Reaction ^{55}Mn$(p,n)^{55}$Fe from E_p = 1.35 to 5.42 MeV

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The total (p,n) reaction cross section for ^{55}Mn has been measured as a function of proton energy in the energy range 1.35 to 5.42 MeV with fine resolution (~ 5 keV). Several strong isobaric analog resonances have been located in the excitation function. The excitation function, averaged over a 200 keV energy interval has been compared with the optical model, Hauser-Feshbach, and Hauser-Feshbach-Moldauer calculations. The strong isobaric analog resonance at $E_p \sim 1.54$ MeV has been shape analyzed to extract the proton width Γ_p, the spreading width W, the spectroscopic factor, and the reduced normalization.

[NUCLEAR REACTIONS ^{55}Mn(p,n), E_p = 1.35–5.42 MeV; measured σ (E); optical model and Hauser-Feshbach analysis, isobaric analog resonance analysis.]

I. INTRODUCTION

In continuation of our program of studies of (p,n) reactions below the Coulomb barrier on medium weight nuclides[1,2] through measurement of excitation functions, the total (p,n) cross section for the reaction ^{55}Mn$(p,n)^{55}$Fe has been measured in the bombarding energy range from 1.35 to 5.42 MeV with fine resolution (~5 keV). The major motivation as discussed in Ref. 1 was to determine the optical model parameters for the target plus proton system at sub-Coulomb energies and to study in detail the isobaric analog resonances (IAR) observed.[2-4] Johnson, Galonsky, and Inskeep[5] have measured the thick target (~75 keV) excitation function for this reaction up to ~5.5 MeV. Other previous studies of this reaction at these energies have been mainly confined to neutron and γ ray yield measurements for IAR studies.[6,6(a)]

The experimental arrangement, procedure, and results are discussed in Sec. II, while the analysis of the measured data is discussed in Sec. III followed by the conclusions given in Sec. IV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental technique and procedure followed in this measurement were the same as those for the earlier measurements described in Ref. 1. The targets prepared by evaporating natural manganese (100% ^{55}Mn; other metallic impurities ~20 ppm) on tantalum backings were placed at the center of a 4π geometry flat response neutron counter.[7] Proton beams of energy ranging from 1.35 to 5.42 MeV, available from the 5.5 MeV Van de Graaff accelerator at our laboratory, were used to bombard the targets. The beam current was in-

tegrated by a current integrator[8] and the total neutron yield was measured by the 4π counter. The absolute cross section for the (p,n) reaction on ^{55}Mn was measured over the bombarding energy range in steps of 5 keV with a target about 5 keV thick for 4 MeV protons. The resulting excitation function is shown in Fig. 1. In order to determine the shape of the strong IAR observed around 1.54 MeV with fine resolution, the excitation function was remeasured in that energy region with 1 keV steps and a thinner target (~1 keV for E_p = 2 MeV). Two independent passes were made over the resonance to reduce the uncertainties arising due to target nonuniformities and beam energy fluctuations. The results are shown in Fig. 2. The target thickness was determined with an error of ±15%, utilizing the back scattering technique described in Ref. 1. The maximum error in the absolute cross section is estimated to be ±20%, comprising errors in target thickness determination: 15%; target nonuniformity: 5%; the efficiency[9] of the 4π counter: 7%; current integration: 1%; and counting statistics: 2%.

