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Channel cross correlation of the $^{31}P(d,\alpha)^{29}Si$ and $^{31}P(d,p)^{32}P$ reactions

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The excitation functions for the α particles and protons from the reactions $^{31}P(d,\alpha)^{29}Si$ and $^{31}P(d,p)^{32}P$ were measured and 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 158±25 keV, which was consistent with the experimental result 198±34 keV within the errors. The ratio $n_d(n_d-1)/n^2$ was determined to be 0.27, which was also in agreement with the theoretical prediction $(2D/\pi\langle \Gamma_\mu \rangle)^{1/2}=0.28\pm0.04$.

NUCLEAR REACTIONS $^{31}P(d,\alpha)$, $^{31}P(d,p)$, $E=3.5-6.2$ MeV; measured $\sigma(E,\theta)$; ^{33}S; deduced n_d, $\langle \Gamma_\mu \rangle$, $\langle \Gamma_\mu \rangle/D$, $\langle \Gamma_d \uparrow \rangle$, natural target.

I. INTRODUCTION

Channel cross correlations[1-3] of nuclear reactions in the light elements have been measured by many authors. Theoretically, the average of the coefficients of channel cross correlations should be zero in the compound nuclear reaction, except when intermediate states are involved in the reaction. The intermediate structure in the compound nuclear reaction has been discussed in detail by Feshbach, Kerman, and Lemmer,[4] while the channel correlation which relates to the intermediate resonances was discussed by Lane[5] and Hsu.[6] The dependence between the escape width $\langle \Gamma_d \uparrow \rangle$ of intermediate resonance and the ratio of the numbers of correlating and open channels, n_d and n, is given by[6]

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

where $\langle \Gamma_\mu \rangle$ is the average total level width and D is the average level spacing of spin zero states. Equation (1) has been confirmed by Hsu *et al.*[7] with the $^{28}Si(d,p)^{29}Si$ reaction and by Huang *et al.*[8] with the $^{27}Al(d,p)^{28}Al$, $^{27}Al(d,\alpha)^{25}Mg$, $^{31}P(d,p)^{32}P$, and $^{31}P(d,\alpha)^{29}Si$ reactions. In the present study, the aim is twofold. First, we would like to confirm Eq. (1) again with an experiment with a larger number of open channels and a greater excitation energy range; second, we would like to see the ratio of the numbers of correlating and open channels, $n_d(n_d-1)/n^2$ or $(n_d/n)^2$, it being a function of $(2D/\pi\langle \Gamma_\mu \rangle)^{1/2}$ as was discovered by Hsu.[9] If this relationship is true, Eq. (1) could be simplified. The data collections are therefore necessary and very important.

The reactions $^{31}P(d,p)^{32}P$ and $^{31}P(d,\alpha)^{29}Si$ have been studied[8] for the channel cross correlations from $E_d=1.5$ to 2.5 MeV, and the total number of open channels n was 14. The present study carried out the experiments from $E_d=3.5$ to 6.2 MeV, and took data from as many as up to 18 open channels. Not only is the range of incident energy greater, but the total number of open channels is also greater than that of the experiment mentioned above. The errors of the finite range data and the statistical error concerned could be expected to be smaller and the results improved.

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 deuterons 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 ^{31}P targets were prepared by vacuum evaporation[10] on a 20 $\mu g/cm^2$ carbon backing and their thicknesses were about 100 $\mu g/cm^2$, which corresponds to an energy loss of about 14 keV for 5 MeV deuterons. The scattered particles were detected by four detectors which were fixed at $\theta_{lab}=\pm 90°$, 40°, and 160° with

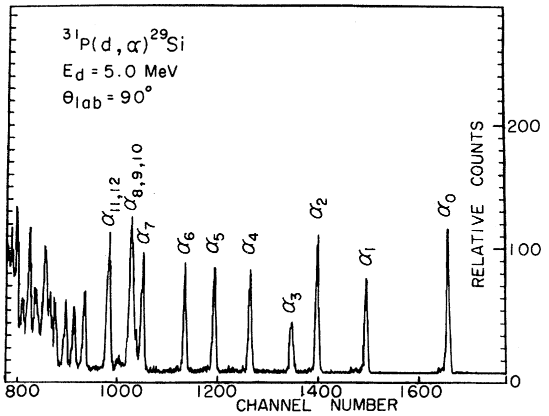

FIG. 1. Typical energy spectrum of the ^{31}P(d,α)^{29}Si reaction at $\theta_{\rm lab}=90°$, $E_d=5.0$ MeV.

