Analog resonances and possible $T_>$ mixing in ^{77}Br†

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The locations and widths of several analog resonances in ^{77}Br have been measured. Comparison of resonance spectroscopic factors to stripping spectroscopic factors show poor agreement, but spectroscopic factor ratios for states of the same spin and parity show good agreement except for the s-wave resonances. It is suggested that this disagreement may be explained by a mechanism of $T_>$ mixing between $\frac{1}{2}^+$ resonances.

[NUCLEAR REACTIONS ^{76}Se(p, p), E = 3.1–4.5 MeV; measured $\sigma(E)$; deduced IAS, Γ, S. ^{76}Se(p, p'), E = 4.1–4.3 MeV; measured $\sigma(E)$.]

A large amount of data has been obtained in recent years relating isobaric analog states to their parent states. Studies of this nature have permitted the comparison of the parent levels in the $P_{N+1,Z}$ nucleus with their analogs in the $Y_{N,Z+1}$ nucleus. These comparisons are usually made in terms of the Coulomb energy shift between parent and analog states and in terms of the spectroscopic factors for these states. In most cases, the levels studied have been relatively well separated and the similarity of the analog and parent states has been high. In a few cases, however,[1] where states of the same spin and parity were not widely separated, the results obtained for parent and analog states do not agree well.

The use of ^{76}Se as a target material for proton elastic scattering studies is interesting in the context of the above discussion since experiments of this type yield information about several pairs of more or less widely separated isobaric analog levels of the same spin and parity. The data for the parent states of these analogs have been determined by Lin.[2]

In this experiment proton elastic scattering excitation functions for the reaction ^{76}Se(p, p)^{76}Se were obtained over a region of incident proton energy from 3.05 to 4.50 MeV. From these data, eight resonances have been located, six of which were sufficiently strong to permit extraction of the resonance energy, spin, parity and spectroscopic factor for the isobaric analog states in ^{77}Br. These results were then compared with information about the corresponding parent states in ^{77}Se. Finally, as a check on the interpretation of the elastic scattering results, inelastic scattering was studied between 4.10 and 4.30 MeV.

EXPERIMENTAL PROCEDURE AND DATA

These proton scattering experiments were performed on the Kansas State University 6 MV EN tandem Van de Graaff accelerator. In this experiment excitation functions were obtained for the reaction ^{76}Se(p, p)^{76}Se at angles of 90°, 120°, and 160°. The incident proton lab energies were varied from 3.05 to 4.5 MeV, which spans the energies where analog resonances are expected corresponding to the ground state and excited states up to 1.35 MeV in ^{77}Se.

The targets used in this experiment were prepared by evaporation of 86.1% isotopically enriched ^{76}Se onto 10 μg/cm^2 carbon backings. These selenium targets were determined to be approximately 40 μg/cm^2. Targets of this nature deteriorated rapidly when bombarded at beams of over 20 nA of protons, and hence it was necessary to deposit a film of 30 μg/cm^2 of ^{27}Al over the selenium. Targets prepared in this manner showed no deterioration when subjected to 0.3 μA of 4 MeV protons. The expected energy resolution resulting from beam energy spread and energy loss in the target is less than 2.5 keV.

These targets were placed in a 76 cm scattering chamber with collimated silicon surface barrier detectors located at laboratory angles of 90°, 120°, and 160°. The detectors were placed at different distances from the target so as to produce approximately equal count rates from each detector. A three slit collimator was used to define the beam striking the target, and hence to eliminate scattering from the tantalum target holder.

The pulses from the four detectors were amplified and multiplexed into a TMC 4096 channel analyzer. The spectra at each energy were recorded on IBM compatible magnetic tape as four 1024 channel spectra. A PDP 15/30 computer was available on line and was used to study the spectra individually. The spectra taken in this manner contained sharply defined peaks from the various elements of the target. A typical spectrum is shown in Fig. 1.

