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PHOTON MONOCHROMATORS

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PHOTON MONOCHROMATORS*

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Most of the information on the photonuclear giant resonance was obtained using the bremsstrahlung from an electron beam. The continuous distribution of the x-rays plagued the experimentalists in that the reaction measured was the integral of the reactions

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over a continuous range of photon energies. A very accurate knowledge of the spectrum shape as well as good statistical accuracy was necessary to get meaningful results and even then one has some reservations regarding their reliability. When finer details are sought it becomes even more difficult to trust the data.

In some cases the methods used bypass this difficulty as in the elastic scattering experiments and in certain (γ, p) and (γ , n) reactions in which the levels are clearly separated in energy. In the latter case the measurement of the energy of the particle identifies the particular photon energy out of the continuous spectrum which was responsible for the reaction.

It is clear, however, that in most cases there are no sharp resonances in the giant resonance region and that it would be useful to have some way of studying the reactions with photons having a well defined energy. Three methods which have been used will be discussed briefly. The first is the use of gamma rays from nuclear reactions which was also the first to be used by Bothe and Gentner (1) in 1937. The second source of monoenergetic photons to be discussed is the positron annihilation spectrometer which has recently become operative in Saclay. The third is the bremsstrahlung monochromator which was first used by Weil and McDaniel (2) in 1952. We will discuss in particular the monochromator scheme which is in operation at the University of Illinois with the 22 MeV betatron.

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I. Monochromatic gamma rays from nuclear reactions

We will summarize briefly the cross sections or yields from the more useful reactions as well as the spectrum, angular distribution and the polarization where these were available. In cases where a specific reference is not given the data compiled in Agzenberg and Lauritsen (3) article was used.

A) H^3 (p,γ) He^4 Q = 19.812 MeV

The absorption of protons by H^3 leads to highly excited states of He^4 which decay to the ground state emitting gamma rays with energies given by $E^*_\gamma = 19.760 + .745 \times E_p$ in MeV in the center of mass system. The cross section and angular distribution for this reaction has been measured by Perry and Bame (4). The cross section at 90° is shown in Fig. 1. The transitions are mainly ${}^1P_1 - {}^1S_8$ (electric dipole) with an angular distribution $I(\theta) \sim \sin^2 \theta$ and with the radiation completely polarized at 90 degrees. There is, however, a small admixture of a d wave in the wave function of the incident protons which modifies the angular distribution to the form $I(\theta) \sim (\sin \theta + a \sin \theta \cos \theta)^2$ where a is about 0.1 at 4 MeV. and 0.5 at 1.88 MeV.

The H^3 (p,n) He^3 reaction has a threshold of $\sim$ 1 MeV and the cross section goes to a broad maximum of 500 mb at 3 MeV. It is particularly convenient to work with the gamma rays from protons on tritium at energies below the neutron threshold but the reaction is a good source of 20 to 30 MeV gammas using proton energies up to

10 MeV. One would, however, need detectors or reactions which are insensitive to neutrons since these would be 1000 times as intense as the photons.

The gamma ray energy varies with the angle because of the Doppler effect according to the relation $E_\gamma(\text{lab}) = E_\gamma^*(1+ \frac{\sqrt{E_p(\text{MeV})}}{86} \text{Cos}\ \theta)$. The use of a limited angular range will usually not allow a very sharp definition of energy since the cross section is not resonant and it would be difficult to get a sufficient yield with a very thin target. Several experiments have been made using this source of gamma rays. Woff and Stephens (5) and Carrol and Stephens (6) measured the absorption coefficients f or gamma rays in C^{12}, N^{14}, O^{16}, and Al^{27} in the photon region of 20 to 21 MeV with a resolution of about 50 KeV.

No fine structure was found. Cohen and Stephans (7) measured the excitation function for the C^{11} activity in C^{12} (γ,n) C^{11} reaction with a resolution of 70 KeV from 20.2 to 21.2 MeV but did not find the fine structure reported in betatron experiments.

b) Li^7 (p,γ) Be^8 $\qquad Q = 17.253$ MeV

This reaction is particularly well known for the strong gamma ray resonance at 440 KeV giving a thick target yield of about 5.10^{-9} gamma ray per proton. The spectrum, however, is not simple but contains two lines. A sharp upper lineat $17.2 + \frac{7}{8} E_p$ which decays to the ground state of Be^8 and a broad line of energy $\sim 14.3 + \frac{7}{8} E_p$ corresponding to transitions to the very broad ($\sim$ 1.9 MeV) level in Be^8 at 2.9 MeV. This level breaks up immediately into to alpha particles with energies of $\sim$ 1.45 MeV which may be useful in coincidence work, or in the selection of a particular gamma energy within the wide level.

The relative intensities of the gamma radiation to the ground state and to the 2.9 MeV state varies with energy. The information on this reaction is summarized in Table I.

In order to separate the effects of the two different gamma energies, one may observe (8) the reactions using photons from the resonance and from a higher energy where the ratio of the two intensities is considerably different. This source has been used extensively for the study of induced radioactivity (9, 10) as well as for the elastic scattering (11) and the observation of the photon spectrum in the Cu(γ,p) Ni reaction, (12). The energy of the upper line varies with angle from 17.52 to 17.88 MeV at the resonance due to the Doppler effect. Fine structure in the $O^{16}(\gamma,n)$ reaction was looked for by Campbell (13) and by Foster (14). Similar studies of Cu, Zn, and Ag were carried out by Bunbury (15). No resonances were found in these experiments.

The angular distribution of the radiation is isotropic within 6% and no appreciable polarization of the gamma rays is expected.

The threshold for the $Li^7(p,n)Be^7$ reaction is 1.88 MeV. So bellow this energy there are no neutrons but above 1.9 MeV the cross section for the production of neutrons is about 200 mb.

c) $B^{11}(p,\gamma)C^{12}$ Q = 15.958 MeV

This reaction has two resonances leading to gamma rays proceeding to the 4,4 MeV level in carbon. The first is at 0.163 MeV (16.11 MeV) with a cross-section of 0.15 mb and a width of about 7 KeV.

It decays primarily by a gamma transition to the 4.4 MeV level in C^{12}. The other is a wider level at 0.675 MeV which also decays to the 4.4 MeV state and has been used as a source of 12 MeV photons (16).

At higher proton energies more of the proton capture radia tions proceed to the ground state. Recently the reaction was studied with protons up to 12 MeV by Gove and Litherland. (17).

A broad resonance was observed at 22.6 MeV about 3 MeV wide which agrees well with that expected from the inverse C^{12} $(\gamma,p)B^{11}$ reaction (17).

Although the B^{11} (p,γ) reaction has not been used as a source of photons, the cross section for the production of 20 - 25 MeV photons is of the order of 10^{-28} cm^2 with protons of 5-10 MeV. Yields of the order of 10^{-8} gammas per proton could be obtained with targets of 1 mg/cm^2 and an energy apread of 10^o KeV. The radiation at 90^o should be polarized since the transitions are expected to be electric dipole.

The threshold for the $B^{11}(p,n)C^{11}$ reaction is at 3.01 MeV so that there will be intense background of fast neutrons accompanying the gamma rays of most interest.

