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ABSTRACT

The differences between the Saclay and Livermore photoneutron cross sections are discussed. It is shown that the differences between the Saclay and Livermore (γ, n) and $(\gamma, 2n)$ cross sections arise from the neutron multiplicity sorting.

1. INTRODUCTION

In the last 20 years, photoneutron cross sections have been measured for many nuclei using monoenergetic photons. Most of this work was carried out by two laboratories: Saclay and Livermore. The available results are compiled in the "Atlas of Photoneutron Cross Sections obtained with Monoenergetic Photons"⁽¹⁾. There is also in the literature a few review articles on the subject but none of these publications has addressed the problem of the differences between the measurements performed by Saclay and Livermore. In this paper we compare the Saclay and Livermore measurements for the nuclei listed in Table I.

The typical differences between Saclay and Livermore data are illustrated in Fig. 1, where the (γ, n) measurements from Saclay and Livermore are shown. The results from Livermore are multiplied by 1.06 in order to show both cross sections in the same absolute scale. The cross sections are in good agreement up to the $(\gamma, 2n)$ threshold. Above this energy there is an important difference: the Livermore cross section vanishes a few MeV above the $(\gamma, 2n)$ threshold, in good agreement with the predictions of the statistical model, while the Saclay cross section has a tail. In ref. 7), the observed tail of the Saclay cross section is interpreted as arising from fast

neutrons that would have escaped detection in the Livermore measurements, leading to the conclusion that for ^{159}Tb the contribution of the "direct effect" in the photoneutron cross section is $n_d = 23 \pm 4$ percent. In Table II the percentages of direct neutrons inferred by Saclay are given for several nuclei.

Figure 2 shows the $(\gamma, 2n)$ cross sections from Saclay and Livermore. The $(\gamma, 2n)$ cross sections differ in shape and magnitude, the Livermore one being much bigger. Eventhough up to the $(\gamma, 2n)$ threshold the (γ, n) cross section from Livermore, $\sigma_{\gamma, n}^L$, and Saclay, $\sigma_{\gamma, n}^S$, differ by only 6 percent in the absolute scale, their integrated cross sections up to 28 MeV are 1413 and 1936 MeV.mb, respectively. While the integrated (γ, n) cross section from Saclay is 37% bigger than the Livermore result, their integrated $(\gamma, 2n)$ cross section is 47% smaller.

2. ANALYSIS OF THE PHOTONEUTRON DATA

In order to understand these differences we reconstructed the total neutron measurements from Saclay and Livermore:

$$\sigma_{\gamma, tn} = \sigma_{\gamma, n} + 2\sigma_{\gamma, 2n} + 3\sigma_{\gamma, 3n} \quad (1)$$

Since $\sigma_{\gamma, tn}$ is the cross section measured and the (γ, n) and $(\gamma, 2n)$ cross sections are obtained by neutron multiplicity

sorting, it is important to compare $\sigma_{\gamma,tn}^S$ and $\sigma_{\gamma,tn}^L$. This comparison has not been discussed in the literature. Figure 3 shows $\sigma_{\gamma,tn}$ from Saclay and Livermore for ^{159}Tb . In figure 4 the ratio $r = \sigma_{\gamma,tn}^S / \sigma_{\gamma,tn}^L$ is shown. The ratio is reasonably constant and the least squares fit of a constant yields the value $r = 1.062 \pm 0.011$. In order to compute \underline{r} we interpolated $\sigma_{\gamma,tn}^S$ and $\sigma_{\gamma,tn}^L$, since their data points are not at the same photon energies. One important conclusion can be derived from figure 3: both laboratories are detecting the same number of neutrons for all photon energies. If there were fast neutrons escaping detection in the Livermore measurements above 20 MeV, \underline{r} should increase above this energy. The value of the constant \underline{r} is the difference in the absolute scale of both measurements. Figure 4 shows $\sigma_{\gamma,tn}^L$ multiplied by 1.06 and $\sigma_{\gamma,tn}^S$, just to illustrate the good agreement between them, when they are plotted at the same absolute scale.

Since both Laboratories agree as to the total number of neutrons detected, the differences in their (γ,n) and $(\gamma,2n)$ cross sections arise from the separation of the total counts into (γ,n) and $(\gamma,2n)$ events (neutron multiplicity sorting).

If we assume that the excess (γ,n) cross section in the Saclay measurement is due to $(\gamma,2n)$ events interpreted as two (γ,n) events, that is, if we compute:

$$\sigma_{\gamma,2n}^{S*} = \sigma_{\gamma,2n}^S + \frac{1}{2} (\sigma_{\gamma,n}^S - 1.06\sigma_{\gamma,n}^L) \quad (2)$$

we obtain for $\sigma_{\gamma,2n}^{S*}$ the solid line shown in figure 5. The modified $\sigma_{\gamma,2n}$ cross section from Saclay agrees well with the $(\gamma,2n)$ cross section from Livermore multiplied by 1.06 (data points).

The same analysis carried out for ^{159}Tb was repeated for the nuclei listed in Table I. The results obtained for $\sigma_{\gamma,tn}$ are shown in part a) of figures 6 to 17, where the solid line represents the Saclay data and the experimental points are from Livermore.

The ratio $\sigma_{\gamma,tn}^S / \sigma_{\gamma,tn}^L$ is shown in part b) of figures 6 to 17. In order to calculate this ratio, the Saclay and Livermore data were interpolated to get both cross sections at the same photon energies. The energy interval, \underline{int} , used in the interpolation is given in each figure. The solid line in each figure results from the least squares fit of a constant to the ratio. For ^{118}Sn , ^{120}Sn , ^{165}Ho and ^{181}Ta , figures 9, 10, 14 and 15, the fitting of a constant is not statistically acceptable, but a comparison between $\sigma_{\gamma,tn}$ from Livermore and Saclay indicates a displacement in the energy scale, because the peaks do not coincide in energy (see as an example figure 14-a) for ^{165}Ho). The ratio $\sigma_{\gamma,tn}^S / \sigma_{\gamma,tn}^L$ was also calculated with a variable e-

energy displacement \underline{d} . The displacement that yields a minimum of the χ^2 for fitting a constant to the ratio is chosen. Figures 18 to 23 show the data from Saclay and Livermore, with the Livermore data displaced by \underline{d} . The value of \underline{d} is given in part a) of the figures for each nucleus. The displacement was negative in all cases, that is, the Livermore data was shifted to lower energies. The displacement of the energy scale of the Livermore data is arbitrary and, of course, the same results can be obtained if the Saclay energy scale is moved up in energy by the same amount. For the nuclei shown in figures 18 to 23, the displacement of the energy scale improves the agreement between the shapes of $\sigma_{\gamma,tn}$, that is, the peaks coincide in energy (compare, as an example, figures 14-a) and 21-a) for ^{165}Ho).

If we accept the displacement of the energy scale, we can conclude that for all nuclei analyzed here, the measurements from Saclay and Livermore are in good agreement as to the number of emitted neutrons versus the incident photon energy, apart from an overall normalization constant. The differences between their (γ,n) and $(\gamma,2n)$ cross sections arise from the neutron multiplicity sorting.

In order to compare the (γ,n) and $(\gamma,2n)$ cross sections from both laboratories in the same energy scale, the Livermore data shown in all figures c), d), e) and f) are multiplied by \underline{r} .

In figures 6-c) to 23-c) we show again the $\sigma_{\gamma,tn}$ cross sections, just to illustrate the good agreement between them, when they are plotted at the same absolute scale.

In figures 6-d) to 23-d) and 6-e) to 23-e) the (γ,n) and $(\gamma,2n)$ cross sections from Livermore and Saclay are shown. Like for ^{159}Tb , above the $(\gamma,2n)$ threshold the (γ,n) cross sections from Saclay are always bigger than the corresponding Livermore cross sections and the $(\gamma,2n)$ cross sections from Saclay are always smaller than those from Livermore.

If the Saclay $(\gamma,2n)$ cross section is modified using equation (2), the resulting $\sigma_{\gamma,2n}^{S*}$ agree well with the Livermore $(\gamma,2n)$ cross sections, as shown in figures 6-f) to 23-f).

The analysis performed here shows that the differences in shape and magnitude in the (γ,n) and $(\gamma,2n)$ cross sections measured by Saclay and Livermore arise from the neutron multiplicity sorting. However, this analysis does not allow to conclude which set of data has the correct multiplicity sorting.

We have measurements of the (e,n) and $(e,2n)$ cross sections for ^{181}Ta . The $(e,tn) = (e,n) + 2(e,2n)$ cross section was measured by detecting the neutrons. The (e,n) cross section was also measured by radioactivity. The $(e,2n)$ cross section is obtained without the use of neutron multiplicity sorting:

7.

$$\sigma_{e,2n} = \frac{1}{2} (\sigma_{e,tn} - \sigma_{e,n}) \quad (3)$$

These results, which will be the subject of a forthcoming publication, indicate that the neutron multiplicity sorting carried out by Livermore is correct.

3. CONCLUSIONS

We have shown that the differences between the measurements from Saclay and Livermore for the (γ, n) and $(\gamma, 2n)$ cross sections in nuclei arise from neutron multiplicity sorting. If the Saclay multiplicity sorting is in error, as indicated by our measurements in ^{181}Ta , there are some important implications.

If the shapes of the (γ, n) and $(\gamma, 2n)$ cross sections from Livermore are correct, the (γ, n) cross sections for medium and heavy nuclei are statistical in nature and there are no large percentages of directly emitted neutrons (~ 20 percent) as deduced from the Saclay results.

More recently Saclay has performed measurements of photoneutron cross sections for photon energies up to 140 Mev⁽¹⁷⁾. Using their neutron multiplicity sorting technique, they unfolded the measured $\sigma_{\gamma,tn}$ into $\sigma_{\gamma,xn}$ cross sections, where x goes from 1 to ~ 10, depending on the nucleus. From the unfolded partial cross sections, the photoabsorption cross sec-

tion, $\sigma_{\gamma, \text{Tot}}$ was obtained:

$$\sigma_{\gamma, \text{Tot}} = \sum_{x=1}^N \sigma_{\gamma, xn} \quad (4)$$

This cross section was in disagreement with the prediction of the modified quasideuteron model^(18,19) and motivated Levinger to change one of the parameters of the model to fit the Saclay data⁽²⁰⁾. If the Saclay multiplicity sorting is in error, the results obtained for $\sigma_{\gamma, \text{Tot}}$ are questionable.

TABLE I

9.

Nuclei measured by Saclay (S) and Livermore (L).

Nucleus	$\int \sigma_{\gamma, n}(E_{\gamma}) dE_{\gamma}$ ^{a)}		$\int \sigma_{\gamma, 2n}(E_{\gamma}) dE_{\gamma}$ ^{a)}		References
	(MeV.mb)		(MeV.mb)		
⁸⁹ Y	1279	S	74	S	2
	960	L	99	L	3
¹¹⁵ I	1470	S	278	S	4
	1354	L	508	L	5
¹¹⁷ Sn	1334	S	220	S	4
	1380	L	476	L	5
¹¹⁸ Sn	1377	S	258	S	4
	1302	L	531	L	5
¹²⁰ Sn	1371	S	399	S	4
	1389	L	673	L	5
¹²⁴ Sn	1056	S	502	S	4
	1285	L	670	L	5
¹³³ Cs	1828	S	328	S	4
	1475	L	503	L	6
¹⁵⁹ Tb	1936	S	605	S	7
	1413	L	887	L	8
¹⁶⁵ Ho	2090	S	766	S	7
	1735	L	744	L	9
¹⁸¹ Ta	2180	S	790	S	7
	1300	L	881	L	10
¹⁹⁷ Au	2588	S	479	S	11
	2190	L	777	L	12
²⁰⁸ Pb	2731	S	328	S	11
	1776	L	860	L	13

a) From reference 1)

TABLE II

10.

Percentage of direct neutrons obtained by Saclay.

Nucleus	n_d (%)	References
⁹⁴ Mo	25 ± 7	14
⁹⁶ Mo	15 ± 7	14
⁹⁸ Mo	10 ± 7	14
¹⁰⁰ Mo	11 ± 7	14
¹³⁹ La	28 ± 5	7
¹⁴⁰ Ce	12 ± 3	15
¹⁴² Ce	10 ± 3	15
Nat _{Sm}	10 ± 3	15
¹⁵⁹ Tb	23 ± 4	7
¹⁶⁵ Ho	23 ± 4	7
Nat _{Er}	11 ± 3	15
¹⁷⁵ Lu	15 ± 3	15
¹⁸¹ Ta	22 ± 2	7
¹⁹⁷ Au	20 ± 4	11
²⁰⁸ Pb	15 ± 4	11
²³⁸ U	14 ± 2	16

REFERENCES

1. Atlas of photoneutron cross section obtained with monoenergetic photons, Bicentennial Edition, Preprint UCRL-78482, edited by B.L. Berman and, B.L. Berman, Rev. Mod. Phys. 47, 713 (1975).
2. A. Lepretre, H. Beil, R. Bergere, P. Carlos, A. Veyssiere and M. Sugawara, Nucl. Phys. A175, 609 (1971).
3. B.L. Berman, J.T. Caldwell, R.R. Harvey, M.A. Kelly, R.L. Bramblett and S.C. Fultz, Phys. Rev. 162, 1098 (1967).
4. A. Lepretre, H. Beil, R. Bergere, P. Carlos, A. Deminiac and A. Veyssiere, Nucl. Phys. A219, 39 (1974).
5. S.C. Fultz, B.L. Berman, J.T. Caldwell, R.L. Bramblett and M.A. Kelly, Phys. Rev. 186, 1255 (1969).
6. B.L. Berman, R.L. Bramblett, J.T. Caldwell, H.S. Davis, M. A. Kelly and S.C. Fultz, Phys. Rev. 177, 1745 (1969).
7. R.L. Bergere, H. Beil and A. Veyssiere, Nucl. Phys. A121, 463 (1968).
8. R.L. Bramblett, J.T. Caldwell, R.R. Harvey and S.C. Fultz, Phys. Rev. B133, 869 (1964).
9. B.L. Berman, M.A. Kelly, R.L. Bramblett, J.T. Caldwell, H.S. Davis and S.C. Fultz, Phys. Rev. 185, 1576 (1969).
10. R.L. Bramblett, J.T. Caldwell, G.F. Auchampaugh and S.C. Fultz, Phys. Rev. 129, 2723 (1963).
11. A. Veyssiere, H. Beil, R. Bergere, P. Carlos and A. Lepretre, Nucl. Phys. A159, 561 (1970).
12. S.C. Fultz, R.L. Bramblett, J.T. Caldwell and N.A. Kerr, Phys. Rev. 127, 1237 (1962).
13. R.R. Harvey, J.T. Caldwell, R.L. Bramblett and S.C. Fultz, Phys. Rev. B136, 126 (1964).
14. H. Beil, R. Bergere, P. Carlos, A. Lepretre, A. Deminiac and A. Veyssiere, Nucl. Phys. A227, 427 (1974).
15. R. Bergere, H. Beil, P. Carlos, and A. Veyssiere, Nucl. Phys. A133, 417 (1969).
16. A. Veyssiere, H. Beil, R. Bergere, P. Carlos, A. Lepretre and K. Kernbach, Nucl. Phys. A199, 45 (1973).
17. P.J. Carlos, Lecture Notes in Phys. 137, 168 (1981).
18. J.S. Levinger, Phys. Rev. 84, 43 (1951).
19. J.S. Levinger, Proc. Intern. Conf. Low and Intermediate Energy Electromagnetic Interactions (Academy of Sciences, USSR, Moscow, 1967) vol. 3, p. 411.
20. J.S. Levinger, Phys. Lett. 82B, 181 (1979).

FIGURE CAPTIONS

Fig. 1 - (γ, n) cross sections from Saclay (solid line) and Livermore (experimental points) for ^{159}Tb . The Livermore data is multiplied by 1.06 in order to show both measurements at the same absolute scale.

Fig. 2 - $(\gamma, 2n)$ cross sections from Saclay (solid line) and Livermore (experimental points) for ^{159}Tb . The Livermore data is multiplied by 1.06 in order to show both measurements at the same absolute scale.

Fig. 3 - $\sigma_{\gamma, \text{tn}}$ from Saclay divided by $\sigma_{\gamma, \text{tn}}$ from Livermore .

$$\sigma_{\gamma, \text{tn}} = \sigma_{\gamma, n} + 2\sigma_{\gamma, 2n} + 3\sigma_{\gamma, 3n}$$

Fig. 4 - $\sigma_{\gamma, \text{tn}}$ from Livermore multiplied by 1.06 (experimental points) and $\sigma_{\gamma, \text{tn}}$ from Saclay (solid line).

$$\sigma_{\gamma, \text{tn}} = \sigma_{\gamma, n} + 2\sigma_{\gamma, 2n} + 3\sigma_{\gamma, 3n}$$

Fig. 5 - $\sigma_{\gamma, 2n}$ from Livermore (experimental points) and the modified (see text) $\sigma_{\gamma, 2n}$ from Saclay (solid line).

Figs. 6 to 17 - The solid line represents the Saclay data and the experimental points are from Livermore.

a) $\sigma_{\gamma, \text{tn}} = \sigma_{\gamma, n} + 2\sigma_{\gamma, 2n} + 3\sigma_{\gamma, 3n}$ from Saclay and Livermore.

b) $\sigma_{\gamma, \text{tn}}$ from Saclay divided by $\sigma_{\gamma, \text{tn}}$ from Livermore. The Saclay and Livermore data were interpolated in order to have both cross sections at the same photon energies. The energy interval, ΔE , used in the interpolation is given in the figure. The solid line shows \bar{r} , the value obtained by fitting a constant to the ratio.

c) $\sigma_{\gamma, \text{tn}}$ from Livermore multiplied by \bar{r} and $\sigma_{\gamma, \text{tn}}$ from Saclay.

d) $\sigma_{\gamma, n}$ from Livermore multiplied by \bar{r} and $\sigma_{\gamma, n}$ from Saclay.

e) $\sigma_{\gamma, 2n}$ from Livermore multiplied by \bar{r} and $\sigma_{\gamma, 2n}$ from Saclay.

f) $\sigma_{\gamma, 2n}$ from Livermore multiplied by \bar{r} and the modified $\sigma_{\gamma, 2n}$ from Saclay. $\sigma_{\gamma, 2n}^{S*} = \sigma_{\gamma, 2n}^S + \frac{1}{2}(\sigma_{\gamma, n}^S - r\sigma_{\gamma, n}^L)$.

Figs. 18 to 23 - a) $\sigma_{\gamma, \text{tn}}$ from Saclay and Livermore. The energy scale of the Livermore data is displaced by ΔE . The value of the displacement is given in the figure.

b), c), d), e) and f) - The same as for figures 1 to 12.