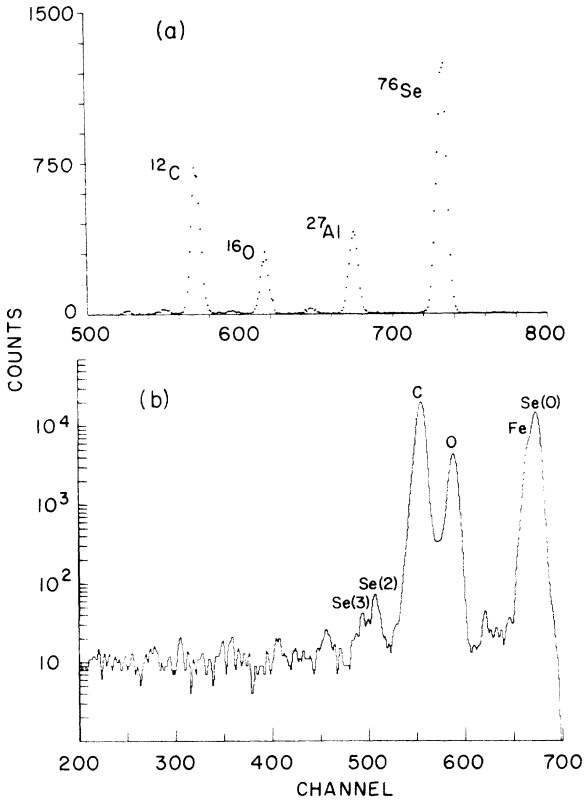

FIG. 1. Typical spectra measured in these experiments. (a) Spectrum measured at 150° with aluminum-covered ^{76}Se which was used to measure elastic scattering excitation functions. (b) Spectrum measured at 120° with iron-covered ^{76}Se target used to measure inelastic scattering excitation functions. The ^{76}Se states at 1.11-MeV [Se(2)] and 1.22-MeV [Se(3)] excitation energy are observed at this angle. The ^{76}Se state at 0.56 MeV is obscured at 120° by the elastic scattering from ^{16}O but is well separated at 150°.

The analysis of these spectra was performed on an IBM 360/50 computer. The area of the peak resulting from protons elastically scattered from

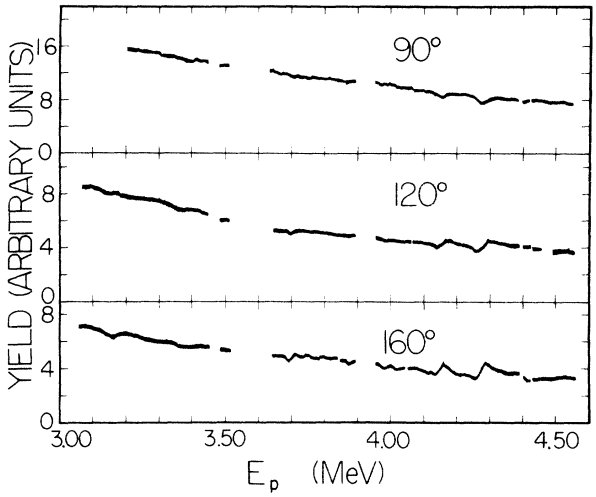

FIG. 2. Measured elastic proton scattering excitation functions for ^{76}Se at three indicated angles. These excitation functions were measured in the neighborhood of expected analog resonances between 3.0 and 4.5 MeV.

^{76}Se was determined by summing the counts between windows set around the peak. Since uniform energy steps were taken in the collection of the spectra, the windows could be moved according to kinematic relations. This allowed a large number of spectra to be analyzed quickly and efficiently. Background corrections were unnecessary since the counts fail to zero between peaks. The measured elastic scattering excitation functions are displayed in Fig. 2. Strong resonances, for which reliable resonance parameters could be determined, are listed in Table I. In addition, weak resonances were observed at laboratory energies of 3.17 and 3.38 MeV. Analysis of these weak resonances did not yield reliable resonance parameters.

Finally, new targets were prepared by evaporating enriched ^{76}Se onto 10 μg/cm^2 carbon backing and then evaporating a thin cover layer of

TABLE I. ^{77}Br analog resonance parameters and ^{77}Se parent state parameters.

