering particles) if Y_D, the contribution of the direct reaction in the compound nuclear formation, were zero. For the angle of scattering particles, $\theta=90°\pm40°$, the maximum value of N is equal to one-half of $(2I+1)(2i+1)(2I'+1)(2i'+1)$. Table II shows the results for the ^{55}Mn(p,α)^{52}Cr reaction. Within the errors, the consistency between C_{cc} and N^{-1} is quite reasonable. The values for α_1 are slightly larger in comparison with N^{-1}, which may be due to the effect of the effective number of degrees of freedom. The reaction

TABLE III. The values of $\langle\Gamma_\mu\rangle/D$ fitted by the formula of Feshbach (Ref. 17).

α_0, $\sigma^2=11.6$, $\langle\Gamma_\mu\rangle/D=3$[a]				α_1, $\sigma^2=11.6$, $\langle\Gamma_\mu\rangle/D=5$[a]		
$\left(\frac{d\sigma}{d\Omega}\right)_{expt}$	$\left(\frac{d\sigma}{d\Omega}\right)_{theor}$	$\left(\frac{d\sigma}{d\Omega}\right)_{expt}/\left(\frac{d\sigma}{d\Omega}\right)_{theor}$	θ_{lab}	$\left(\frac{d\sigma}{d\Omega}\right)_{expt}$	$\left(\frac{d\sigma}{d\Omega}\right)_{theor}$	$\left(\frac{d\sigma}{d\Omega}\right)_{expt}/\left(\frac{d\sigma}{d\Omega}\right)_{theor}$
0.165 ± 0.025	0.155	1.07 ± 0.016	90°	0.209 ± 0.031	0.270	0.77 ± 0.12
0.165 ± 0.025	0.153	1.08 ± 0.016	125°	0.335 ± 0.050	0.280	1.20 ± 0.18
0.153 ± 0.023	0.136	1.13 ± 0.017	160°	0.229 ± 0.034	0.307	0.75 ± 0.11

[a]The error is about $\pm15\%$, which takes account of the error of the absolute cross section.

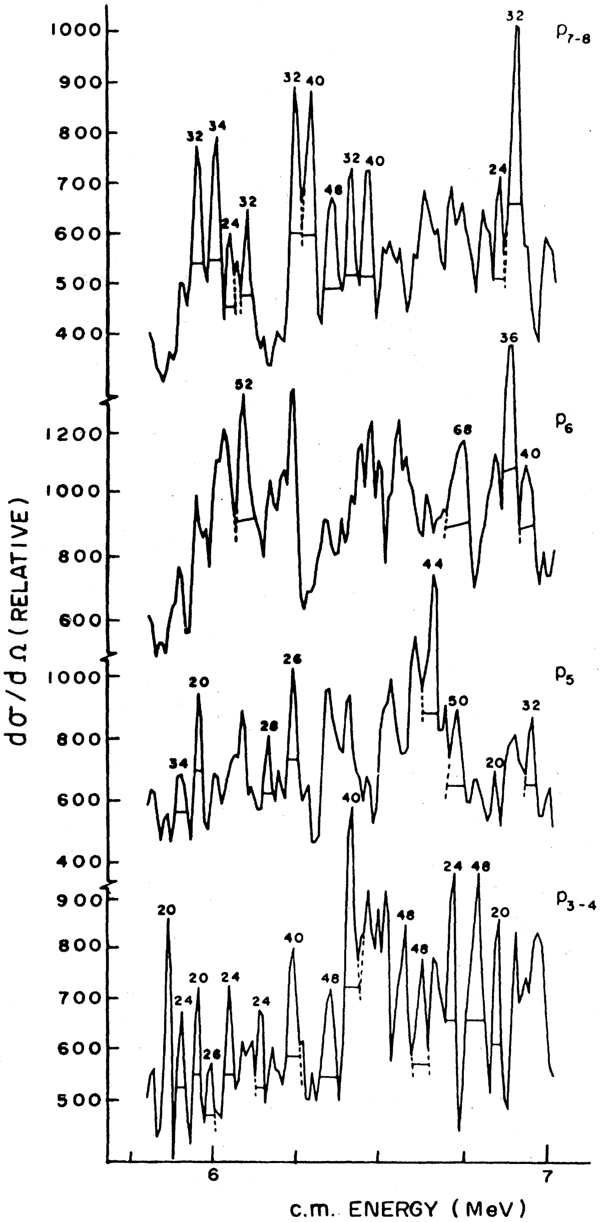

FIG. 4. Typical excitation functions averaged over the energy interval of 20 keV. The numbers given in the figure are the width of the intermediate resonances.