It can be seen from Fig. 1, that the excitation function exhibits strong resonances as well as weaker fine structures having widths around 10 keV. The arrows indicate the expected positions of IARs assuming the Coulomb displacement energy $\Delta E_c (^{56}$Fe-^{56}Mn) = 8.590 MeV. The IARs observed in the lower energy region by previous workers[6] are also seen in the present work, except for the analog of the ground state of ^{56}Mn which is expected at about 1.34 MeV. Due to the difficulty in running the accelerator at energies below 1.5 MeV, the excitation function could not be extended to lower energies. At higher energies some of the stronger resonances can be correlated with the ex-
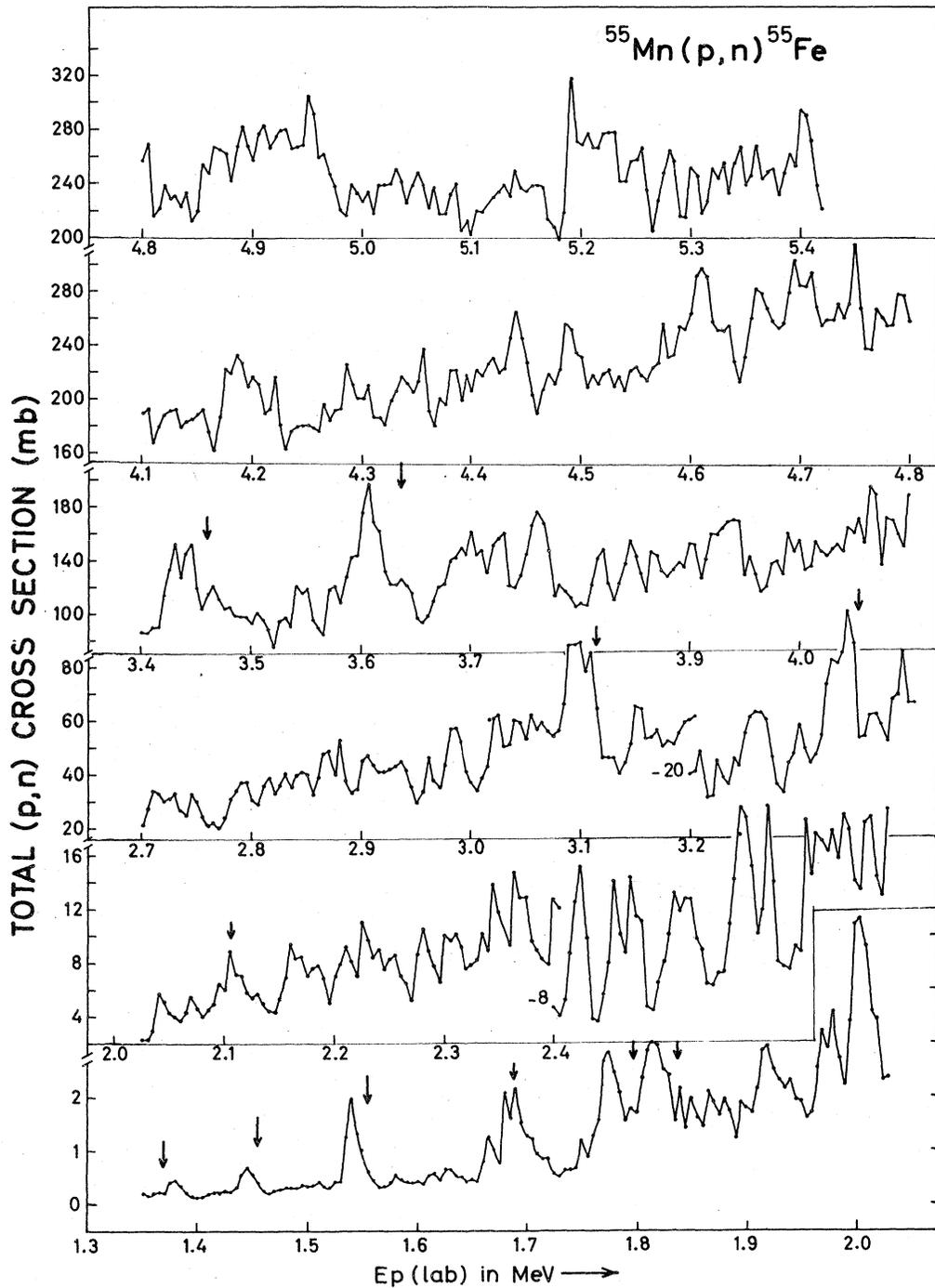
FIG. 1. Fine structure excitation function for the reaction ^{55}Mn(p,n) ^{55}Fe measured in 5 keV steps from E_p = 1.35 to 5.42 MeV. The arrows indicate the expected positions of IAR based on the Coulomb energy shift ΔE_C = 8.590 MeV. Note the change in cross section scale at 2.4 and 3.2 MeV.
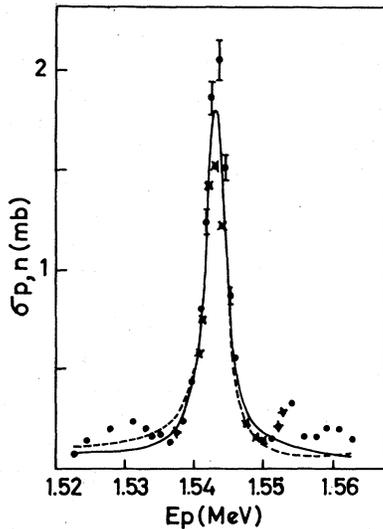
FIG. 2. Shape of the IAR at $E_p \sim 1.54$ MeV measured with the ~ 1 keV target. The dots and crosses represent two separate runs over the resonance. The continuous curve is the fit to data with the Breit-Wigner formula with $\sigma_{max} \sim 1.72$ mb, $E_0 \approx 1.543$ MeV, and $\Gamma_0 \approx 3.4$ keV. The dashed curve is the fit to data with the Robson-Johnson (RJ) formula (Ref. 3), with $T_p* = 0.000\,0525$, $\Delta \approx -22$ keV, $E_0 \approx 1.543$ MeV, and $\Gamma_0 \approx 3.3$ keV.