D) C^{13} (p,γ) N^{14} $Q = 7.546$ MeV

Resonances for the emission of gamma rays are observed at proton energies of 0.55, 1.16, 1.25, 1.47, 1.76, 2.10 and 3.11 MeV. The strongest of these at 0.55, 1.76, and 3.11 MeV have yields above that from the lithium resonance of about 10^{-8} gamma rays per proton (18). Although there are states in N^{14} at 2.31 MeV, 3.95 MeV and at many higher energies the strong levels decay primarily to the ground state. The 8.06 MeV gamma rays from the 0.55 MeV resonance have an isotropic distribution while the 9.17 MeV gamma rays at 1.76 MeV have an intensity at 90 degrees which is twice that at 0 degrees (19). The polarization of 9.17 MeV photons emmitted (90 degrees to the incident beam) is at right angles to the proton beam. (20).

The parameters of the 9.17 MeV resonance have been studied by means of the resonance absorption in liquid nitrogen (21). The maximum absorption cross section was found to be about 7.2 barns with a width of 77 eV. By detailed balance this would lead to a proton capture cross section of 200 mb rather than the 11 mb observed directly. The properties of these resonances are summarized in table II. The values for the 0.55 and 3.11 MeV resonances are from Ajzenberg and Lauritsen (3) but the thick target yields are adjusted to the value obtained by Hanna and Meyer Schutzmeister (21) at 1.76 MeV. With higher energy protons one might expect a yield of high energy photons corresponding to the inverse of the photodisintegration of N^{14} but the use of them would be complicated with neutron backgrounds at energies above the neutron threshold at 3.23 MeV.

E) N^{15} $(p,\alpha\gamma)C^{12}$

This reaction is a strong source of 4.43 gamma rays following alpha particle transitions to the 4.43 MeV $J = 2^+$ state of C^{12}. The radiation from this reaction has been used to study resonant scattering and absorption of the 4.43 MeV resonance in carbon by Rasmussen, Metzger and Swann. (22). Angular distributions of the gamma rays for 1040 and 1640 KeV are reported by Kraus (23) and at 1210 KeV and higher energies by Bashkin and Carlson (24).

The data on the strong resonances are summarized in Table III. The coefficients listed under "Angular Distribution" are those appearing in the following expression for the angular distribution

$$Y(\theta) = 1 + a_2 P_2 (\cos \theta) + a_4 P_4 (\cos \theta)$$

In the special case where the gamma ray transition is a pure multipole and the gamma ray is observed at 90 degrees the ratio P of the intensities parallel and perpendicular to the plane defined by the reaction is given by

$$P = \frac{1_o + a_2 + a_4}{1_o - 2a_2 - 0.25a_4}$$ for no parity change and by the reciprocal of this expression for a parity change. For example: the radiation from the three MeV resonance has the electric vector perpendicular to the incident proton beam twice as often as parallel.

F) $F^{19}(p,\alpha\gamma)O^{16}$

This reaction has a number of well known resonances leading to the emission of 5 alpha particle groups, one to the ground state, one to the 0^+ pair emitting state and the three which serve as gamma ray sources of 6.14, 6.91 and 7.14 MeV. All groups show strong resonance effects with relative intensities varying greatly with bombarding energy.

The total cross section and the relative intensities of these lines are summarized in Table IV. The thick target yield from the 340 KeV resonance is about 1.8 $10^{-8}\gamma$/proton leading largely to the gamma rays from the 6.14 MeV level. The angular distribution and polarization of gamma rays have been measured by Fagg and Hanna. (25). An extensive survey of the elastic scattering of these gamma rays from a number of elements have been made by Reibel and Mann (26).

G) Resonance Fluorescence

The cross sections for the resonant scattering of gamma rays can be large and it was suggested by Schiff (27) in 1946 that resonance scattering of photons from the continuous bremsstrahlung spectrum would be observable. The first well defined and clearly identified radiation scattered from a bremsstrahlung spectrum, was the 15.1 MeV gamma rays from C^{12} observed by Hayward and Fuller (28) in 1957. This radiation scattered at angles greater than 90° is the only appreciable radiation above 10 MeV and has been useful in the study of the parameters of the nuclear resonance as well as the details of the shape and polarization of the bremsstrahlung spectrum. The parameters of this resonance as well as those of other resonances are given in Table V.

Although the integrated cross sections are low, good sources of resonant radiation can be obtained from the high current linear accelerators now available. At the University of California at Livermore, Koch and Fultz observed a source of 10^8 photons/sec. of 15.1 MeV photons scattered from a bloch of carbon just behind a thick tantalum target (29). The radiation at 90° to the incident bremsstrahlung beam is totally linearly polarized which may be useful in some applications. The background problems are considerable and a meter or more of special shielding may be necessary for many applications. Even with optimum shielding the lines below 8 MeV are not clearly separated from the background.

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II. Positron annihilation monochromator

The capture of relativistic positrons in flight produces photons which are uniquely related to the angle of emission. The energy of the photons emitted in the forward direction carry most of the energy.

$$E_{\gamma}(0^{\circ}) \approx E_{+} + \frac{3}{2} m_{o} c^{2}$$

while the energy in the backward direction is $\cong \frac{1}{2} m_{o} c^{2}$. At small angles

$$\frac{E_{\gamma}(\theta^{\circ})}{E_{\gamma}(0^{\circ})} \approx 1 - \frac{E + \theta^{2}}{2m_{o}}$$

The angle energy correlation permits selection of the desired energy range by restricting the solid angle in which photons are used.

The experimental arrangement used by Tzara's group in Saclay (30) is shown in Fig. 2. Electrons from a linear accelerator of 30 MeV are incident upon a 2.9 mm platinum target (1). Positrons produced in this target are selected and focussed by two orange sector type magnets separated by an adjustable slit (2 and 3). A 1 mm Lithium annihilation target is located in the field of the second magnet and is shaped so that the tangents of the paths of the particles in the lithium (4) converge to a point chosen as the photon target (E) while the positrons are focussed far from this point.

The number of useful 15 MeV positrons whithin an energy range of 1.5 per cent and a solid angle of 0.027 steradian was about 10^9/sec or 10^{-5} per incident electron. The performance of the monochromator was checked by observing photons scattered by the 15.1 MeV level in carbon. The scattering was observed at 90° from a target 1.7 gm/cm^2 over a projected area of 10 by 10 cm. The data for the scattering from carbon is shown in Fig. 3. The background in this work was somewhat large and can be improved. Its width at half height is 0.5 MeV and the flux of 15 MeV photons for a 10 μa incident electrons beam is 2.9×10^4 sec or 4.6×10^{-10} photons per incident 30 MeV electron in rough agreement with the calculated value.

Further calculations were made by S. Penner for a monochromator proposed for the National Bureau of Standards (31).

These calculations for a 100 MeV linac indicate a useful yield of photons in a 1.5% energy range which increases with energy up to 50 MeV to 2×10^{-9} photons per incident electron.

Although thicker annihilation targets can be used for higher energies, the annihilation cross section decreases with the energy according to the relation

$$\varphi_{an} = \pi r_0^2 \frac{m_0 c^2}{E_+} \left[\ln \frac{2E_+}{m_0 c^2} - 1 \right]$$

The bremsstrahlung cross section causing background radiation, however increases somewhat with energy and may be troublesome at high energies where it will limit some applications.