E_p (lab) (MeV)	E_p (c.m.) (MeV)	J^π	Γ_{total} (keV)	Γ_p (keV)	$(2J+1)S_A$	E_x (^{77}Se) [a] (MeV)	$(2J+1)S_n$ [a]
3.698	3.650	$\frac{3}{2}^-$	10 ± 2	0.4 ± 0.1	0.16 ± 0.03	0.522	0.34
3.870	3.820	$\frac{5}{2}^+$	15 ± 2	0.3 ± 0.1	0.75 ± 0.20	0.682	1.23
4.146	4.092	$\frac{1}{2}^+$	23 ± 2	3.0 ± 0.2	0.35 ± 0.02	0.956	0.25
4.213	4.158	$\frac{3}{2}^-$	18 ± 2	0.5 ± 0.1	0.08 ± 0.01	1.013	0.17
4.271	4.216	$\frac{1}{2}^+$	30.7 ± 2	6.2 ± 0.2	0.63 ± 0.02	1.134	0.76
4.417	4.360	$\frac{5}{2}^+$	24 ± 2	1.0 ± 0.2	0.92 ± 0.15	1.258	1.11

[a] These results are from Ref. 2.

iron onto the selenium. The inelastic proton scattering from the iron did not interfere with the observation of inelastic scattering from ^{76}Se. These targets were used to study the ^{76}Se inelastic scattering from 4.1 to 4.3 MeV. A typical spectrum from this target is displayed in Fig. 1(b). Excitation curves for inelastic protons populating the first three excited states of ^{76}Se between laboratory bombarding energies of 4.1 and 4.3 MeV are shown in Fig. 3.

EXCITATION FUNCTION ANALYSIS

The excitation functions for proton elastic scattering from ^{76}Se were analyzed using the code ANSPEC.[3] This code utilized a single level expression for the differential scattering cross section. Compound elastic contributions resulting from energy averaging over the fine structures are included. Elastic scattering from $T_<$ states is approximated by an absorption term in an optical potential; the mixing between resonances and this absorptive term is considered in terms of a resonance mixing phase ϕ_0^R. These details are discussed in detail by Thompson, Adams, and Robson.[4]

The optical model potential used in these calculations is of the form

$$V(r) = -(V + iW)f(r) - iW'g(r) - V_s h(r)\vec{\sigma}\cdot\vec{I} + V_c(r), \quad (1)$$

where

$$f(r) = \{1 + \exp[(r-R)/a]\}^{-1},$$

$$g(r) = r\exp[(r-R)/a']\{1 + \exp[(r-R)/a']\}^{-2},$$

$$V_c(r) = Z_p Z_T(e^2/2R)[3 - (r/R)^2], \quad r < R$$

$$= Z_p Z_T(e^2/r), \quad r > R,$$

$$h(r) = (ra)^{-1}\exp[(r-R)/a]\{1 + \exp[(r-R)/a]\}^{-2}.$$

The parameters used in the potential were developed by Balamuth, Couchell, and Mitchell,[1] and had the following values: $V = 57$ MeV, $W = 0$, $W' = 5.0$ MeV, $V_s = 7.5$ MeV, $R = 5.32$ fm, $a = 0.65$ fm, and $a' = 0.47$ fm.

The analysis of proton elastic scattering in this experiment was simplified by the fact that only the proton channels were open. The resonances in the excitation function were sufficiently separated so that the single level formalism, upon

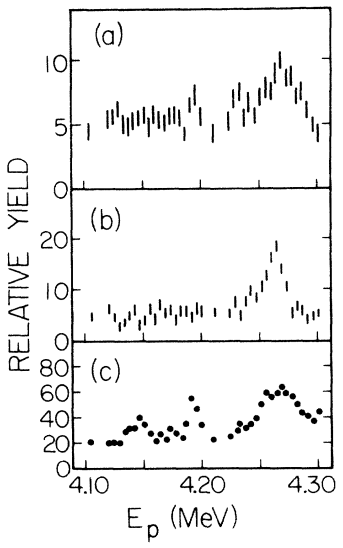

FIG. 3. Inelastic proton scattering excitation functions for the first three excited states of ^{76}Se: (a) inelastic scattering to the 2+ state at 1.22-MeV excitation at a laboratory angle of 120°; (b) inelastic scattering to the 0+ 1.11-MeV state at 120°; (c) inelastic scattering to the 2+ 0.56-MeV state at 150°.