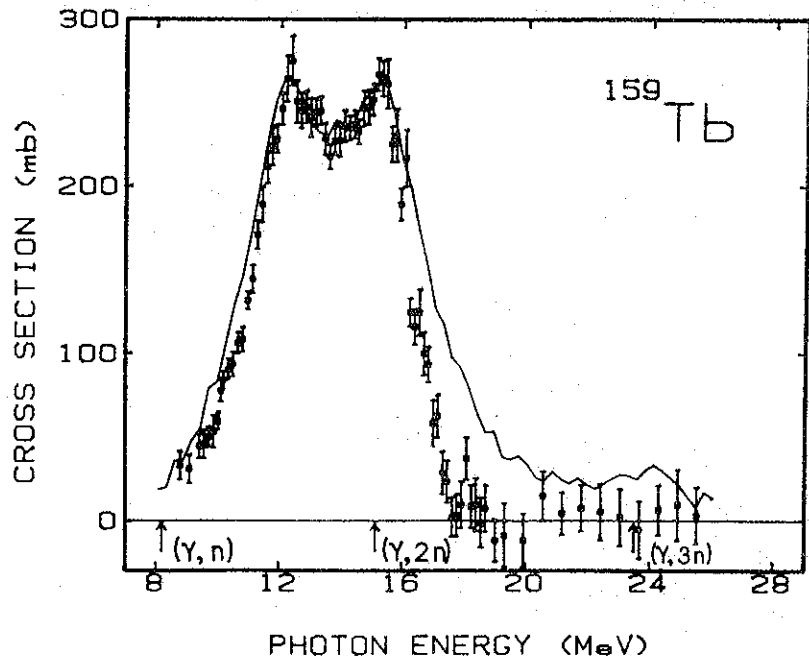


FIG. 1

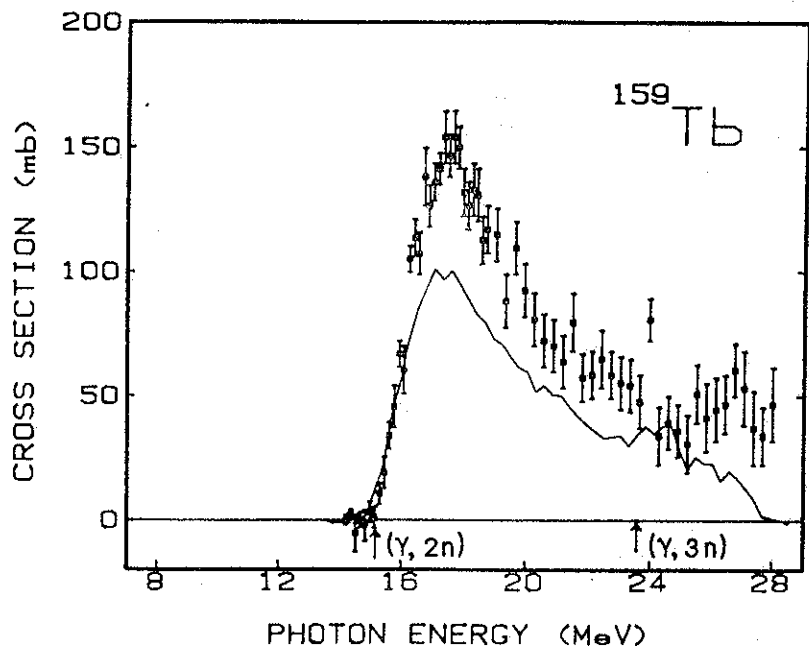


FIG. 2

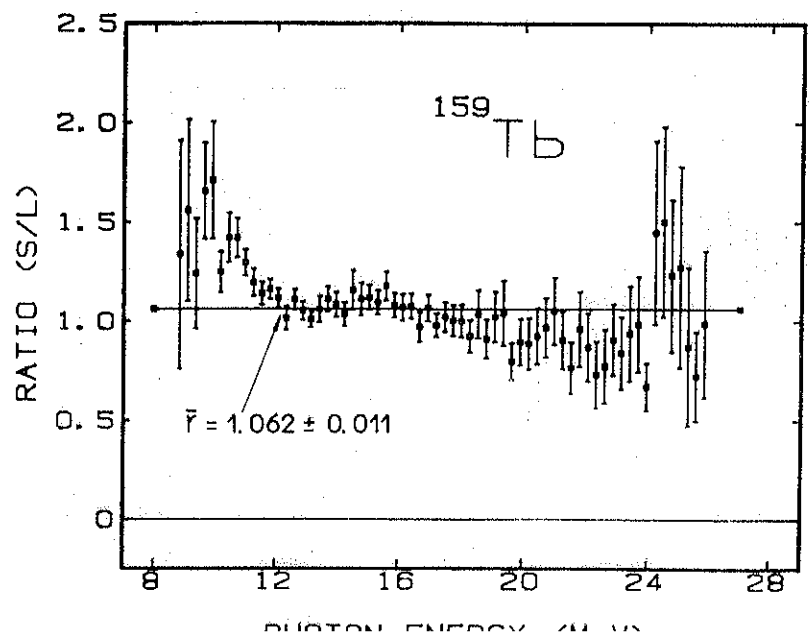


FIG. 3

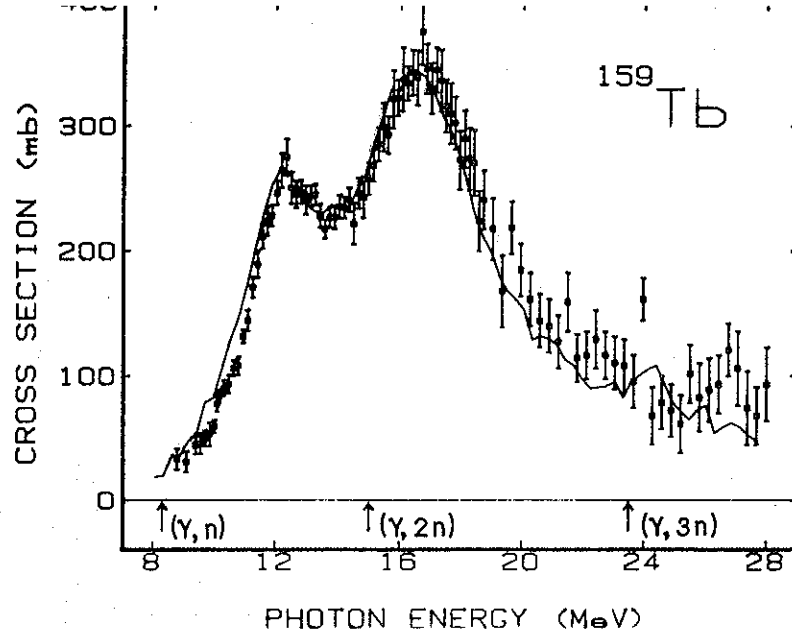


FIG. 4

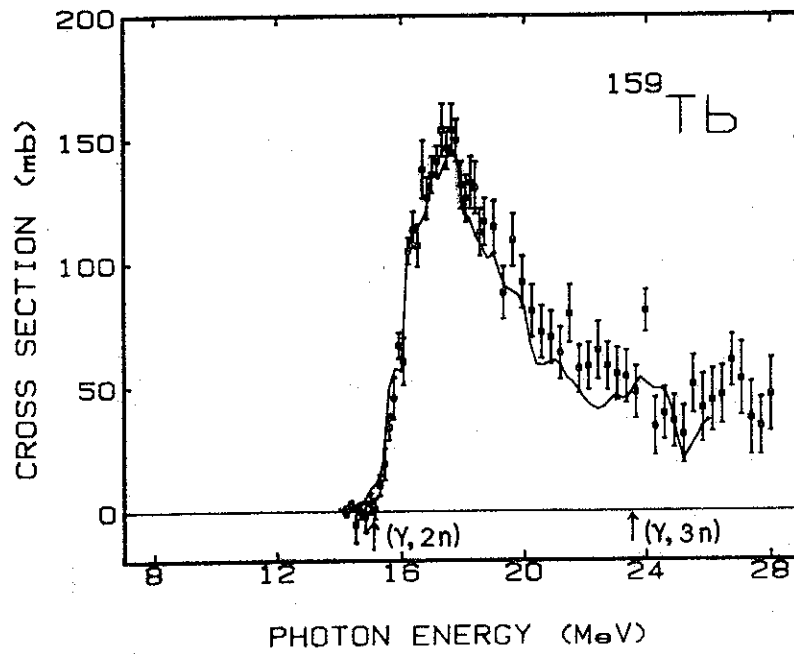


FIG. 5

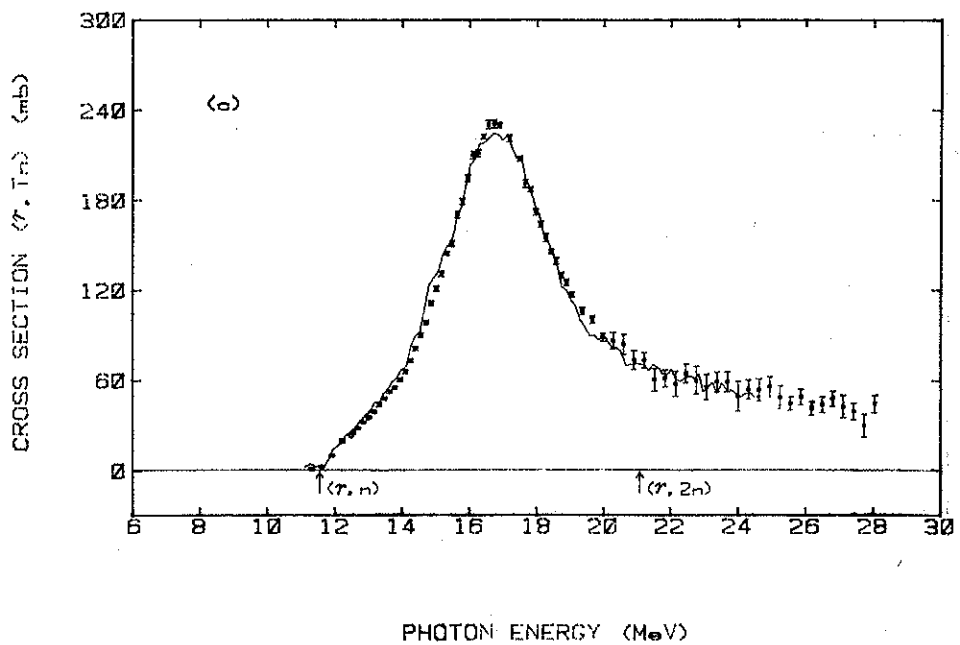
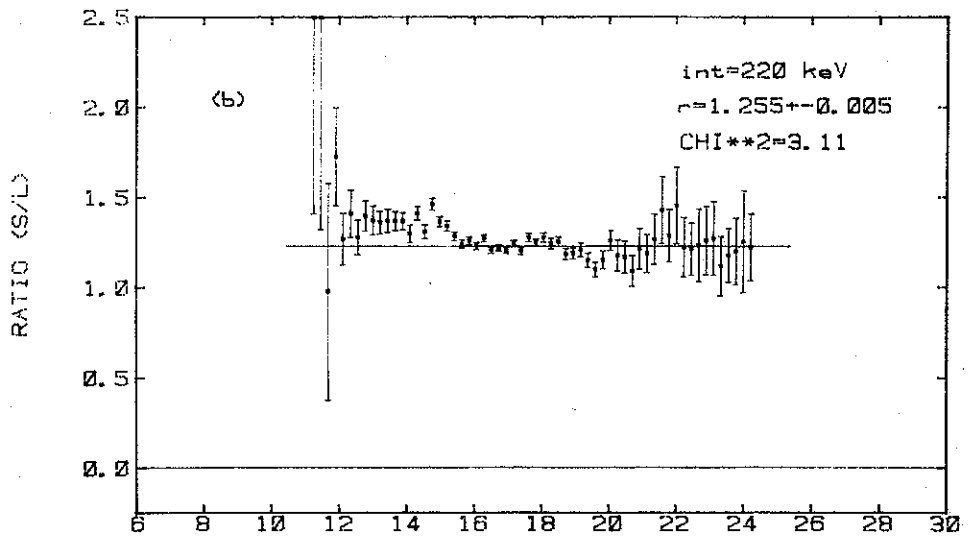
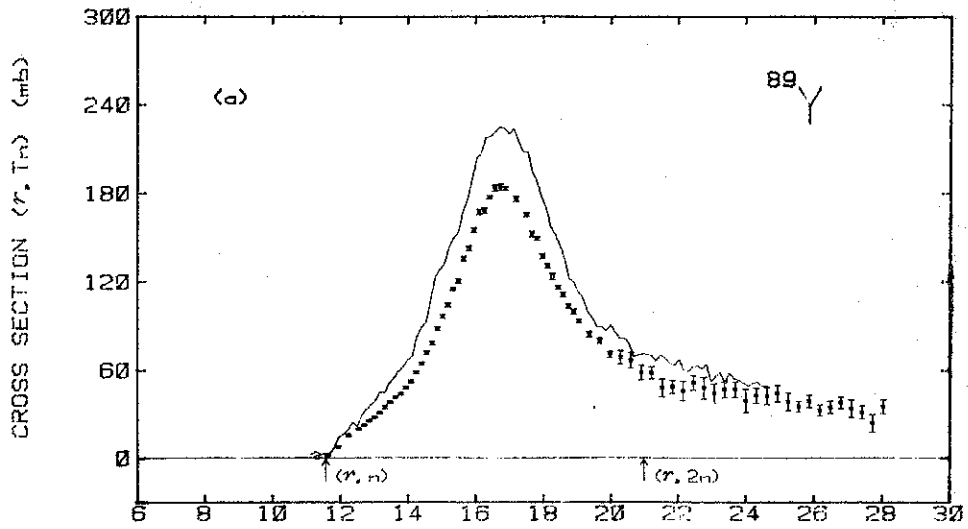