^{55}Mn(p,α)^{52}Cr of the present measurements therefore could be assumed to be a pure compound nuclear formation, and the energy averaged absolute cross sections of the α particles for $\theta_{\rm lab}=90°$, 125°, and 160° were analyzed by the theoretical formula of Feshbach,[17] where the spin-cutoff parameter $\sigma^2=11.6$ (Ref. 8) was used. The results are shown in Table III, where the values of $\langle \Gamma_\mu \rangle /D$ are 3 and 5, with respect to the cross sections of α_0 and α_1, respectively. The average value of $\langle \Gamma_\mu \rangle /D$ is 4.0 ± 0.87, and the error is deduced from the errors of the absolute cross sections. The width $\langle \Gamma_d \uparrow \rangle$ was then calculated by Eq. (1) to be 27 ± 11.7 keV.

On the other hand, the excitation functions were averaged numerically with the energy interval $\Delta E = 20$ keV, since $\Gamma_\mu \ll \Delta E < \Gamma_d \uparrow$ (Ref. 19). Figure 4 shows the typical excitation functions averaged over a 20 keV energy interval. The numbers given in the figure are the widths of the intermediate resonances $\langle \Gamma_d \uparrow \rangle$. The widths $\langle \Gamma_d \uparrow \rangle$ obtained from such excitation functions are shown as the histogram of Fig. 5. The curve in the figure is a normal distribution and the standard deviation is 8 keV. The histogram covers the width obtained from the excitation functions of α particles and protons for $\theta_{\rm lab}=90°$, 125°, and 160°. From Fig. 5 it can be seen that the most probable value is 36 ± 8 keV. Within the errors, this result is in good agreement with the calculated width $\langle \Gamma_d \uparrow \rangle = 27\pm11.7$ keV. Relationship (1) was then confirmed. Finally, we can conclude that the experimental value $[n_d(n_d-1)/n^2]_{\rm expt}$ could take the place of the theoretical value $[n_d(n_d-1)/n^2]_{\rm theor}$ quite well in this excitation energy region. For the ratio of the numbers of correlating and open channels, $n_d(n_d-1)/n^2$ was determined to be 0.62 ± 0.08, 0.65 ± 0.09, and 0.63 ± 0.09 for $\theta_{\rm lab}=90°$, 125°, and 160°, respectively. The average value of the ratio is 0.63 ± 0.15 within the errors, which is consistent with the predicted value[7]

$$(2D/\pi\langle \Gamma_\mu \rangle)^{1/2}=0.40\pm0.09 \ ,$$

which means $n_d(n_d-1)/n^2$ is equal to $(2D/\pi\langle \Gamma_\mu \rangle)^{1/2}$, and Eq. (1) could be simplified to

$$\langle \Gamma_d \uparrow \rangle = \langle \Gamma_\mu \rangle / R \ ,$$

where

$$R = n_d(n_d-1)/n^2 = (2D/\pi\langle \Gamma_\mu \rangle)^{1/2} \ .$$

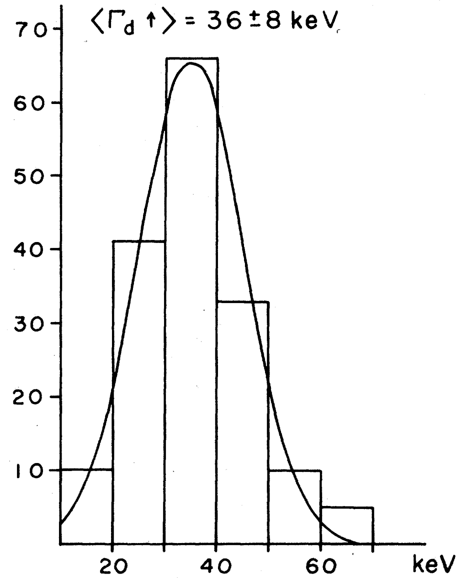

FIG. 5. Histogram of the $\langle \Gamma_d \uparrow \rangle$ obtained from the averaged excitation functions.

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