Isobaric Analogue States in Heavy Nuclei. IV. Samarium Isotopes*

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Isobaric analogue resonances in the target-nucelus-plus-proton system have been studied for the target nuclei of Sm^{144}, Sm^{148}, Sm^{150}, Sm^{152}, and Sm^{154}. All resonances were observed via elastic proton scattering, while some resonances for the target nuclei of Sm^{144} and Sm^{148} were also observed via (p,n) reactions. The low-lying resonances have been analyzed using a single-resonance formula yielding the various resonance parameters. Results are compared with (d,p) and other studies on the neutron-plus-target analogue states. Coulomb displacement energies are presented.

I. INTRODUCTION

RECENTLY, a great deal of interest has been shown in the observation of isobaric analogue states as resonances in the target-nucleus-plus-proton compound system. The experiments of Fox *et al.*[1] and several other groups[2–6] have demonstrated the use of the study of such resonances for spectroscopic analyses of the neutron analogue states, viz., those populated via (d,p) reactions on the target nucleus. As part of a program to explore the range of applicability of this aforementioned resonances with the target nuclei of Sm isotopes concurrently with deuteron-stripping studies on the same target nuclei being carried out at that time by Jolly and Moore.[7] Sm^{144} has 82 neutrons, so that the low-lying neutron analogue states have large spectroscopic factors and are rather well separated. Consequently, the corresponding proton analogue states would be relatively easier to observe. The neutron analogue states become more numerous as one goes to heavier Sm nuclei, so that it is interesting to observe their proton analogues and thus compare the information from the two experiments.

Two resonances corresponding, respectively, to the ground and the first excited states of Sm^{145} were observed.[8] Extension of this work to resonances at higher bombarding energies and also to resonances in other Sm target nuclei was temporarily halted by the frequent breakdown of the Florida State University tandem Van de Graaff accelerator at high terminal voltages (>5 MV). Thus, the measurements were discontinued until change of an accelerating tube and the insulating gas permitted terminal voltages higher than 5 MV. Since then several resonances have been observed with the target nuclei of Sm^{144}, Sm^{148}, Sm^{150}, and Sm^{152}. Only three of these resonances were observed via (p,n) reactions, whereas all the resonances reported in this paper were observed via proton elastic scattering. The results and their discussion are presented in the following sections.

II. EXPERIMENT AND DATA REDUCTION

The experimental procedure for the measurements presented here has been discussed previously,[1,9] so that we shall only describe it very briefly. For elastic scattering, a well-collimated beam of protons from the Florida State University tandem Van de Graaff accelerator (Model EN-HVEC) bombarded the target, and the scattered protons were detected by solid-state detectors placed at 90°, 125°, and 165° with respect to the proton beam. The detector pulses after preamplification and amplification were analyzed by three TMC multichannel analyzers. The data for Sm^{144}, Sm^{148}, and Sm^{150} were measured several times, while those for Sm^{152} and Sm^{154} were measured only once.

For (p,n) reactions, a different arrangement designed to minimize the neutron background was used. All the slits before the target were eliminated. The beam was focused on the target using only the quadrupole magnetic lenses and was stopped in carbon at a distance of 12 ft from the target. The neutrons were detected in a long BF_3 counter placed at 90° relative to the beam.

The results presented in this paper have mostly been obtained from the analysis of elastic proton-scattering data. In these data, the resonances that have been analyzed are well separated from other resonances of the same spin and parity. The shape of each resonance can then be fitted using the Coulomb-pulse-single-level formula suggested by Lane and Thomas.[10] This result has been programmed[11] for an IBM-709 Computer.