respect to the beam direction. For α particles, two surface barrier detectors ($\sim$500 μm) were used at $\theta_{\rm lab}=90°$ and 160°, while for the detection of the protons, a third surface barrier detector of 1500 μm thickness was used at $\theta_{\rm lab}=-90°$, which was covered by an Al foil of 0.040 mm thickness in front of the window to avoid the interference of the α particles. The fourth detector, a 500 μm thickness surface barrier detector, was fixed at $\theta_{\rm lab}=40°$ as a monitor to see the elastic scattering deuterons. The signals from the four detectors were, respectively, fed via a preamplifier, an amplifier, and to an Ortec 6260 computer-based multichannel analyzer system. The beam current was kept at 300 nA and the dead times were negligibly small. Figure 1 shows the typical energy spectrum of the ^{31}P(d,α)^{29}Si reaction. The energy resolution of this system is about 65

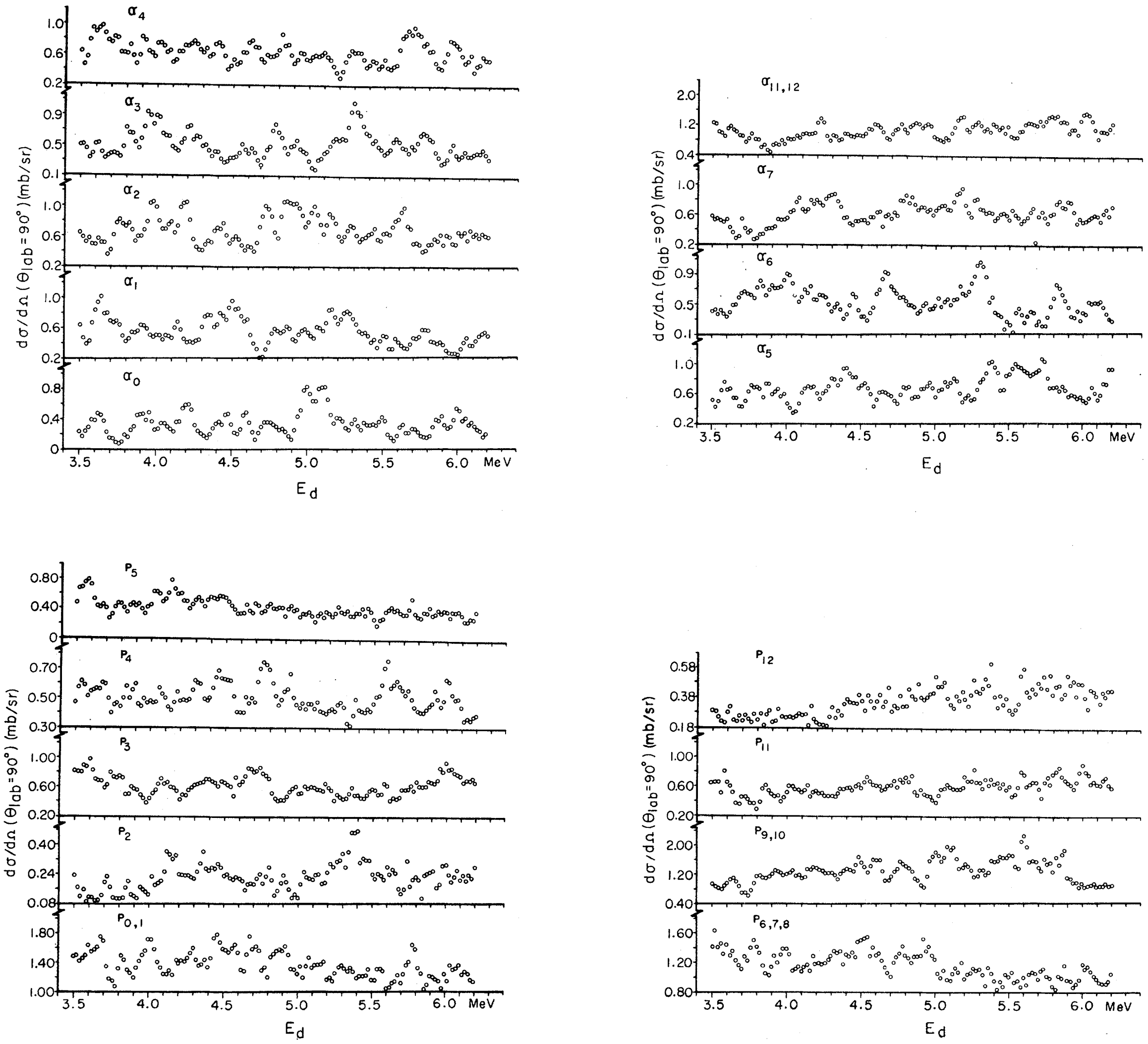

FIG. 2. Excitation functions for the ^{31}P(d,p)^{32}P and ^{31}P(d,α)^{29}Si reactions at $\theta_{\rm lab}=90°$.

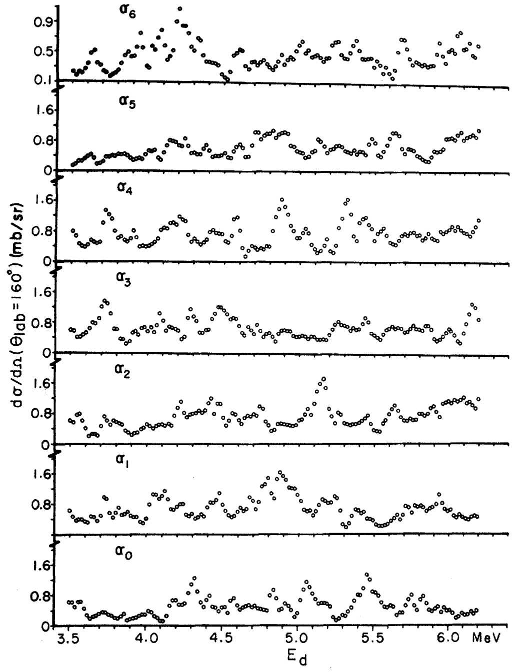

FIG. 3. Excitation functions for the ^{31}P(d,α)^{29}Si reactions at $\theta_{\text{lab}}=160°$.

