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GAMMA RADIATION FROM POLONIUM NEUTRON SOURCES

(Information Report)

BY

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TABLE OF CONTENTS

	Page
INTRODUCTION	6
INSTRUMENTATION	6
EXPERIMENTAL PROCEDURE	8
SOURCES	10
RESULTS AND DISCUSSION OF SPECTRAL MEASUREMENTS	11
Polonium-Lithium Source	11
Polonium-Beryllium Source	15
Polonium-Boron Source	15
Polonium-Fluorine Source	17
Polonium-Sodium Source	20
Polonium-Magnesium Source	20
Polonium-Aluminum Source	22
INTENSITY DETERMINATION	25
CONCLUSIONS	25
REFERENCES	26

ABSTRACT

A NaI (Tl) crystal scintillation spectrometer was used to investigate the gamma spectrum from polonium-alpha bombardment of Li, Be, B, F, Na, Mg and Al. The principal gamma energies observed are: Li, 0.483 Mev, Be, 4.45 Mev, B, 3.68 and 2.36 Mev; F, 1.28 and 1.51 Mev, Na, 1.83 and 2.57 Mev, Mg, 1.30, 1.82 and 4.0 Mev, Al, 1.25, 2.28, and 3.55 Mev. The probable origin of the gamma radiation is described. A comparison of experimental neutron spectrum curves with a calculated curve shows a value of 0.7 γ/n for a Po-Be source. *aw*

INTRODUCTION

Gamma radiation had been observed from the action of alpha particles on some light nuclei^{1,2} prior to the discovery of the neutron. Subsequent investigation established the existence of gamma radiation, in addition to neutron emission, from the bombardment of lithium, beryllium, boron, fluorine, sodium, magnesium, and aluminum by alpha particles.³

Neutron sources, prepared by mixing polonium-210 with various target materials, produce gamma radiation in addition to that to be expected from the polonium. An investigation of the energy and intensity of this radiation will be of interest to users of neutron sources, as well as of assistance in studies of neutron spectra and efficiency of neutron production. With the establishment of crystal-scintillation counting techniques and with crystals and associated electronic components available from commercial sources, it became practicable to make such an investigation with a minimum cost for research and development.

This report describes the evaluation of gamma radiation from neutron sources by means of a NaI(Tl) single-crystal scintillation spectrometer. Data are presented for polonium-lithium, polonium-beryllium, polonium-boron, polonium-calcium fluoride, polonium-sodium, polonium-magnesium, and polonium-aluminum sources.

INSTRUMENTATION

The single-crystal scintillation spectrometer gives direct information on gamma energies in the form of pulses, the peak voltage of which is directly proportional to the energy expended in the crystal by the incident gammas. The detecting portion of the equipment consists of a Harshaw-mounted NaI(Tl) crystal 1.5 inches in diameter and 1 inch in thickness coupled through a Lucite light-pipe to a Radio Corporation of America Type 5819 photomultiplier tube. Pulses from the phototube are amplified by an Atomic Instrument Company Type 205-B pre-amplifier and a Type 204-B linear amplifier having added input delay-line pulse-shaping. The high-level output of the linear amplifier is coupled to an Atomic Instrument Company Type 510 single-channel pulse-height analyzer. Output pulses from the analyzer are counted by a conventional scaling circuit. High voltage (800 to 1,000 v) is supplied to the phototube by an Atomic Instrument Company Type 326 high-voltage power supply. A block diagram of the equipment is shown in Figure 1.

Stability of the equipment as received was poor because overheating occurred in the individual wooden cases. This was remedied by placing the equipment in a cabinet rack with a large exhaust fan which provided adequate ventilation. Excellent stability was obtained, and results were reproducible over a period of several weeks with negligible change in gain or high-voltage settings.

A mercury-relay pulse generator and an oscilloscope with internally-triggered sweep were used for alignment of the pulse-height analyzer. The alignment procedure described in the analyzer instruction book was followed. Because of changes in tube characteristics, performance

7

FIG. 1

BLOCK DIAGRAM OF SCINTILLATION SPECTROMETER

of the analyzer was found to deteriorate after extended periods of operation and a complete check of alignment was found to be desirable at least every three months. For maximum stability, all equipment including the high-voltage supply to the phototube was kept in continuous operation.

The photomultiplier tube was selected so as to provide good resolution. The wiring diagram of the tube base is shown in Figure 2.

Adjustment of the equipment was tested by determining the positions of the photoelectric peaks for mercury-203, cesium-137, polonium-210, cobalt-60, and the 4.45 Mev energy level of carbon-12 excited in a polonium-beryllium neutron source. Work by Terrell⁴ and Bell and Jordan⁵ indicates that the value of this last energy level is known with sufficient accuracy for use as a high-energy standard. Results of these tests were plotted as known energy of peaks vs position of peaks on the analyzer base-line scale. When the equipment was correctly adjusted a straight line was obtained which was extrapolated to zero. This confirmed the adjustment and checked the analyzer base-line zero setting. With all equipment in optimum working condition, energies to 4.5 Mev could be determined with less than two per cent error. Values of gamma energies for the standards used, taken from National Bureau of Standards Circular 499,⁶ are given in Table I.