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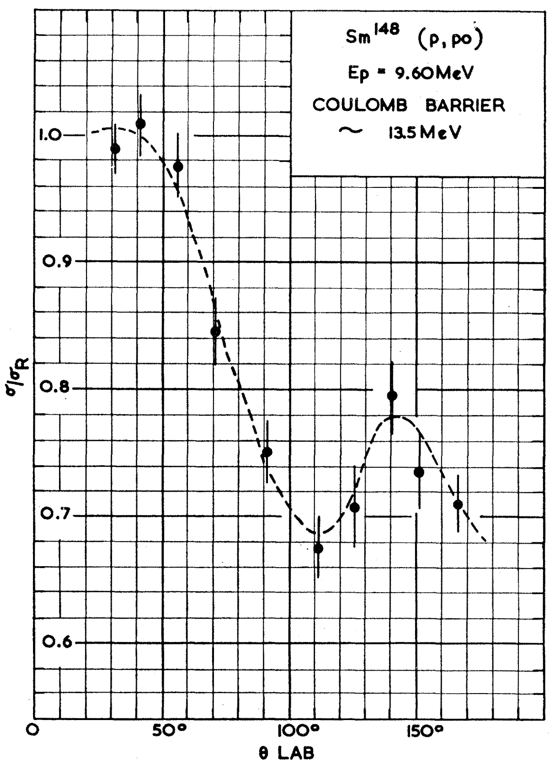

FIG. 1. A plot of σ/σ_R for $Sm^{148}(p,p_0)$ at $E_p=9.60$ MeV. The broken curve drawn through the points is merely a visual aid to the trend of the data. The first resonance (analogue of the ground state of Sm^{149}) in Fig. 4 occurs at 9.96-MeV.

The computer program searches for the values of the various resonance parameters (viz., E_J–the resonance energy, Γ_p–the proton width, Γ_J–the total width, and ϕ_l–the partial phase shift) that yield the best fit to the shape of the resonance. The orbital angular momentum associated with the resonance is determined from both the shape of the resonance and its variation with angle, while the total angular momentum of the resonance is taken from (d,p) or other angular-correlation studies on the neutron states. The on- and off-resonance partial phase shifts were set equal to zero for simplicity in the analysis for the present work because the other resonance parameters were found to be somewhat insensitive to moderate variations in the value of the phase shifts.

The nonresonant background in the analysis outlined above has been assumed to be Rutherford scattering. It can be easily seen from an examination of Fig. 1 that this is an oversimplification, particularly at large scattering angles, and thus leads to partial widths that are somewhat in error. Accordingly, partial widths obtained by the procedure outlined above have been corrected by determining the ratio of the nonresonant scattering cross section to the Coulomb scattering cross section and using the following formula suggested by Robson[12]:

$$\Gamma_p{}^J(\text{correct})\simeq\Gamma_p{}^J\times[\sigma/\sigma_R]^{1/2}. \qquad (1)$$

The approximate equality in Eq. (1) is due to the fact that nuclear phase shifts have been ignored in arriving at the above result.

The results in the various Sm nuclei studied in the present work and their comparisons with those from other sources are given in the following sections.

TABLE I. Comparison of the data from $Sm^{144}(p,p_0)$ and $Sm^{144}(d,p)$ measurements.

$Sm^{144}(p,p_0)$					$Sm^{144}(d,p)$ (Ref. 7)		
E_p (MeV)	$E_p-9.31$ (MeV)	l_p	Γ (keV)	Γ_p (keV)	E_{ex} (MeV)	l_n	J^π
9.31	0.00	3	46	7	0.00	3	$\frac{7}{2}^-$
10.19	0.88	1	74	23	0.90	1	$\frac{3}{2}^-$
10.95	1.64	(1?)	···	···	1.62	1	$\frac{3}{2}^-$
(11.01?)	(1.71?)	···	···	···	1.67	3	$\frac{5}{2}^-$
11.19	1.88	···	···	···	1.88	(3?)	$(\frac{5}{2}^-?)$
11.35	2.04	(3?)	···	···	2.01	(3?)	$(\frac{5}{2}^-?)$