FIG. 6

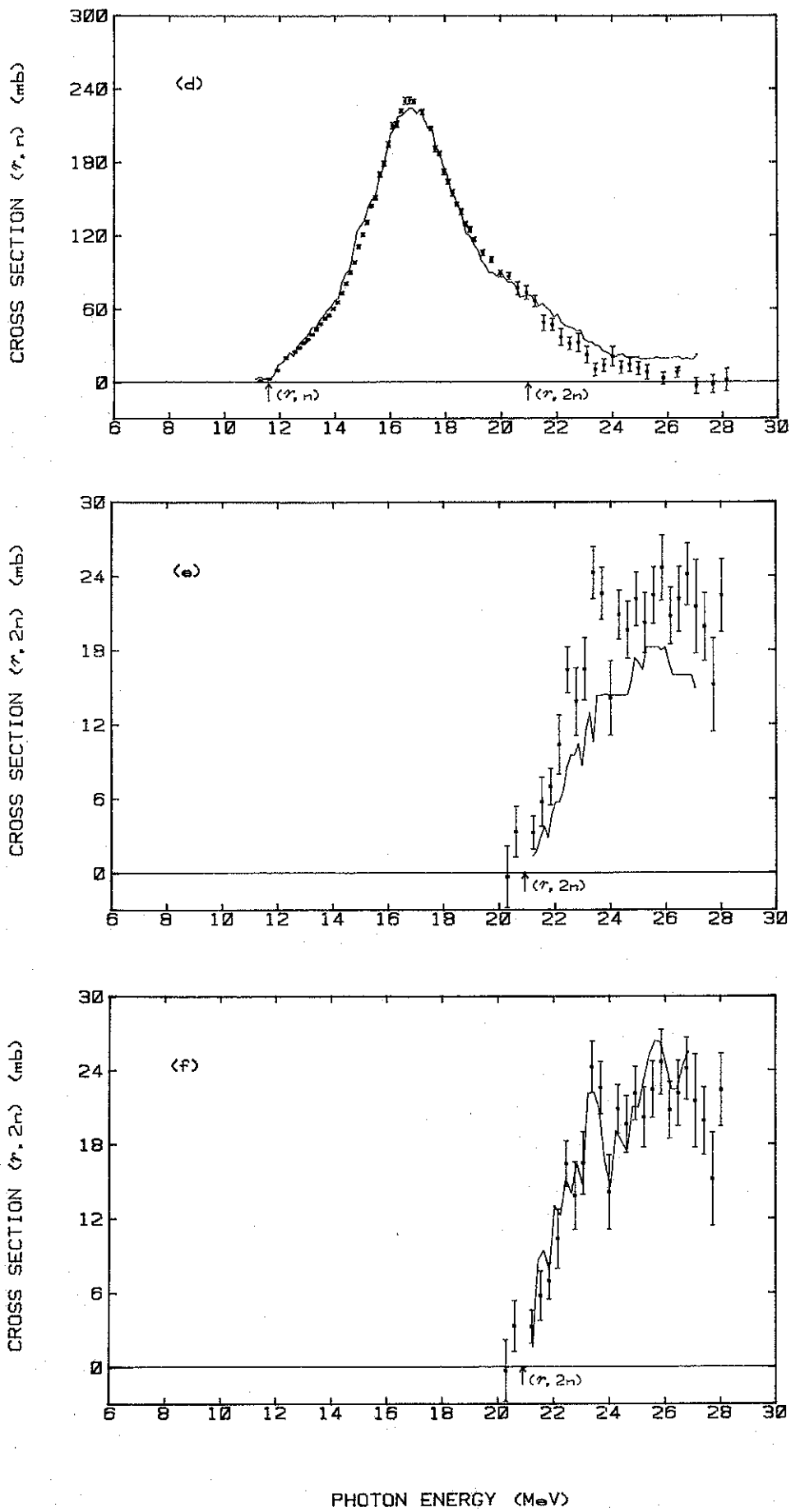


FIG. 6

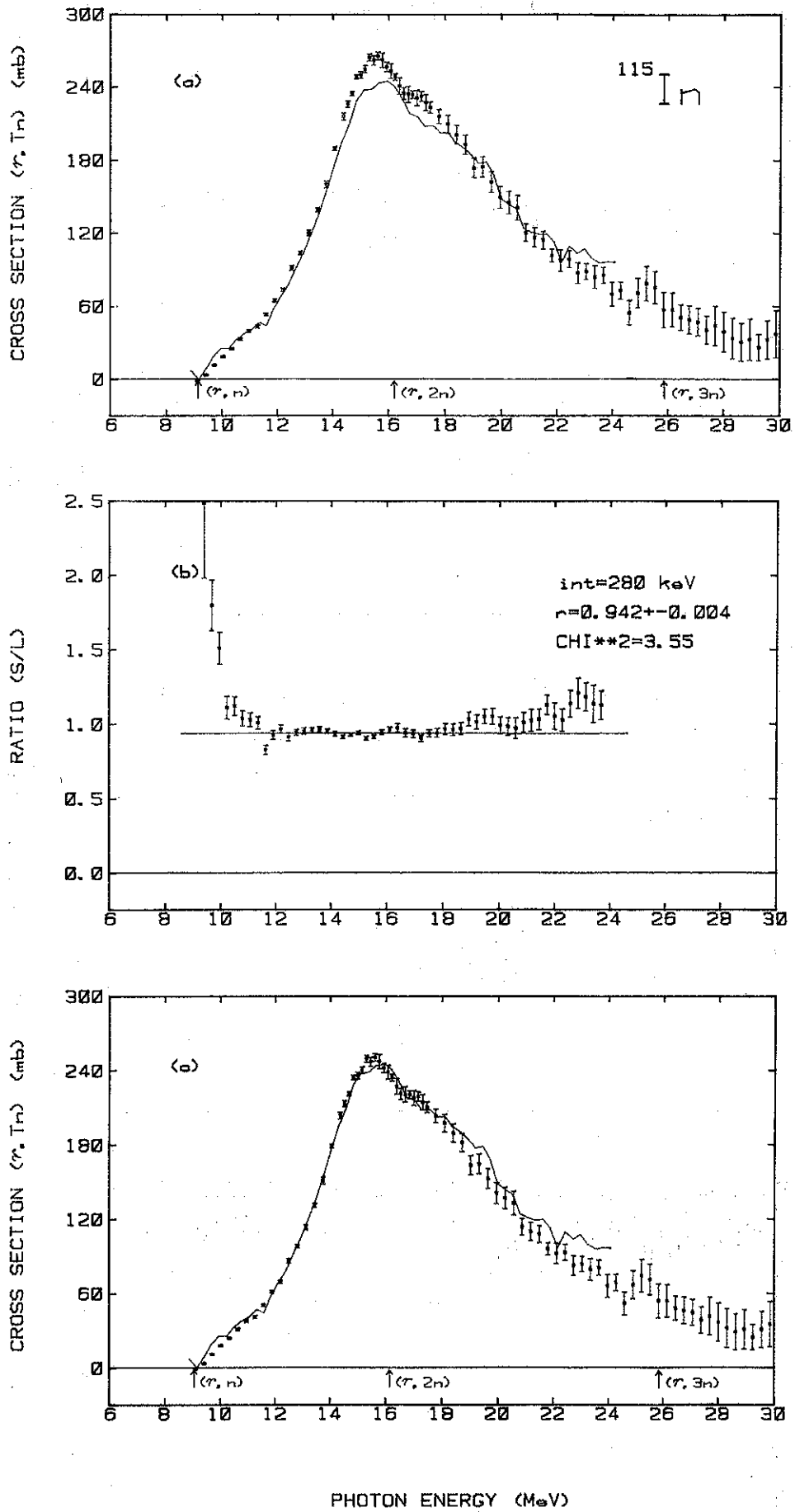


FIG. 7

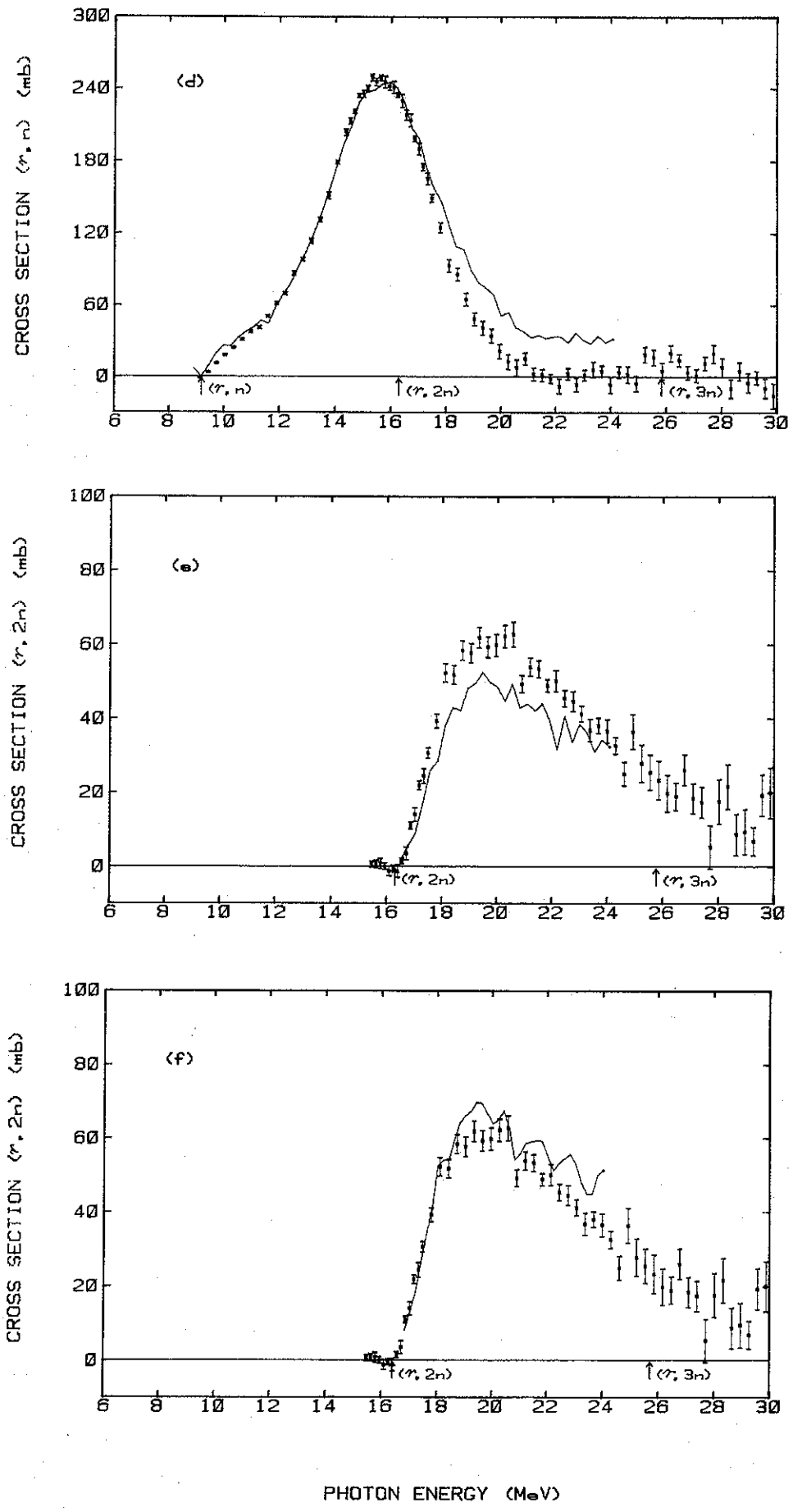


FIG. 7

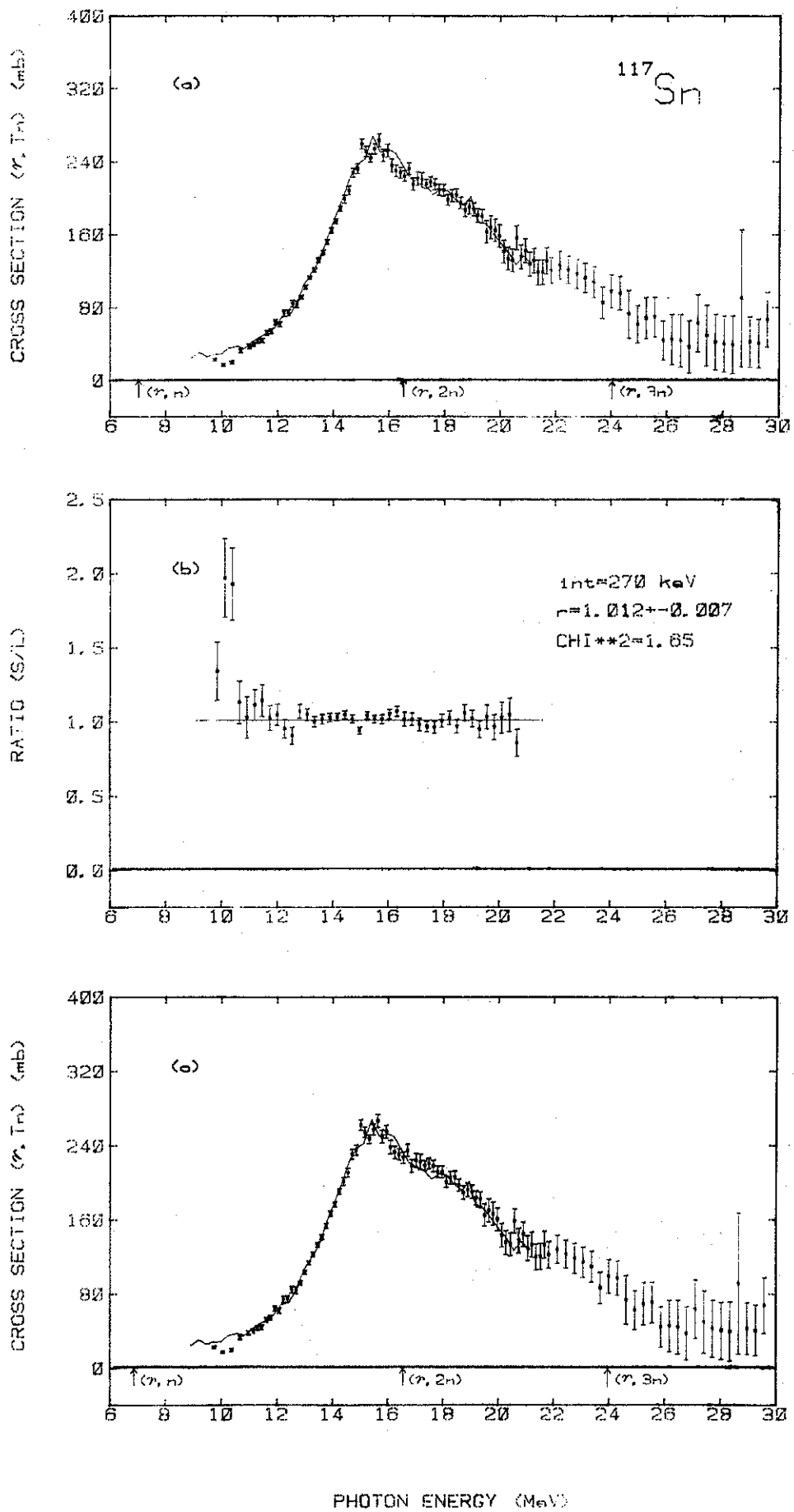


FIG. 8

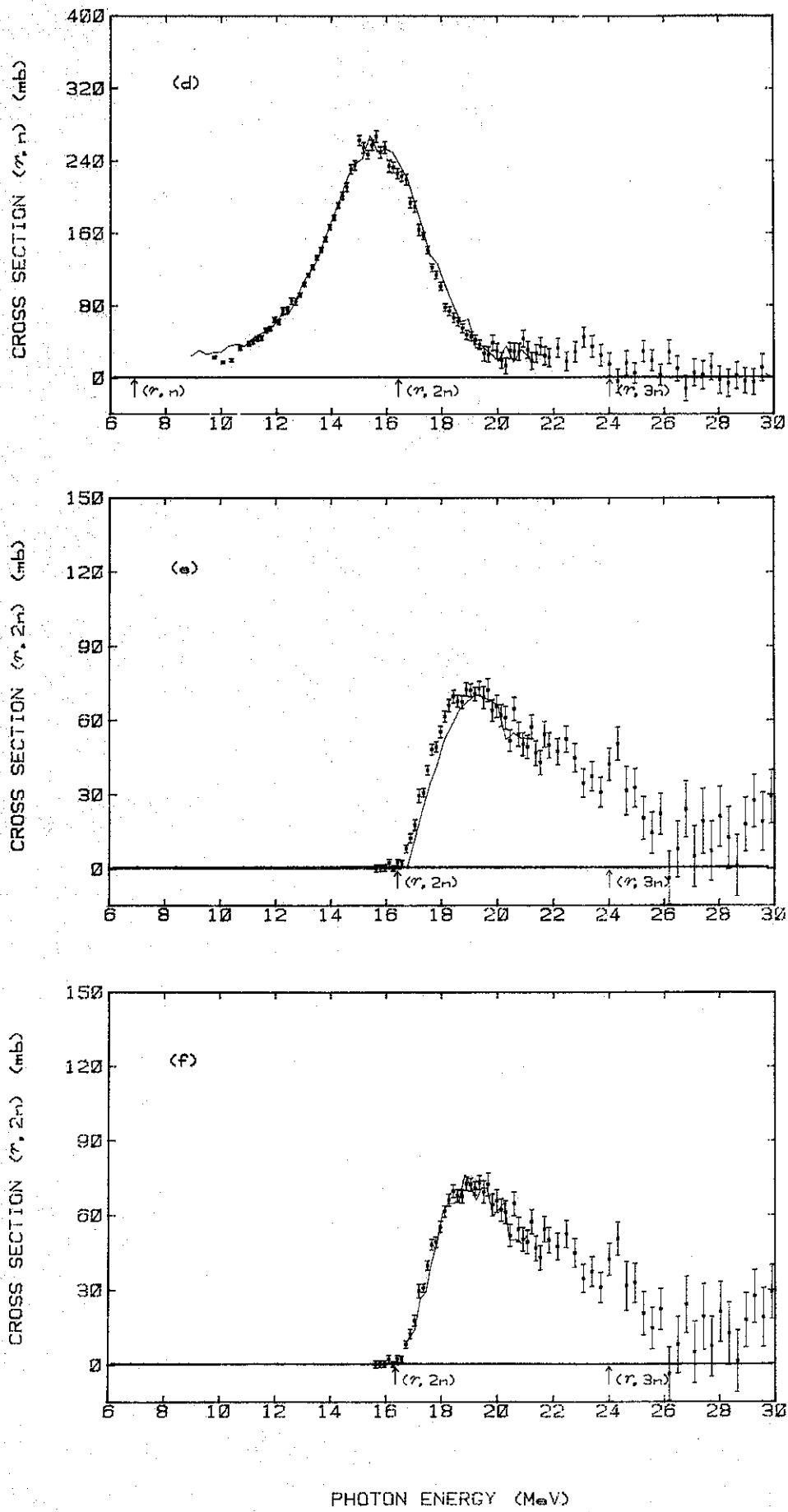


FIG. 8

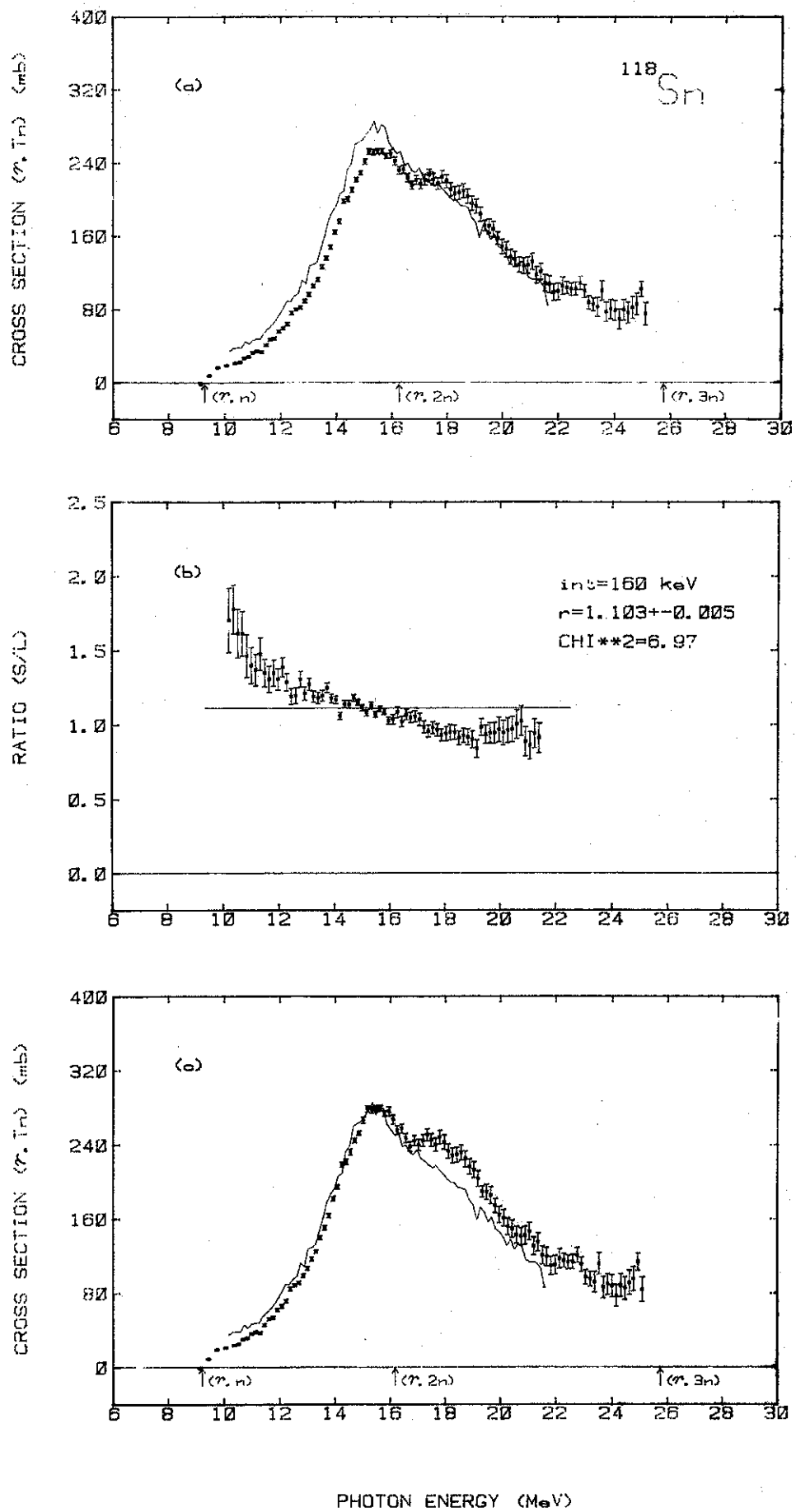


FIG. 9

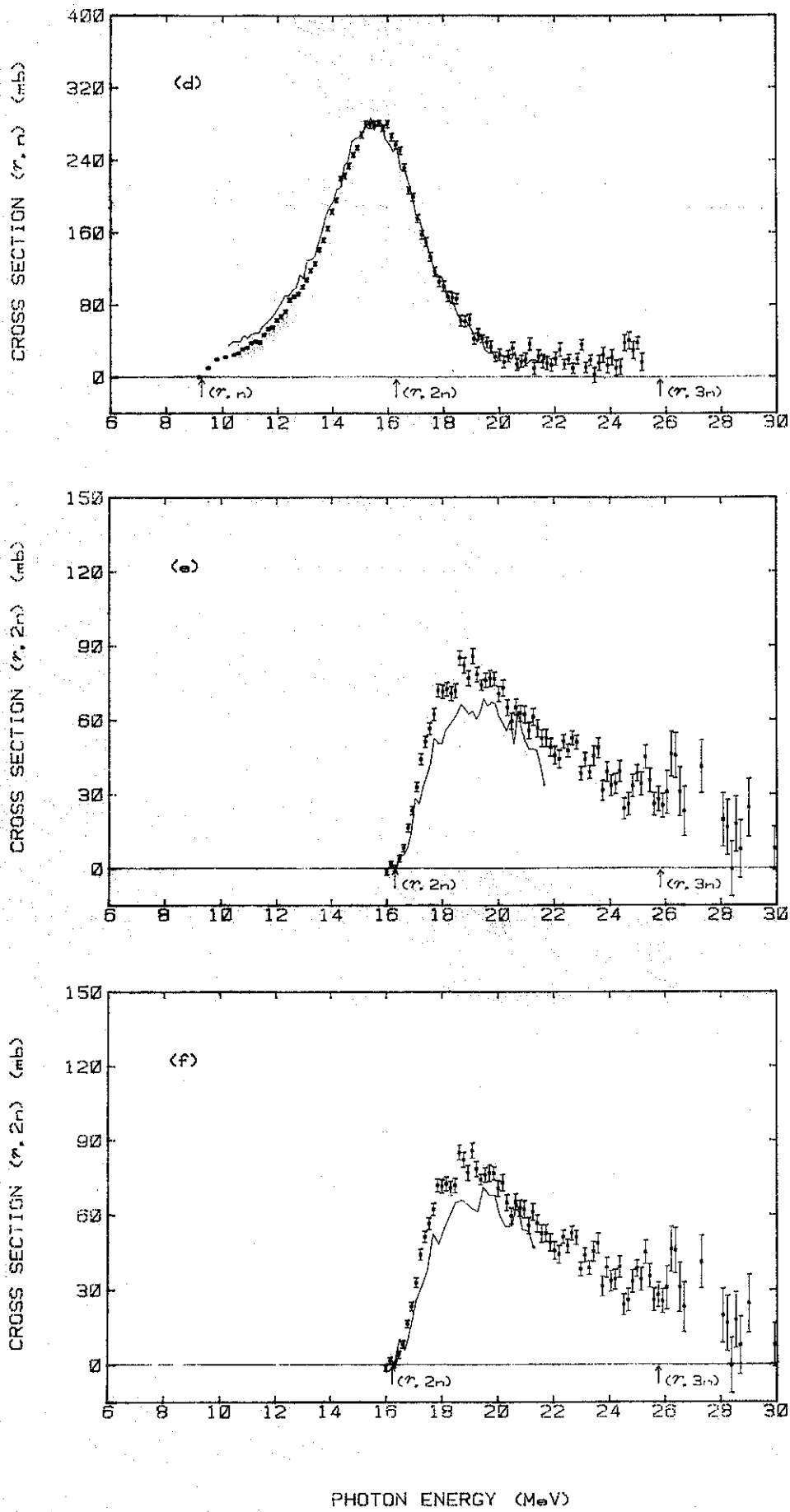


FIG. 9

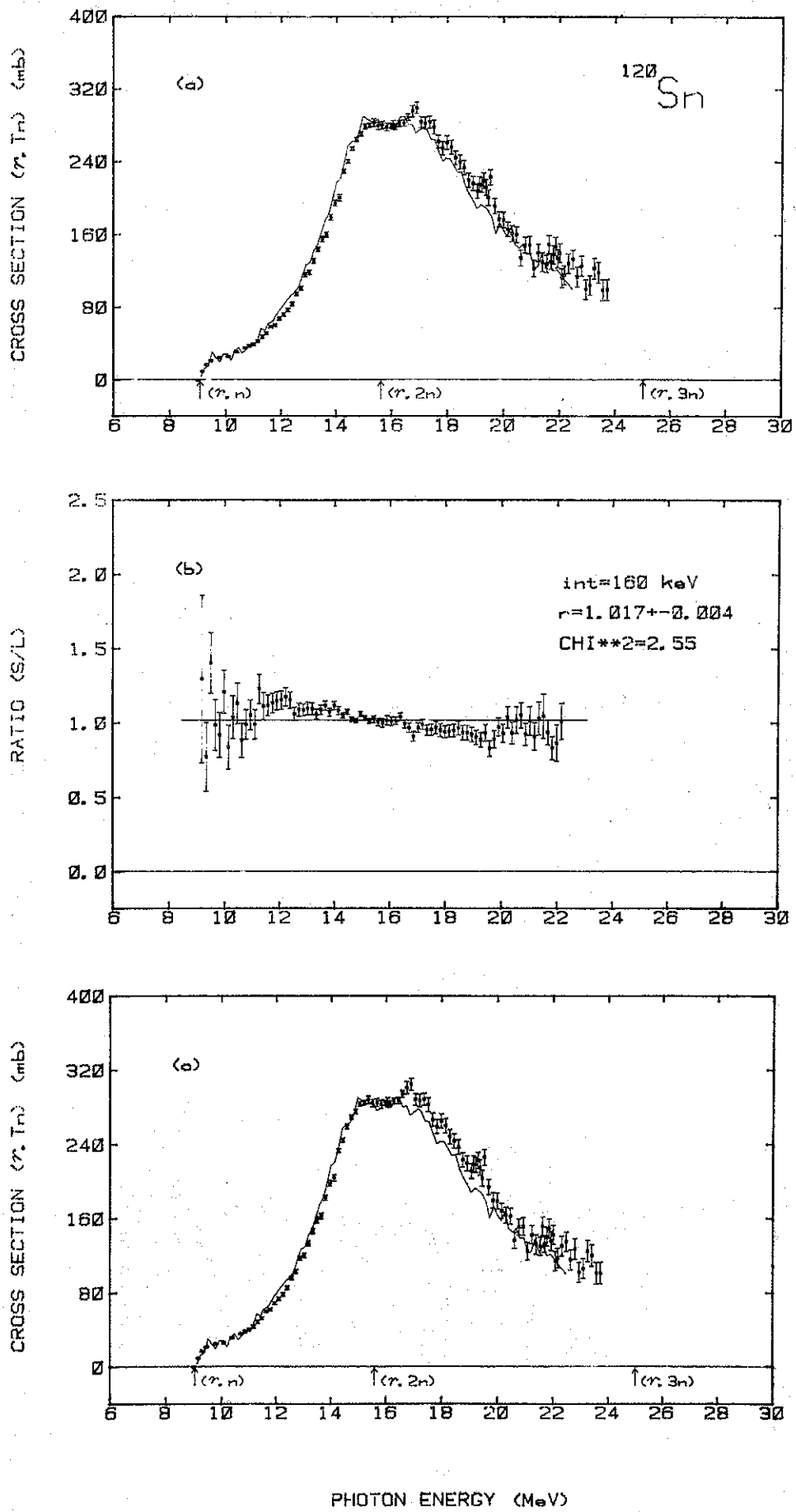


FIG. 10

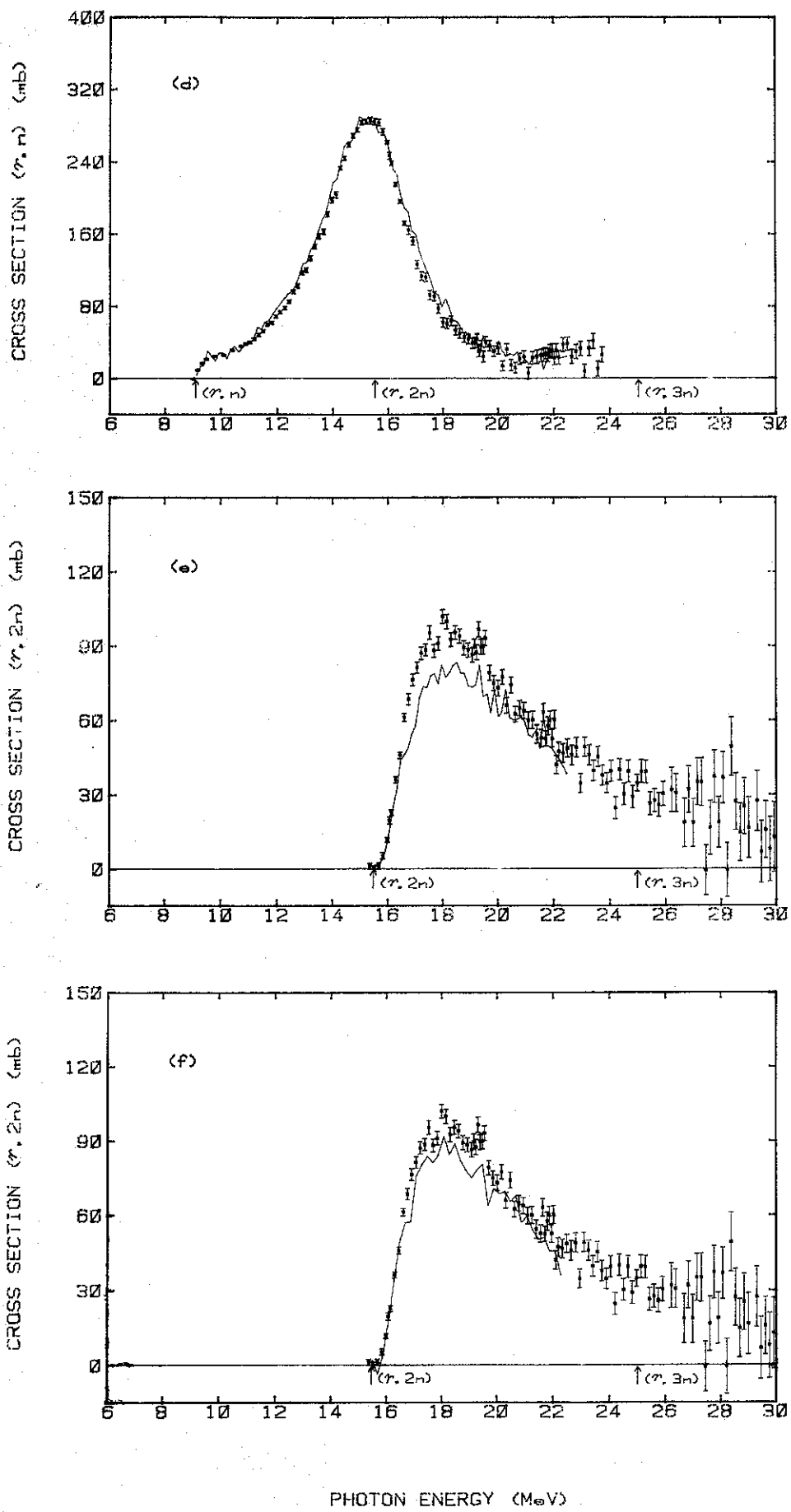


FIG. 10

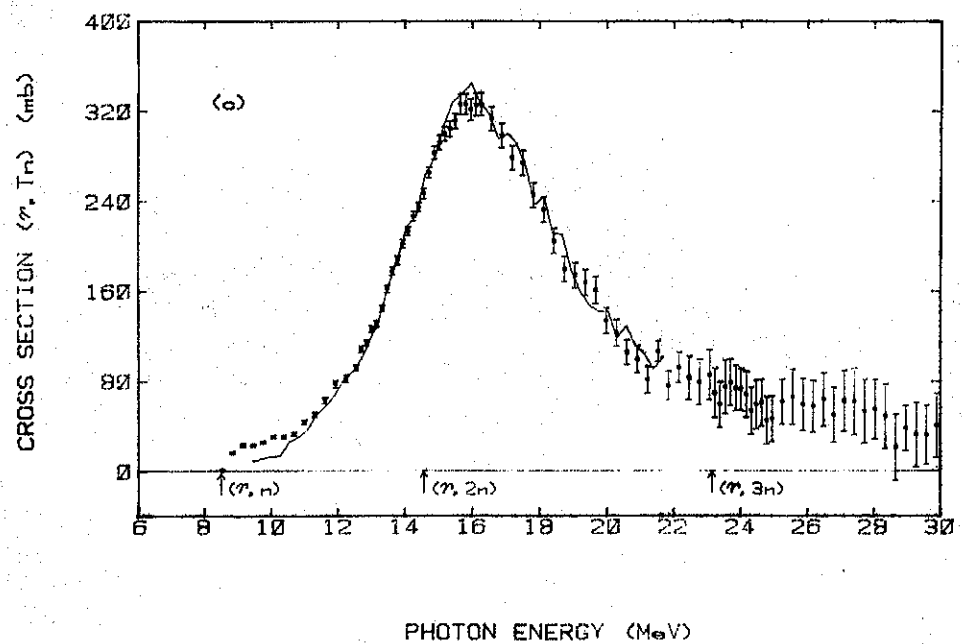
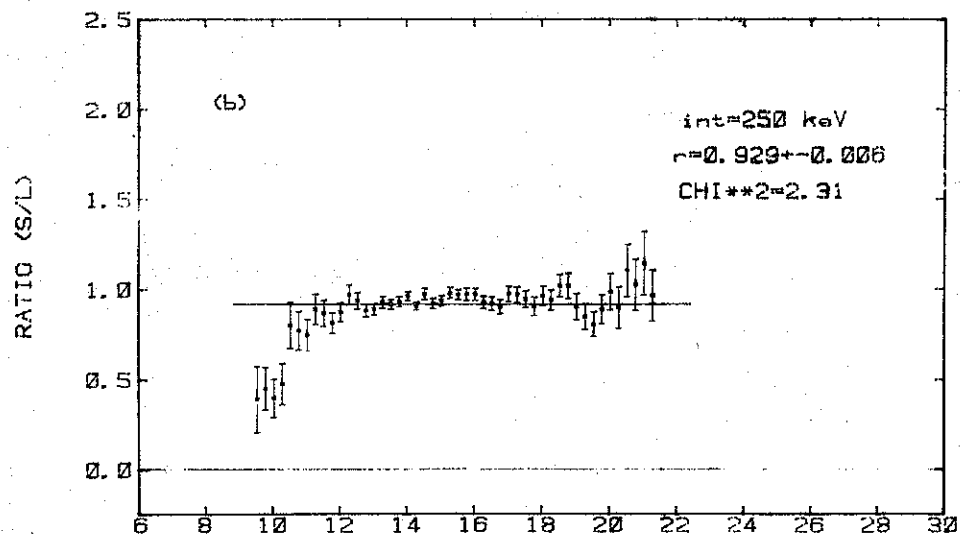
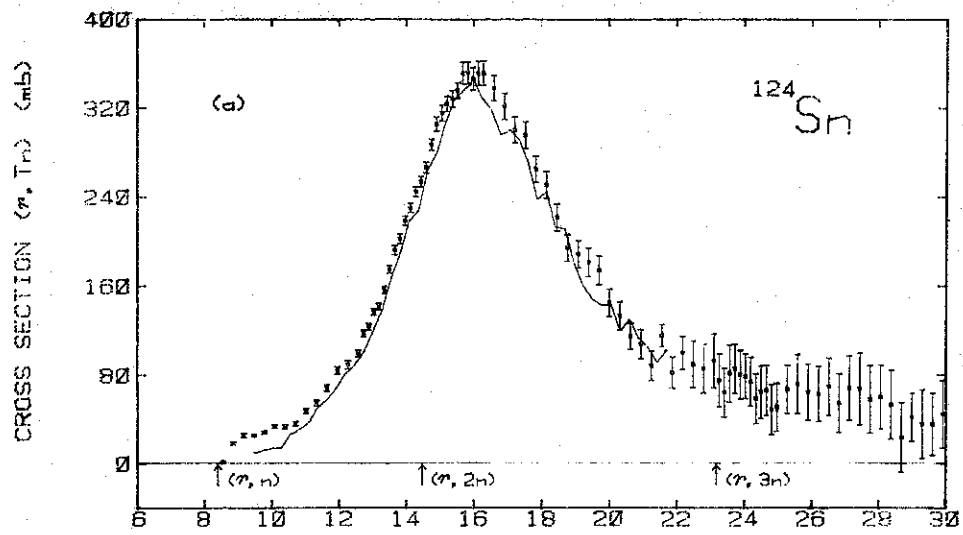
