where the ρ-meson propagator $\Delta_F{}^{\mu\nu}(s)$ defines $\Delta_F(s)$ through the relation

$$\Delta_F{}^{\mu\nu}(s)=\Delta_F(s)\left(g^{\mu\nu}-\frac{P_\rho{}^\mu P_\rho{}^\nu}{m_\rho{}^2}\right). \tag{A3}$$

In virtue of the assumption made above, the function $A(s)[F_\pi(s)]^{-1}$ is analytic in the whole s plane and thus reduces to a constant. Since $F_\pi(0)=1$, $\Delta_F(0)\cong -1/m_\rho{}^2$, we have

$$A(s)=A(0)F_\pi(s), \tag{A4}$$

where

$$A(0)=+\frac{8}{3m_\rho{}^2}\frac{\gamma_{\rho\pi\pi}{}^2}{4\pi}. \tag{A5}$$

Now unitarity tells us that

$$\frac{1}{2i}[A(s+i\epsilon)-A(s-i\epsilon)]=Q^3s^{-1/2}|A(s)|^2. \tag{A6}$$

Hence, with an obvious choice for the contour Γ,

$$\begin{aligned} I(s)&=\frac{1}{2\pi i A(0)}\int_\Gamma \frac{F_\pi(s')ds'}{s'(s'-s)}\\ &=\frac{3m_\rho{}^2}{8}\frac{1}{(\gamma_{\rho\pi\pi}{}^2/4\pi)}\left[\frac{F_\pi(s)-1}{s}\right]. \end{aligned} \tag{A7}$$

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Negative Pion Photoproduction from Bismuth Accompanied by Neutron Emission*

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The reaction $\gamma+\mathrm{Bi}^{209}\rightarrow\pi^-+\mathrm{Po}^{209-x}+xn$ has been investigated using 250-MeV bremsstrahlung. Alpha counting technique has been selected since it permits unambiguous identification of the produced radioactivity as coming from polonium. The effective cross section σ_x for the production of Po^{209-x} peaks at $x=2$. This result is in fair agreement with calculations based on an impulse approximation model which assumes (1) the π^- is photoproduced from a free neutron close to the surface, (2) the π^- is emitted without undergoing any collision, (3) the neutron emission results from the interaction of the recoiling proton with the Bi^{208} "spectator" nucleus, (4) this process can be treated as a (p,xn) reaction initiated by a free proton. The sum of the cross sections σ_x is $\sim$2.5 mb. This value is approximately 20 times that for π^- photoproduction from a free neutron, and is therefore compatible with a surface interaction model.

PHOTOPRODUCTION of negative pions from bismuth is an example of the possibility of using pion photoproduction for the investigation of problems in nuclear structure. This reaction yields several polonium isotopes via

$$\gamma+\mathrm{Bi}^{209}\rightarrow\pi^-+\mathrm{Po}^{209-x}+xn. \tag{1}$$

The process involves the emission of a π^- by one of the neutrons from the doubly magic Pb^{208} core. The residual proton is forced to leave the core, since the core is closed for protons. However, if polonium is to be formed, the proton must stay in the nucleus. The Po^{209} nucleus is de-excited via the emission of x neutrons ($x=0, 1, 2, \cdots$). An experiment has been performed to measure the cross sections for the reactions (1) and to investigate the probability distribution of x.

Six grams of anhydrous spectroscopically pure $BiCl_3$ were irradiated for 8 h by 250-MeV bremsstrahlung from the University of Illinois 300-MeV betatron. The integrated gamma flux was measured with a calibrated ionization chamber and vibrating reed electrometer. The irradiated sample was dissolved in 6*N* HCl and the polonium extracted with tributyl phosphate in dibutylether.[1] The organic phase was washed with 6*N* HCl to decontaminate from bismuth, and the polonium stripped from the organic phase with concentrated HNO_3. After evaporation of the HNO_3 the polonium activity was taken up in 0.5*N* HCl and plated on a 1 cm² silver foil at 97°C,[2] adding a drop of 3% KCN solution every 20 min. The extraction and plating efficiencies are estimated to be better than 98%.[1,2] The entire process requires 3–4 h.

The plated polonium sample was placed at a distance of a few mm from a 3 cm² solid-state detector coupled into a low-noise, charge-sensitive preamplifier and a 512 channel analyzer. Only alpha particles were detected and the energy spectra were printed every hour for 2 days. The over-all energy spread of the system for each alpha group is less than 40 keV. The alpha counting technique has been selected since it permits unambiguous identification of the radioactivity as coming from polonium. It should be noted that