III. RESULTS

A. $Sm^{144}(p,p_0)$ and $Sm^{144}(p,n)$

The various resonances observed in elastic proton scattering are presented in Fig. 2. The first two resonances seen in elastic scattering were also seen in (p,n) reactions and are presented in Fig. 3. These resonances, observed at proton bombarding energies of 9.31 and 10.19 MeV, are found to be the isobaric analogues of the $f_{7/2}$ ground state and the $p_{3/2}$ first excited state of Sm^{145}.[7] Apart from these, four more resonances at proton bombarding energies of 10.95, (11.01?), 11.19, and 11.35 MeV can be seen in Fig. 2. The 10.95-MeV resonance seems to be the analogue of the 1.62-MeV $p_{3/2}$ state of Sm^{145}, as the angular dependence of its shape is very similar to that for the 10.19-MeV (p-wave) resonance. From (d,p) work of Jolly and Moore,[7] one expects another nearby resonance corresponding to the 1.67-MeV $f_{5/2}$ state of Sm^{145}. The rather flat minimum in the 125° data and relatively sharp maximum (e.g., compared with the 1.65° data for the 10.19-MeV resonance) in the 165° data in the vicinity of 11.00 MeV indicate that there might be an f-wave resonance at ~11.01 MeV.

The 11.19- and 11.35-MeV resonances are the analogues of the 1.88- and 2.01-MeV states of Sm^{145}. From the work of Jolly and Moore,[7] both of these states are believed to be $f_{5/2}$. One can see some semblance of an f-wave capture in the case of the 11.35-MeV resonance in Fig. 2, but the l value for the 11.19-MeV resonance is completely uncertain. The high density of states in the region of the last four resonances did not permit any fitting of their data for the purpose of extracting the various resonance parameters. Conse-

[12] D. Robson (private communication).

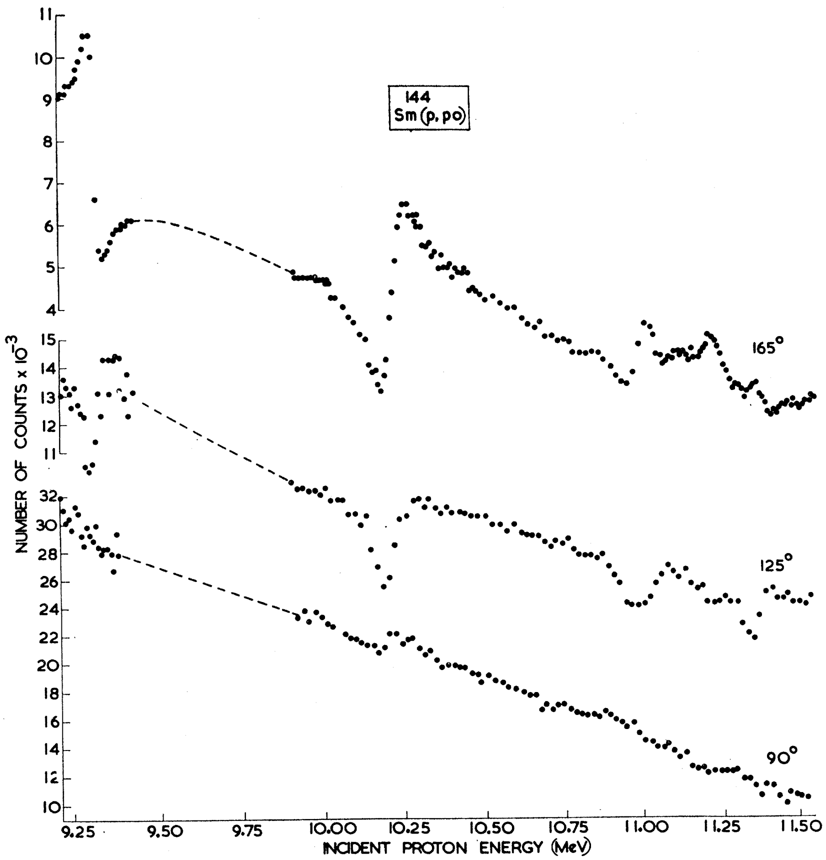

FIG. 2. $Sm^{144}(p,p_0)$ excitation functions measured at 165°, 125°, and 90° (lab). The best-fit parameters for the analyzed resonances are listed in Table I.

quently, only their resonance energies have been listed in Table I.