keV; thus, as many of the particles of different channels as could be resolved were measured in this experiment using the data of up to $n=18$ and 7 channels at $\theta_{\text{lab}}=90°$ and 160°, respectively. The excitation functions were carried out from $E_d=3.5$ to 6.2 MeV in steps of 20 keV, and the results are shown in Figs. 2 and 3. The absolute cross sections were measured at $E_d=3.5$ MeV with elastic deuterons, which was in quite good agreement with Rutherford scattering. The errors were estimated to be about ±15%.

III. ANALYSIS AND DISCUSSION

Channel cross correlations and channel correlations[1–3] for all combinations of measured protons and α particles were calculated by the same procedures as those described by Lee *et al.*[13] and Hsu *et al.*[11,12] N_d (Refs. 7 and 8) is obtained from the number of channels of which the cross correlation is larger than its error. The results were 63 and 3; thus the number of correlating channels n_d was deduced to be 12 and 3 for $\theta_{\text{lab}}=90°$ and 160°, respectively, with the following relationships:

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

TABLE I. Comparisons between the C_{cc} and $1/N$ for α particles at $\theta_{\text{lab}}=90°$.

Emitted particle	α_0	α_1	α_2	α_3	α_4	α_5	α_6	α_7
$C_{cc}\pm\Delta C_{cc}$	0.307±0.079	0.104±0.025	0.062±0.015	0.092±0.022	0.053±0.013	0.038±0.009	0.176±0.043	0.044±0.011
$\frac{1}{N}$	0.167	0.083	0.055	0.083	0.055	0.042	0.042	0.033

TABLE II. The values of $\langle \Gamma_\mu \rangle / D$ fitted by the formula of Feshbach (Ref. 13).