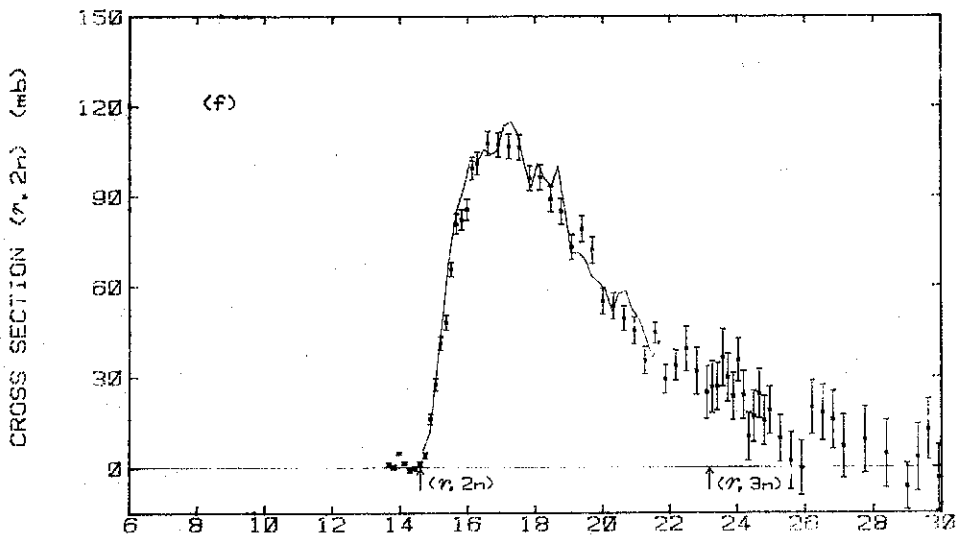
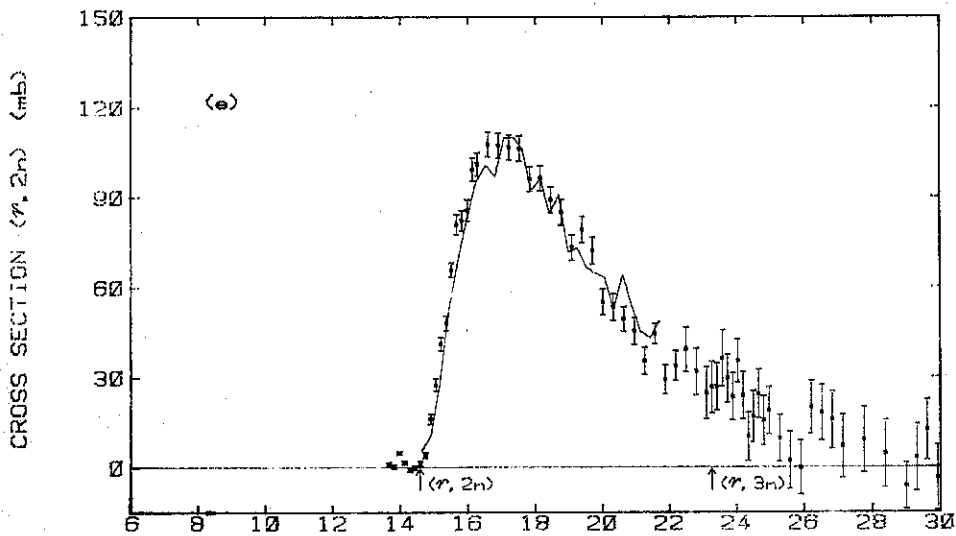
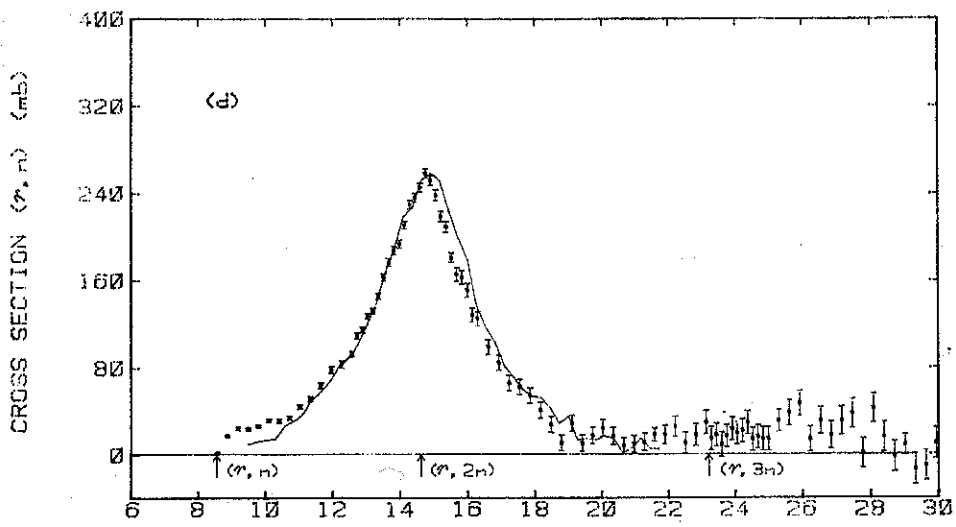


FIG. 11



PHOTON ENERGY (MeV)

FIG. 11

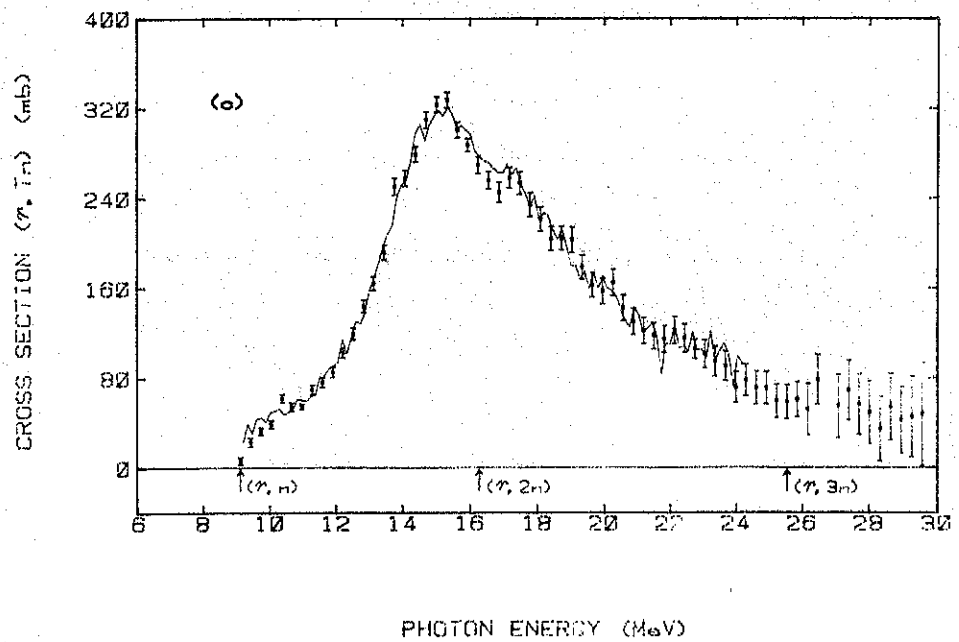
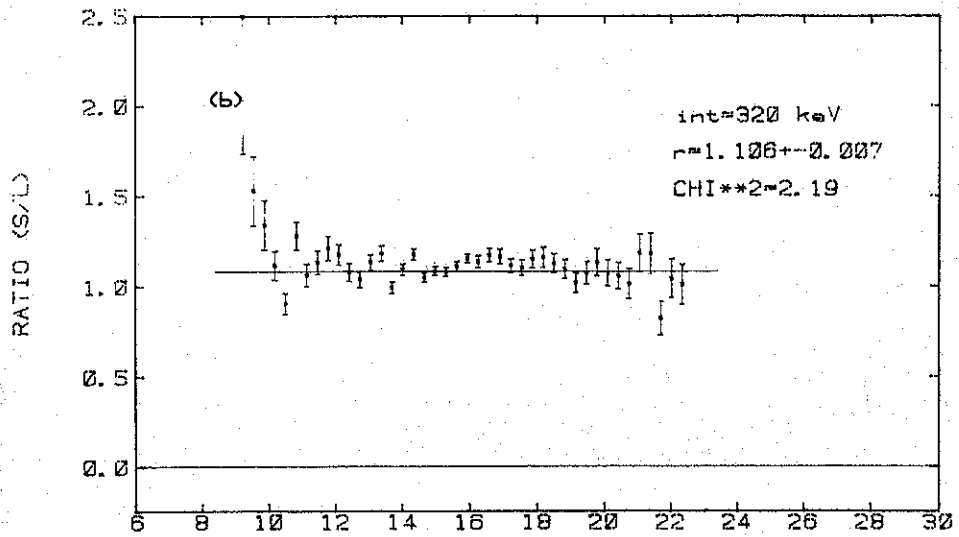
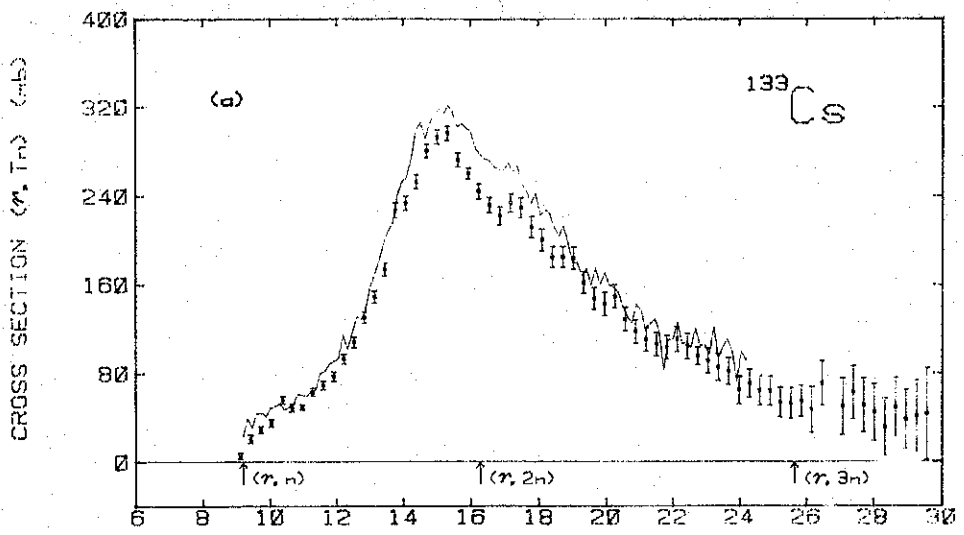


FIG. 12

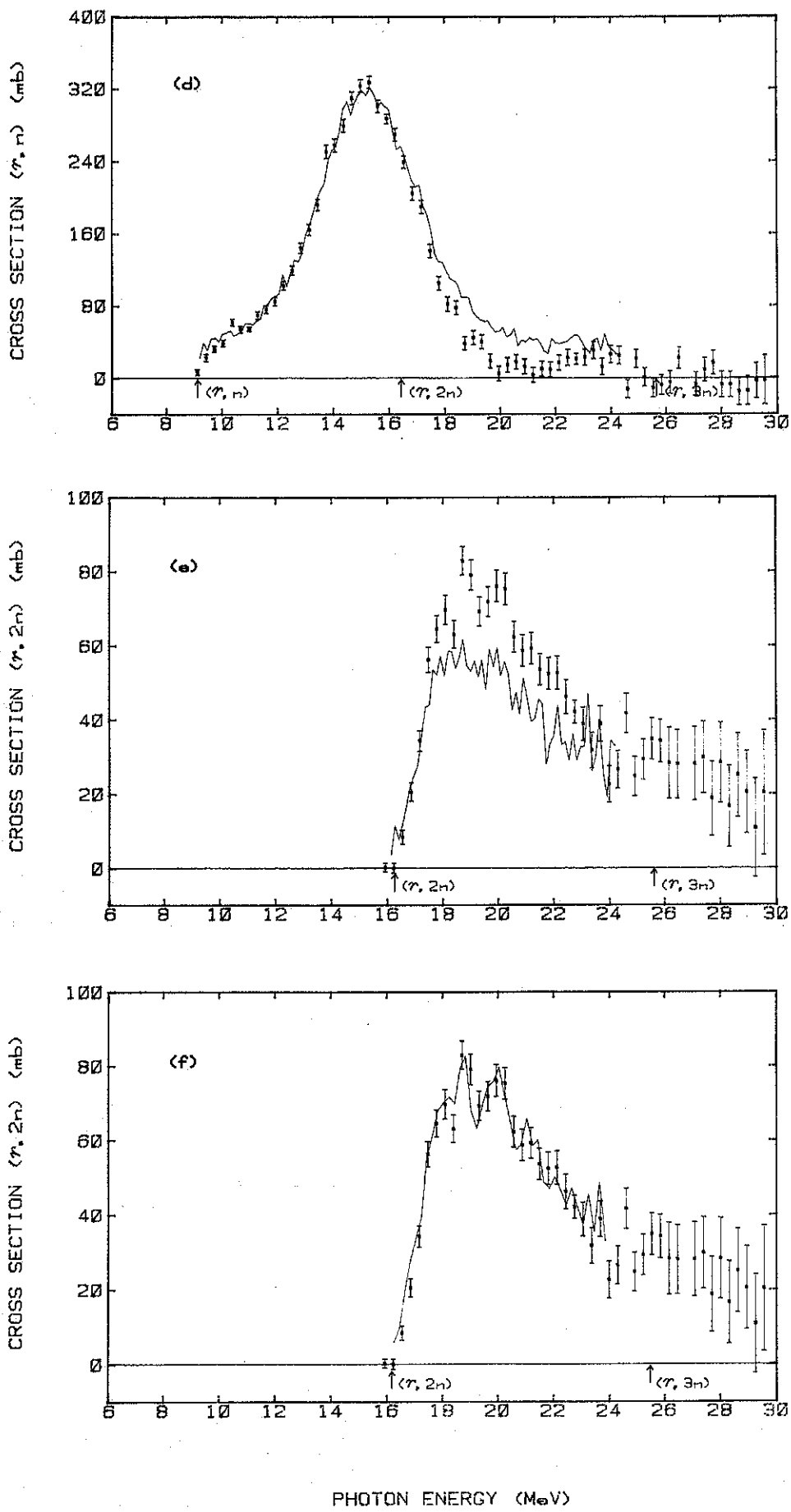


FIG. 12

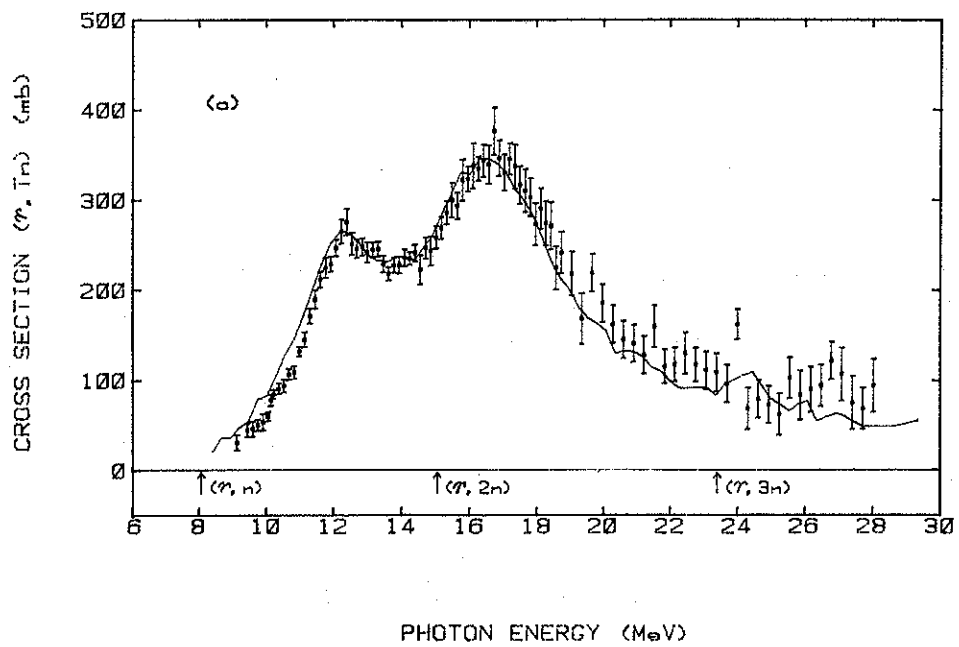
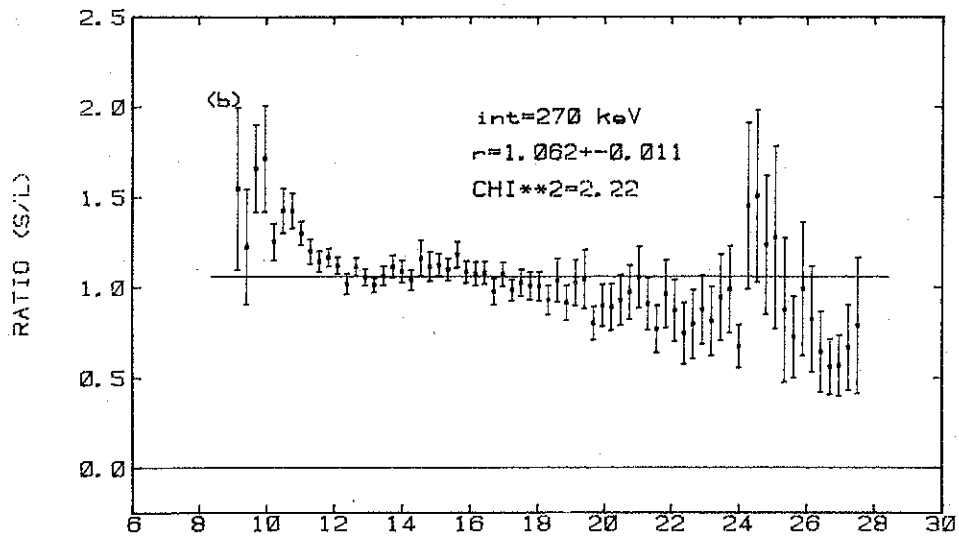
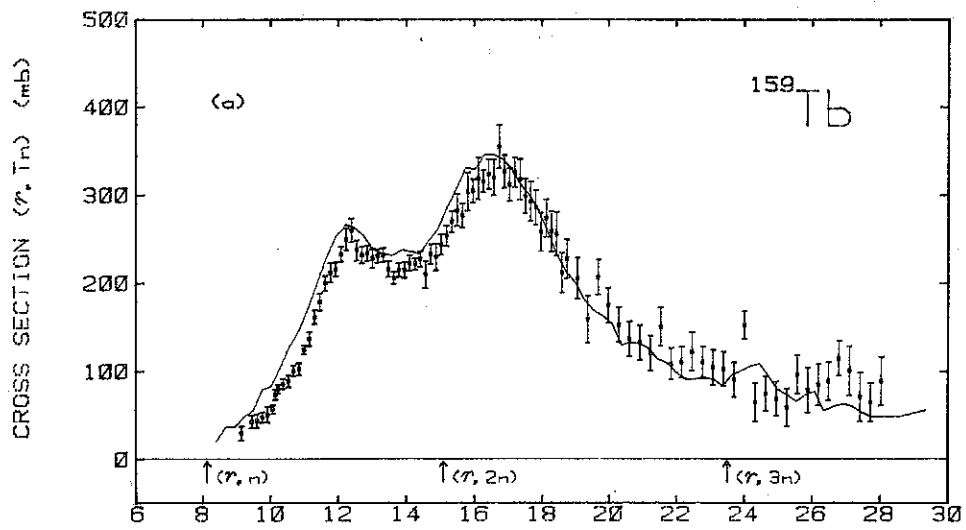
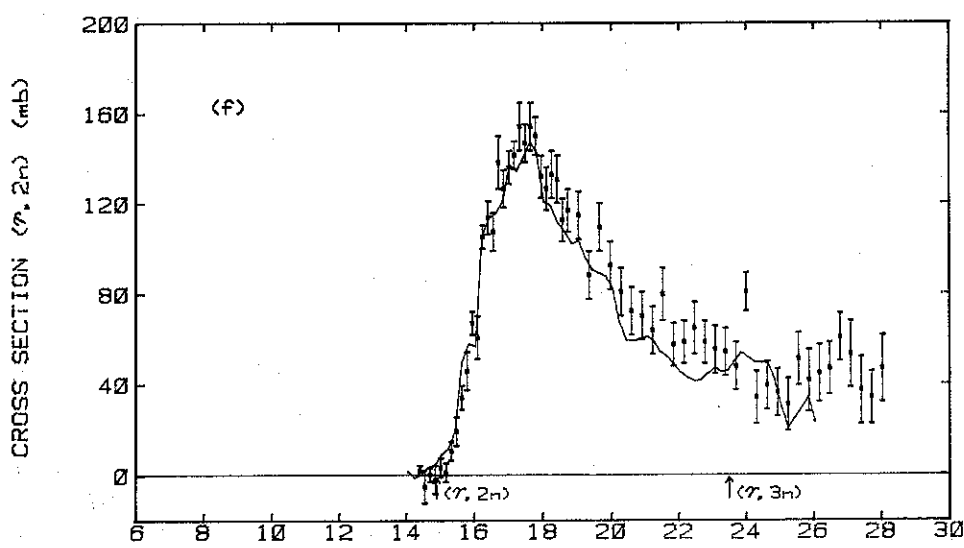
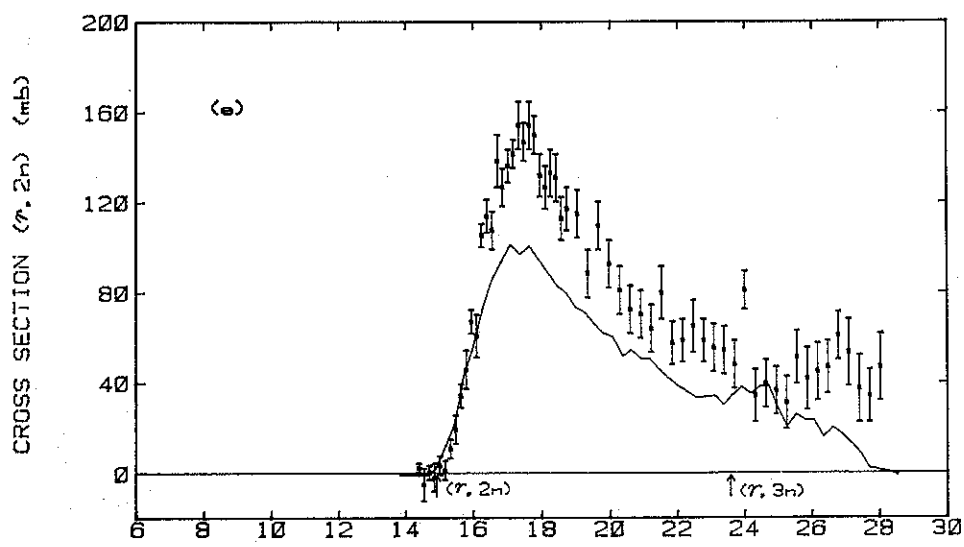
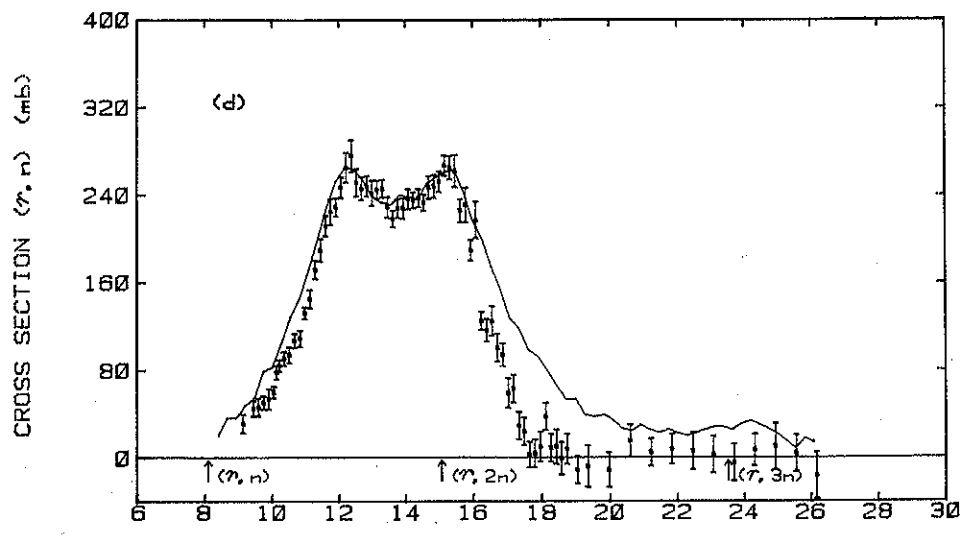