pected positions of IARs; however, for many cases the structure observed around the arrow mark is weak. This indicates that the special significance of IAR is lost as the excitation energy increases.

No presence of any intermediate structure was noted when the excitation function was averaged over 100 and 200 keV energy intervals as can be seen from Figs. 3(a) and 3(b), respectively. The averaged $\sigma_{p,n}$ values agree well with those of Johnson *et al.*[5]
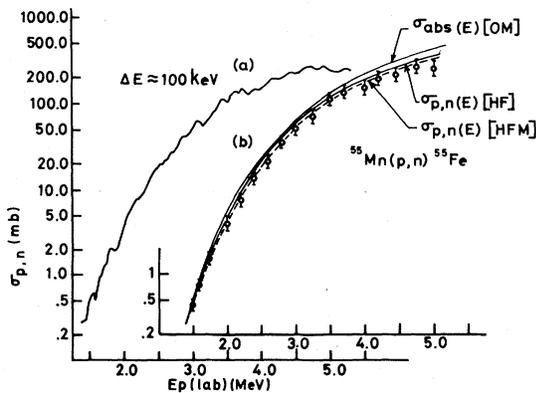

FIG. 3. (a) The fine structure excitation function averaged over 100 keV energy interval. (b) Optical model $\sigma_{abs}(E)$ (OM), Hauser-Feshbach $\sigma_{p,n}(E)$ (HF), and Hauser-Feshbach-Moldauer $\sigma_{p,n}(E)$ (HFM) fits to the ^{55}Mn$(p,n)^{55}$Fe reaction excitation function averaged over the ~ 200 keV energy interval.