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III. The bremsstrahlung monochromator

This monochromator scheme involves the selection of photons of a given energy from the continuous bremsstrahlung spectrum. This is done by making a time coincidence between a post bremsstrahlung electron and an event caused by the associated gamma ray. This scheme was used by Weyl and McDaniel (2) at Cornell and by Goldemberg and Kerst (32) at the University of Illinois. Two years ago a group in Illinois (33) decided to make a further development of the scheme which is shown in figure 4. A beam of 20 MeV electrons from the betatron is incident upon the thin bremsstrahlung converter. In the event illustrated the electron radiates a 15 MeV photon in the forward direction while the electron now having 5 MeV is deflected by the magnet into an electron counter. The scattered photon, the photoneutron or other particle produced by the associated photon is detected in coincidence with the energy degraded electron. This coincidence identifies the energy of the photon as 15 MeV.

The experimental arrangement including the betatron and the dispersion magnet is shown in figure 5. Electrons from the betatron are focussed to the point F1 by a quadrupole pair and passed through a 65° double focussing magnet upon a thin bremsstrahlung converter. Electrons of the appropriate energy are selected by the spectrometer magnet to strike one of the electron detectors.

The first experiment was arranged to measure the elastic scattering of photons.

Three electron channels were used rather than just the one shown. The scattered photon were detected by a 5" × 4" sodium iodide crystal A coincidence between one of the electron signals and the photon detector opened up a gate which passed the slower pulse height information into a 100 channel analyzer where it is possible to separate the desired events by use of the pulse height distributions.

The energy resolution and the efficiency of the monochromator was checked by the detection of the gamma rays in the direct beam and by observing the 15.1 MeV resonance level in C^{12}. The energy resolution was about 150 KeV and it is expected that this can be improved very much if required. The measurements in the direct beam indicated that one photon was detected for every 4 electrons counted in an electron channel. It was possible to use a beam of 10^{-9} amperes for the scattering from carbon since the background was negligible and one obtained counting rates up to 6 counts/minute per channel.

The principal experiment was a check on the elastic scattering of photons from gold. (34). In this case the scattering of low energy photons made the accidental rate high and the intensity of the beam was reduced to avoid excessive backgrounds. The data taken was obtained at a rate of 7.2 counts per hour in each of three channels. The data on gold is shown in Fig. 6. The solid line in the figure is that obtained from the absorption cross section and the dispersion relations.

The counting rate could be increased by using wider channels or by increasing the number of the channels but the counting rate will remain low.

The monochromator may be more useful where a high resolution is required. A special feature of this system is that to a first approximation the energy of the photons selected can be independent of the energy of the incident electrons. This feature is useful if one arranges the magnetic field in the dispersion and analyzer magnets so that when the energy of the incident beam increases, the energy of the secondary electron selected increases by the same amount.

For the study of charged particle reactions the counting rates are low because of the limited amount of material which may be used. With cross section of one millibarn one would expect only a few counts per hour per channel.

For the study of neutrons one can use large amounts of material but only a small portion of the neutrons will be emitted in monoergetic groups suitable for fast coincidence detection. The exploration of such groups with the bremsstrahlung monochromator has some advantages over other monochromatic sources in that it already has a time reference for the birth of the photoneutron event.

For 5 MeV neutrons the time delays are conveniently about 30 nano-seconds per meter so that slow neutrons can be eliminated.

The low counting rates are a problem for all the experiments but the knowledge of the energy of the photon is worth the extra effort in many cases. The immediate plan is to use the present monochromator for other studies of gamma ray scattering and to begin some work with photoneutrons. We believe there is also a good oportunity for new ideas using this equipment.

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REFERENCES

1 - W. Bothe and W. Gentner - Z. Physik 106, 236 (1937).

2 - J. W. Weil and B. D. McDaniel - Phys. Rev. 92, 391 (1953).

3 - F. Ajzenberg-Selove and T. Lauritsen - Nuclear Physics 11.1 (1959).

4 - J. E. Perry and S. J. Bame - Phys. Rev. 99, 1368 (1955).

5 - M. M. Wolf and W. E. Stephens - Phys. Rev. 112, 890 (1958).

6 - F. E. Carrol and W. E. Stephens - Phys. Rev. 118, 1256 (1960).

7 - L. D. Cohen and W. E. Stephens - Phys. Rev. Letters 2.263 (1959).

8 - J. H. Carver and H. I. Hay - Phil. Mag. 44, 1191 (1957).

9 - O. Huber, O. Lienard, T. Scherrer and H. Waffler - Helv. Phys. Acta 15.312 (1942); 16, 33 (1943).

10 - O. Huber, O. Lienhard and H. Waffler - Helv. Phys. Acta 17, 195 (1944).

11 - M. B. Stearns - Phys. Rev. 87, 706 (1952).

12 - R. Chastel - J. Phys. Rad. 14, 459 (1954).

13 - J. G. Campbell - Aust. J. Phys. 8, 449 (1955).

14 - D. C. Foster - Doctoral Thesis - Cornell University - 1956. (unpublished).

15 - D. St. Bunbury - Proc. Phys. Soc. 67A, 1106 (1954).

16 - T. Huns and R. B. Day - Phys. Rev. 91, 599 (1953).

17 - H. E. Gove and A. E. Litherland (Preliminary Data - Private comunication).

18 - J. D. Seagrave - Phys. Rev. 85, 197 (1952).

19 - H. H. Woodbury, R. D. Day and A. V. Tollestrup - Phys. Rev. 92, 1199 (1953).

20 - A. A. Strasseburg, R. E. Hubert, R. W. Krone and F. W. Prosser - Bull. Am. Phys. Soc. 3, 372 (1958).

21 - S. S. Hanna and L. Meyer Schutzmeister - Phys. Rev. 115, 986 (1959).

22 - V. V. Rasmussen, F. R. Metzger and C. P. Swan - Phys. Rev. 110, 154 (1958).

23 - A. A. Kraus - Phys. Rev. 94 ,975 (1954).

24 - S. Bashkin and R. R. Carlson - Phys. Rev. 106, 261 (1957).

25 - L. W. Fagg and S. S. Hanna - Phys. Rev. 92, 372 (1953).

26 - K. Reibel and A. K. Mann (quoted by W. E. Stephens in Chapter IV - Nuclear Spectroscopy - Edited by F. Ajzenberg-Selove, Acad. Press (1960).

27 - L. I. Schiff - Phys. Rev. 70, 751 (1946).

28 - E. Hayward and E. G. Fuller - Phys. Rev. 106, 991 (1957).

29 - H. W. Koch and S. Fultz (private communication).

30 - J. Miller, C. Schuhl, G. Tamas and C. Tzara (private communication).

31 - S. Penner - Positron and annihilation Yields of the proposed linac (NBS Internal Report - 1959).

32 - J. Goldemberg - Phys. Rev. 93, 1426 L (1954).

33 - P. Axel, A. O. Hanson, J. Goldemberg, H. E. Hall, D. Jamnik, J. O'Connell and P. Tipler.

34 - J, O'Connell, P. Tipler and P. Axel (private communication).