FIG. 13



PHOTON ENERGY (MeV)

FIG. 13

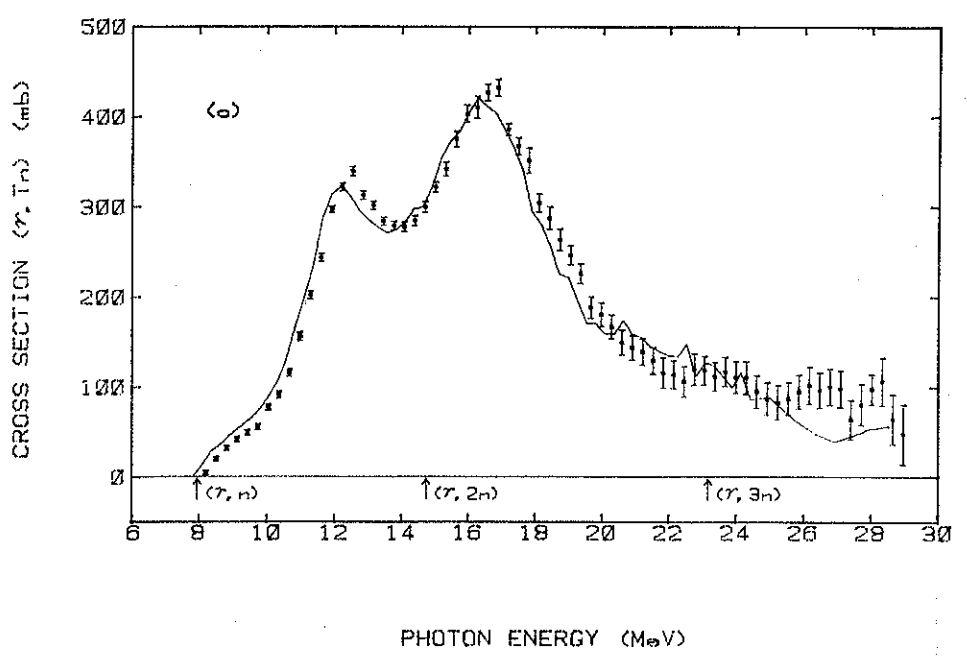
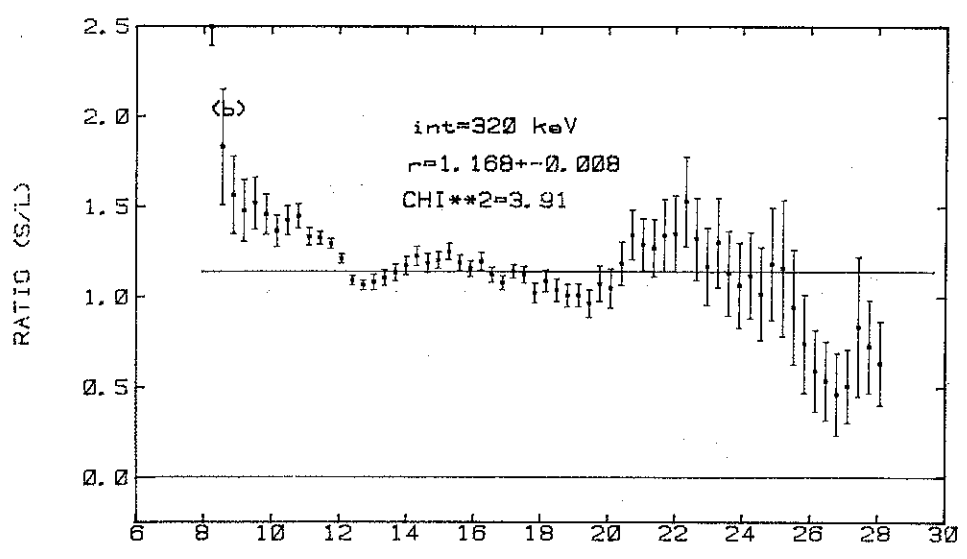
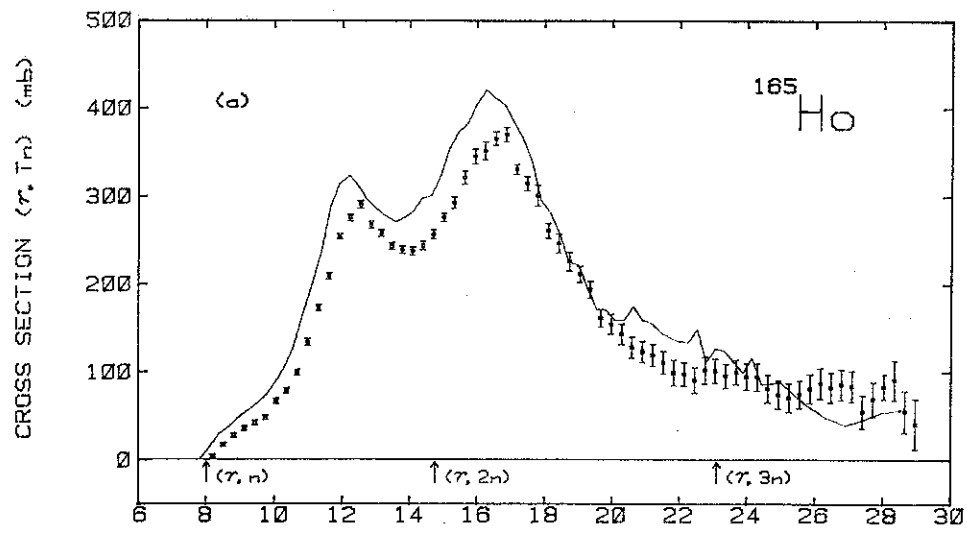
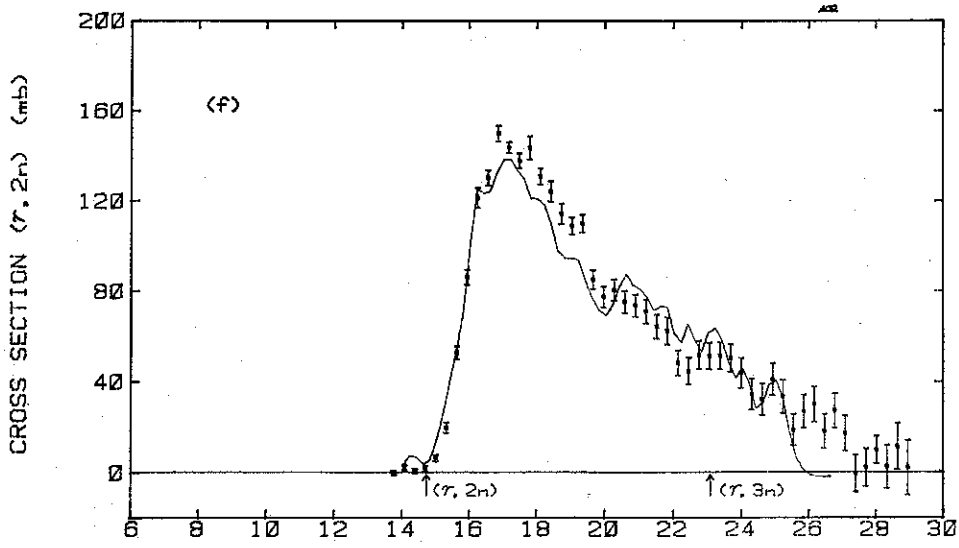
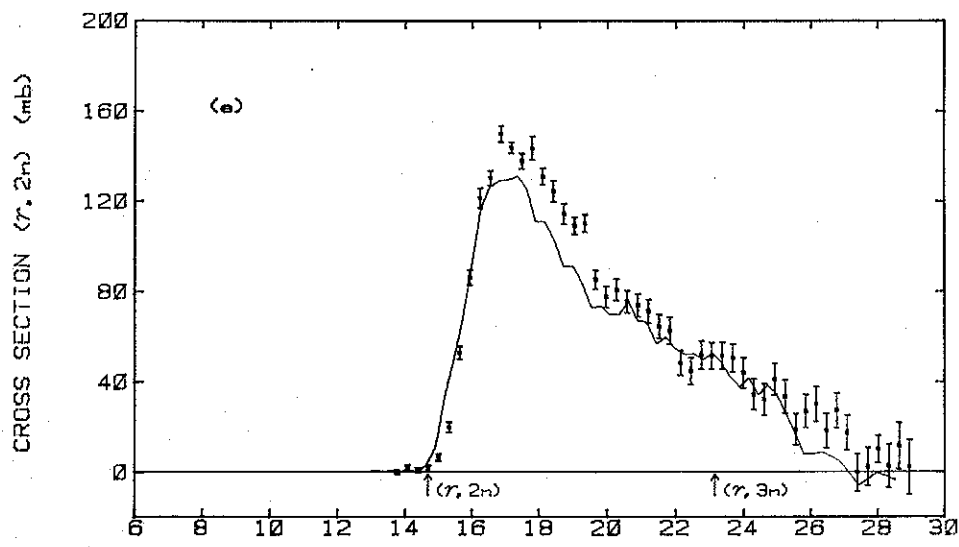
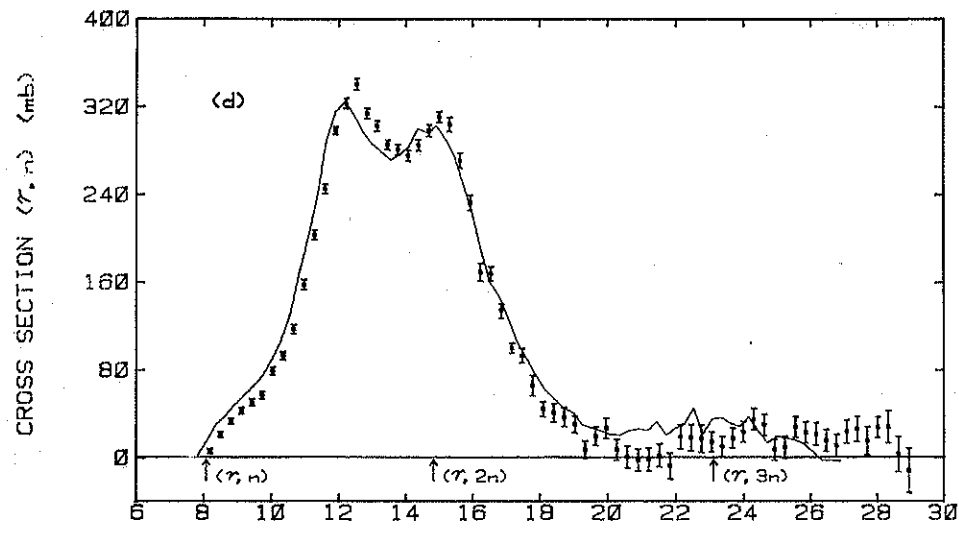


FIG. 14



PHOTON ENERGY (MeV)

FIG. 14

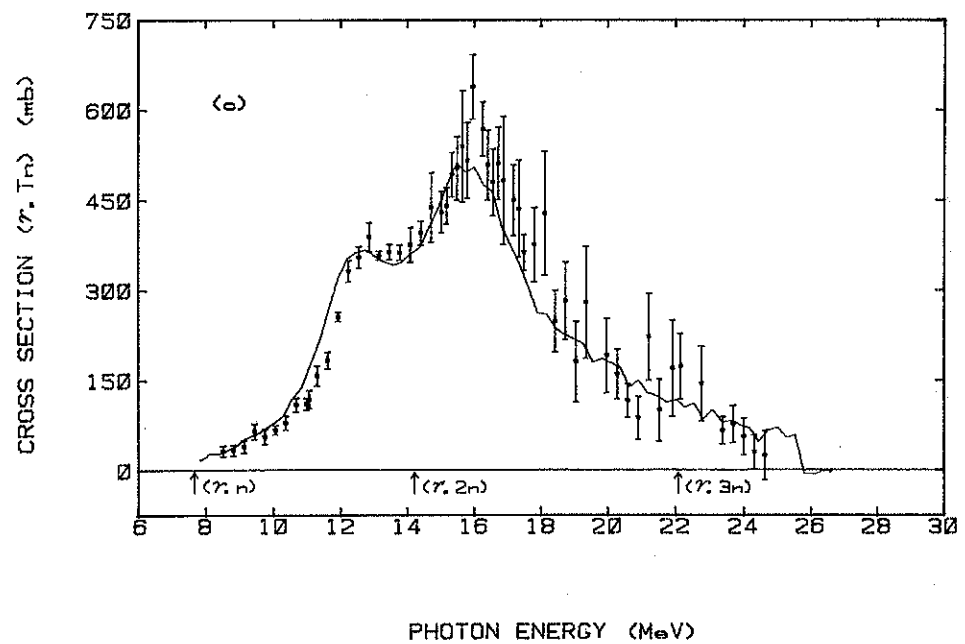
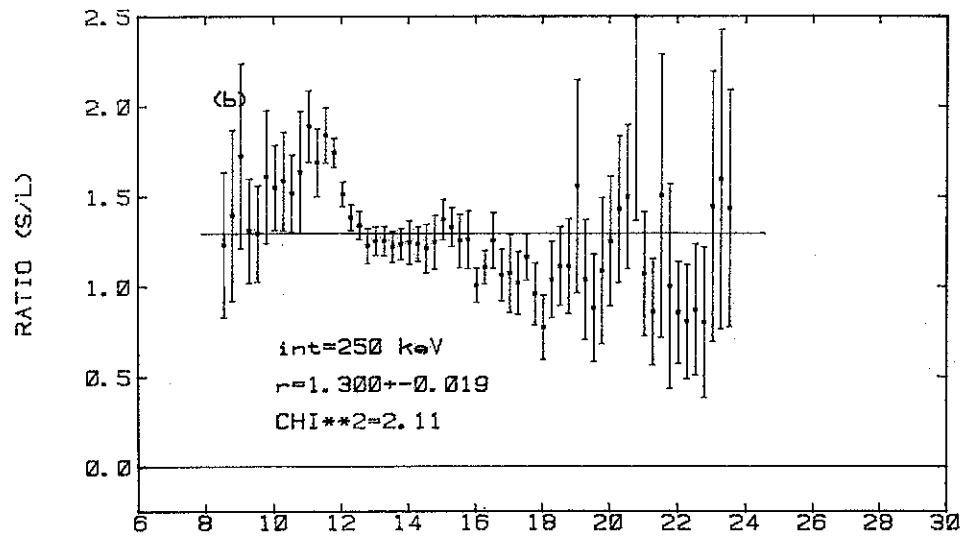
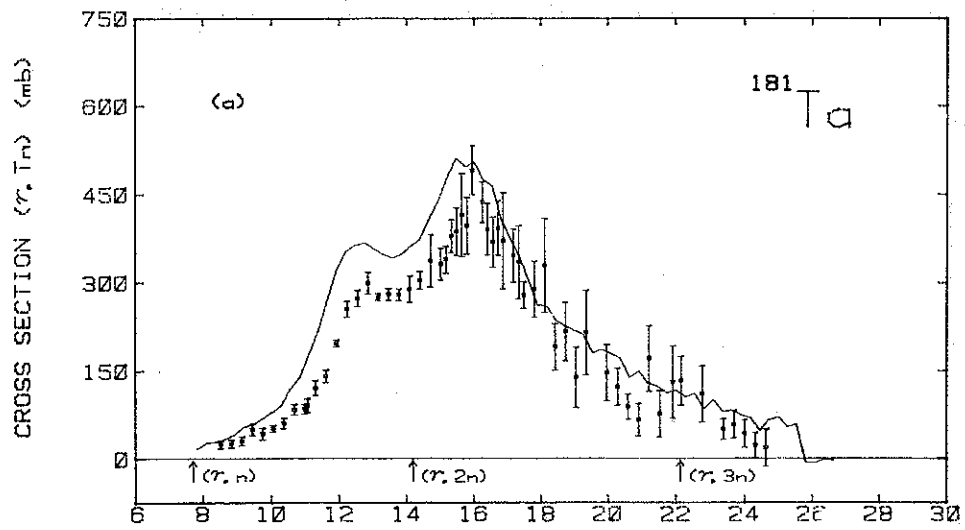