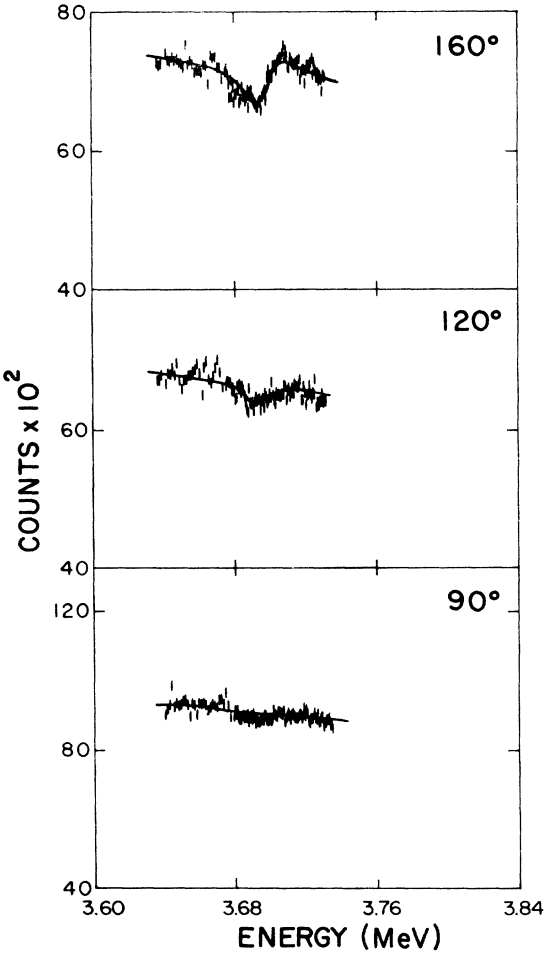

FIG. 4. Elastic proton scattering and fit in neighborhood of the 3.7-MeV resonance. The data are fit with an $l = 1$ resonance with the parameters given in Table I.

which ANSPEC is based, was adequate for the analysis. Initially, the orbital angular momentum of the level producing each resonance was determined by inspection of the shape of the resonance. Following this, a fit was generated for each resonance using the ANSPEC code. The proton partial widths and total widths for resonances located in the elastic scattering excitation function are listed in Table I.

Fits were made to the data using the J values listed in Table I. These J values are in accord with the suggestions of Lin[2] and Urone, Lee, and Raman.[5] Table I also contains the proton partial widths and the total widths determined from the excitation function fits. The states in ^{77}Br from which these resonances result are the analogs of "parent" states in ^{77}Se. Figures 4 through 8 present the excitation functions in the vicinity of the observed resonances together with the fits to the data generated by the code ANSPEC.

An energy comparison of the analog states with the corresponding parent states can be made by taking into account the Coulomb energy difference between these states. Table I includes a list of excited states in ^{77}Se which we identify as the parent states of the observed states in ^{77}Br.

The equivalent neutron spectroscopic factors S_A for the observed analog states in ^{77}Br are defined by the relation

$$S_A = \gamma_{2\lambda}{}^2(2T_0+1)/(\gamma_{n\lambda}^{\mathrm{sp}})^2 , \tag{2}$$

where T_0 is the isospin of the ^{76}Se ground state ($T_0 = 4$). The proton reduced width $\gamma_{p\lambda}{}^2$ is related to the observed proton partial width $\Gamma_{p\lambda}$ by the relation