TABLE I

GAMMA STANDARDS

STANDARD	GAMMA ENERGY (Mev)
Hg ²⁰³	0.280
Cs ¹³⁷	0.665
Po ²¹⁰	0.800
Co ⁶⁰	1.17, 1.33

With the analyzer set for a channel width of one volt, resolutions of approximately 16 per cent for mercury-203 and 10 per cent for polonium-210 were obtained. With complex gamma spectra, resolution for lower-energy gammas was considerably reduced because of additional scattered radiation from higher-energy gammas.

EXPERIMENTAL PROCEDURE

The pulse-height analyzer is designed to accept pulses from the linear amplifier in the range of 0 to 100 volts in height, and to pass output pulses to a scaler only for those input pulses which fall within a narrow height range. A base-line voltage control determines the height of pulses to be selected while a channel-width control determines the height range. Thus, with a base-line setting of 55 volts and a channel width of 1 volt, only those input pulses between 55 and 56 volts in height will produce output pulses to the scaler. (See Van Rennes⁷ for a general discussion of single-channel pulse-height analyzers.)

To determine the gamma-energy spectrum of a source, counting rates were obtained for one-volt-wide channels at intervals of one volt in pulse height. Results were plotted as

BASE WIRING DIAGRAM OF RCA-5819 PHOTOMULTIPLIER TUBE

BASED ON DIAGRAM FURNISHED TO R.L.SHIPP OF MOUND LABORATORY BY P.R.BELL OF OAK RIDGE

FIGURE 2

counts per second per channel *vs* pulse height in volts. Sources were positioned on the axis of the tube and crystal at such a distance that the integral counting rate over the entire pulse-height range would be less than 10,000 counts per second. In most of the tests, a total count per channel of at least 5,000 was obtained, although this was reduced to 2,000 counts when the counting rate was less than 10 counts per second. Backgrounds were negligible in all tests.

Three processes of energy loss by gamma radiation in the crystal must be considered⁸ for interpretation of the curves: (1), the photoelectric effect, in which all the energy of the gamma is given to an electron; (2), Compton scattering, in which part of the gamma energy is transferred to an electron; and (3), pair production, in which the gamma is converted to an electron-positron pair. In this last process, the positron, after slowing down is annihilated by combining with an electron, the resultant energy appearing in the form of two 0.51-Mev gamma quanta. In each case, energy dissipated within the crystal results in the emission of light which, acting on the photocathode of the photomultiplier tube, generates a pulse proportional in height to the energy expended.

SOURCES

The neutron sources consisted of intimate mixtures of the polonium-210 alpha-emitter and the target material. For polonium-lithium, polonium-beryllium, polonium-sodium, polonium-magnesium, and polonium-aluminum sources, polonium was volatilized into an empty nickel container. The pure target material was then added, after which the container was closed and coated with nickel. After the sealing was completed, the container was heated to distribute the polonium throughout the target material. For the calcium fluoride source, a hydrofluoric acid solution of polonium was evaporated onto the target material which was placed in the container and sealed. For the boron source, a hydrochloric acid solution of polonium was evaporated onto boron powder which was placed in a container and sealed. In addition, two containers having polonium only were available for gamma-intensity comparisons. These containers were right cylinders having a total wall thickness of 0.10 inch. Specifications of the sources are listed in Table II.

TABLE II

SPECIFICATIONS OF SOURCES

SOURCE NO	TYPE	POLONIUM-210 (C)	TOTAL NEUTRON EMISSION (n/sec)
I	Po	0.592	—
II	Po	2.572	—
III	Po-Li	2.87	1.06×10^5
IV	Po-Be	0.039	0.69×10^5
V	Po-B	1.34	7.72×10^5
VI	Po-CaF ₂	1.94	2.03×10^5
VII	Po-Na	3.20	1.34×10^5
VIII	Po-Mg	6.98	2.07×10^5
IX	Po-Al	9.14	1.79×10^5

RESULTS OF SPECTRAL MEASUREMENTS

POLONIUM-210 SOURCE

The gamma spectrum obtained for polonium-210 is shown in Figure 3. The only nuclear gamma observed from polonium, of energy 0.800 Mev, is shown as a photoelectric peak. The slight rise at 0.53 Mev is principally the maximum of the Compton distribution for the 0.800-Mev gamma but probably includes a 0.48-Mev gamma from neutron capture by boron in the glass of the photomultiplier tube.⁹

The peak at 0.19 Mev is interpreted to be the result of secondary Compton gamma from 0.800-Mev gammas scattered outside of the crystal. The peak at about 80 kev is in good agreement with the energy of the K X-ray of lead-206. A further amplification of the curve has also made possible the observation of the 11-kev L X-ray.