Emitted particle	σ^2	$\theta_{\rm lab}=90°$ $\langle\Gamma_\mu\rangle$[a]/D	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt}$ (mb/sr)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm theor}$ (mb/sr)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt} / \left(\frac{d\sigma}{d\Omega}\right)_{\rm theor}$	$\theta_{\rm lab}=160°$ $\langle\Gamma_\mu\rangle$[a]/D	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt}$ (mb/sr)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm theor}$ (mb/sr)	$\left(\frac{d\sigma}{d\Omega}\right)_{\rm expt} / \left(\frac{d\sigma}{d\Omega}\right)_{\rm theor}$
α_0	9	7.5	0.3372	0.2879	1.1712	7.5	0.5679	0.4983	1.1397
α_1	9	7.5	0.5361	0.5502	0.9744	7.5	0.7703	0.7856	0.9805
α_2	9	8.5	0.6803	0.6496	1.0473	8.5	0.8103	0.7287	1.1120
α_3	9	7.5	0.5109	0.5502	0.9286	7.5	0.7566	0.7856	0.9631
α_4	9	8.5	0.6358	0.6496	0.9788	8.5	0.8271	0.7287	1.1350
α_5	9	9.0	0.6885	0.6616	1.0407	9.0	0.6772	0.6130	1.1047
α_6	9	10	0.5311	0.5614	0.9460	10	0.5315	0.4967	1.0701

[a]The errors are about ±15%, which takes account of the error of the absolute cross section.

The averaged value of $n_d(n_d-1)/n^2$ for $\theta_{\rm lab}=90°$ and 160° is obtained to be 0.27. For a theoretical calculation of the width $\langle \Gamma_d \uparrow \rangle$ in Eq. (1), the values of the ratio $\langle \Gamma_\mu \rangle / D$ and $\langle \Gamma_\mu \rangle$ are necessary. Since the autocorrelation coefficient $C_{\rm cc}$ is equal to $(1-Y_D{}^2)/N$ (Refs. 14 and 15), $C_{\rm cc}$ would be equal to $1/N$ (where N is a constant depending on the spins of the incident particle, target nucleus, emitted particle, and residual nucleus) if Y_D—the contribution of the direct reaction in the compound nuclear formation—were zero. The results for the ^{31}P$(d,\alpha)^{29}$Si reaction are shown in Table I. Within error, the consistency between the $C_{\rm cc}$ and $1/N$ is quite good except for α_0 and α_6, but this may be due to the effect of the effective number of degrees of freedom. The reaction ^{31}P$(d,\alpha)^{29}$Si therefore could be assumed to be a pure compound nuclear formation, and the energy averaged absolute cross sections of the α particles for $\theta_{\rm lab}=90°$ and 160° were analyzed by the theoretical formula of Feshbach[16] with the Hsu-Gonsior technique,[17] where the spin-cutoff parameter $\sigma^2=9$ (Ref. 18) was used. The results are shown in Table II, which shows that the values of $\langle \Gamma_\mu \rangle / D$ among the different α particles have good consistency. The average value is $\langle \Gamma_\mu \rangle / D = 8.4 \pm 1.3$. The error is deduced from the error of the absolute cross section. The value $\langle \Gamma_\mu \rangle$ was determined by the autocorrelation function.[1–3] The results are shown in Table III; the averaged value is $\langle \Gamma_\mu \rangle = 45 \pm 2$ keV [finite range of data (f.r.d.) error]. The width $\langle \Gamma_d \uparrow \rangle$ was then calculated to be 158±25 keV.

On the other hand, the excitation functions were averaged numerically with the increasing energy intervals of 20, 40, 80, 120, 160, 200, 280 keV, respectively. Figure 4 is a typical excitation function averaged over several different energy intervals, and Fig. 5 shows the typical excitation functions averaged over a 160 keV energy interval. The widths $\langle \Gamma_d \uparrow \rangle$ of the intermediate resonances can be obtained from such excitation functions. The results are shown as the histogram of Fig. 6. The curve in the figure is a normal distribution, and the standard deviation is ±34 keV. The histogram covers all the widths obtained from the excitation functions of α particles and protons for $\theta_{\rm lab}=90°$ and 160°. From Fig. 6 it can be seen that the most probable value is 198±34 keV. Within error, this result is in agreement with the calculated width $\langle \Gamma_d \uparrow \rangle = 158 \pm 25$ keV. The relationship (1) was again confirmed, and the experimental value

TABLE III. The values of $\langle \Gamma_\mu \rangle$ determined by the autocorrelation functions. The average value is 45±2 keV (f.r.d).