III. ANALYSIS

A. Optical model and Hauser-Feshbach analysis

The fine structure excitation function of Fig. 1 was averaged over a 200 keV energy interval and compared with the optical model (OM) predictions following the procedure described in Ref. 1, assuming $\sigma_{abs} \approx \sigma_{p,n}$. Preliminary results of this analysis have been reported earlier.[10] The computer codes OMGLOB[11] and HAUFES[12] were used to calculate the total reaction cross section predicted by optical model and $\sigma_{p,n}$ predicted by Hauser-Feshbach (HF) theory, respectively. The proton parameters of Becchetti and Greenlees[13] were used as the initial set. No spin orbit potential was used because the total reaction cross section is insensitive to such potentials. The imaginary potential depth V_I was decreased to 5 MeV in accordance with our previous experience with ^{54}Cr and ^{59}Co (Ref. 1). The data were then fitted with the optical model using least squares search technique varying V_I. The search on the radius and diffuseness parameter of the imaginary potential did not improve the fits appreciably. The fits to the data are shown in Fig. 3(b). It is seen that at lower energies the total cross section predicted by the optical model and $\sigma_{p,n}$ (experimental) are very similar, thus varifying the assumption that at these energies the relation $\sigma_{abs} \approx \sigma_{p,n}$ is valid. At higher energies however, σ_{abs} is higher than experimental values, and the more accurate HF calculation, with the same proton optical model potential and Wilmore and Hodgson's local equivalent neutron potential,[14] fitted the data very well. The inclusion of Moldauer's level width fluctuation correction[15] (HFM) in the HF calculation, however, did not improve the fit appreciably. The optical model parameters determined through this procedure and used for calculating the fits in Fig. 3(b) are listed in Table I.

TABLE I. Optical model parameters used for calculating the fits shown in Fig. 3(b). The proton parameters are determined in this work, as described in the text, starting with those given in Ref. 13. The neutron parameters are taken from Ref. 14.

	^{55}Mn $+p$	^{55}Fe $+n$
V_R	$58.8 - 0.32E_p$	47
R_R	1.175	1.3
a_R	0.75	0.62
V_I	$6 - 0.25E_p$ [a]	5 [b]
R_I	1.32	0.71
a_I	0.574	0.62

[a] Woods-Saxon derivative form for V_I.

[b] Gaussian form for V_I.

As in the previous work[1] the only significant de-
parture of the present results from the optical
model parameters determined at higher energies[13]
has been the much lower value of V_I, the depth of
imaginary potential. The energy dependence of V_I
given in Ref. 13 would yield a value of $V_I \approx 12$ MeV
for a 4 MeV bombarding energy while the best fit
value from our analysis yields a value of ~5 MeV
for V_I at that bombarding energy. It is under-
standable that V_I should be smaller at lower ener-
gies as the level density is very much reduced at
the corresponding low excitation energies.

B. Shape analysis and extraction of spectroscopic factor for the IAR at 1.54 MeV

The strong resonance measured at 1.54 MeV and
shown in Fig. 2 can be identified as the IAR
formed by an $l = 1$ proton leading to a 2^+ level in
the compound nucleus ^{56}Fe which is the analog of
the 0.213 MeV level in the parent nucleus ^{56}Mn,
studied through ^{55}Mn$(d,p)^{56}$Mn reaction.[16] How-
ever, the subsequent (n,γ) measurement[17] on ^{55}Mn
has revealed that the parent state in question is a
doublet with energies 212 and 215 keV with spins
4^+ and 1^+ or 2^+, respectively. Similarly, the
^{55}Mn$(p,\gamma)^{56}$Fe work[6(a)] has shown that there are two
levels in ^{56}Fe at $E_x = 11699$ and 11 705 keV with
spins 4^+ and 2^+, respectively, which could be the
isobaric analogs of 212 and 215 keV levels of ^{56}Mn.
In the present (p,n) work, as our energy resolu-
tion is better than 2 keV, two levels separated by
6 keV as measured in (p,γ) work should be seen
distinctly. However, there is no evidence for a
second resonance in the neighborhood of the peak
at 1.543 MeV as seen in Fig. 2 where the width of
the resonance is only 3 keV. Considering the spins
of the levels concerned, it can be seen that the 4^+
levels (the lower of the doublet) would be only
weakly excited as a resonance in the (p,n) excita-
tion function because of the extremely reduced
penetrability of the partial wave for the outgoing
neutron channel. Assuming that only the ground
state of the residual nucleus ^{55}Fe [with $J^\pi = (\frac{3}{2})^-$]
would be energetically open for $E_p = 1.54$ MeV, the
outgoing neutron from the 4^+ IAR would have an
energy of about 400 keV and would have to carry
away an angular momentum of three units. The
penetrability for this partial wave would be negli-
gible compared with that for the neutron coming
out due to the decay of the 2^+ IAR which would have
similar energy but would have to carry away an
angular momentum of one unit only. Thus the ob-
served single strong resonance could be inter-
preted as the analog of the 215 keV 2^+ state of the
parent nucleus ^{56}Mn. This is in fact supported by
the (p,n) and (p,γ) measurement of Otto et al.[6]