The positions of the gamma peaks in the neutron source curves were calculated relative to the 0.800-Mev peak from polonium. A summary of the possible reactions, reaction energies observed gamma energies, and values from the literature is given in Table III. The reaction energies, Q , were calculated from mass values given by Friedlander and Kennedy.¹⁰ The peaks from polonium will be omitted in the following analyses of the neutron-source gamma spectra.

POLONIUM-LITHIUM SOURCE

The following nuclear reactions are energetically possible in a polonium-lithium source: $\text{Li}^7 (\alpha, n) \text{B}^{10}$, $Q = -2.80$ Mev; $\text{Li}^7 (\alpha, p) \text{Be}^{10}$, $Q = -2.58$ Mev; $\text{Li}^6 (\alpha, n) \text{B}^9$, $Q = -3.98$ Mev; $\text{Li}^6 (\alpha, p) \text{Be}^9$, $Q = -2.12$ Mev. Since lithium-6 constitutes only 7.5 per cent of the total target material, it is not expected to be the source of a significant portion of the total radiation. Shepherd, Haxby, and Hill¹¹ investigated a radium C' - lithium source (for RaC , $E_\alpha = 7.7$ Mev) for protons and obtained a negative result.

Siegbahn and Slaetis¹² detected a single gamma of 0.462 Mev from a polonium-lithium source. Speh¹³ observed a gamma of 0.48 Mev which was accompanied by gammas of 1.5 and 0.4 Mev when the full energy of the polonium alpha was used. Both attributed the 0.48-Mev gamma to inelastic scattering of the alpha particle by the lithium-7 nucleus. This was confirmed by Hornyak, Lauritsen, and Rasmussen¹⁴ who observed a gamma of 0.476 Mev from inelastic scattering of protons by lithium-7. Slaetis³ and Schnetzler¹⁵ reported gamma radiation beginning at $E_\alpha = 2.3$ Mev, while the latter did not detect neutrons until the alpha reached 4.6 Mev. Curie and Joliot¹⁶ reported neutron or proton radiation beginning at an alpha energy greater than 3 Mev. This further justifies the selection of the inelastic scattering process as responsible for the 0.48-Mev gammas.

Bennett, Roys, and Toppel¹⁷ observed gamma emission from lithium bombarded by 1.4-Mev alphas and attributed it to the $\text{Li}^7 (\alpha, \gamma) \text{B}^{11}$ reaction. Levels in boron-10 at 0.77, 1.32, and 2.01 Mev were observed by Haxel and Stuhlinger¹⁸ from the study of neutrons from the thorium C - lithium source.

Figure 4 shows the gamma spectrum from polonium-lithium Source III. A gamma of energy 0.483 Mev was observed in agreement with the work cited above. No other gamma could be detected at a counting rate above one count per second. This indicates a simple neutron spectrum for a polonium-lithium source.

A simple neutron spectrum occurs when the neutrons leave all residual nuclei at the ground state [no gamma radiation from the (α, n) reaction] or at the same excited state [gamma radiation of the same energy from each (α, n) reaction]. The variation of energy of the