$$\gamma_{p\lambda}{}^2 = \Gamma_{p\lambda}/2P_p^{\mathrm{opt}} . \tag{3}$$

The single particle neutron reduced width $(\gamma_{n\lambda}^{\mathrm{sp}})^2$

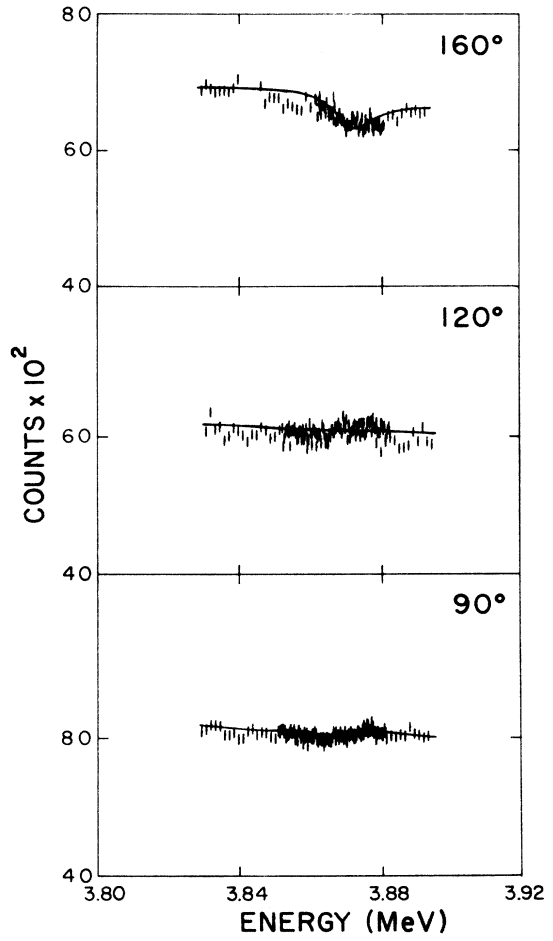

FIG. 5. Elastic proton scattering and fit in neighborhood of the 3.87-MeV resonance. The data are fit with an $l = 2$ resonance with the parameters given in Table I.

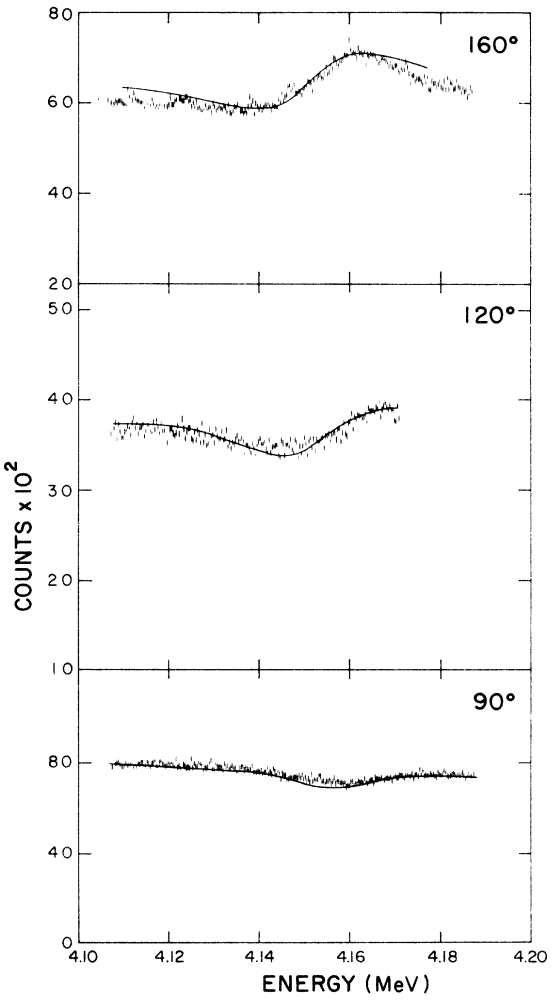

FIG. 6. Elastic proton scattering and fit in neighborhood of the 4.14-MeV resonance. The data are fit with an $l = 2$ resonance with the parameters given in Table I.

is determined from standard optical model calculations. The proton penetrability P_p^{upl} is calculated at the radius $Q_c = 6.4$ fm. This is slightly larger than the radius $(1.05A^{1/3} + 1.5)$ suggested by Robson[6] as the desirable choice for matching radius. However, this radius is close to the nuclear surface and is in the range where the spectroscopic factor varies slowly with matching radius as suggested by Thompson, Adams, and Robson[4] (see Fig. 9).

If the theoretical analysis is correct, one should find that the spectroscopic factor S_A is identical with the neutron spectroscopic factor for the parent states.

The spectroscopic factors quoted in this paper were calculated using the code ANSPEC.[3] The calculated spectroscopic factors for the analog states are presented in Table I along with corresponding parent state spectroscopic factors obtained from deuteron stripping experiments. The agreement is seen to be rather poor. This is not surprising in light of the variations shown in Fig. 9 and the possibility of a difference in normalization between the distorted-wave Born-approximation (DWBA) calculations for the parent and the optical model calculations for the analog spectroscopic factors.