where one finds only one structure at this proton
energy in the (p,n) reaction but more than one
structure in the case of the (p,γ) reaction.

After having established the fact that only one of
the two IARs in this energy region is observed in
the (p,n) reaction, a detailed shape analysis of
this IAR has been performed following (a) Robson-
Johnson (RJ)[3] and (b) Breit-Wigner (BW) methods
to extract the proton partial width Γ_p, spreading
width W, and neutron spectroscopic factor S_n.
The extraction of the IAR parameters and W was
performed in the manner as described in Ref. 2.
In Fig. 2 the theoretical fits to the data based on
RJ and BW methods are shown, and as expected
both approaches yield nearly equivalent fits to the
data (as discussed by Jones,[18] at sub-Coulomb en-
ergies the Robson-Johnson expression reduces to
the conventional Breit-Wigner formula). The Γ_p
and W values are calculated as a function of chan-
nel radius and are shown in Fig. 4. As expected
these values depend significantly on the channel
radius. It is seen that Γ_p passes through a mini-
mum at $R \sim 4.25$ fm. Corresponding to this radius
the optimum Γ_p and W values are 0.0078 ± 0.0001
and 2.50 ± 0.03 keV, respectively. The partial
width extracted from BW analysis are as follows:

$$\Gamma_1 = 0.0075 \pm 0.0002 \text{ keV},$$

$$\Gamma_2 = 3.39 \pm 0.06 \text{ keV}.$$

The Γ_p extracted from the RJ formula is very
nearly equal to the value of Γ_1 extracted from the
BW analysis. The larger of the partial widths Γ_2
in the BW analysis is of the order of the spreading
width W extracted from the RJ procedure. We thus
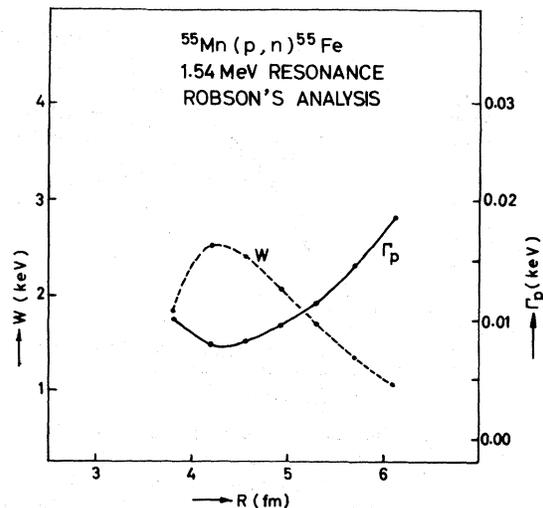find that combining these two methods of analyses,

FIG. 4. Variation of Γ_p and W as a function of the
channel radius R.

an unambiguous value of Γ_p can be obtained. The present results are similar to those obtained by Mehta *et al*.[2] in their analysis of the IAR in the $^{51}V(p,n)^{51}Cr$ reaction. The mean value of Γ_p determined in the present analysis is 0.0076 ± 0.0002 keV. The errors quoted on the values of Γ_p and W are those determined from the fitting procedure and reflect the scatter of points (i.e., statistical and uncertainties due to nonuniformity of the target). The absolute errors on these quantities, however, would have a maximum value of $\pm 15\%$ reflecting the absolute error in the cross section measurement. The absolute error quoted here is smaller (thick target excitation function has an error of $\pm 20\%$) as the thinner target thickness has been measured with an error of $\pm 10\%$ as compared with the thick target measurement which has an error of $\pm 15\%$ (Sec. II).