FIG. 15

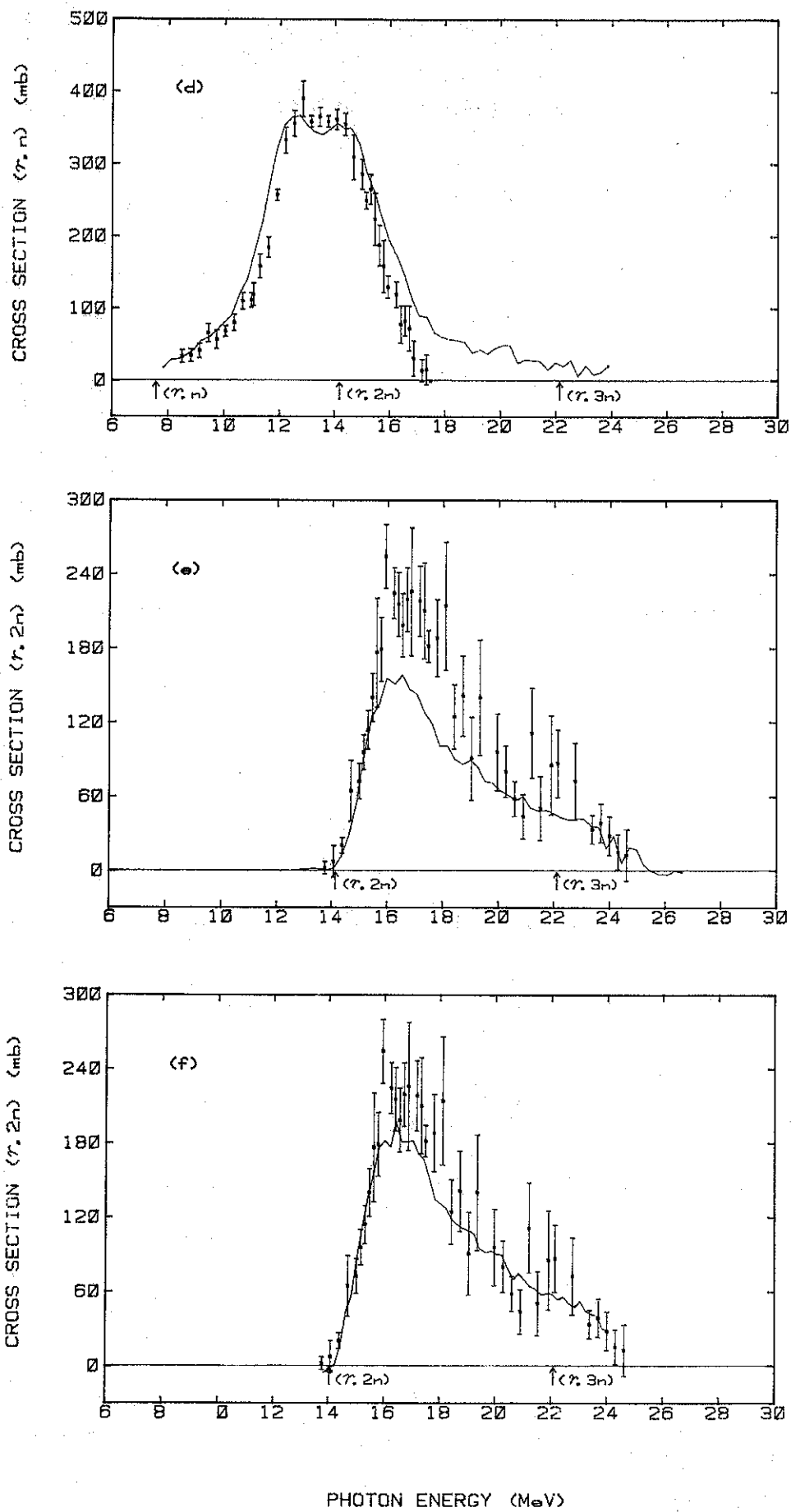
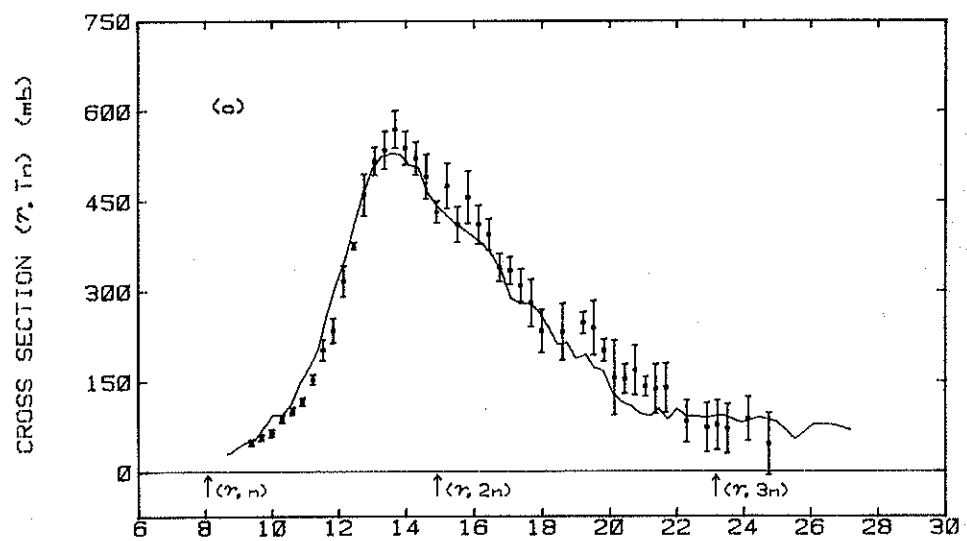
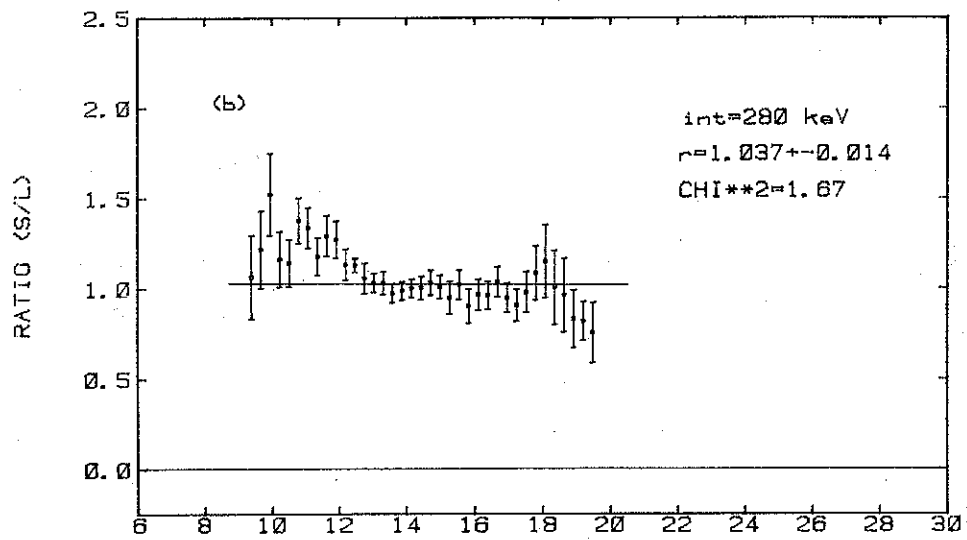
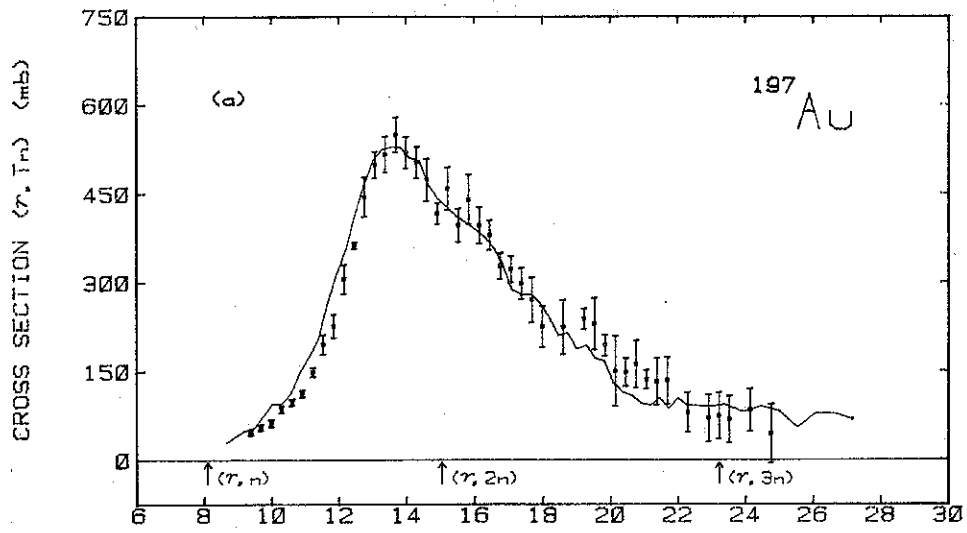
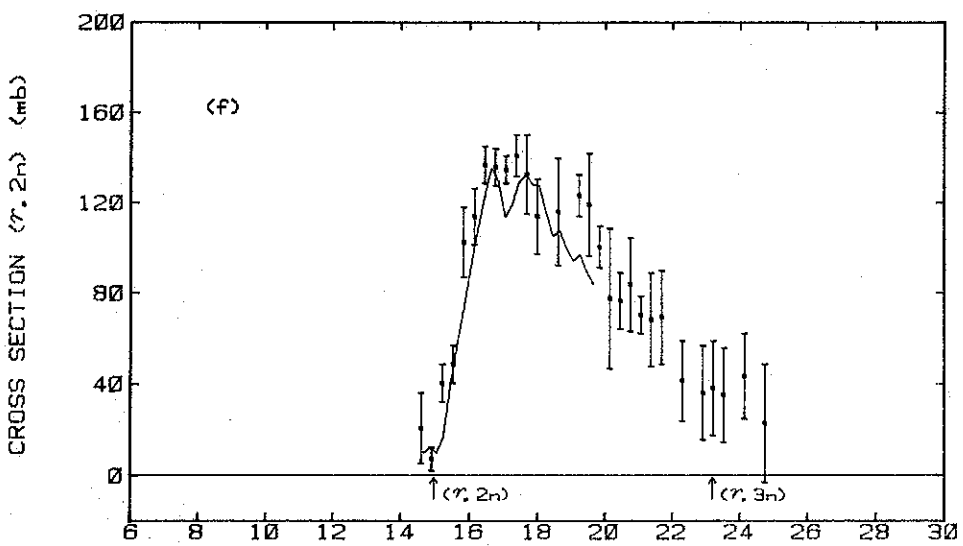
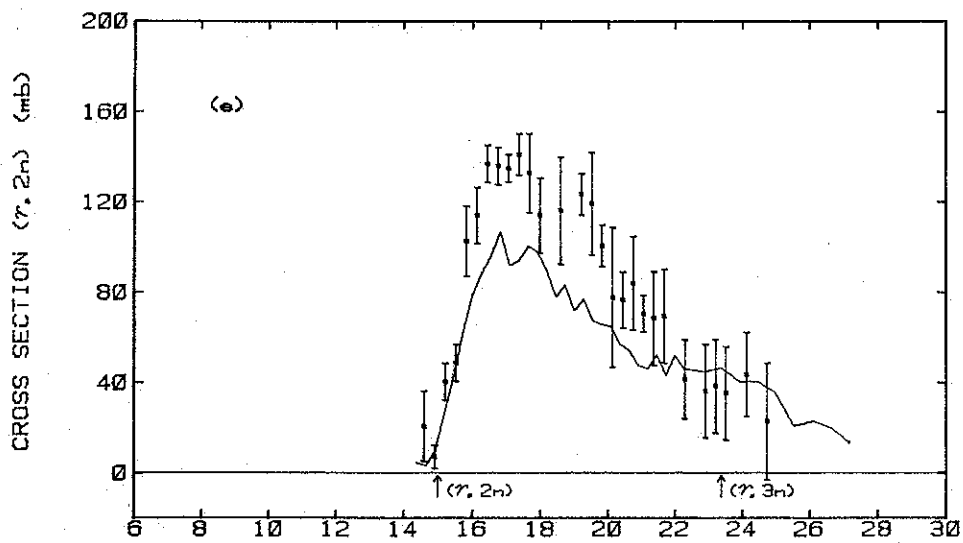
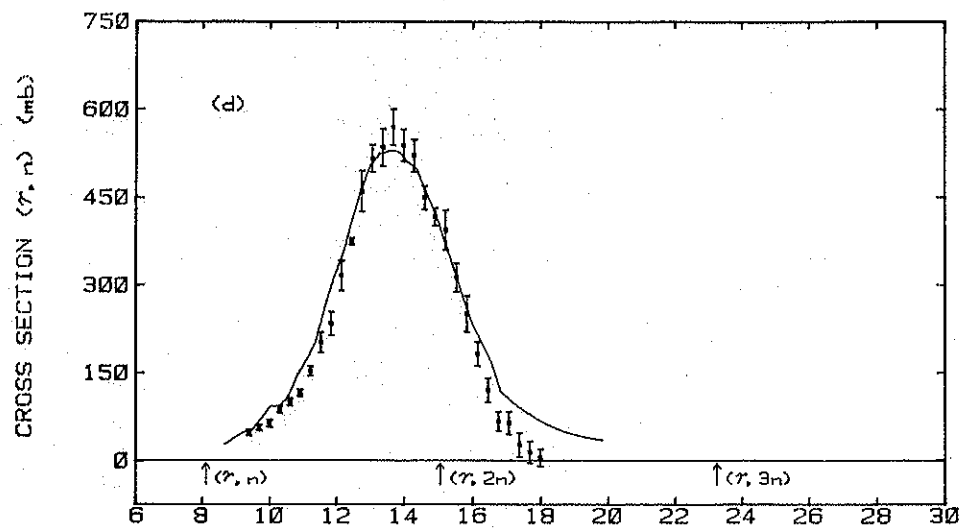


FIG. 15



PHOTON ENERGY (MeV)

FIG. 16



PHOTON ENERGY (MeV)

FIG. 16

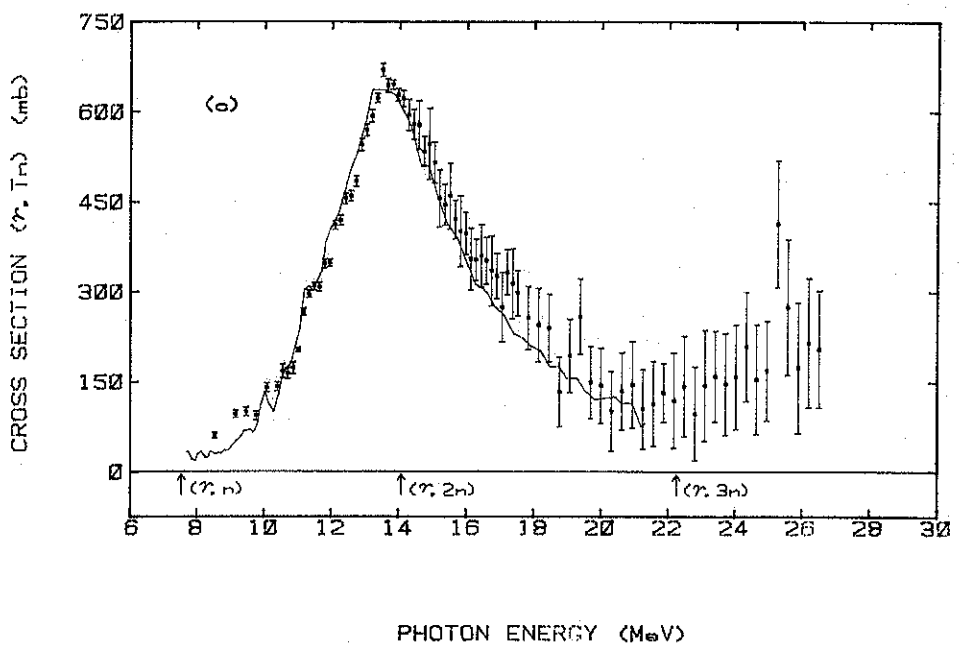
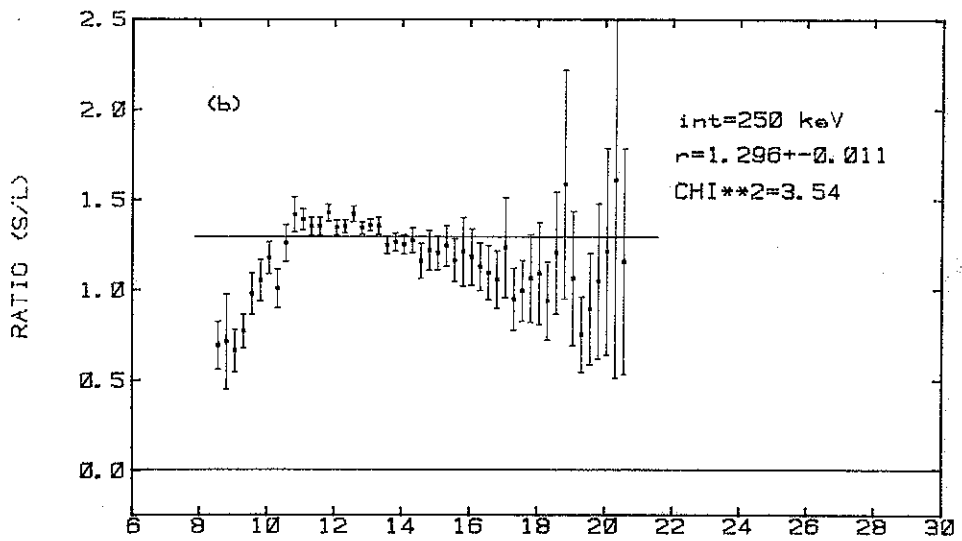
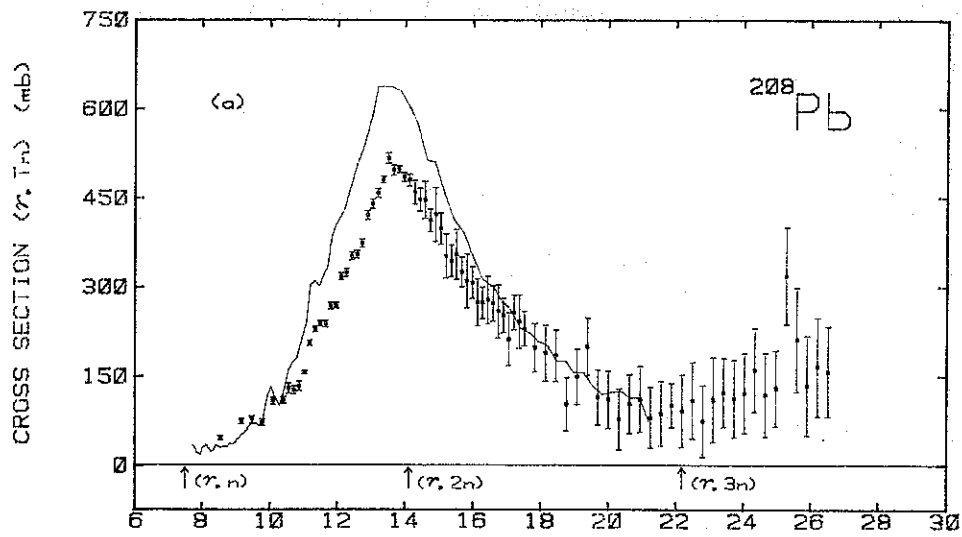


FIG. 17

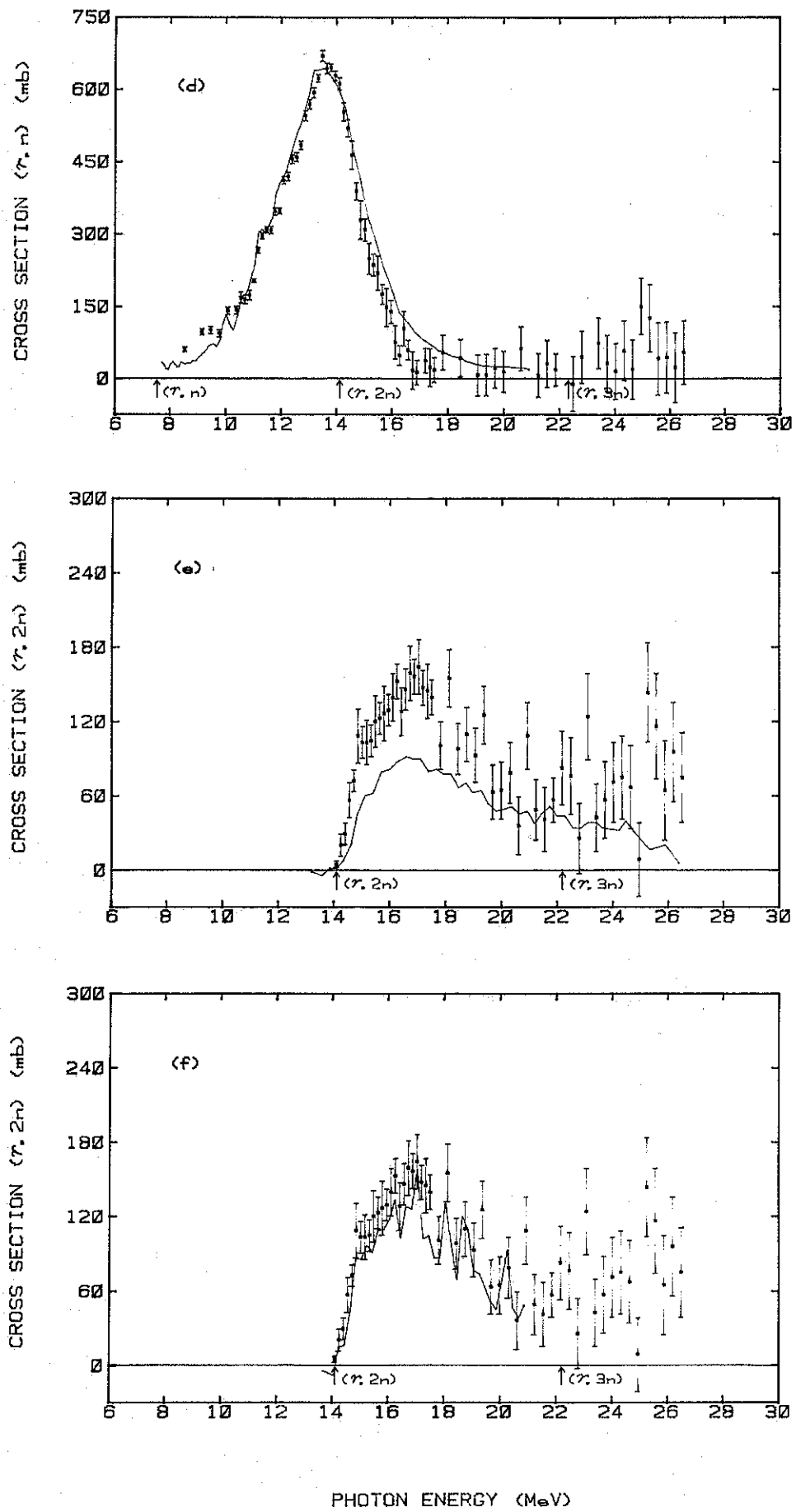


FIG. 17

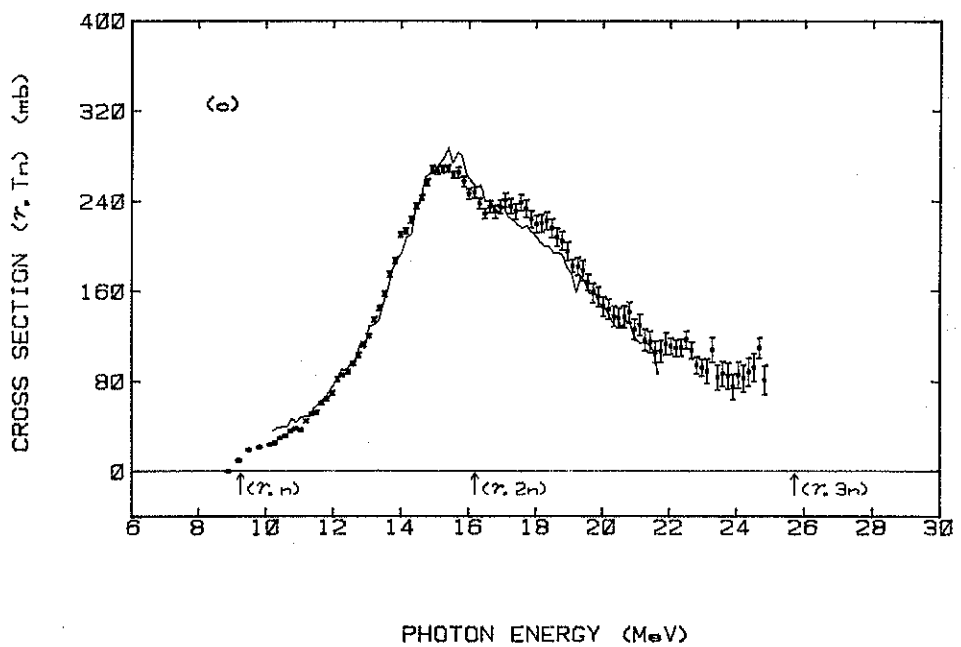
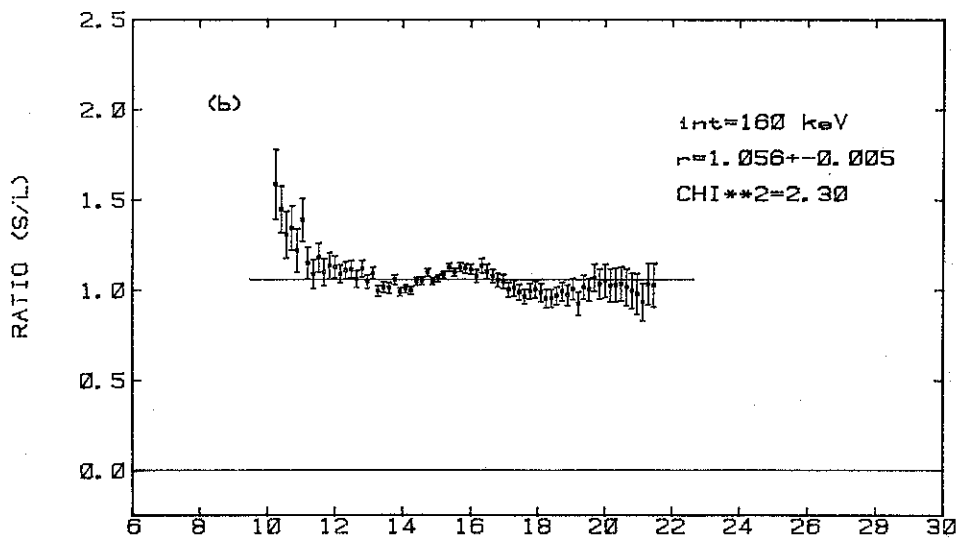
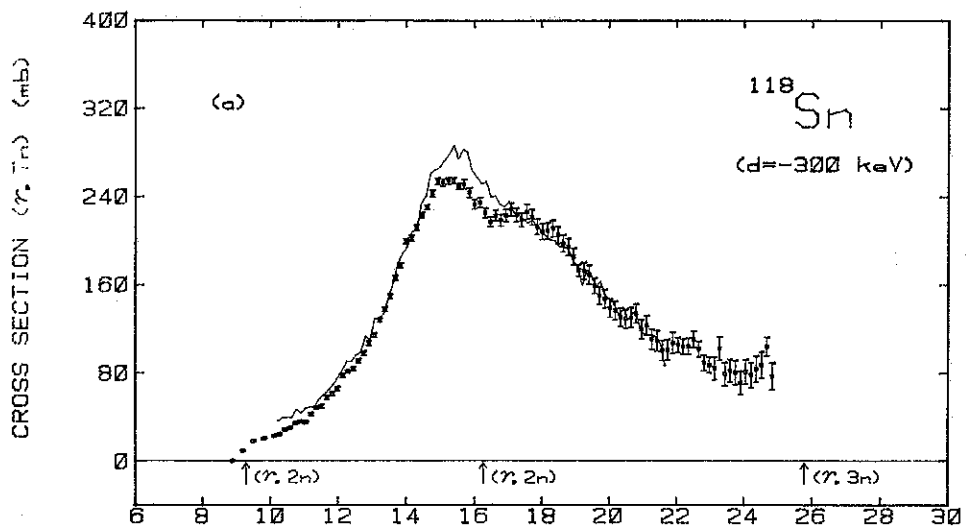