5569

FIGURE 3

TABLE III
ENERGIES OF GAMMAS FROM NEUTRON SOURCES

TARGET ELEMENT	POSSIBLE REACTIONS	REACTION ENERGY (Mev)	OBSERVED GAMMA ENERGY (Mev)	VALUES FROM LITERATURE (Mev)		
Li	$\text{Li}^7 (\alpha, n) \text{B}^{10}$	-2.80	-	-		
	$\text{Li}^7 (\alpha, p) \text{Be}^{10}$	-2.58	-	-		
	$\text{Li}^6 (\alpha, n) \text{B}^9$	-3.98	-	-		
	$\text{Li}^6 (\alpha, p) \text{Be}^9$	-2.12	-	-		
	$\text{Li}^7 (\alpha, \alpha') \text{Li}^7$	-	0.483	0.462 ¹²	0.48 ¹³	0.476 ¹⁴
Be	$\text{Be}^9 (\alpha, n) \text{C}^{12}$	5.74	4.45	4.37 ²³	4.4 ²⁴	4.4 ²⁵
				4.44 ⁵	4.45 ⁴	
	$\text{Be}^9 (\alpha, n) 3 \alpha$	-1.59	-	-		
B	$\text{B}^{11} (\alpha, n) \text{N}^{14}$	0.27	2.36	2.2 ⁴¹	2.35 ⁴²	2.35 ⁴³
	$\text{B}^{10} (\alpha, n) \text{N}^{13}$	1.37	-	-		
	$\text{B}^{11} (\alpha, p) \text{C}^{14}$	0.88	-	-		
	$\text{B}^{10} (\alpha, p) \text{C}^{13}$	4.08	3.68	3.76 ³⁴	3.84 ³³	
F	$\text{F}^{19} (\alpha, n) \text{Na}^{22}$	-1.9	-	-		
	$\text{Na}^{22} \rightarrow \text{Ne}^{22} + \beta^+$	-	1.28	1.34 ⁵	1.277 ⁴³	
	$\text{F}^{19} (\alpha, p) \text{Ne}^{22}$	1.0	1.28			
			1.51			
				1.51 ¹³	1.41 ⁴⁴	
Na	$\text{Na}^{23} (\alpha, n) \text{Al}^{26}$	-1.6	-	-		
	$\text{Na}^{23} (\alpha, p) \text{Mg}^{26}$	2.0	0.43	0.44 ⁴⁷		
			1.13	1.18 ⁴⁸		
			1.83	1.91 ⁴⁷	1.825 ⁴⁹	1.85 ⁵²
			2.57	2.85 ⁴⁷	2.972 ⁴⁹	2.80 ⁵²
Mg	$\text{Mg}^{25} (\alpha, n) \text{Si}^{28}$	2.0	4.0	4.3 ⁵²		
	$\text{Mg}^{26} (\alpha, n) \text{Si}^{29}$	-1.7	-	-		
	$\text{Mg}^{24} (\alpha, p) \text{Al}^{27}$	-1.5	1.01	1.02 ⁴⁷		
	$\text{Mg}^{25} (\alpha, p) \text{Al}^{28}$	-1.1				
	$\text{Mg}^{26} (\alpha, p) \text{Al}^{29}$	-3.4				
	$\text{Al}^{28} \rightarrow \text{Si}^{28} + \beta^-$	-	1.82	1.85 ⁵²	1.78 ⁵⁷	
	$\text{Al}^{29} \rightarrow \text{Si}^{29} + \beta^-$	-	1.30	1.25 ⁵⁵		
			2.32	2.35 ⁵⁵		
Al	$\text{Al}^{27} (\alpha, n) \text{P}^{30}$	-2.2	-	-		
	$\text{Al}^{27} (\alpha, p) \text{Si}^{30}$	2.3	1.25	1.28 ³²	1.3 ³¹	
			2.28	2.28 ^{59, 60}	2.16 ³⁷	
				2.32 ³²	2.3 ³¹	
			3.55	3.66 ^{59, 62}	3.49 ³⁰	3.54 ³⁷
				3.63 ³²	3.6 ³¹

FIGURE 4

bombarding alphas and of direction of neutron emission results in a distribution of the neutrons over a finite energy range, this distribution has a single maximum

POLONIUM-BERYLLIUM SOURCE

Neutrons are produced from a polonium-beryllium source by the reaction $\text{Be}^9(\alpha, n)\text{C}^{12}$ with $Q = 5.74$ Mev. Crussard and Gorodetzky,¹⁹ Giegerl and Broda,²⁰ Bjerger²¹ and Stuhlinger²² have detected a neutron group of about 0.1 Mev which they suggest as arising from the reaction $\text{Be}^9(\alpha, n)3\alpha$. This process begins at about $E_\alpha = 4.8$ Mev.^{20, 22} No gamma radiation has been detected in coincidence with these neutrons.

Neutrons resulting from the $\text{Be}^9(\alpha, n)\text{C}^{12}$ reaction may leave the carbon-12 nucleus in an excited state decaying to the ground state by gamma-emission. In most of the recent studies of gamma emission from a polonium-beryllium source a single gamma from the 4.4-Mev level of carbon 12 has been observed. The gamma energy found was 4.44 Mev by Bell and Jordan,⁵ 4.45 Mev by Terrell,⁴ 4.37 Mev by Artemov and Vlasov,²³ and 4.4 Mev by Harries and Davies.²⁴ Pringle, Roulston, and Standil²⁵ observed a gamma of 4.4 Mev and found indications of a gamma of 7.2 Mev. Neutron-spectrum work by Guier, Bertini, and Roberts²⁶ and Guier and Roberts²⁷ indicated a neutron group leaving the carbon-12 nucleus in an excited state between 7 and 8 Mev.

Slaetis³ and Szalay and Zimonyi²⁸ observed gamma radiation beginning at an alpha energy of about 1.7 Mev.

The polonium-beryllium gamma spectrum from source number IV is shown in Figure 5. A gamma was observed with an energy of 4.45 Mev, an average of the photoelectric peak at 4.42 Mev and the pair-production peaks at 3.93 and 3.48 Mev. In averaging these values, 0.51 and 1.02 Mev were added to the values of 3.93 and 3.48 Mev, respectively, to allow for the energy lost by the electron-positron annihilation gammas of 0.51 Mev escaping from the crystal. In the case of the 3.93-Mev peak, one of the annihilation gammas is captured in the crystal; when both escape the peak at 3.48 Mev results. No gamma energy other than 4.45 Mev was detected.