In view of these difficulties and the lack of good agreement between parent and analog state spectroscopic factors, it becomes interesting to consider ratios between spectroscopic factors for states of the same orbital angular momentum.

The consideration of spectroscopic factor ratios has several advantages. The ratios obtained are approximately independent of problems in penetrability estimates and single-particle widths for

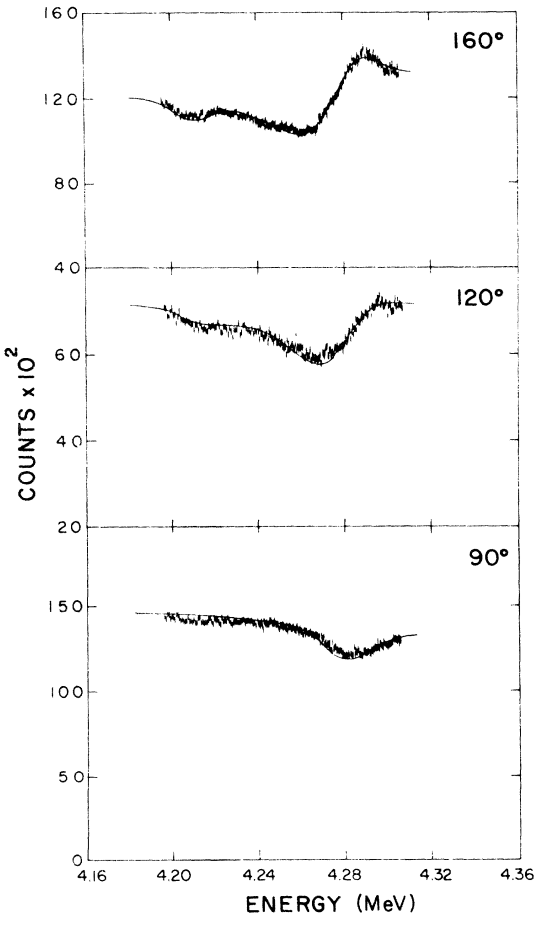

FIG. 7. Elastic proton scattering and fit between 4.2 and 4.31 MeV. The data are fit with an $l = 1$ resonance and an $l = 0$ resonance with the parameters given in Table I.

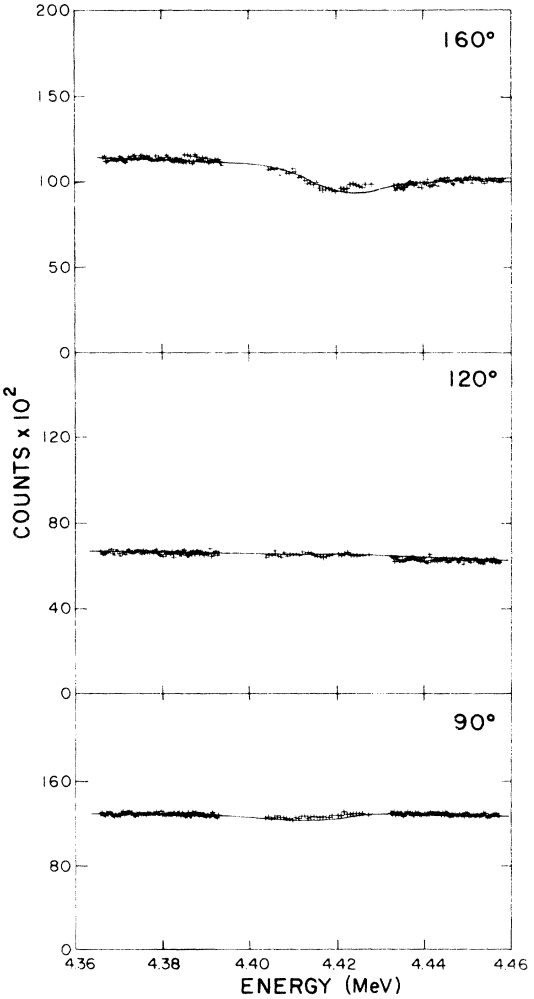

FIG. 8. Elastic proton scattering and fit in neighborhood of the 4.42-MeV resonance. The data are fit with an $l = 2$ resonance with the parameters given in Table I.

the analog resonances. Analysis of the stripping experiments to the parent states also suffer from model dependence. This model dependence is minimized also by considering spectroscopic factor ratios. Finally, the possibilities of a difference of spectroscopic factor normalization between parent and analog state is eliminated in the ratio. Table II contains a comparison of these spectroscopic factor ratios for levels of the same l value. The resonances considered here were assumed to have the same J values.