FIG. 18

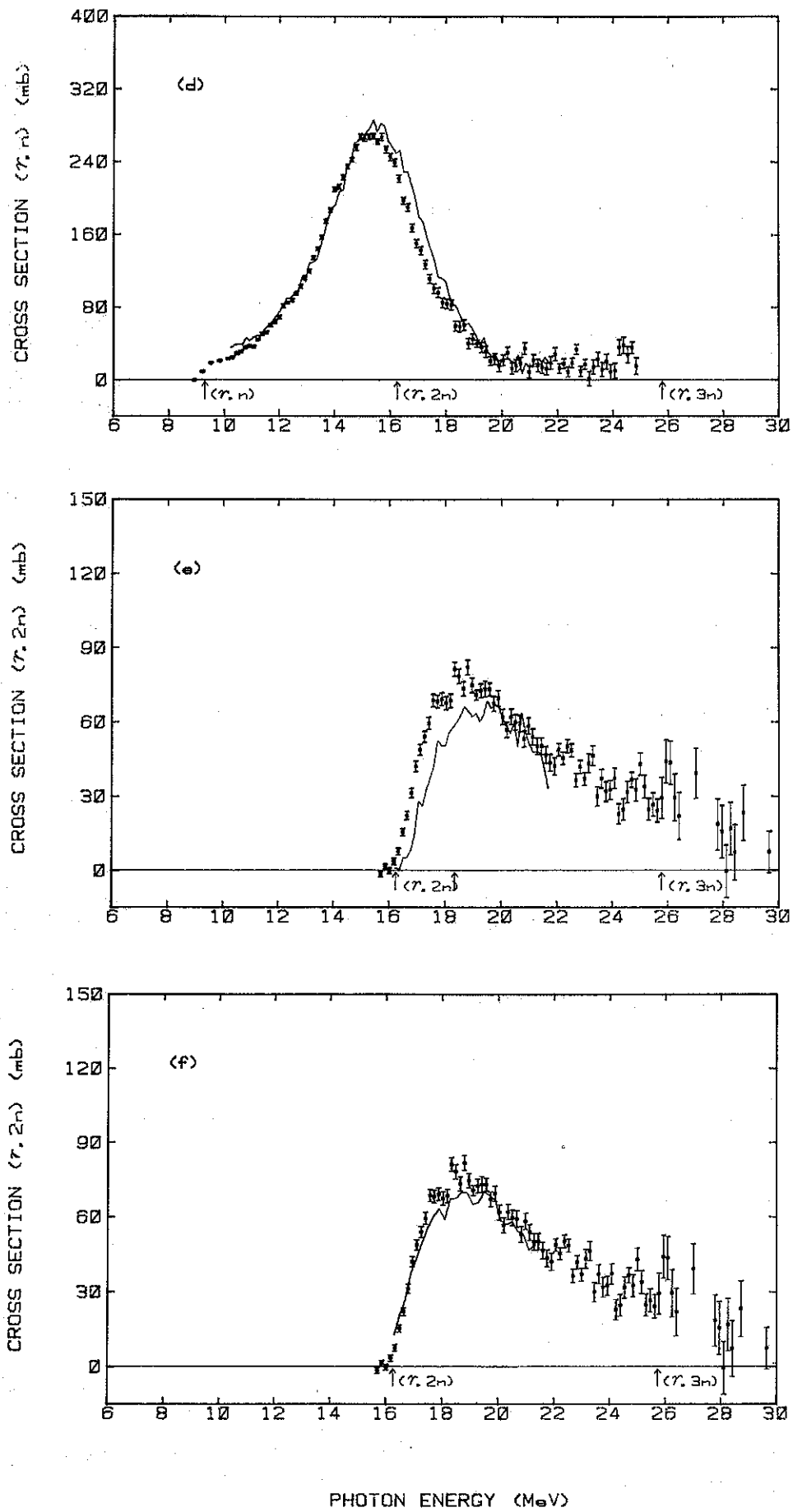


FIG. 18

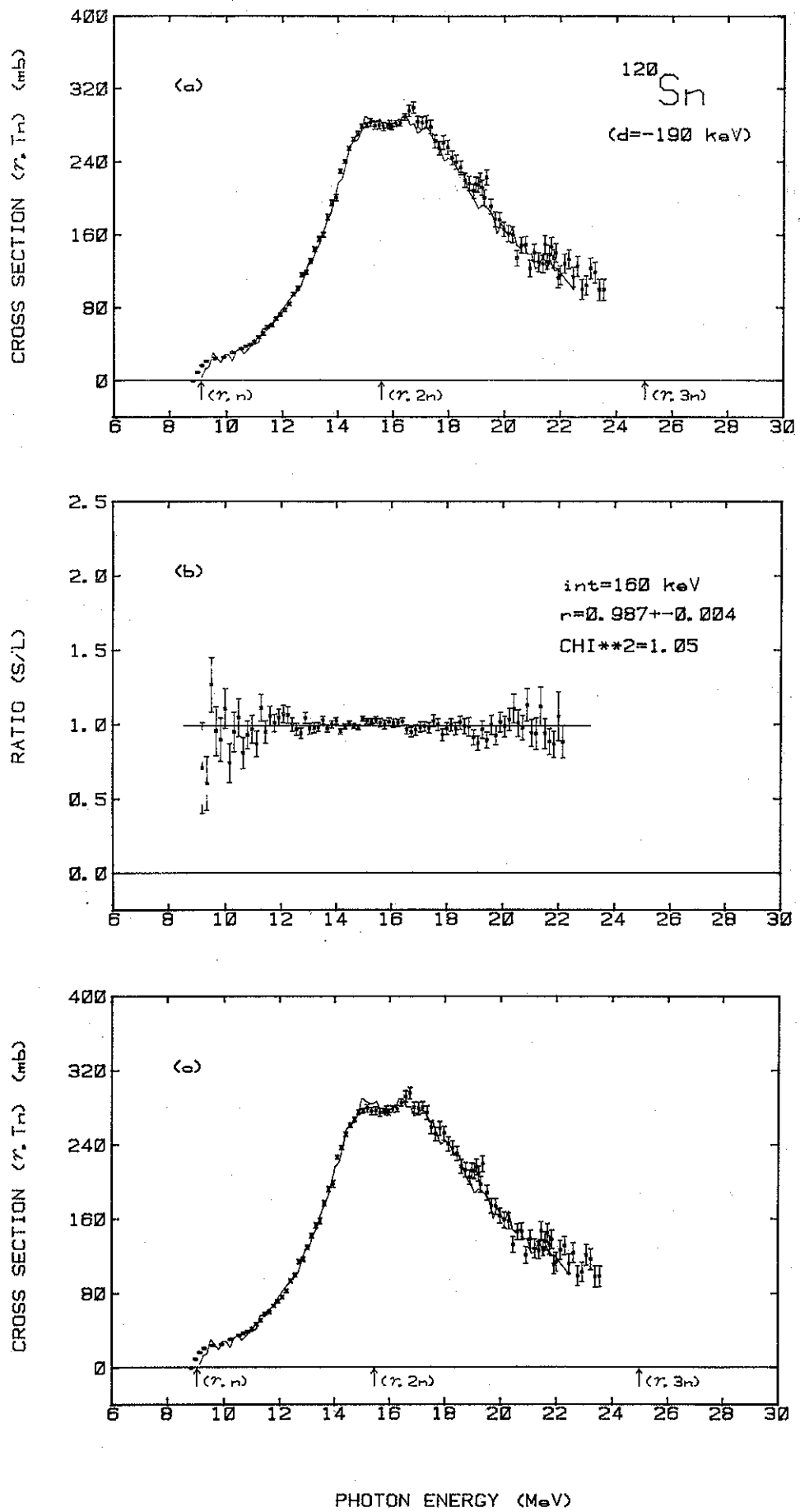


FIG. 19

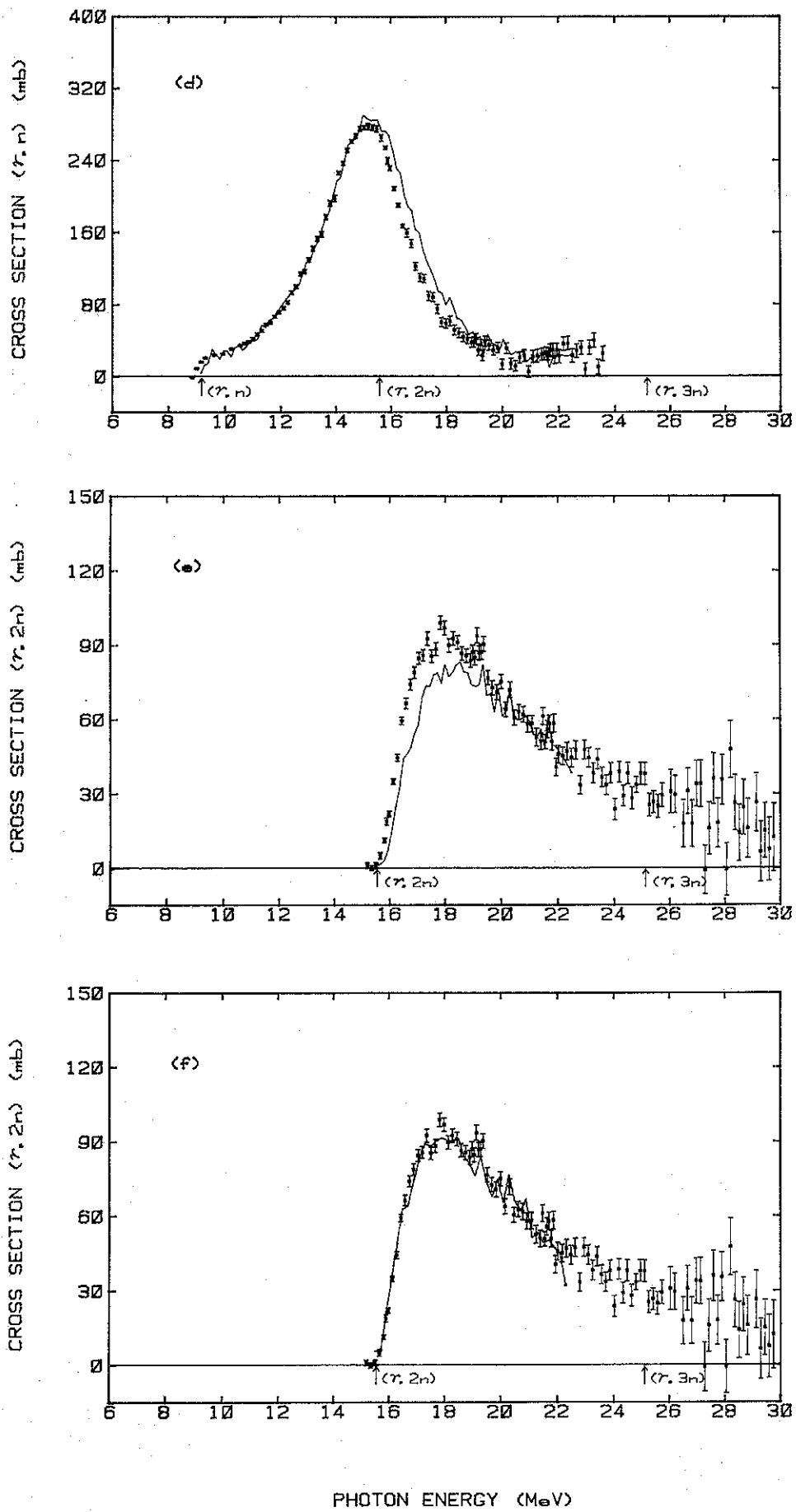


FIG. 19

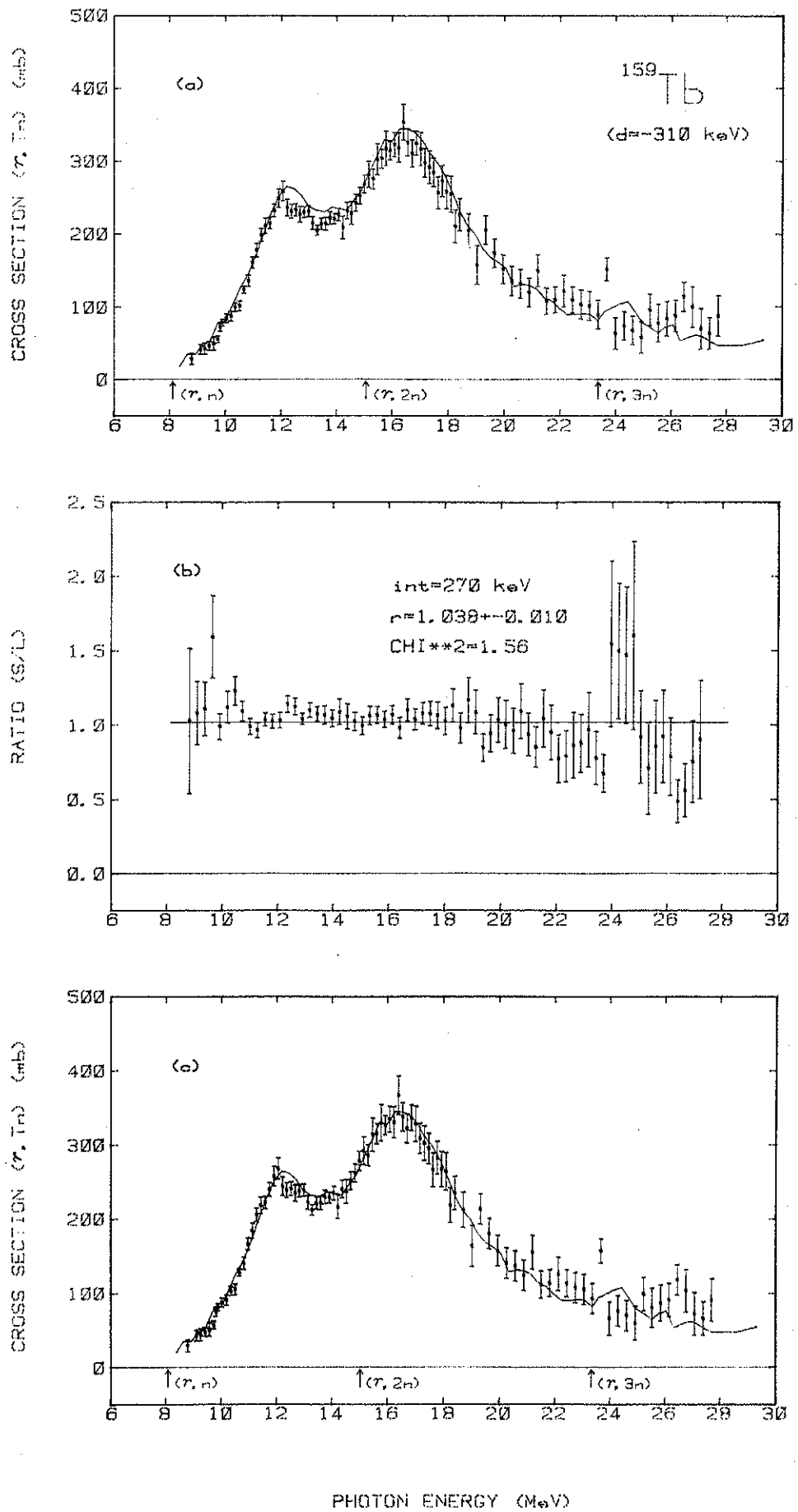
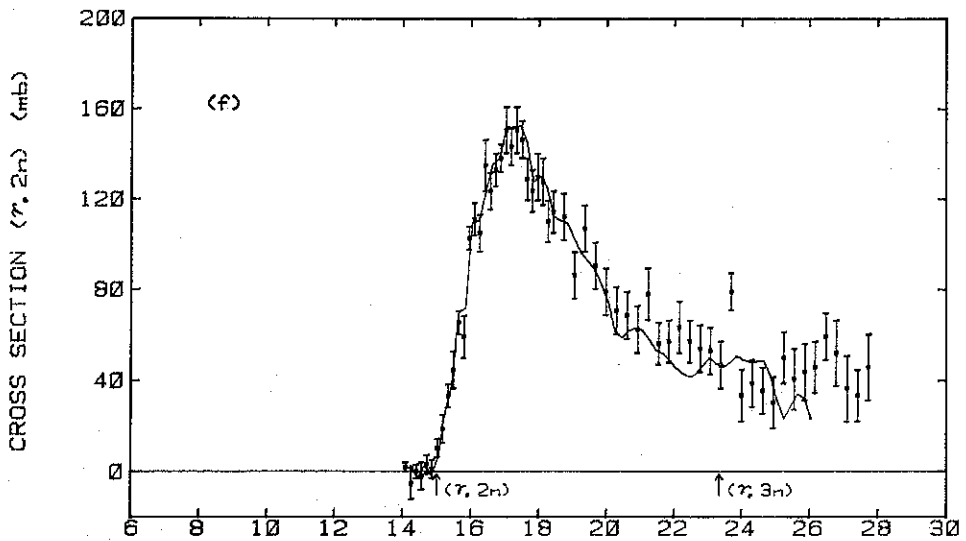
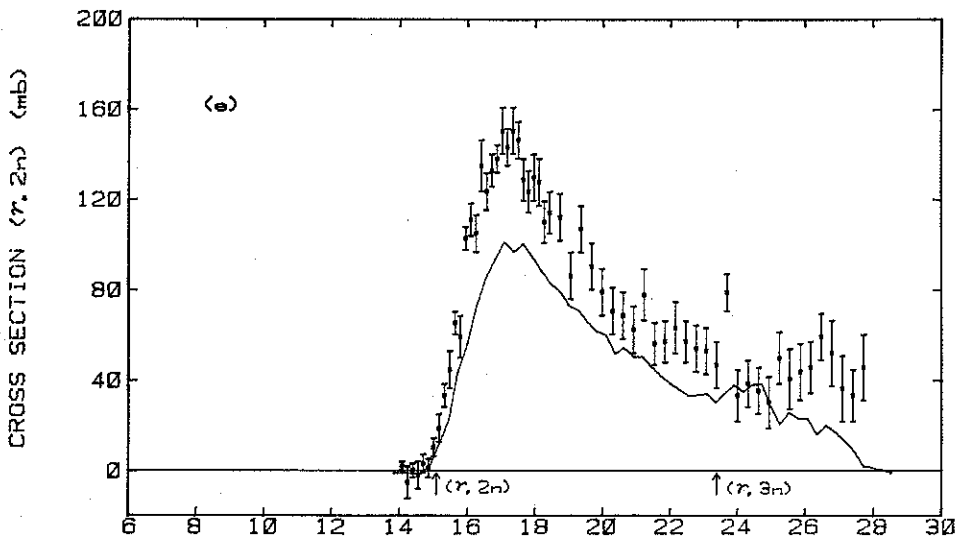
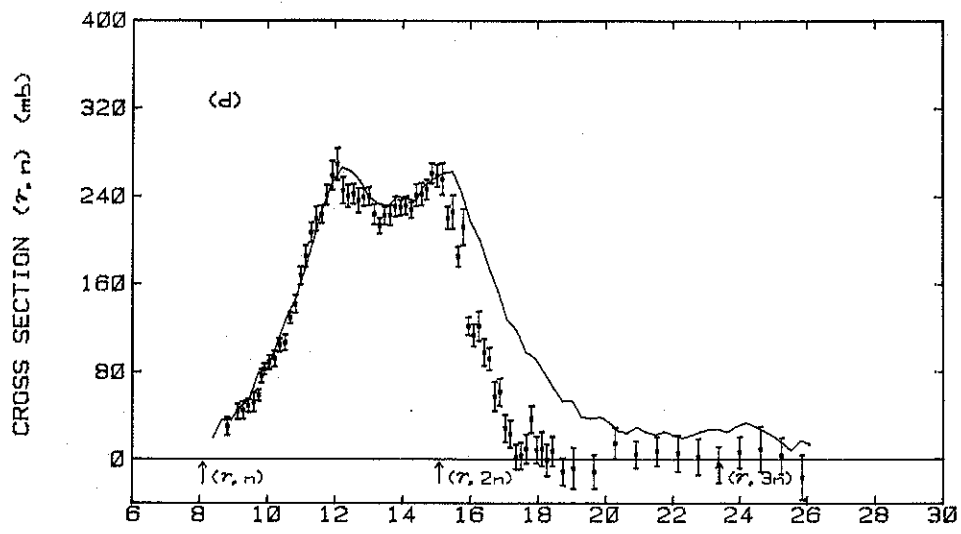
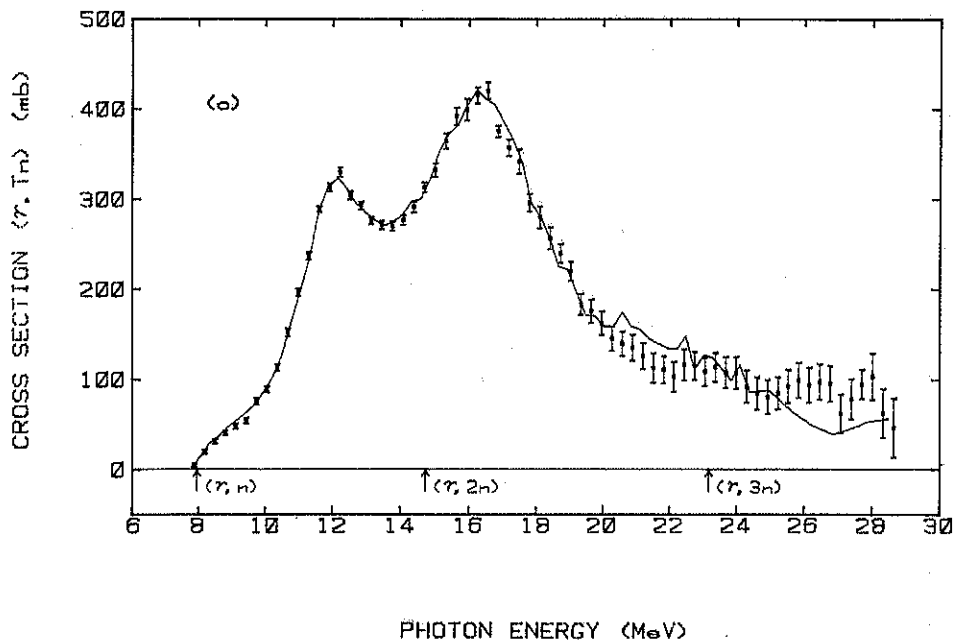
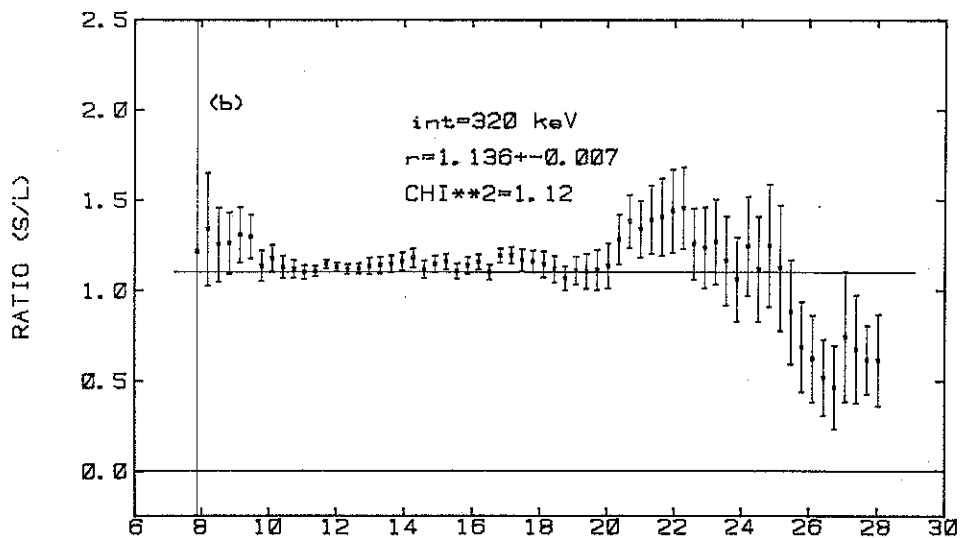
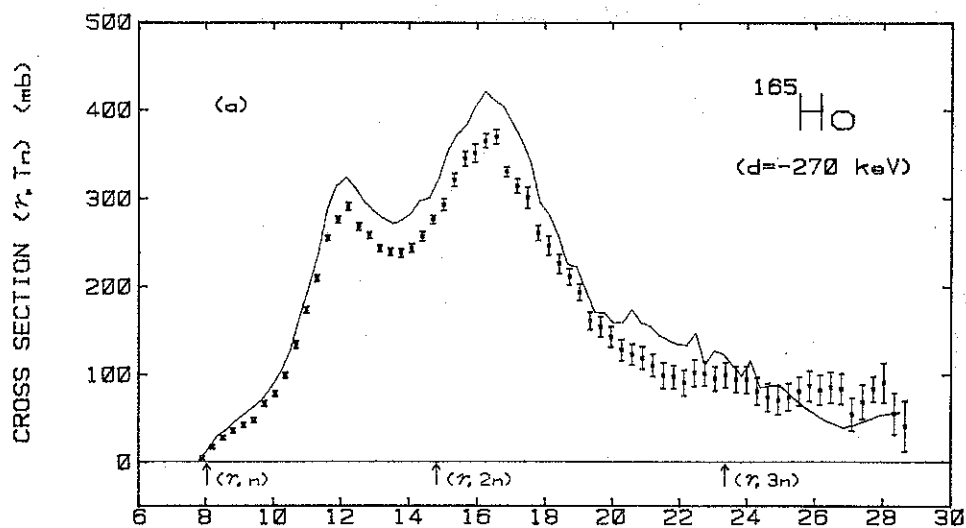