POLONIUM-BORON SOURCE

Both neutrons and protons are energetically possible from polonium-alpha bombardment of boron-10 and boron-11. $\text{B}^{11}(\alpha, n)\text{N}^{14}$, $Q = 0.27$ Mev; $\text{B}^{10}(\alpha, n)\text{N}^{13}$, $Q = 1.37$ Mev; $\text{B}^{11}(\alpha, p)\text{C}^{14}$, $Q = 0.88$ Mev; $\text{B}^{10}(\alpha, p)\text{C}^{13}$, $Q = 4.08$ Mev. Nitrogen-13 emits a positron and has a 10-minute half-life. Carbon-13 is a beta-emitter and has a half-life greater than 5,000 years.

Boron-10 is about 19 per cent of the target material. Anderson²⁹ presents evidence which indicates that the neutron emission from boron-10 is about $\frac{1}{25}$ of the total emission. Richards, Speck, and Perlman³⁰ could detect no group structure in a polonium-boron neutron source, whereas Stuhlinger,²² Bonner and Mott-Smith,³¹ and Rogers, Odencrantz, and Plain³² found a number of groups. Frye and Wiedenbeck³³ observed five proton groups from polonium-alpha bombardment of boron and attributed these to the boron-10 reaction. Creagan³⁴ bombarded boron with 7.45 and 6.46-Mev alphas and observed a number of proton groups, he attributed one of these to a 3.76-Mev level in carbon-13. Heidenreich,³⁵ Perkin,³⁶ and Slaetis, Hjalmar, and Carlsson³⁷ have also observed proton groups from alpha bombardment of boron.

Becker and Bothe³⁸ observed a 3.1-Mev gamma and two proton groups from polonium-boron. Bothe and Maier-Leibnitz³⁹ found two proton groups with no coincident gammas, whereas v Baeyer⁴⁰ recorded proton-gamma coincidences from alphas on boron.

FIGURE 5

Beghian Grace and Halban⁴¹ observed a 2.2 ± 0.2 -Mev gamma from polonium-alpha bombardment of boron 11 and attributed it to an excited state of nitrogen-14. Curie and Joliot¹⁶ detected gamma radiation from boron, beginning at $E_\alpha = 2.85$ Mev, which was confirmed by Szalay and Zimonyi²⁸ at $E_\alpha = 2.7$ Mev. In work done more recently, Slaetis³ did not detect any gamma until an alpha energy of 3.7 Mev was reached.

The gamma spectrum obtained for polonium-boron Source V is shown in Figure 6. Interpretation of the curve yields a photoelectric peak at 3.68 Mev with its pair-production peaks at 3.25 and 2.72 Mev and a second photoelectric peak at 2.36 Mev with its pair-production peaks at 1.84 and 1.31 Mev. Since the pair-production peaks are considerably broadened by the Compton distribution, values of 3.68 and 2.36 Mev are taken as the energies of the original gamma rays. The value of 3.68 Mev is in agreement with the value of 3.76 Mev attributed to a carbon-13 level by Creagan. Further confirmation of this gamma arising from the $B^{10}(\alpha, p)C^{13}$ reaction is the Q value of 0.24 Mev for protons attributed to this reaction by Frye and Wiedenbeck.³³

The value of 2.36 Mev for a gamma from nitrogen-14 is in agreement with the value of Beghian, Grace and Halban⁴¹ and is further substantiated by a gamma energy of 2.35 Mev found by Hicks, Husain, Sanders and Beghian⁴² with the reaction $C^{13}(p, \gamma)N^{14}$. Also, Cowie, Heydenburg, and Phillips⁴³ observed a 2.35-Mev level of nitrogen-14 with proton scattering.

A polonium-boron source containing 96 per cent boron-10 was obtained after this report was submitted for publication. The gamma spectrum curve for this source contains a single photo-peak at 3.71 Mev with its two pair-production peaks at 3.23 and 2.71 Mev. This result confirms the selection of the high-energy peak of Source V as coming from the $B^{10}(\alpha, p)C^{13}$ reaction.

POLONIUM-FLUORINE SOURCE

Polonium-alpha bombardment of fluorine may result in neutron emission through the $F^{19}(\alpha, n)Na^{22}$ reaction with a Q of -1.9 Mev, or proton emission through the $F^{19}(\alpha, p)Ne^{22}$ reaction with a Q of -1.0 Mev. Sodium-22 is a positron-emitter with a half-life of about 2.8 years.