B. $Sm^{148}(p,p_0)$ and $Sm^{148}(p,n)$

The excitation functions for elastic proton scattering and (p,n) reactions from Sm^{148} are given in Figs. 4 and 5, respectively. Seven resonances have been identified at the various bombarding energies listed in Table II. Out of these, only the first resonance at 9.96-MeV bombarding energy has been observed in (p,n) reactions. The angular dependence of the shape of this resonance in Fig. 4 shows it to result from an f-wave capture which agrees with the previously known[13] spin and parity $\frac{7}{2}-$ of the ground state of Sm^{149}. The correspondence between the strongly excited states in (d,p)

TABLE II. Comparison of the data from $Sm^{148}(p,p_0)$ and $Sm^{148}(d,p)$ measurements.

$Sm^{148}(p,p_0)$					$Sm^{148}(d,p)$ (Ref. 14)		
E_p (MeV)	$E_p-9.96$ (MeV)	l_p	Γ (keV)	Γ_p (keV)	E_{ex} (MeV)	l_n	J^π
9.96	0.00	3	102	~10	0.00	3	$\frac{7}{2}-$
10.31	0.35	···			0.38	(1+3?)	···
10.48	0.52	1	~50	~7	0.53	1	($\frac{3}{2}-$?)
10.68	0.72	(1?)			0.71	1	($\frac{3}{2}-$?)
10.99	1.03	(1?)			1.03	(1?)	···
11.13	1.17	(3?)			1.17	3	···
11.47	1.51	···			1.49	(1?)	···

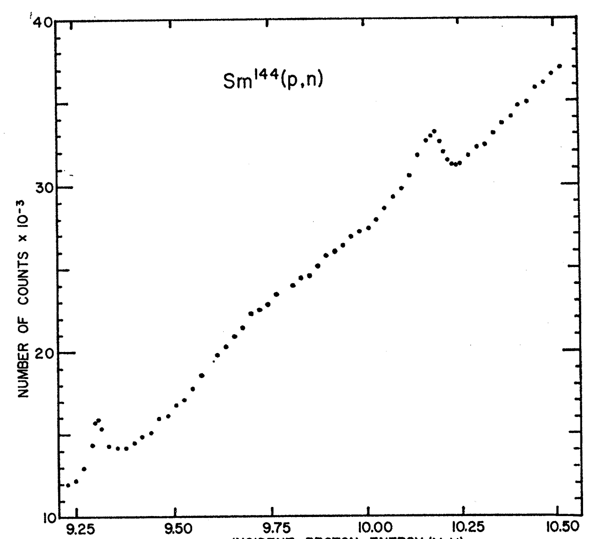

FIG. 3. An excitation function for the $Sm^{144}(p,n)$ reaction.

[13] *Nuclear Data Sheets*, Compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., NRC05-2-16.

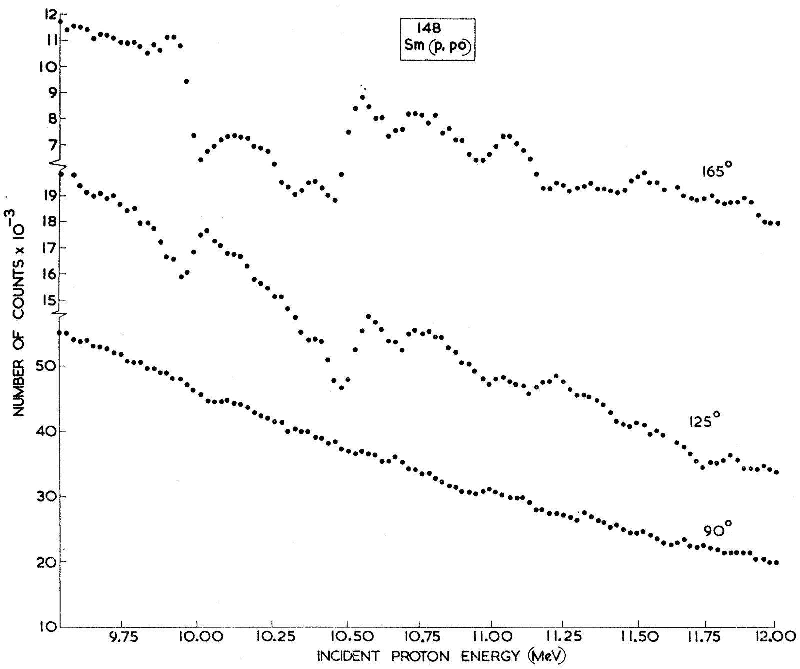

FIG. 4. $Sm^{148}(p,p_0)$ excitation functions measured at 165°, 125°, and 90° (lab). See Table II for the various resonance parameters.