Emitted particle		α_0	α_1	α_2	α_3	α_4	α_5	α_6	α_7	$\alpha_{11,12}$	$p_{0,1}$	p_2	p_3	p_4	p_5	p_{6-8}	$p_{9,10}$	p_{11}	p_{12}
$\theta_{\rm lab}=90°$	$\langle \Gamma_\mu \rangle$ (keV)	60	60	40	44	43	40	52	50	50	40	36	42	40	40	38	37	42	36
$\theta_{\rm lab}=160°$		52	48	44	52	40	40	48											

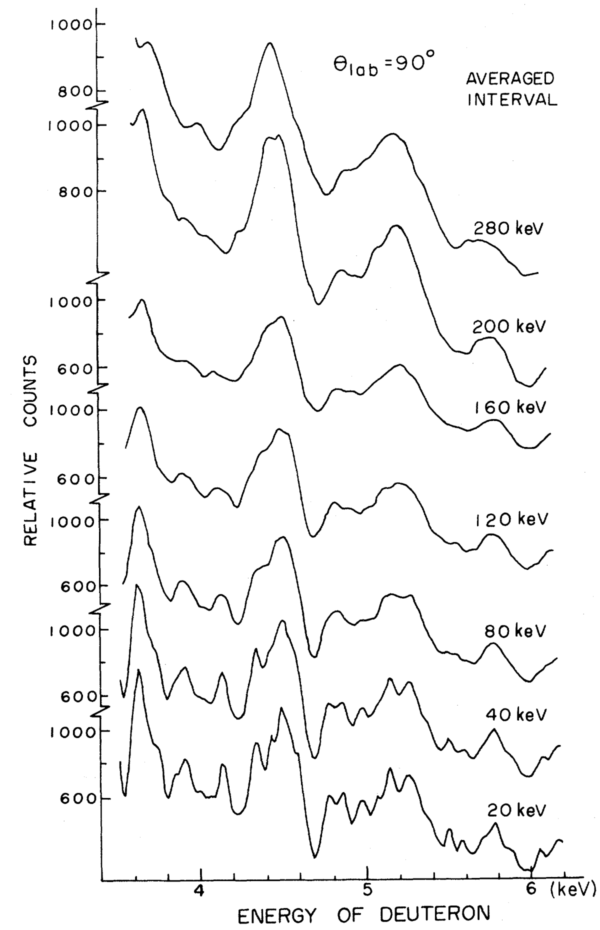

FIG. 4. Excitation function for the ^{31}P(d,α_1)^{29}Si reaction averaged over different energy intervals as indicated in the figure.

$$[n_d(n_d-1)/n^2]_{\text{expt}}$$

could be used for the theoretical value

$$[n_d(n_d-1)/n^2]_{\text{theor}}$$

quite successfully. For the ratio of the numbers of correlating and open channels, $n_d(n_d-1)/n^2$ were determined to be 0.41 for $\theta_{\text{lab}}=90°$ and 0.12 for $\theta_{\text{lab}}=160°$. The average value of the ratio is 0.27, which is consistent with the predicted value