Jolley and Champion⁴⁴ bombarded fluorine with polonium alphas and found levels of neon-22 at 0.4 and 1.41 Mev from proton studies. Speh¹³ observed a single gamma of 0.5 Mev with 4.6-Mev alphas, but observed additional gammas of 0.4 and 1.51 Mev with the full polonium-alpha energy. The energy of the gamma from sodium-22 decay has been given as 1.3 Mev by Good, Peaslee and Deutsch⁴⁵ and as 1.277 Mev by Alburger.⁴⁶

The gamma spectrum of polonium-calcium fluoride Source VI is shown in Figure 7. The small peak at 1.51 Mev is probably the result of a gamma from an excited state of neon-22, as observed by Jolley and Champion and Speh. The 1.28-Mev photoelectric peak is in good agreement with Alburger's value for the sodium-22 decay gamma. It must be assumed, however, that the major part of the 1.28-Mev peak is the result of the $F^{19}(\alpha, p)Ne^{22}$ reaction, which leaves the neon-22 nucleus at the 1.28-Mev excited state. Since the age of the polonium-calcium fluoride source was $2\frac{1}{2}$ months when its gamma spectrum was observed, sodium-22, with a half-life of 2.8 years, could not have decayed in sufficient quantities to account for the large peak at 1.28 Mev in Figure 7. Also, a prominent peak at 0.51 Mev would be expected from the annihilation of positrons from sodium-22 decay.

Another source, with fluorine comprising the major target constituent, was two years old when it was investigated. The 1.28-Mev peak and a peak at 0.51 Mev from positron-annihilation gammas were more intense in this source than the polonium peak at 0.800 Mev. This tends to confirm the above interpretation of the gamma spectrum of Source VI.

5572

FIGURE 6

FIGURE 7

POLONIUM-SODIUM SOURCE

Polonium-alpha bombardment of sodium-23 may result in the $\text{Na}^{23} (\alpha, n) \text{Al}^{26}$ reaction with a Q of -1.6 Mev, or the $\text{Na}^{23} (\alpha, p) \text{Mg}^{26}$ reaction with a Q of 2.0 Mev. Aluminum-26 is a positron-emitter and has a seven-second half-life.

Alburger and Hafner⁴⁷ interpreted a large number of proton studies from the $\text{Na}^{23} (\alpha, p) \text{Mg}^{26}$ reaction and assigned the following energy levels to magnesium-26: 0 , 0.44 , 1.91 , 2.85 , 4.0 , and 5.0 Mev. Humphreys and Pollard⁴⁸ found a level at 1.18 Mev, in addition to most of the others listed above. Endt, Haffner, and Van Patter⁴⁹ observed levels in magnesium-26 at 1.825 and 2.972 Mev with deuteron bombardment of magnesium-25. Swann, Mandeville, and Whitehead⁵⁰ observed levels in aluminum-26 at 2.00 , 3.63 , and 5.13 Mev with deuteron bombardment of magnesium-25.

Pollard and Alburger⁵¹ bombarded sodium-23 with 7.2 -Mev alphas and observed a 2.3 -Mev gamma. In later work, Alburger⁵² detected two gammas of 1.85 ± 0.15 Mev and 2.80 ± 0.25 Mev from 7 -Mev alpha bombardment of sodium-23. Slaetis³ found gamma emission beginning at $E_\alpha = 4.6$ Mev, whereas Kovacs⁵³ found gamma emission beginning at $E_\alpha = 2.7$ Mev, with a second component beginning at $E_\alpha = 3.5$ Mev. She attributed this gamma to the $\text{Na}^{23} (\alpha, p) \text{Mg}^{26}$ reaction.

The two major constituents of the gamma spectrum shown in Figure 8, from polonium-sodium Source VII are at 1.83 and 2.57 Mev, and are in agreement with Alburger's values within his stated probable errors. They probably correspond to the 1.91 and 2.85 -Mev levels in magnesium-26 given by Alburger and Hafner. This would also agree with Kovacs' suggestion that two gamma rays come from the $\text{Na}^{23} (\alpha, p) \text{Mg}^{26}$ reaction. Smaller peaks at 1.13 and 0.43 Mev could correspond to the 1.18 -Mev level in magnesium-26 found by Humphreys and Pollard and the 0.44 -Mev level in magnesium-26 given by Alburger and Hafner. Inelastic scattering of the alphas at the 0.44 -Mev level of sodium-23 observed by Donahue, Jones, McEllistrem, and Richards⁵⁴ could also account for the 0.43 -Mev peak. Since there is no indication that any gamma radiation arises from the $\text{Na}^{23} (\alpha, n) \text{Al}^{26}$ reaction, a simple neutron spectrum is suggested.