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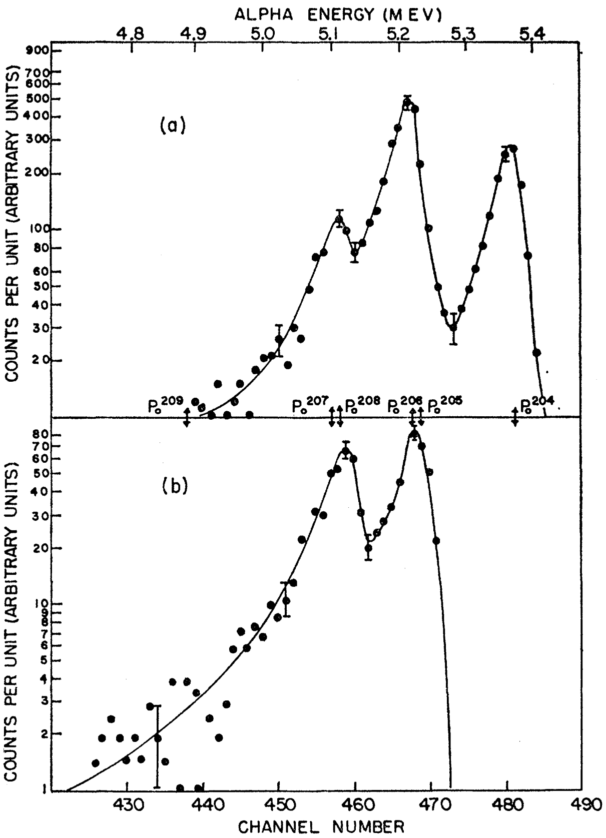

FIG. 1. Observed alpha spectra of $Po^{204-209}$ taken (a) $\sim$15 h after the beginning of 8 h irradiation, and (b) 3 weeks later.

polonium can be photoproduced from bismuth only via π^- emission.

Table I lists the relevant information concerning the investigated polonium isotopes.[3] The alpha energies of the various isotopes differ by more than 100 keV and are easily distinguishable, except for the two pairs: Po^{208}-Po^{207} and Po^{206}-Po^{205}. The large variation of half lives, however, allows the clear separation of members of each pair.

The alpha-energy spectrum and energy calibration are given in Fig. 1. Figure 1(a) is the spectrum taken a few hours after the irradiation, and Fig. 1(b) is the spectrum from the same target taken three weeks later. The energy determination and stability are better than 10 keV (one channel). The number of counts per hour under each peak is shown in Fig. 2 as a function of time. Figure 2(a) shows the 3.5-h activity of Po^{204}. Figure 2(b) shows the 8.8-day activity of Po^{206}; there is no indication of any contribution from the 1.8-h activity of Po^{205}, probably because the counting did not start until 5 h and 40 min after the end of the irradiation. Figure 2(c) shows that there is more than one half-life involved in the peak at 5.10–5.11 MeV; and the data are compatible with the assumption of two half-lives: (1) the 6-h half-life of Po^{207}, and (2) the 3-yr half-life of Po^{208}.

The effective cross section σ_x for the production of Po^{209-x} obtained by assuming that the actual cross section is constant in the energy region $E_{th,x} \leq E_\gamma \leq E_0$, is given by

$$\sigma_x = t_0 C_x(t) e^{\lambda_x(t-t_0)} \Big/ GWN(1-e^{-\lambda_x t_0})\beta_x \times \int_{E_{th,x}}^{E_0} N(E_\gamma) dE_\gamma, \quad (2)$$

TABLE I. Alpha energies, half-lives, and probabilities of alpha emission from Po^{209-x} isotopes.

Mass number	x	Alpha energy (MeV)	Half-life	β_x
209	0	4.88	103 yr	0.988
208	1	5.11	3 yr	1.0
207	2	5.10	6 h	$\approx 10^{-4}$
206	3	5.22	8.8 day	5×10^{-2}
205	4	5.23	1.8 h	7.4×10^{-4}
204	5	5.37	3.5 h	$\approx 10^{-2}$

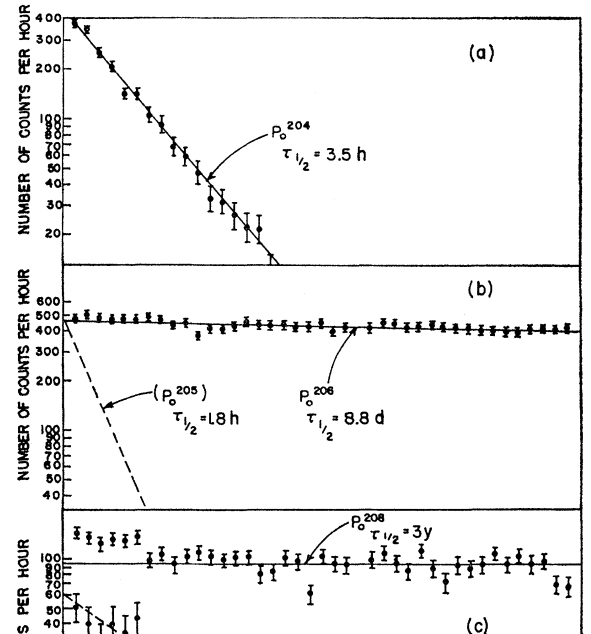

FIG. 2. Observed counting rates as a function of time for (a) Po^{204}, (b) Po^{206} (and Po^{205}), and (c) Po^{207} and Po^{208}. The dashed curve in (b) corresponds to the slope of the unobserved Po^{205}, and the dashed curve in (c) corresponds to Po^{207} after a subtraction of the Po^{208} contribution (solid curve).