Thompson, Adams, and Robson[19] have discussed the relationship between Γ_p for an IAR and the corresponding spectroscopic factor S_n for the parent state, which can be utilized to determine S_n in the present case. In addition to Γ_p, this calculation involves the proton plus target (analog nucleus) and neutron plus target (parent nucleus) optical parameters and the proton channel radius a_c. It can be seen that S_n determined this way will be dependent on all these quantities. In order to study the sensitivity of the value of S_n to change in the neutron plus target optical parameters, especially the radius parameter (r_{no}) and the diffuseness parameter (a_n), S_n values were calculated for a set of r_{no} and a_n values in the following manner. For each value of r_{no} and a_n, the S_n was calculated as a function of a_c utilizing the computer code SSEARCH[20] based on the expressions given in Ref. 19. In general S_n is expected to go through a minimum[19] as a function of a_c. It was found that this was not true in case of some r_{no} values. However, in all cases the S_n versus a_c curves exhibited a plateau, where the values of S_n became insensitive to variation in a_c. This value of S_n (corresponding to $a_c \sim 6.4$ fm in the present case) was chosen as an indicative value to study its variation with r_{no} and a_n. Results of these calculations are shown as curves numbered (3) and (4) in Fig. 5 which indicate the strong dependence of S_n on r_{no} and a_n. The S_n value was not very sensitive to the proton optical model parameters. The parameter set used in this calculation is given below:

$$V_R = 58.0, \quad R_R = 1.175, \quad a_R = 0.65 = a_{so}$$

$$V_{so} = 6.0, \quad R_{so} = 1.2.$$

The spectroscopic factor obtained from the (d,p) reaction is also similarly dependent upon neutron potential parameters.[21] We have reanalyzed the
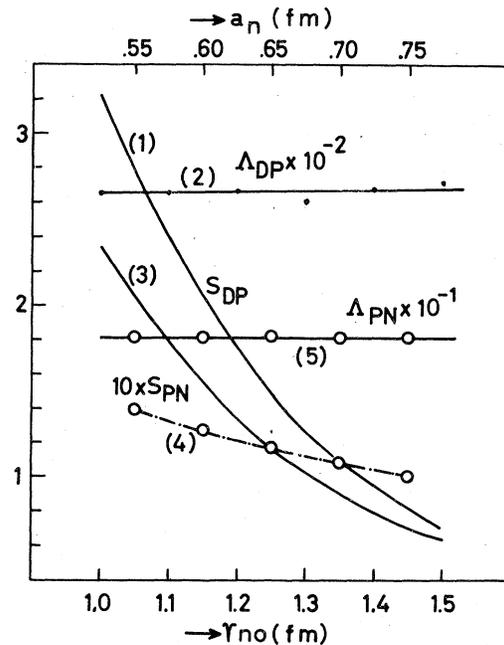

FIG. 5. Variation of spectroscopic factor S and reduced normalization Λ with r_{n0} and a_n. Curves numbered (1) and (2), respectively, show the variation of S_{DP} and Λ_{DP} as a function of the neutron radius parameter r_{n0} (a_n fixed at 0.65 fm). Curves numbered (3) and (4), respectively, show the variation of S_{PN} with r_{n0} ($a_n = 0.65$ fm) and with a_n (r_{n0} fixed at 1.25 fm). Curve numbered (5) gives the variation of Λ_{PN} with r_{n0} (a_n fixed at 0.65 fm). The subscripts DP and PN refer to the spectroscopic factor extracted from (d,p) and (p,n) data, respectively.