reaction studies on a Sm^{148} target[14] and their proton analogues observed here is shown in Table II. The excitation energies and l values (wherever these have been determinable) are in reasonable agreement with those determined from (d,p) studies. The widths have been extracted by the shape-fitting procedure discussed above in Sec. II. The l values and the widths for the 9.96- and 10.48-MeV resonances have also been measured by Bassani *et al.*[3] There is qualitative agreement between their results and those presented here, except that their partial widths (~30 keV) are larger than those measured in the present work. The absence of any structure in the 90° data in Fig. 4 simply means that all of the resonances observed here are analogues of the odd-parity neutron states of Sm^{149} in the f-p $82<N\leqslant 126$ shell.

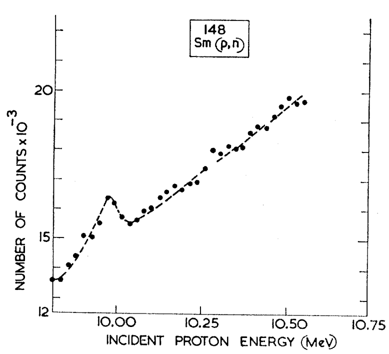

FIG. 5. An excitation function for the $Sm^{148}(p,n)$ reaction.

[14] R. K. Jolly and C. F. Moore (to be published).

C. $Sm^{150}(p,p_0)$

The excitation function for the elastic-scattering yield from Sm^{150} is presented in Fig. 6. Two resonances at 10.25 and 10.50 MeV are clearly identifiable. Their l values and widths are listed in Table III. These two resonances have also been observed by Bassani *et al.*, and our l values and total widths agree with their results. A comparison with the $Sm^{150}(d,p)Sm^{151}$ measurements of Kenefick *et al.*[15] (see Table III) shows that the 10.25-MeV resonance is not the analogue of the ground state of Sm^{151}, but rather that of the 0.060-MeV first-excited state. The excitation energies of the neutron analogues of the other two resonances are listed in Table III. Their relative-energy spacings agree quite well with those for the proton analogue state. No (d,p) angular-distribution measurements were made for l_n and J assignments. We have listed the relative intensities of the various proton groups in the deuteron stripping measurements of Kenefick *et al.*[15] in Table III.

TABLE III. Comparison of data from $Sm^{150}(p,p_0)$ and $Sm^{150}(d,p)$ measurements.

$Sm^{150}(p,p_0)$					$Sm^{150}(d,p)$ (Ref. 15)	
E_p (MeV)	$E_p-10.25$ (MeV)	l_p	Γ (keV)	Γ_p (keV)	E_{ex} (MeV)	Relative intensity (45°) (arbitrary units)
···	···	···	···	···	0.000	1.84
10.25	0.00	3	~80	~4	0.060	17.00
10.50	0.25	1	~70	~7	0.307	26.40
(~10.65?)	0.40	···	···	···	0.447	5.14

[15] R. A. Kenefick and R. K. Sheline, Phys. Rev. **139**, T1479 (1965).