[3] For a complete bibliography, see *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1962).

where $E_{\mathrm{th},x}$ is the threshold energy for the production of Po^{209-x}; E_0 is the maximum bremsstrahlung energy; λ_x is the decay constant for Po^{209-x}; t_0 is the irradiation time; $C_x(t)$ is the alpha counting rate for Po^{209-x} at time t, measured from the beginning of the irradiation; G is the effective solid angle of the detector in units of 4π sr; W is the number of ergs of photon beam averaged over the target; N is the number of Bi nuclei per cm^2; β_x is the probability of alpha emission; and $N(E_\gamma)$ is the number of photons per MeV per erg of beam energy. The observed counting rates $C_x(t=13.15\mathrm{h})$ and relative values of the effective cross sections σ_x are given in Table II. The value of σ_1 (for the reaction $\gamma+\mathrm{Bi}^{209}\rightarrow \pi^-+\mathrm{Po}^{208}+n$) is 0.35 ± 0.15 mb.

The uncertainty in the value of σ_1 is due mainly to the uncertainties in the effective solid angle and in the counting rate. The uncertainty in the relative values of σ_x is large and is due mainly to the uncertainty in β_x.[3] An 8-h irradiation was also performed at $E_0=125$ MeV in order to determine the possible contribution of secondary processes, such as (p,xn) to the polonium photoproduction. This contribution was found to be smaller than 1% and can therefore be ignored here.

Reactions (1) necessarily involve the following processes: (a) A photon interacts with the Bi nucleus causing a core neutron to change into a π^- and a proton; (b) The π^- leaves the nucleus; (c) The recoiling proton stays in the nucleus; (d) x neutrons are emitted. In order to understand the behavior of σ_x we propose an impulse approximation model for the π^- production by assuming (1) the π^- is photoproduced from a free neutron close to the surface,[4] (2) the π^- is emitted without undergoing any collision, (3) the neutron emission results from the interaction of the recoiling proton with the Bi^{208} "spectator" nucleus, (4) this process can be treated as a (p,xn) reaction initiated by a free proton. Using these assumptions, σ_x can be expressed as

$$\sigma_x=\int dE_\gamma N(E_\gamma)\int dT_p P_x(E_\gamma,T_p)\frac{d\sigma(E_\gamma,T_p)}{dT_p}\Big/\int dE_\gamma N(E_\gamma)\,, \quad (3)$$

where T_p is the kinetic energy of the recoiling proton, $d\sigma(E_\gamma,T_p)/dT_p$ is the differential cross section for π^- photoproduction from a neutron resulting in a proton with kinetic energy T_p, $P_x(E_\gamma,T_p)$ is the probability of production of x neutrons by the recoiling proton, and the integration is performed over all the possible energies.

A rough calculation based on this model—using the Schiff bremsstrahlung spectrum as computed by Leiss,[5] the meson photoproduction cross sections as tabulated by Beneventano *et al.*,[6] and the probability distribution for the emission of x neutrons by a proton as computed by Jackson[7]—yields a maximum for σ_x at $1\leq x\leq 2$. This is in fair agreement with the experimental result (Table I), although the experimental distribution seems narrower. Our observed maximum at $x=2$ might alternatively be accounted for by assuming pair correlation between neutrons in addition to the odd-even effects which are accounted for in the binding energies. As an indication of such a possibility we mention that some enhancement at $x=2$ for (p,xn) reactions has been observed by Bell and Skarsgard.[8] Such a maximum, however, can hardly be explained by any one step or "direct" mechanism. The question of pair correlation might be determined by a future investigation of the probability distribution of x as a function of E_γ for narrow gamma-energy bins.

Although the total cross section for π^- photoproduction from bismuth has other channels (notably those with proton emission), the Po^{209-x} contribution is presumably a major fraction of the total. The value of $\sim$2.5 mb for the sum of the cross sections is approximately 20 times that for a free neutron. This number is compatible with a surface interaction model.

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TABLE II. Observed counting rates and effective production cross sections for Po^{209-x} isotopes relative to Po^{208}.

Mass number	x	$C_x(t=13.15\text{ h})$ (counts per hour)	σ_x/σ_1
209	0	≤1.5	≤0.5
208	1	95 ± 25	1.0
207	2	60 ± 15	$4.5\pm50\%$
206	3	470 ± 25	$1.0\pm20\%$
205	4	<70	<2
204	5	480 ± 25	$0.55\pm$?

[4] We ignore some volume contribution to this surface process. The volume process involves a volume photoproduction of π^0 followed by a charge-exchange collision of the π^0 with a surface neutron. The resulting π^- escapes while the recoiling proton stays in the nucleus, and x neutrons are emitted. This process is less probable mainly because of the small cross section for π^0 photoproduction for the photon energy range in this experiment.

[5] J. E. Leiss, Tables of Bremsstrahlung Spectra, Physics Research Laboratory, University of Illinois, 1957 (unpublished).

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