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TABLE I

Li^7 (p,γ) Be^8 Reaction

E_p(KeV)	Width (KeV)	E_γ	σ(mb)	$\frac{I(17)}{I(14)}$
.200				0.5
441.5	12.2 ± 0.5	17.64	6.0	1.7
.600				1
1.030	168	18.15	$\lesssim$0.18	0.66
up to 3.500	no resonances		$\lesssim$0.18	0.66

TABLE II

C^{13} (p,γ) N^{14}

E_p(KeV)	σ (mb)	Γ(KeV)	Yield per proton x 10^{-8}	Angular Distr. $\frac{Y(0º)}{Y(90º)} - I$	Spectrum (MeV)
550	1.44	32.5	0.7	0	8.06(89%)4.0(11%)
1.760	200	0.077±0.012	0.77	- 0.48±0.03	9.17(90%)6.5(10%)
3.110	0.7	30.0	2.5	- 0.4 ±0.02	10.43(90%)6.5(10%)

TABLE III

N^{15} $(p,\alpha\gamma)$ C^{12}

E_p(KeV)	σ(mb)	Width (KeV)	Angular Distribution **	
			a_2	a_4
429	200	0.9		
898	800	2.2		
1040	15	140		
1210	425	22.5	.45 ± .01	- .30± .01
1640	340	68	.18 ± .005	0
1979	35	23	.25 ± .01	. 105± .01
3000	750	45	.22 ± .007	0

** a_2 and a_4 are the coefficients in the expression:

$$Y(\theta) = 1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)$$

TABLE IV

F^{19} (p,$\alpha\gamma$) O^{16}

E_p (KeV	σ (mb)	Γ (KeV)	E_1 = 6.14 MeV	E_2 = 6.93 MeV	E_3 = 7.14 MeV
$p = \frac{N//}{N\perp}$ *			0.9 ± 0.1	1.9 ± 0.3	0.4 ± 0.3
340	160	3.3	0.97	0.04	0.26
484	32	0.9	0.78	~ 0.01	~ 0.21
597	7.1	30	0.99	< 0.01	< 0.01
672	57	6	0.81	0.01	0.10
874	540	5	0.68	0.24	0.08
935	180	8.6	0.76	0.03	0.21
1283	29	18.6	~ 0.74	~ 0.08	~ 0.18
1384	89	5.6	0.55	0.13	0.32
1375	30	11.0	0.87	0.08	0.05

* p is the ratio of the number of photons with electric vector parallel and perpendicular to the normal to the reaction plane $(\vec{p} \times \vec{k})$.

$\vec{p}$ - direction of the proton beam

$\vec{k}$ - propagation vector of the photon beam.

TABLE V

Observed Resonance Fluorescence

Nucleus	E_γ(MeV)	Γ(eV)	$\int \sigma\, dE$ MeV x mb	Ref.
C^{12}	15.1	79 ± 16	109	a
B^{11}	4.46		0.079	b
	5.03		0.078	b
	7.3			c
	8.9			c
Li^6	3.56	8.2	0.73	b
N^{14} *	9.17	77	0.87	d
O^{16}	69			c
Si^{28}	9.4			c
	11.2			c
Mg	10.5			c

* Not observed from bremsstrahlung. Values based on data from reference _d_ below

a - E. Hayward and E. G. Fuller - Phys. Rev. 106, 991 (1957).

b - L. Cohen, R. Tobin and J. McElhiney (to be published in Phys. Rev. 1960).

c - F. D. Seward, H. W. Koch, R. E. Shafer and S. C. Fultz - Bull. Am. Phys. Soc. 1, 68 (1960).

d - S. S. Hanna and L. Meyer-Schutzmeister - Phys. Rev. 115, 986 (1959).

TABLE VII

SOURCES OF MONOCHROMATIC γ-RAYS

Reaction	Energy (MeV)	Total yield of γ's/sec (per 10 μA of protons)	Polarization $p = N_{//}/N_{\perp}$	Remarks Remarks
I. NUCLEAR REACTIONS				
He^3 (p,γ) He^4	20-30	$\sim 10^6$	yes ($\sim\infty$)	E_p = 4000 KeV (thick target)
Li^7 (p,γ) Be^8	17.2 + 7/8 E_p	$\sim 3.10^5$	no	E_p = 441 KeV
	14.2 + 7/8 E_p	$\sim 2.10^5$	no	"
B^{11} (p,γ) C^{12}	18-26	$\sim 10^6$	yes ($\sim\infty$)	E_p = 7000 KeV (E ~ 200 KeV)
C^{13} (p,γ) N^{14}	9.17	$\sim 10^5$	yes	E_p = 1750 KeV
N^{15} (p,$\alpha\gamma$)C^{12}	4.43	$\sim 10^8$	yes	E_p = 898 KeV
F^{19} (p,$\alpha\gamma$)O^{16}	6.14	$\sim 10^7$	no	E_p = 935 KeV
	6.91	$\sim 10^5$	yes ($\sim$1.9)	"
	7.14	$\sim 10^6$	yes ($\sim$0.4)	"
RESONANT FLUORESCENCE	15.1	$\sim 10^8$	yes ($\sim\infty$)	for 1 ma of electrons at 20 MeV
II. POSITRON ANIHILATION MONOCHROMATOR				
	0 - 100	$\sim 10^6$ *		
III. BREMSSTRAHLUNG MONOCHROMATOR				
	5 and up	$\sim 5.10^4$ **	yes	

TABLE VIII

RESEARCH WITH MONOCHROMATORS

Method / Experiment	Nuclear Reactions	Ref.	Bremsstrahlung Monochromator	Ref.	Positron Anihilation Monochromator	Ref.
Photo Absorption	yes	a,b	yes	i	yes	
Photo Activation	yes	c,d e,f	not		yes **	
Photo Scattering	yes	g	yes	j	yes	e
Photo Protons	yes	h	yes	k	yes	
Photo Neutrons	not		not *		yes	

* Good for measurement of definite groups of neutrons combining time of flight with fast electron coincidence.

** Bremsstrahlung background always present increasing with energy.

a - M. M. Wolf and W. E. Stephens - Phys. Rev. 112, 890 (1958).

b - E. E. Carrol and W. E. Stephens - Phys. Rev. 118, 1250 (1960).

c - H. Waffler and O. Hirzel - Helv. Phys. Acta 21, 200 (1948).

d - J. G. Campbell - Aust. J. Phys. 8, 449 (1955).
D. St. P. Bunbury - Proc. Phys. Soc. 67", 1506 (1954).

e - L. D. Cohen, W. E. Stephens - Phys. Rev. Letters 2, 263 (1959).

f - B. D. McDaniel, R. L. Walker and M. B. Stearns - Phys. Rev. 80, 807 (1959).

g - M. B. Stearns - Phys. Rev. 87, 706 (1952).

h - R. Chastel - J. Phys. Rad. 15, 459 (1954).

i - J. Goldemberg - Phys. Rev. 93, 1426 L (1954).

j - J. O'Connell, P. Tipler and P. Axel (private communication).

k - J. W. Weil and B. D. McDaniel - Phys. Rev. 92, 391 (1953).

l - J. Miller, G. Schul, G. Tamas and C. Tzara - (private communication).

.:.:.:.:.:.

NOTES AT THE TABLE VI:

* - This is the yield at ~15 MeV with a resolution of 1.5% according to the calculations of Penner (31) for an electron current of 200 μA.

** - This yield is in a solid angle of $\pi\left[\frac{m_oc^2}{E}\right]^2$ and in a energy bin of 0.1 MeV.

.:.:.:.:.:.

FIGURE CAPTIONS

Fig. 1 - $T(p,\gamma)\ He^4$ cross-section.

Fig. 2 - Layout of positron anihilation monochromator in operation at Saclay.

1. Pt target.
2, 3. Orange-sector magnets.
4. Lithium anihilation target.
5. Plexiglass collimator.
6. Xenon ionization chamber.
7. Aluminium absorber.

A. Target area
B. Magnet.
C. Slit.
D. Magnet.
E. Experimental area.

Fig. 3 - Elastic scattering of γ-rays from the 15.1 MeV C^{12} line as measured by the positron anihilation monochromator.

Fig. 4 - The Bremsstrahlung monochromator.