The ratio of the spectroscopic factors for the $l=2$ analog resonances located at incident proton energies of 4.40 and 3.87 MeV compare very well with that resulting from (d, p) studies on the parent states. Similarly, the ratio of the spectroscopic factors for the $l=1$ analog resonances is in accord with the ratio of the spectroscopic factors from (d, p) work.

The comparison of the two $l=0$ resonances located at incident proton energies of 4.27 and 4.14 MeV produces unexpected results. The ratio of the spectroscopic factors for these analog states is determined from ANSPEC to be 1.8 ± 0.1. This result is in strong disagreement with the ratio of 2.9 resulting from the (d, p) work of Lin.[2] It can be seen from Fig. 9 that even large changes in the optical model parameters and matching radius used in the calculation of the analog state spectroscopic factors cannot bring their ratio up to the value of 2.9.

It should be noted that Balamuth *et al.*[1] report that a variation of parameters resulted in a change in spectroscopic factor ratio from 0.08 to 0.14 for the $\frac{1}{2}+$ resonances in ^{79}Br. However, recalculation using their quoted parameters results in a ratio of 0.14 with a resonance mixing phase of almost 58°. This mixing phase results in a reversal of the shape of the s-wave resonance at 150° scattering angle and, therefore, a totally unacceptable fit to the experimental data. Our experience indicates that all variations of parameters which result in acceptable fits to data produce at most 15% change in the spectroscopic factor ratios.

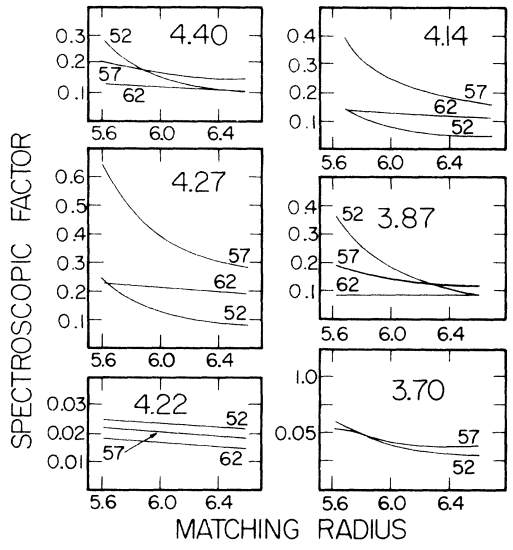

FIG. 9. The variation of resonance spectroscopic factor with well depth and matching radius. The spectroscopic factors listed in Table I were obtained using a well depth of 57 MeV and a matching radius of 6.4 fm.

DISCUSSION OF RESULTS

The spectroscopic factor ratios obtained for $l=1$ and $l=2$ analog states in ^{77}Br observed in this experiment agree with the spectroscopic factor ratios obtained for the corresponding parent states in ^{77}Se. The states involved in this comparison are widely separated in energy and there is no reason to expect anything other than good agreement.

This is not the case for the $l=0$ states observed in this experiment. These resonances are separated by less than 130 keV. A study of the proton elastic scattering from ^{76}Se and of the ^{76}Se$(d, p)^{77}$Se reaction reveals experimental observations inconsistent with the interpretation that the $l=0$ states in ^{77}Br are the exact analogs of two completely separated $l=0$ states in ^{77}Se.

We would like to suggest a possible explanation for these results. This explanation assumes that the $\frac{1}{2}+$ states in ^{77}Br are not the exact isobaric analogs of the corresponding states in ^{77}Se. We suggest that the $\frac{1}{2}+$ states in ^{77}Se are a mixture of configurations and that variations in the Coulomb energy difference for these configurations results in the $T_>$ states in ^{77}Br having a slightly different mixture of configurations. A small change in the configuration mixing of these states between parent and analog nuclei would then change the spectroscopic factor ratios and produce the change in energy spacing observed for the parent and analog states. This will then be a

TABLE II. Ratios of spectroscopic factors for ^{77}Br analog states and ^{77}Se parent states.