$$(2D/\pi\langle\Gamma_\mu\rangle)^{1/2}=0.28\pm0.04$$

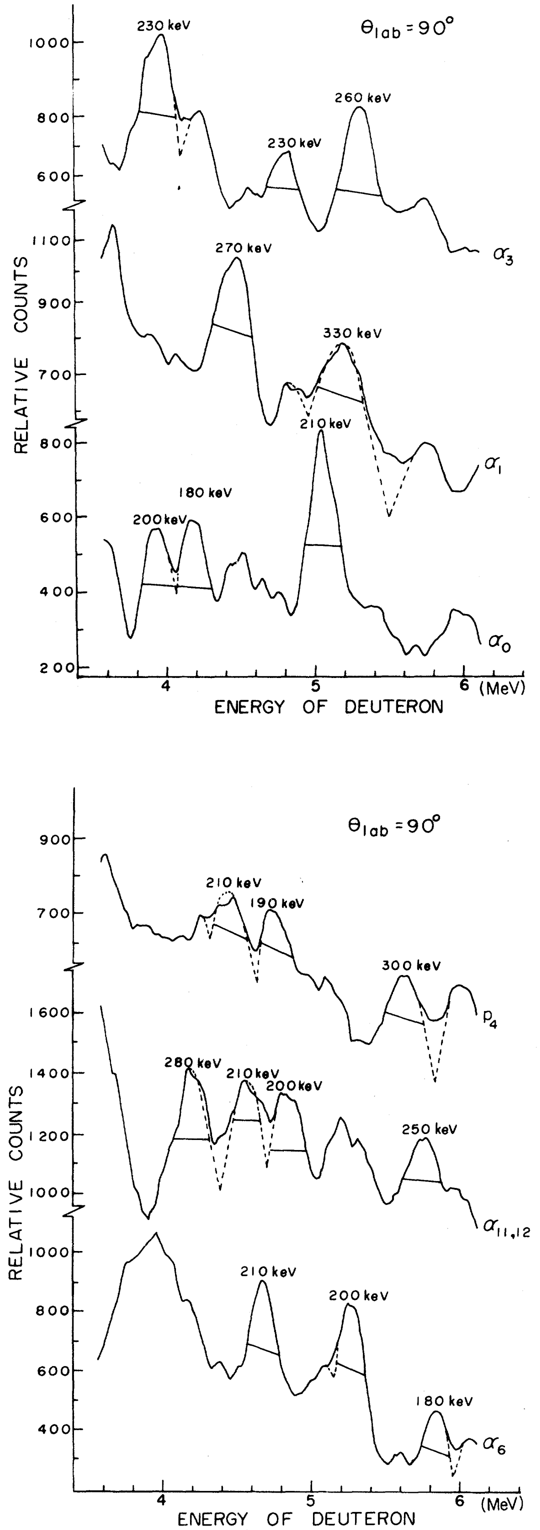

FIG. 5. Typical excitation functions averaged over the energy interval of 160 keV. The numbers given in the figure are the widths of the intermediate resonances.

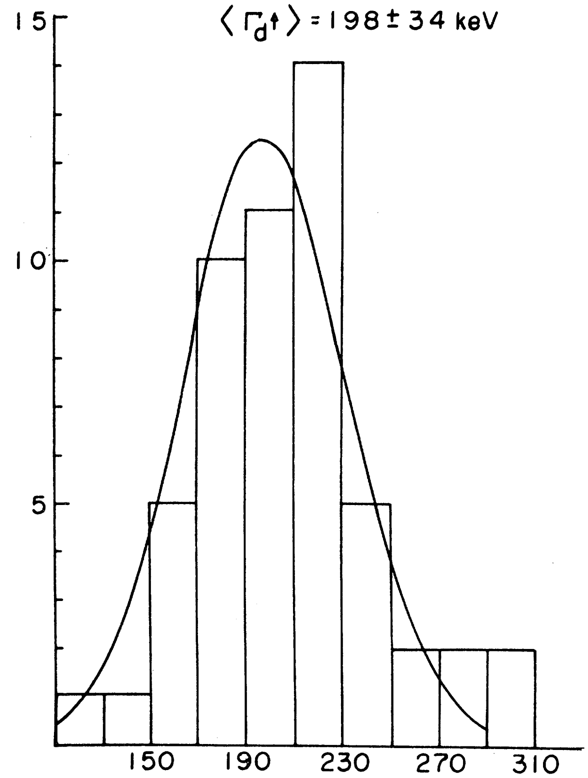

FIG. 6. Histogram of the $\langle \Gamma_d\uparrow \rangle$ obtained from the averaged excitation functions.

(Ref. 9). Finally, we can conclude that the experimental value

$$[n_d(n_d-1)/n^2]_{\text{expt}}$$

can take place of the theoretical value

$$[n_d(n_d-1)/n^2]_{\text{theor}} ,$$

and Eq. (1) could then be simplified to be

$$\langle \Gamma_d\uparrow \rangle = \langle \Gamma_\mu \rangle / R , \tag{3}$$

where

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

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