Fig. 5 - Layout of bremsstrahlung monochromator in operation at the University of Illinois.

Fig. 6 - Elastic scattering of γ-rays in gold as measured by the Bremsstrahlung monochromator.

::*:*:*:*:*

Addendum to Section I

H. Thermal neutron capture γ-rays.

The capture of thermal neutrons, easily obtained in high power reactors, may give fairly intense sources of γ radiation. In most cases the spectrum is very complicated and one cannot consider them useful as monochromatic sources. In a few elements however one or two lines are predominant. The γ-spectra from neutron capture have been summarized by Groshev et al. and Table VI gives the properties of the most promising elements for this purpose.

The γ-spectra for Ni and Pb are shown in Fig. 7.

Typical fluxes of γ-rays that can be obtained at research reactors are of the order of 10^6 γ's/ sec although higher fluxes are possible.

An investigation of the $Be^9(\gamma, n)Be^8$ reaction was made by Eriksen and Zaleski using the γ lines from S, Ti, Fe and Cu. The background problems in this type of experiment can be quite serious.

The investigation of the polarization of the emitted γ-rays from several elements when the incident neutron beam is polarized was made by Trumpy.

L. V. Groshev, V. N. Lutsenko, A. M. Demikov and V. I. Pelikov Atlas of γ-rays spectra from radiative capture of thermal neutrons - Pergamon Press, 1959.

V. O. Eriksen and C. P. Zaleski - J. Phys. et Rad. 15, 492 (1954).

G. Trumpy - Nuc. Phys. 2, 664 (1957).

TABLE VI

Thermal neutron capture γ-rays

Element	Capture cross-section (barns)	Energy of predominant γ-rays (MeV)
H	0.332 ± 0.002	2.23
Al	0.215 ± 0.008	7.73
S	0.49 ± 0.02	5.44
Ca	0.43 ± 0.02	6.41
Ti	5.6 ± 0.4	6.75 , 6.42
Fe	2.53 ± 0.06	7.64
Ni	4.6 ± 0.2	8.99 , 8.51
Cu	3.62 ± 0.04	7.91
Pb	0.17 ± 0.01	7.40

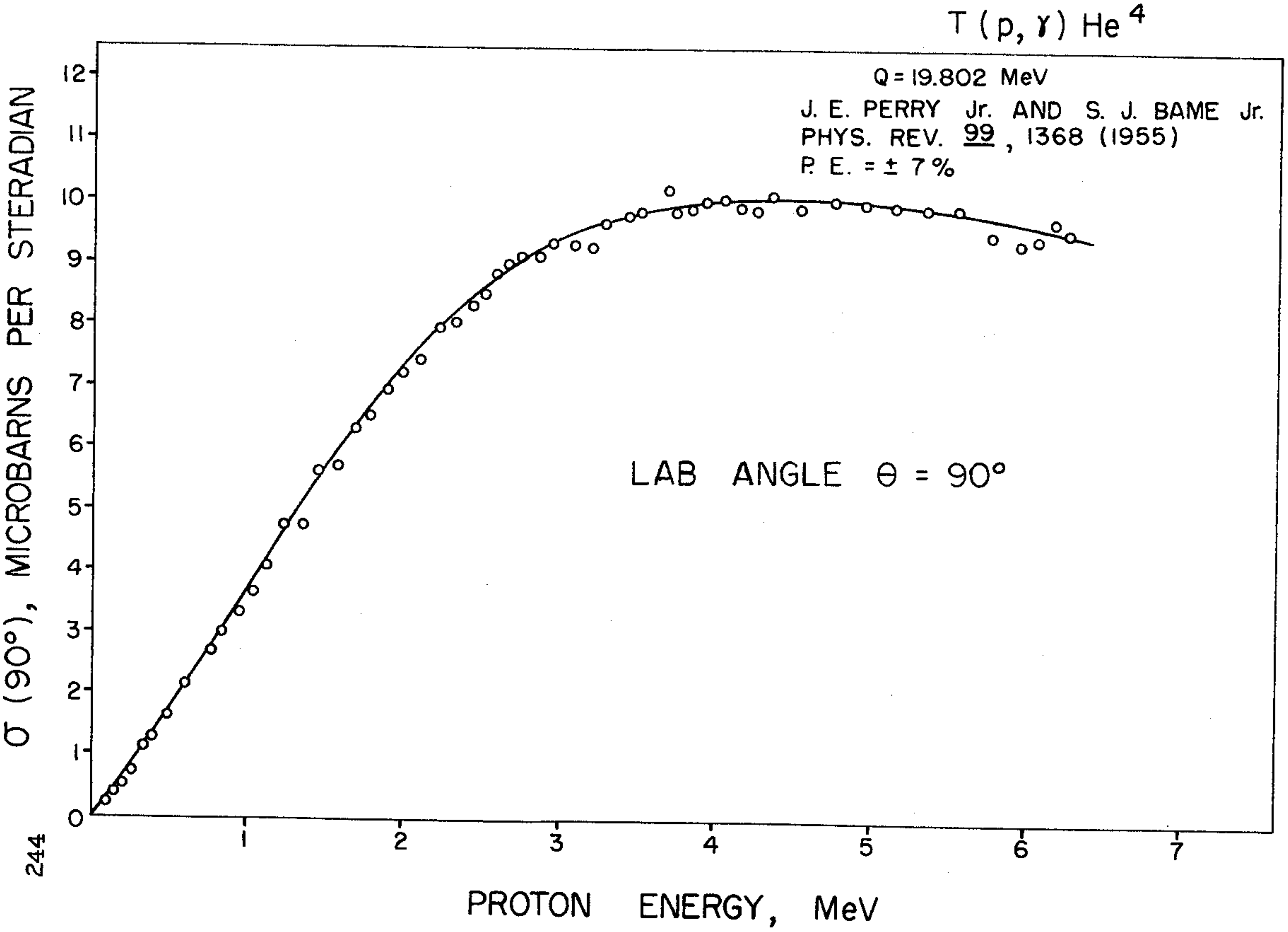

T (p, γ) He 4
Q = 19.802 MeV
J. E. PERRY Jr. AND S. J. BAME Jr.
PHYS. REV. 99, 1368 (1955)
P. E. = ± 7 %
LAB ANGLE Θ = 90°
σ (90°), MICROBARNS PER STERADIAN
0
1
2
3
4
5
6
7
8
9
10
11
12
1
2
3
4
5
6
7
PROTON ENERGY, MeV