Resonances located at E_1/E_2	l	Analog S_1/S_2 from ANSPEC	Parent S_1/S_2 [a]
3.70/4.22	1	2.1 ± 0.4	2.0
4.27/4.14	0	1.8 ± 0.1	2.9
4.41/3.87	2	1.2 ± 0.3	0.95

[a] From Ref. 2

mixing between $T_>$ states of the same spin and parity, distinct from the usual mixing between $T_>$ and $T_<$ states.

Let us denote the pair of observed analog states $|1\rangle$ and $|2\rangle$ and the parent states $|X\rangle$ and $|Y\rangle$. In the usual discussion of Coulomb energies,[7] only diagonal matrix elements of the Coulomb potential between pure isospin states are considered. If we consider the isobaric analog states of $|X\rangle$ and $|Y\rangle$, $|X_A,\ T,\ T-1\rangle$ and $|Y_A,\ T,\ T-1\rangle$, there is a matrix element

$$V_{XY} = \langle X_A,\ T,\ T-1 | V_c | Y_A,\ T,\ T-1\rangle . \qquad (4)$$

This matrix element, which is usually assumed to be zero, is the cause of the $T_>$ mixing. If we assume this $T_>$ mixing significantly mixes only states $|X_A\rangle$ and $|Y_A\rangle$ together to produce states $|1\rangle$ and $|2\rangle$, we can determine the strength of the mixing from the experimental results as follows:

States $|1\rangle$ and $|2\rangle$ are linear combinations of $|X_A\rangle$ and $|Y_A\rangle$:

$$|1\rangle = \alpha |X_A\rangle + (1-\alpha^2)^{1/2} |Y_A\rangle , \qquad (5)$$

$$|2\rangle = (1-\alpha^2)^{1/2} |X_A\rangle - \alpha |Y_A\rangle . \qquad (6)$$

Their energy difference is given by

$$E(1) - E(2) = [\alpha(1-\alpha^2)^{1/2}]^{-1} V_{XY} = \frac{E(X_A) - E(X_B)}{2\alpha^2 - 1} . \qquad (7)$$

The resonance spectroscopic factors will be related to the stripping spectroscopic factors by

$$\frac{S(1) - S(2)}{S(1) + S(2)} = \frac{(2\alpha^2 - 1)[S(X) - S(Y)] + 4\alpha(1-\alpha^2)^{1/2}[S(X)S(Y)]^{1/2}}{S(X) + S(Y)} . \qquad (8)$$

The observed spectroscopic factors and energy difference are satisfied by $\alpha^2 = 0.986$ and $V_{XY} = 14.8$ keV.

The unmixed analog states would then be separated by 120 keV. The Coulomb energy difference (ΔE_c) for the state with the larger s-wave spectroscopic factor is 58 keV less than ΔE_c for the other $\frac{1}{2}+$ state. Although this appears to be a large shift, we observe that in ^{79}Se and ^{79}Br a similar difference of 54 keV in ΔE_c is found[1,2] for $\frac{1}{2}+$ states which show no evidence of $T_>$ mixing. We believe that these results make it plausible that the observed ^{77}Br $\frac{1}{2}+$ analog resonances are analog resonances which have suffered $T_>$ mixing.

If this explanation of the experimental results is correct, it is of interest to investigate what configurations are mixed with the $S_{1/2}$ configuration and produce the $T_>$ mixing of the analog states. The inelastic scattering results (Fig. 3) indicate that both $\frac{1}{2}+$ resonances have significant parentage from the one-phonon 2+ 0.57 MeV state, while only the 4.27 MeV resonance has significant parentage from the two-photon 0+ and 2+ state at 1.1 and 1.2 MeV.

In summary, we have observed several analog resonances in ^{77}Br, extracted the spectroscopic factors for these resonances, and compared these spectroscopic factors to those obtained for the parent states in ^{77}Se. This comparison shows disagreement between the two sets of spectroscopic factors but agreement between spectroscopic factor ratios except for the ratio for the $\frac{1}{2}+$ ratios. We suggest an explanation for this disagreement may lie in the $T_>$ mixing of these two resonances.

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