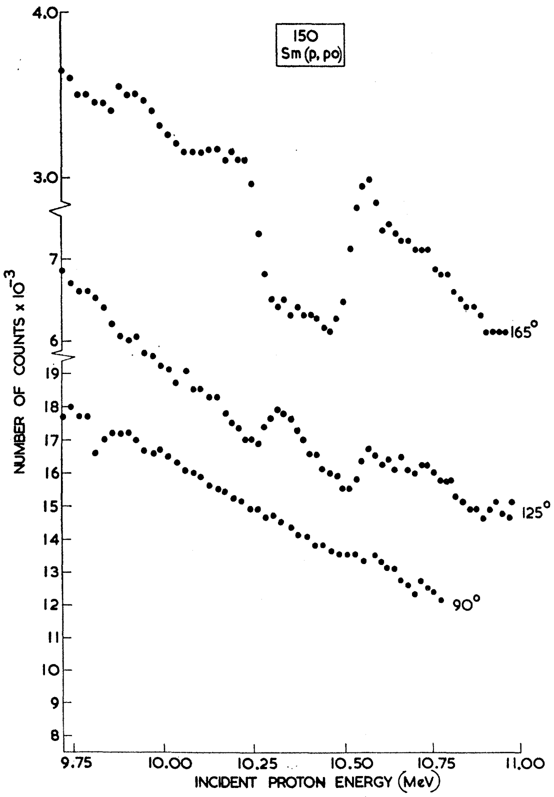

FIG. 6. $Sm^{150}(p,p_0)$ excitation functions measured at 165°, 125°, and 90° (lab). See Table III for the various resonance parameters.

It is easily seen why the proton analogues of the ground and 0.477-MeV states were difficult to observe in proton elastic scattering.

D. $Sm^{152}(p,p_0)$ and $Sm^{154}(p,p_0)$

The Sm^{152} data is shown in Fig. 7. It shows two broad bumps in the excitation function for 165° at 10.32- and 10.62-MeV bombarding energy, in agreement with the observations of Bassani *et al.*[3] Contrary to the experience in the previous three cases, the 125° excitation function does not show any perceptible structure. An examination of $Sm^{152}(d,p)$ spectra[15] in the region of the neutron analogues of these resonances shows several proton groups of similar intensities, thus making the identification of these resonances almost impossible. Sm^{152} being a deformed-nucleus, prediction of the resonance energy for the proton analogue of the ground state of Sm^{153} is made difficult by the fact that the

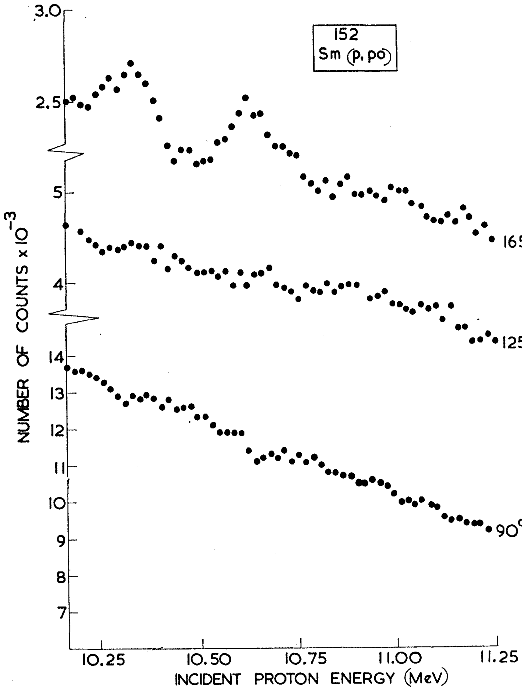

FIG. 7. $Sm^{152}(p,p_0)$ excitation functions measured at 165°, 125°, and 90° (lab). See also Table IV.

Coulomb displacement energy may be quite different from that predicted from the systematic data for the previous three nuclei (see Table IV.)

The excitation functions for $Sm^{154}(p,p_0)$ are presented in Fig. 8. The data is even less informative than in the case of Sm^{152}. This, however, is not entirely unexpected, due to the increasing complexity of the neutron-state spectrum as one goes to heavier Samarium isotopes.

E. Coulomb Displacement Energies

Coulomb interaction energy of the proton with the core for a certain proton analogue resonance can be calculated using the result

$$E_c = B_n + E_p^{\text{c.m.}}, \qquad (2)$$

where B_n is the binding energy of the neutron in the neutron analogue state and $E_p^{\text{c.m.}}$ is the energy of incident protons in the center-of-mass system at which the proton analogue resonance is observed. The values of E_c, B_n, and $E_p^{\text{c.m.}}$ are listed in Table IV for those cases where the resonance energies are known with resonable certainty. Excitation energies and B_n values

TABLE IV. Coulomb displacement energies (all energies in MeV).