FIG. 1

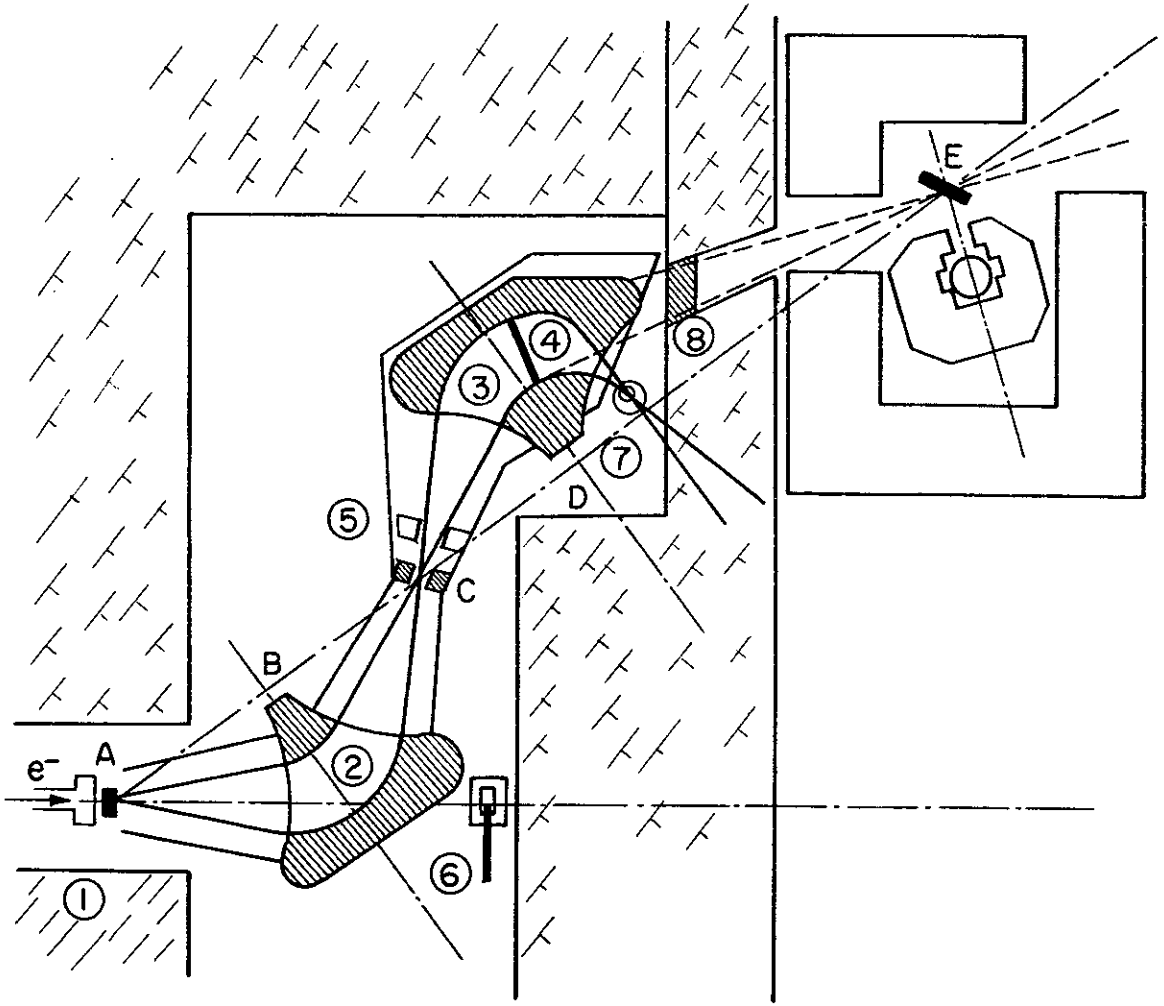


FIG. 2

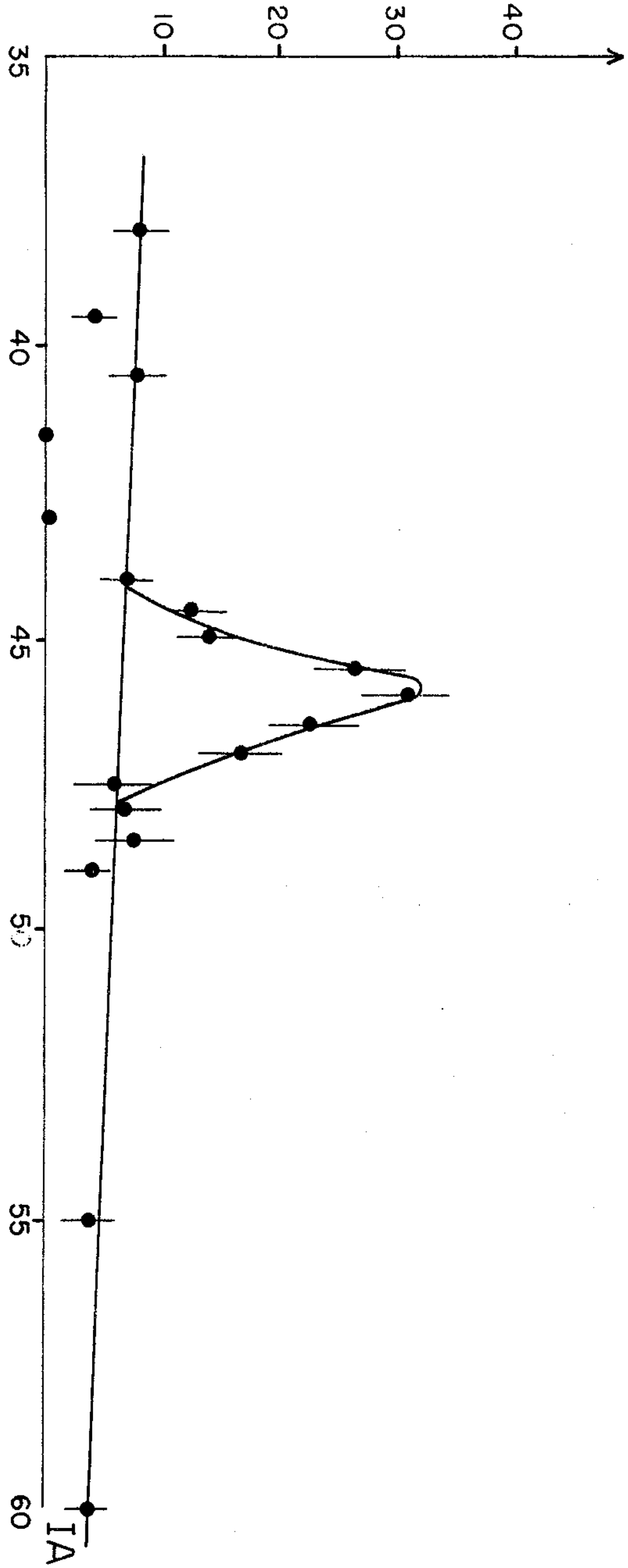