POLONIUM-MAGNESIUM SOURCE

The three isotopes of magnesium ($A = 24, 25, 26$) are present in the natural element in the ratio, $78.8: 10.1: 11.1$, respectively. The following reactions are energetically possible with polonium-alpha bombardment: $\text{Mg}^{25} (\alpha, n) \text{Si}^{28}$, $Q = 2.0$ Mev; $\text{Mg}^{26} (\alpha, n) \text{Si}^{29}$, $Q = -1.7$ Mev; $\text{Mg}^{24} (\alpha, p) \text{Al}^{27}$, $Q = -1.5$ Mev; $\text{Mg}^{25} (\alpha, p) \text{Al}^{28}$, $Q = -1.1$ Mev; $\text{Mg}^{26} (\alpha, p) \text{Al}^{29}$, $Q = -3.4$ Mev. Aluminum-28 and aluminum-29 are beta-emitters with half-lives of 2.3 and 6.6 minutes, respectively. The $\text{Mg}^{24} (\alpha, n) \text{Si}^{27}$ reaction is not allowed energetically.

Bombarding magnesium with 7 -Mev alphas, Alburger⁵² observed gammas of 1.8 and 4.3 Mev. Seidlitz, Bleuler, and Tendam⁵⁵ using 18 -Mev alphas produced aluminum-29, from which they found two beta components followed by gammas of 1.25 and 2.35 Mev in an intensity ratio of three to one. Sheline and Johnson⁵⁶ and Motz and Alburger⁵⁷ have observed a 1.78 -Mev gamma from the beta decay of aluminum-28. Szalay and Csongor⁵⁸ have studied the gamma rays from polonium-alpha bombardment of magnesium. They discuss the reactions to account for a gamma of about 3.8 Mev and conclude that the $\text{Mg}^{25} (\alpha, n) \text{Si}^{28}$ and $\text{Mg}^{26} (\alpha, n) \text{Si}^{29}$ reactions are the only two energetically allowed and suggest the first as being the more probable.

Considering the large number of possible residual nuclei, it is comparatively difficult to assign the observed peaks to the proper reactions. The gamma spectrum of Source VIII,

FIGURE 8

shown in Figure 9, has three large peaks at 1.30, 1.82, and 2.97 Mev, a small peak at 1.01 Mev; and a possible peak at 2.32 Mev. The 1.82-Mev peak is probably from the decay of aluminum-28, as reported by Sheline and Johnson and Motz and Alburger. The 1.30 and 2.32-Mev peaks would correspond to Seidlitz's description of aluminum 29 decay. The relative size of these two peaks would be expected from the intensity ratio stated above and also from the decreased counting efficiency of the crystal at higher energies. The photoelectric peak at 1.01 Mev can be attributed to an excited state of either aluminum 27 or aluminum 29, as reported by Alburger and Hafner.⁴⁷

The low counting rate at 3 Mev prevented investigation past this point. This leaves a question as to the identity of the peak at 2.97 Mev. Considering the size and shape of the peak, it is probable that it is a pair-production peak which would put the gamma energy at about 4 Mev. This is approximately the energy of the gamma found by Alburger and assigned to the $\text{Mg}^{25}(\alpha, n)\text{Si}^{28}$ reaction by Szalay and Csongor.

POLONIUM-ALUMINUM SOURCE

Proton and neutron radiation from polonium-alpha bombardment of aluminum may arise from the $\text{Al}^{27}(\alpha, p)\text{Si}^{30}$ reaction with a Q of 2.3 Mev and the $\text{Al}^{27}(\alpha, n)\text{P}^{30}$ reaction with a Q of -2.2 Mev. Phosphorus-30 is a positron-emitter with a half-life of 2.5 minutes.

Numerous studies have been made of protons from alpha bombardment of aluminum. Using 7.3-Mev alphas, Benson⁵⁹ found silicon-30 levels at 2.28, 3.66, and about 4.6 Mev. He also observed proton-gamma coincidences for protons from the 2.28 and 3.66 Mev levels. Brolley Sampson, and Mitchell⁶⁰ bombarded aluminum with 22 Mev alphas and found proton groups from silicon-30 levels at 2.28, 3.49, 7.18 Mev and others. Slaetis, Hjalmar, and Carlsson³ found levels in silicon-30 at 2.16 and 3.54 Mev using polonium alphas.

Landon⁶¹ bombarded aluminum with 7.5 Mev alphas and suggested the following decay scheme for silicon-30: a gamma cascade from 4.9 Mev to 3.6 Mev to ground, with other transitions from 3.6 and 2.3 Mev to ground. Allen, May, and Rall⁶² investigated proton-gamma coincidences from 7.8-Mev alpha bombardment of aluminum. They suggested a double cascade process from the third excited state, one cascade going to the second level and then to ground, the other cascade going to the first excited state and then to ground. Values of 1.28 and 3.66 Mev were assigned to the gamma energies from the first cascade; both gamma energies were thought to be between 2.2 and 2.7 Mev for the second cascade. Independent of cascades, gamma energies of 3.63 and 2.32 Mev were found. Alburger⁵² detected a gamma of 3.5 Mev with 7-Mev alphas on aluminum and attributed it to the $\text{Al}^{27}(\alpha, p)\text{Si}^{30}$ reaction.