$^{55}Mn(d,p)^{56}Mn$ reaction data of Comfort[16] (pertaining to the state at 0.213 MeV which is the parent of the present IAR) using his potential parameters and the code DWUCK[22] to obtain neutron spectroscopic factors for the parent state for various values of r_{no}. The variation of this S_n (called S_{DP} in Fig. 5) with r_{no} is also shown as curve numbered (1) in Fig. 5 for comparison with S_n (called S_{PN} in Fig. 5) obtained from the present IAR study.

Comparison between the spectroscopic factors extracted from (d,p) and IAR data is done better using the reduced normalization Λ[21,23] which is less sensitive to parameter variations. The quantity Λ has been obtained in the present work following the method of Clarkson, Von Brentano, and Harney,[23] where $\Lambda \propto S_n|U_n|^2$. Harney and Weidenmuller[24] have shown that $S_n|U_n|^2$ (U_n being the normalized bound state neutron wave function) is independent of neutron potential parameters at a radius a_c where the proton wave function is zero. In the present investigation this value of a_c is again chosen at 6.4 fm, where S_n as a function of a_c shows a plateau as discussed earlier. The Λ val-

ues (called Λ_{PN}) calculated by the above proce-dure[23] (utilizing the S_n values at $a_c = 6.4$ fm) are also shown in Fig. 5 as a function of r_{no}. It is found that the Λ_{PN} value is constant to within 1%. Similar calculations have been done for (d,p) data as well and in this case the value (called Λ_{DP}) is found to be constant to within 4% as indicated in Fig. 5.

The above detailed discussion would indicate the difficulties in comparing the results of (d,p) and (p,n) analysis of the IARs due to the parameter dependence of S_n. The usefulness of the reduced normalization Λ in this regard is also demon-strated. However, the comparison between the corresponding numbers in the present case shows that the values of optimum S_n as well as Λ ob-tained in the present (p,n) analysis (S_{PN} and Λ_{PN}) are lower by almost an order of magnitude com-pared with S_{DP} and Λ_{DP}. The disagreement up to a factor of 5 has been previously observed in such comparisons.[25] On the other hand, due to the fact that Comfort[16] in his (d,p) work has not resolved the doublet around 215 keV, the S_n obtained in this work would represent the combined strength of the two levels, while the present (p,n) work only mea-sures the spectroscopic factor of the 215 keV 2^+ level. Van Assche et al.[17] in a study of the ^{55}Mn$(n,\gamma)^{56}$Mn reaction have estimated the contri-bution from the two states and found only 40% being contributed by the 2^+ states. This would indicate a change in the values of S_n and Λ in the right direc-tion to be consistent with the (p,n) results. The analysis technique described here has been sub-sequently used in a similar study of the ^{80}Se$(p,n)^{80}$Br reaction[26] at our laboratory where the agreement between the S_{PN} and S_{DP} is very good. This work

also indicated that the analysis of IAR observed in the (p,n) reaction is likely to provide better spec-troscopic factors than those obtained through (p,p) studies for resonances much below the Coulomb barrier.

IV. CONCLUSION

The present work has resulted in the determina-tion of proton optical model parameters for ^{55}Mn at sub-Coulomb energies through optical model and Hauser-Feshbach analysis of (p,n) excitation func-tion. It is found that the value of the imaginary potential is smaller than that determined at higher energy. It should be mentioned again that this method of extraction of proton optical model pa-rameters by fitting (p,n) data is most reliable at sub-Coulomb proton energies as the more conven-tional method of fitting the (p,p) angular distribu-tion would not be suitable at these low energies due to large Coulomb effects. The S_n calculated from this work does not agree with that extracted from (d,p) work because of the fact that (d,p) deals with an unresolved doublet and the present work deals with only one of the two levels (2^+ level) in the doublet.

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