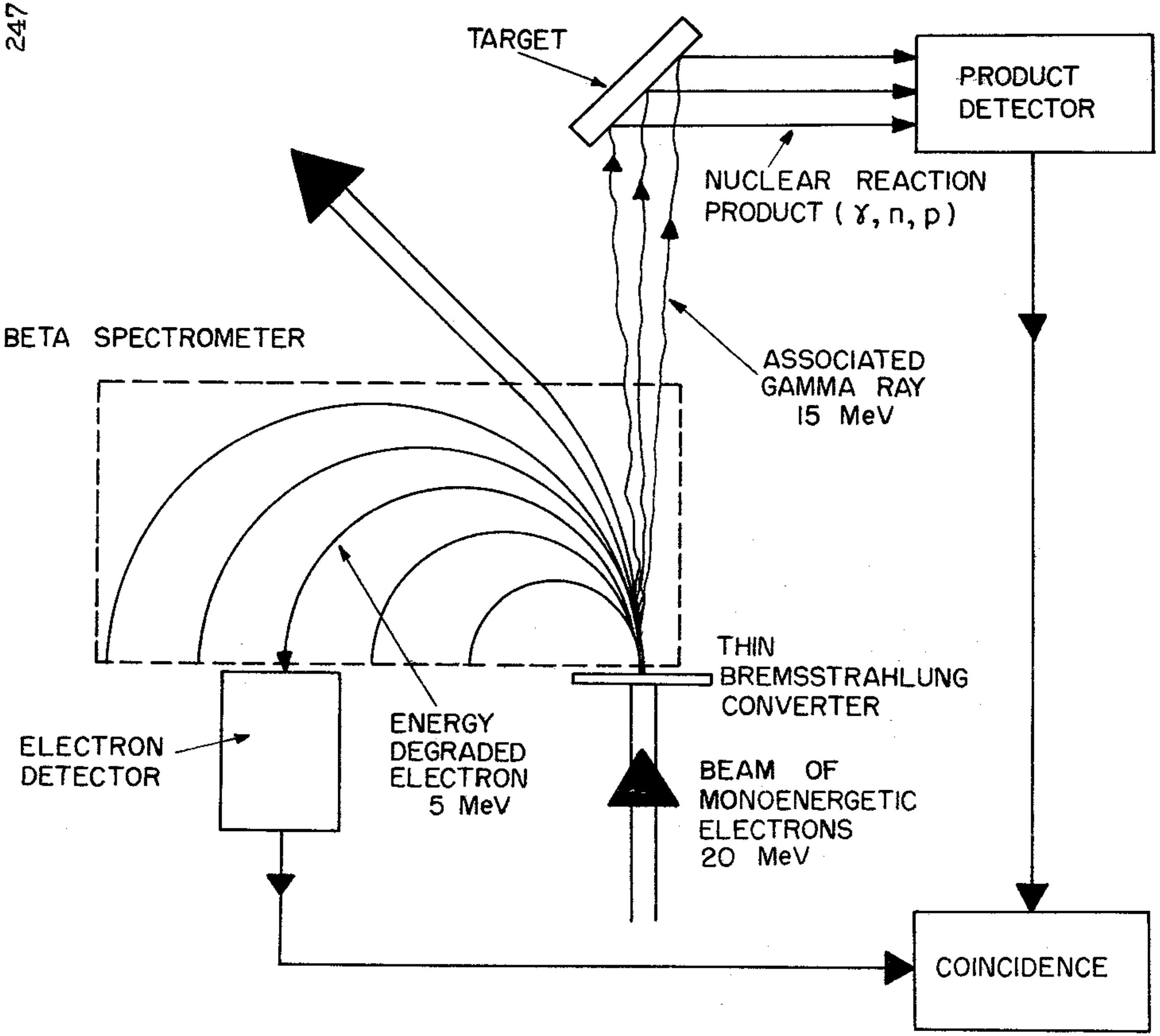
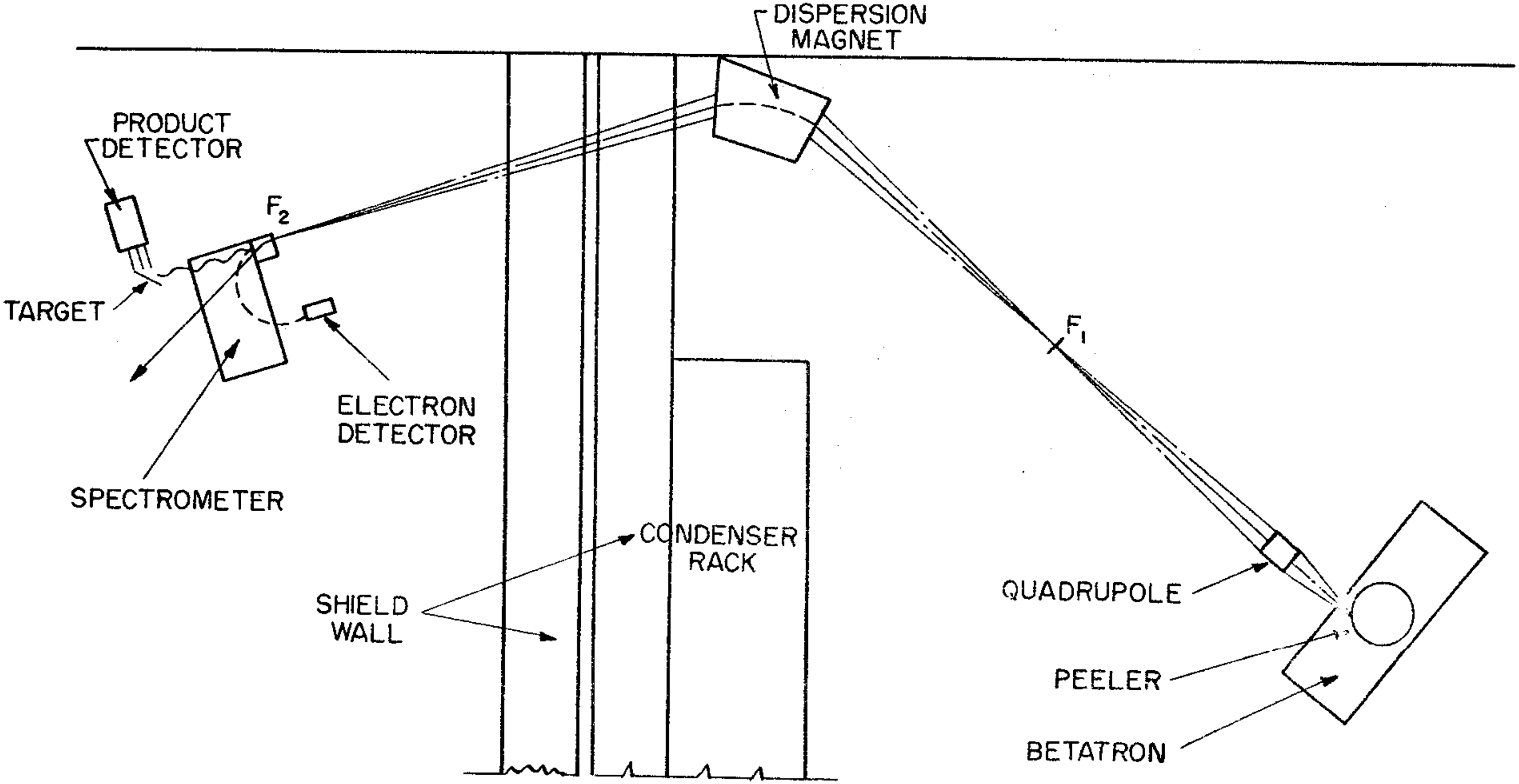