${}_{62}Sm^{145}$-${}_{63}Eu^{145}$				${}_{62}Sm^{149}$-${}_{63}Eu^{149}$				${}_{62}Sm^{151}$-${}_{63}Eu^{151}$			
E_{ex}	$E_p^{\text{c.m.}}$	B_n	E_c	E_{ex}	$E_p^{\text{c.m.}}$	B_n	E_c	E_{ex}	$E_p^{\text{c.m.}}$	B_n	E_c
0.00	9.23	6.76	15.99	0.00	9.89	5.87	15.76	0.06	10.17	5.53	15.70
0.90	10.12	5.86	15.98	0.53	10.42	5.34	15.76	0.31	10.41	5.28	15.69

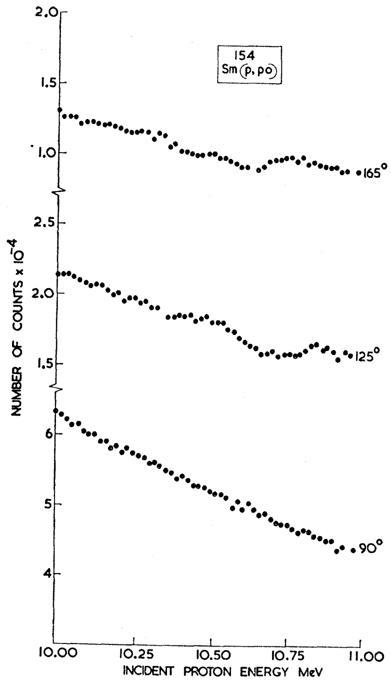

FIG. 8. $Sm^{154}(p,p_0)$ excitation functions measured at 165°, 125°, and 90° (lab). See Sec. IV for a discussion of the absence of any structure.

for the neutron analogue states were taken from the work of Kenefick *et al.*[15]

IV. DISCUSSION AND CONCLUSIONS

Sm^{144} seems to be a good closed neutron-shell nucleus, as the low-lying neutron states of Sm^{145} are well separated and have large spectroscopic factors.[7] However, as one goes to heavier isotopes, the level density at low excitation energies increases, resulting in a sharing of the total strength of a certain single-particle state among several states instead of one or two. This will have the effect of decreasing the partial widths for the proton analogue resonances for a certain single-particle state. On the other hand, the total resonance widths tend to increase (in general) with increasing mass number due to a greater number of deexcitation channels that become open to a heavier-compound nuclear system. Thus, the result of decreasing partial widths combined with increasing total widths and level densities is that resonance effects which are prominent and well separated for Sm^{144} become more flattened and crowded as one goes to increasingly heavier isotopes. Consequently, most resonances that are observed cannot be fitted with a simple single-level-plus-Coulomb formula. A many-level formula including interference contributions from nearby resonances of the same spin and parity becomes necessary for extracting meaningful resonance parameters. The situation is worsened in the transition from spherical ground state Sm^{150} to deformed Sm^{152} and Sm^{154} nuclei where the core deformation further adds to the increase in level density at low excitation energies. Consequently, one sees complete obliteration of any structure in the Sm^{154} data. Thus, one concludes that in very heavy nuclei, spectroscopic studies with isobaric analogue resonances in elastic proton scattering can be profitably made only in some favorable cases where the spectroscopic factors are large and level densities are rather small.

It may be noted that no attempt has been made to list any spectroscopic factors, as most of the partial widths are somewhat uncertain due to the difficulties mentioned above.

An interesting feature of the data presented here is that the 90° excitation functions do not show any resonance effects for any of the five nuclei, indicating the absence of any even l-value resonances of appreciable partial width (with the exception of $l=6$ and possibly $l=4$, which are difficult to observe even in favorable cases).

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