FIG. 20



PHOTON ENERGY (MeV)

FIG. 20



PHOTON ENERGY (MeV)

FIG. 21

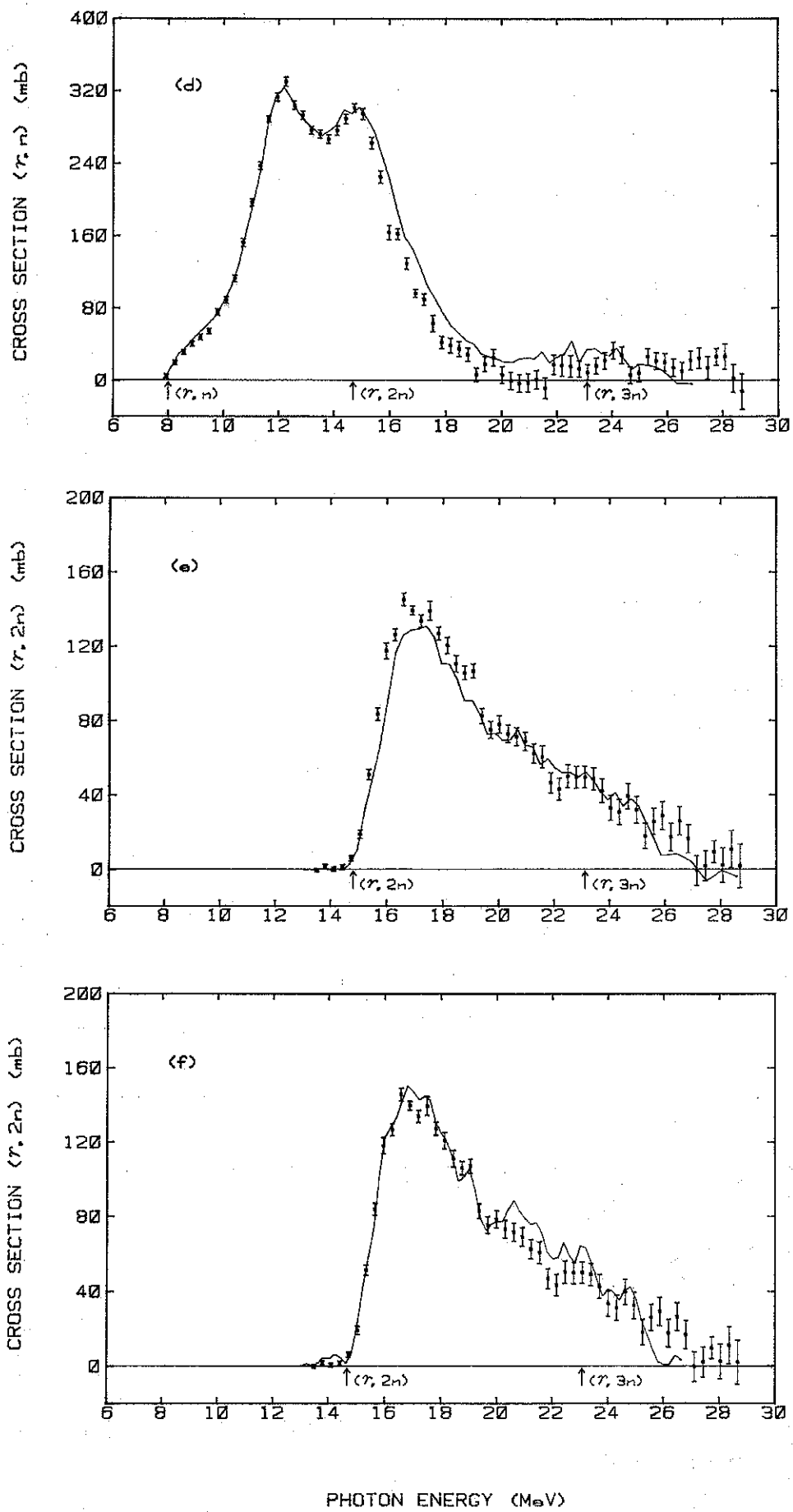


FIG. 21

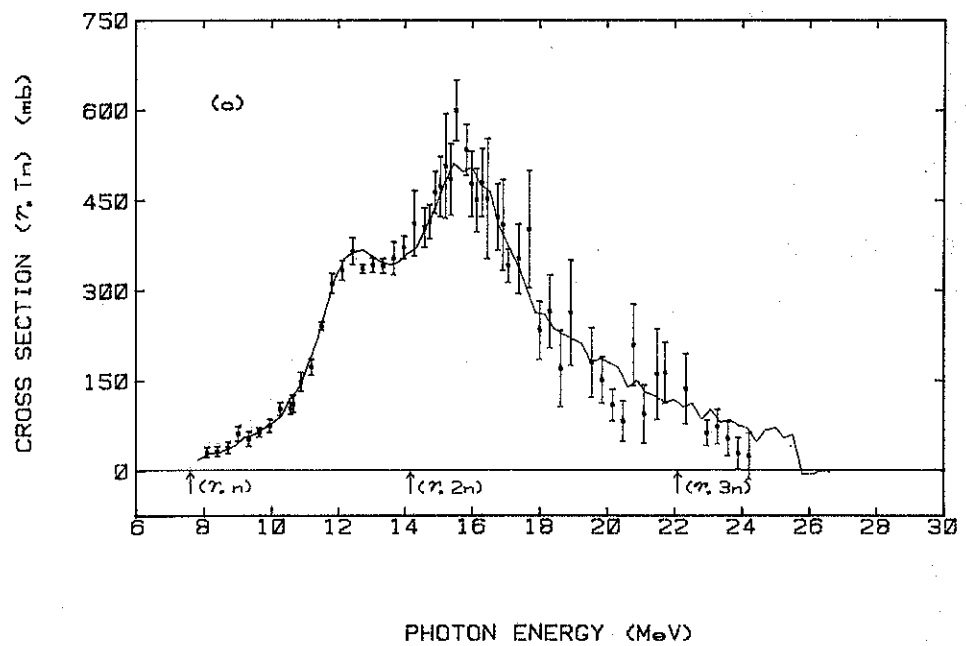
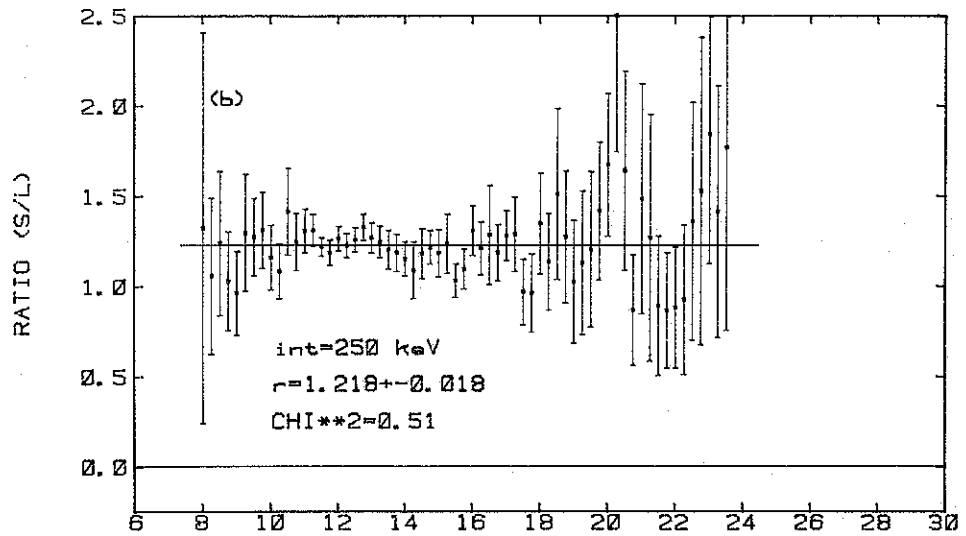
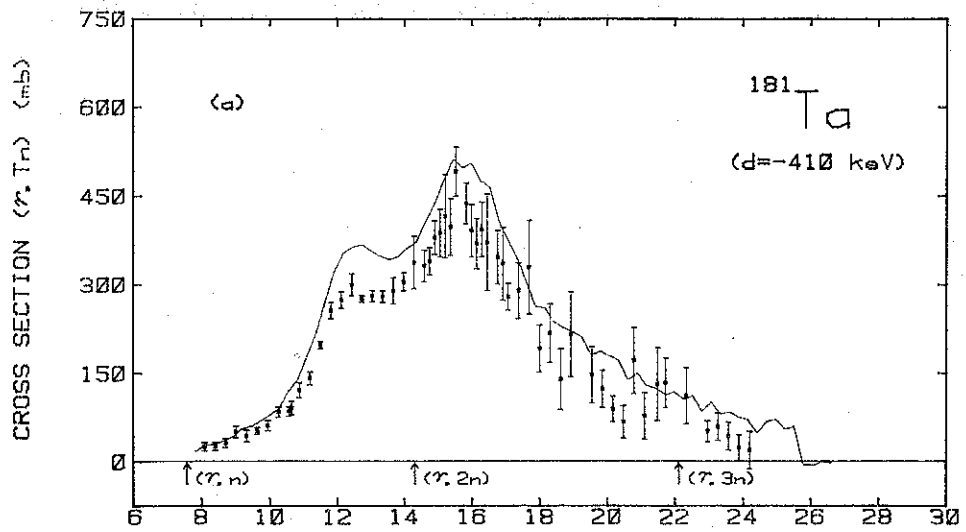


FIG. 22

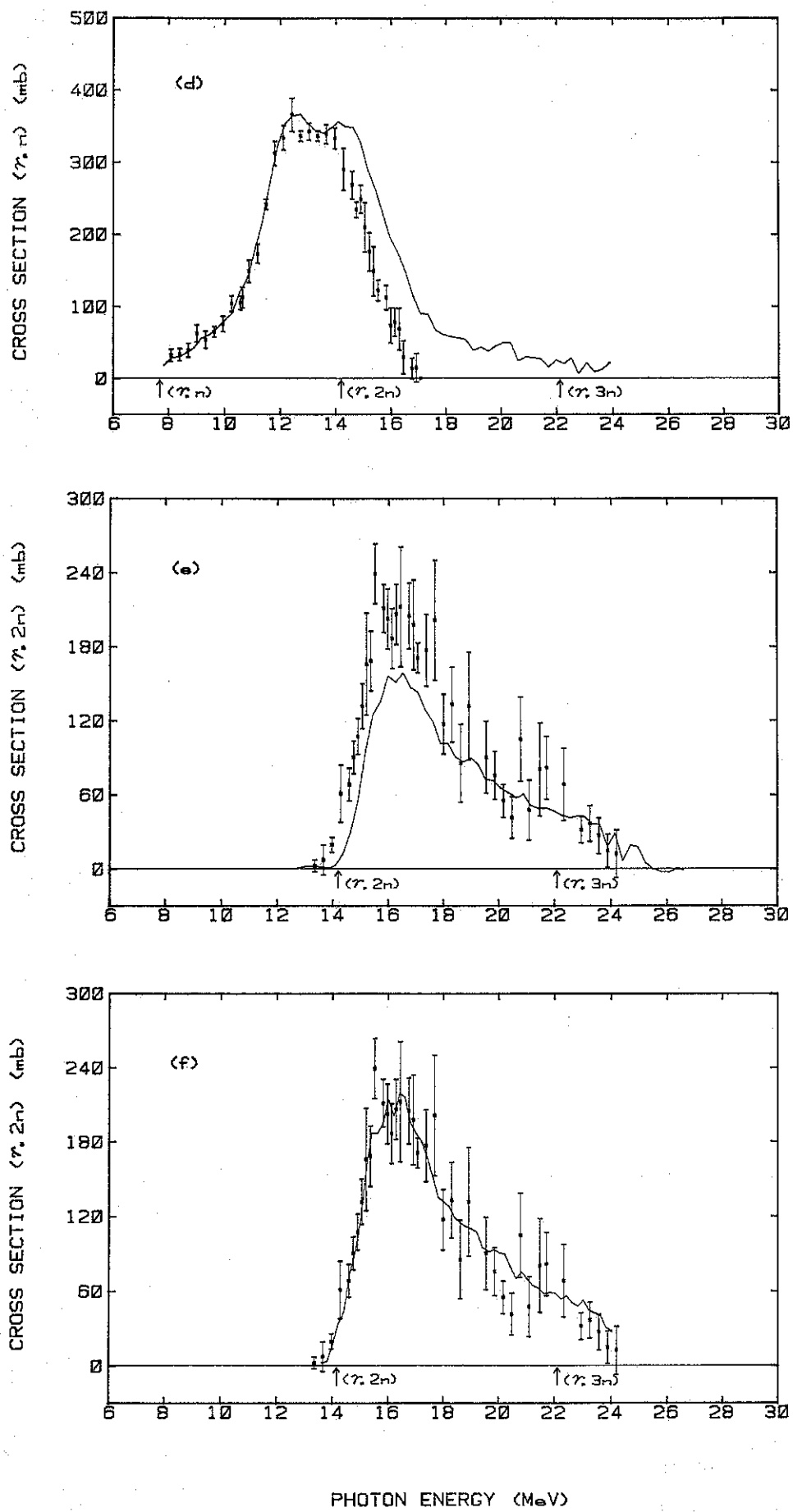


FIG. 22

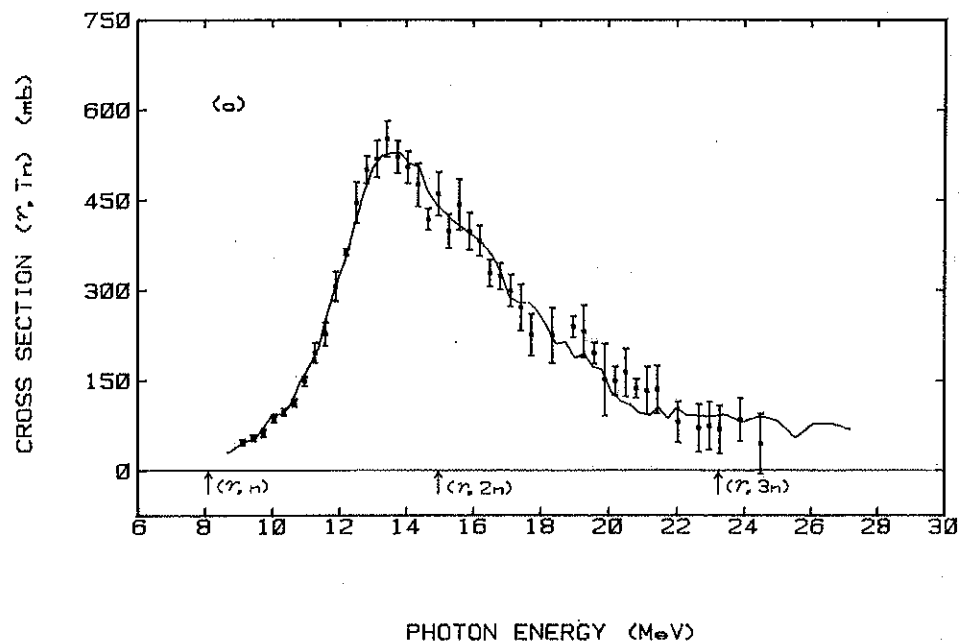
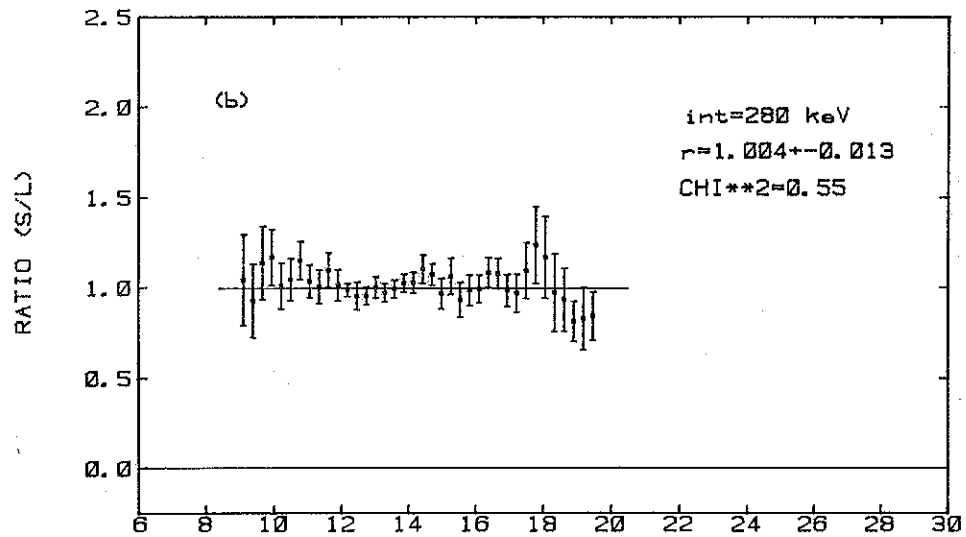
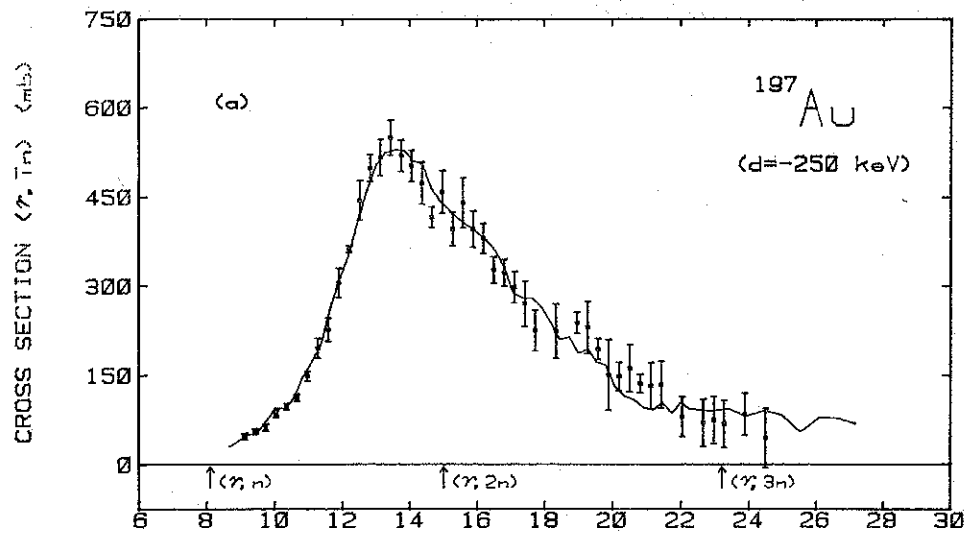


FIG. 23

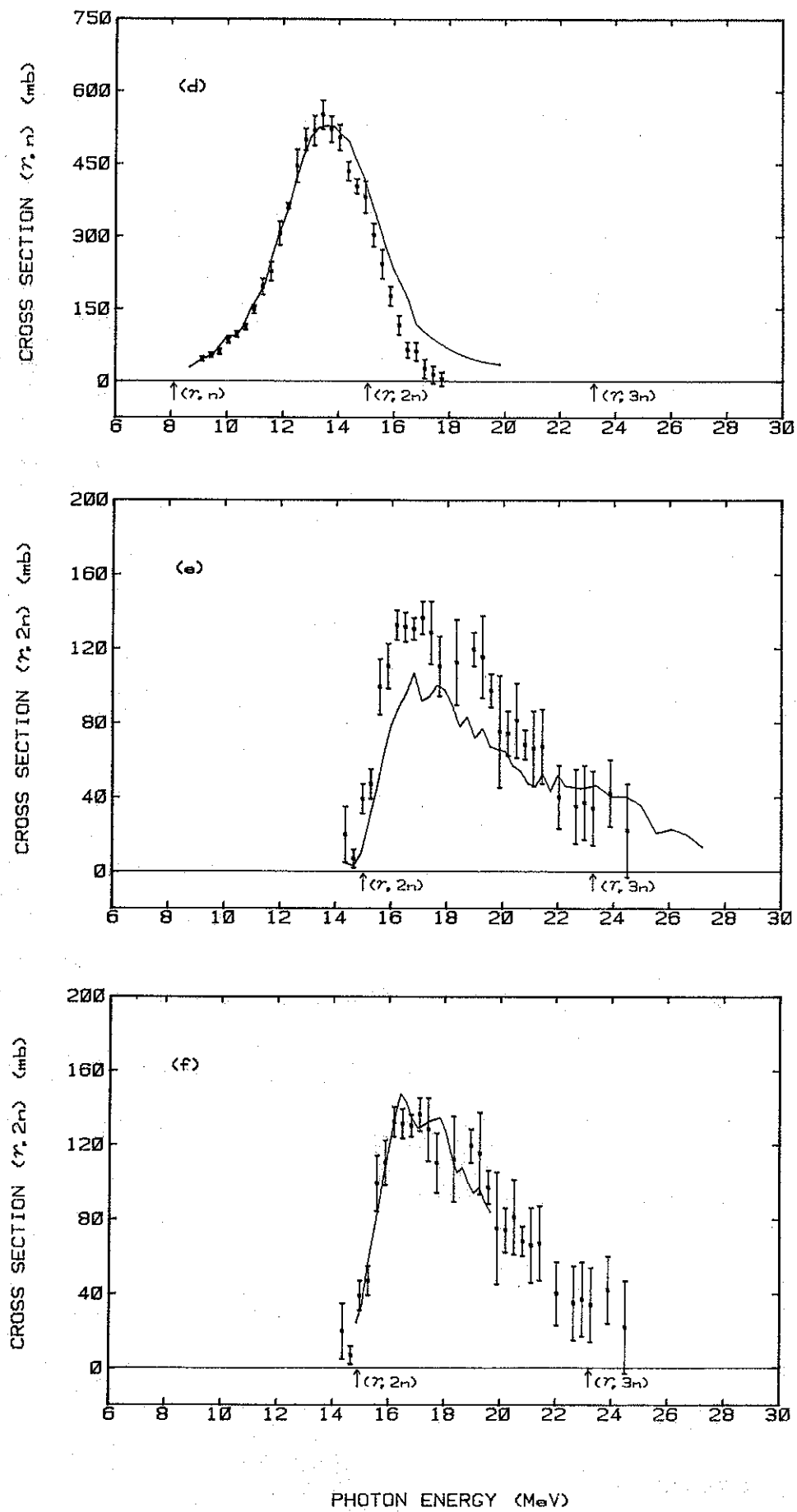


FIG. 23