FIG. 3



PHOTON MONOCHROMATOR PRINCIPLE

FIG. 4



MONOCHROMATOR EXPERIMENT LAYOUT

FIG. 5

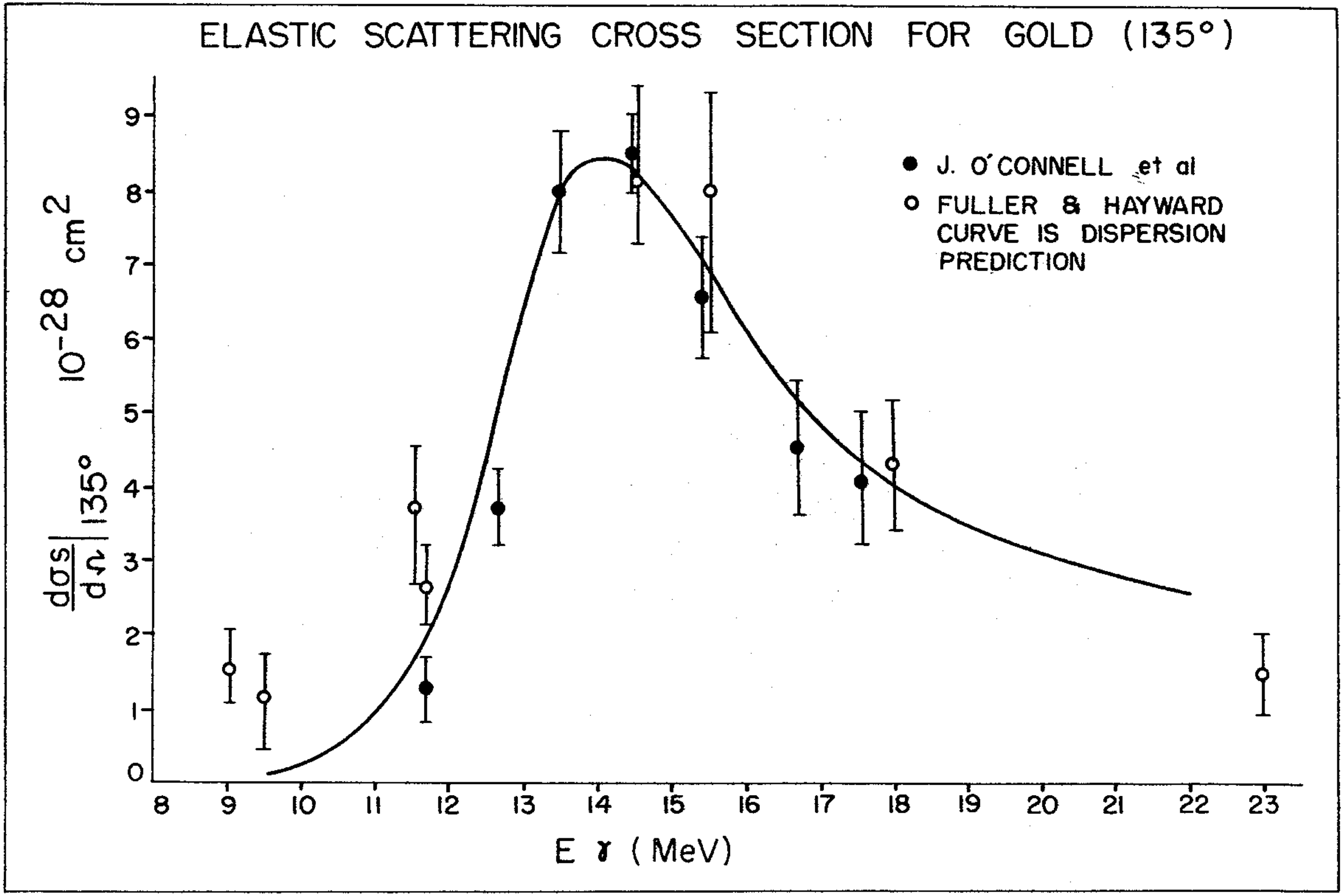

ELASTIC SCATTERING CROSS SECTION FOR GOLD (135°)
$\frac{d\sigma s}{d\Omega}\Big|_{135°}$ 10^{-28} cm^2
0
1
2
3
4
5
6
7
8
9
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
E γ (MeV)
● J. O'CONNELL et al
○ FULLER & HAYWARD
CURVE IS DISPERSION PREDICTION

FIG. 6

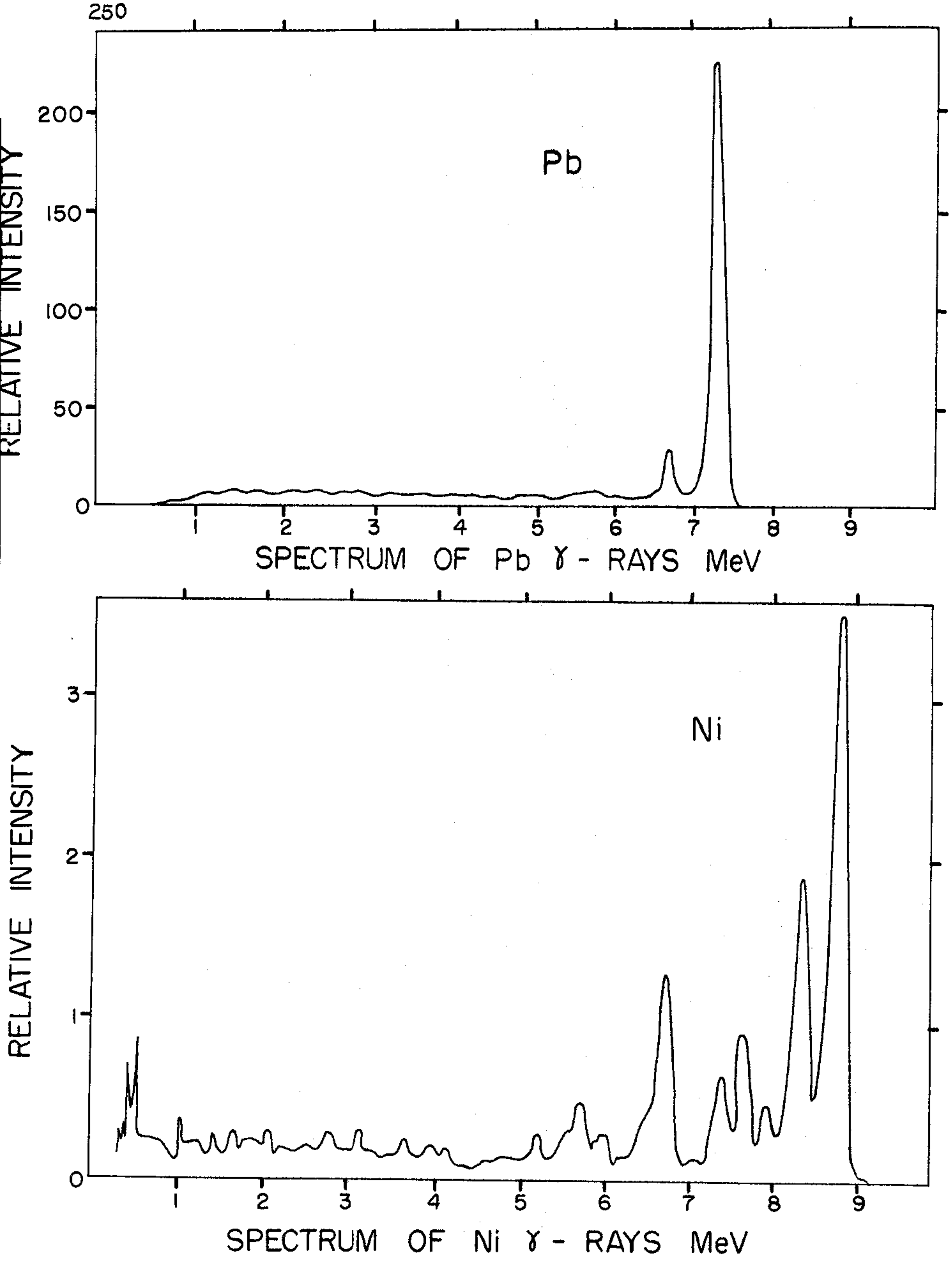

250
200
150
100
50
0
RELATIVE INTENSITY
Pb
1
2
3
4
5
6
7
8
9
SPECTRUM OF Pb γ - RAYS MeV
3
2
1
0
RELATIVE INTENSITY
Ni
1
2
3
4
5
6
7
8
9
SPECTRUM OF Ni γ - RAYS MeV

FIG. 7