Peck⁶³ observed a 1.02-Mev level in phosphorus-30 from 7.6-Mev alpha bombardment of aluminum. Mandeville, Swann, Chatterjee, and VanPatter⁶⁴ found phosphorus 30 levels at 0.75, 1.46, and 2.00 Mev from 1.4-Mev deuterons on silicon. Slaetis³ and Szalay and Zimonyi²⁸ observed gamma emission beginning at alpha energies of 4.1 and 3.9 Mev, respectively.

The gamma spectrum curve for polonium aluminum Source IX is shown in Figure 10 and is interpreted as follows: the 3.55 Mev peak - photoelectric peak; the 3-16 Mev peak - pair production from the 3.55 Mev gamma with loss of one annihilation photon and distortion by the Compton distribution of the same gamma; the 2.56 Mev peak - pair production from the 3.55-Mev gamma with loss of both annihilation gammas; the 2.28 Mev peak - photoelectric peak; the 1.83-Mev peak - pair production from the 2.28 Mev gamma with loss of one annihilation photon plus Compton distribution; the 1.25 Mev peak - photoelectric peak broadened by the 2.28-Mev-gamma pair-production peak with loss of both annihilation photons.

FIGURE 9

5576

FIGURE 10

The gamma energies found in this work are in essential agreement with the values given above. Landon's decay scheme of silicon-30 seems to be preferred over the scheme of Allen, May, and Rall, although the peak at 2.56 Mev interpreted as resulting from pair production, may contain the photoelectric peak to complete Allen's second cascade process. Since no gamma energies can be ascribed to the $\text{Al}^{27}(\alpha, n)\text{P}^{30}$ reaction a simple neutron spectrum is suggested.

INTENSITY DETERMINATION

The determination of intensity of gamma radiation with the scintillation spectrometer was generally unsuccessful. Of the large number of low-energy counts, most were probably caused by backscattering and could not be properly subtracted to enable evaluation of the true counts. Collimation of the gammas was not feasible, since neutron-capture gammas would have introduced more discrepancies.

Slaetis³ gives relative intensities of gamma radiation from polonium-alpha bombardment of the target materials discussed above. His values, uncorrected for variation of Geiger-Mueller counter efficiency with energy, are as follows: lithium 61, beryllium, 340; boron, 9.0; fluorine, 9.0; sodium, 9.5; magnesium, 3.7; and aluminum 7.9. Since Slaetis did not evaluate his neutron emission, it is not possible to make a direct application of his values; efficiency of neutron production is a variable in both methods.

An independent approach was taken in determining the intensity of the 4.45-Mev gamma from a polonium-beryllium source. A hypothetical neutron spectrum was calculated for a polonium-beryllium source by the method of Whitmore and Baker,⁶⁵ on the basis that all neutrons left the carbon-12 nucleus in the ground state (no gamma radiation). The thick-target neutron-excitation curve of Segre and Wiegand⁶⁶ was used for this calculation. The experimental neutron spectrum curves of Whitmore and Baker⁶⁵ and Richards⁶⁷ were normalized and superimposed on the calculated curve. The percentage of area of the experimental curve overlapping the calculated curve was taken as the percentage of neutrons leaving the residual nucleus in the ground state. The rest of the neutrons were assumed to have a gamma associated with them.

From the curve of Whitmore and Baker, it was indicated that 26 per cent of the neutrons had no associated gammas, while the curve of Richards yielded a value of 34 per cent; from an average of the two values, a ratio of 0.7 gamma per neutron was obtained. From Table II it can be calculated that polonium-beryllium Source IV emits 47 neutrons per 10^6 alphas. On the basis of 0.7 gamma per neutron, the gamma intensity should be 33 gammas per 10^6 alphas.

If a polonium-beryllium source were 100 per cent efficient ($77\text{ n}/10^6\alpha$), the gamma intensity would be about 54 gammas per 10^6 alphas. This is to be compared to the polonium-210 intensity of 17 gammas per 10^6 alphas, an average of the values of Grace, Allen, West, and Halban⁶⁸ and Barber and Helm.⁶⁹ On the basis of Slaetis' values, polonium-beryllium would be the only source with gamma radiation of a greater intensity than that from polonium itself.

CONCLUSIONS

The results of the spectral measurements and their comparison to past work revealed four of the sources, lithium, fluorine, sodium, and aluminum, as having no gamma associated with the (α, n) reaction. If thick target neutron-excitation curves were available for these four target elements, fairly accurate neutron spectra curves could be calculated readily.

Work on intensity determination with the scintillation spectrometer was generally unsuccessful. It was concluded, however, that only in the case of beryllium is the gamma intensity from the source reaction greater than that from the polonium in the source.

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