We have measured the activation curve for the combined reactions up to 27 Mev, making no attempt to separate the two half-lives. Thin lead and copper disks of identical shape were irradiated together in the betatron beam and counted alternately with an end-window counter. The known $Cu^{63}(\gamma, n)Cu^{62}$ activation curve[2] thus served as a monitor for the lead reactions. The energy thresholds for the (γ, p) reactions in Pb^{208} and Pb^{207} are 7.7 and 7.8 Mev, respectively,[3] but due to the high potential barrier for protons the yields below 15 Mev were too small to be counted.

Although the counting geometries were the same for both types of sample, the corrections for self-absorption in lead and copper were quite different. Because of the changing angular distribution of beta-particles from circular disks as a function of sample thickness, it is necessary to measure specific activities in extremely thin samples in order to make this correction. This was not possible in the case of the lead samples, so a curve of specific activity *versus* sample thickness was measured using saturation backscattering, and a correction given by Yaffe and Justus[4] was applied.

The resulting activation curve was analyzed by the photon difference method[5] to determine the sum of the contributing photonuclear cross sections. This is plotted as the solid curve (a) in Fig. 1. A cross section maximum of 5.3 millibarns occurs at 26 Mev.

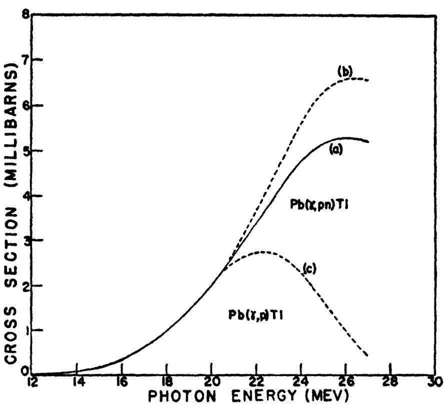

FIG. 1. Cross-section curves for (γ, p) and (γ, pn) reactions in lead. (a) Observed cross-section curve assuming that only the reactions $Pb^{207}(\gamma, p)Tl^{206}$ and $Pb^{208}(\gamma, p)Tl^{207}$ produced the measured activities. (b) Sum of (γ, p) and (γ, pn) cross sections computed from (a) and statistical theory. (c) The (γ, p) cross section computed from (a) and statistical theory. The difference in ordinates between curves (b) and (c) represents the (γ, pn) cross section.

It is possible to draw some theoretical conclusions regarding the contribution of the various possible reactions to this cross-section curve. In the following considerations we assume the (γ, d) reaction cross section to be small compared to those for the (γ, p) and (γ, pn) reactions.

If the absorption of high energy photons results in the formation of a compound nucleus, then, according to the statistical theory of Weisskopf,[6] protons will be emitted with an energy distribution.

$$I(E_p) \propto E_p\sigma(E_p) \exp 2[a(h-Q-E_p)]^{\frac{1}{2}}, \tag{1}$$

where E_p is the proton energy, $\sigma(E_p)$ is the capture cross section for protons of energy E_p by the residual nucleus, and the exponential factor represents the level density of the residual nucleus at the excitation in which it is left after the proton emission. This residual nucleus will decay by γ-ray emission, or, if the energy is sufficient, by neutron emission (thus resulting in a (γ, pn) reaction). Since proton emission becomes easier as the nuclear excitation is raised, it is probable that the majority of the (γ, pn) events observed here involved the prior emission of a proton in the above manner.

With the value $a=10$ $(\text{Mev})^{-1}$ for $A=207$, proton energy distributions corresponding to photon energies between 15 and 27 Mev were computed. It was then assumed that the fractional part of the distribution, which would leave the residual nucleus sufficiently excited to emit a neutron, would result in a (γ, pn) reaction (this fraction was negligible below 20 Mev). The observed cross-section curve (a) of Fig. 1 is the sum of (γ, p) cross sections in two lead isotopes and a (γ, pn) cross section in Pb^{208}. Thus, assuming equal cross sections in the different lead isotopes at a given photon energy, it was possible to find what fraction of curve (a) represented the $Pb^{208}(\gamma, pn)Tl^{206}$ reaction at any photon energy. Curve (b) is the computed sum of (γ, p) and (γ, pn) cross sections in lead, and curve (c) is the (γ, p) cross section alone. These two curves are insensitive to the nuclear radius assumed in the computations.

The above value of a from Eq. (1) for the description of Tl level densities is a smooth extrapolation of Weisskopf and Blatt's values.[6] From the work of Stelson and Goodman[7] and of Whitmore[8] on the inelastic scattering of 14-Mev neutrons from lead, a value $a=22$ $(\text{Mev})^{-1}$ may be obtained for the "magic number" lead nuclei. This larger value would decrease the peak position of curve (c) by less than one Mev. On the other hand, if many of these photoprotons are directly excited in the nucleus and escape before a compound nucleus can be formed,[9,10] the (γ, p) cross sections will comprise a much larger fraction of curve (a). To settle such questions it is necessary to determine the energy distribution of the photoprotons from lead.

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Yields of α-, n-, and γ-Radiation from Chlorine Bombarded with Protons

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THE $Cl(p, \gamma)A$ reaction was first studied by Curran and Strothers[1] who found indications of three broad resonances at 650, 800, and 1000 kev. Tangen *et al.*[2,3] found four sharp resonances at 427, 447, 500, and 532 kev.

Weimer, Kurbatow, and Pool[4,5] found that bombardment of chlorine with fast protons resulted in a radioactive gas with a half-life of 34 days. They ascribed the activity to A^{37} formed in the process $Cl^{37}(p, n)A^{37}$. Richards *et al.*[6,7] detected the neutrons from this process and studied the excitation function. They found the threshold energy of the protons to be 1639 kev.

Using targets of unseparated chlorine ($PbCl_2$) and with the technique of proton bombardment and γ-detection previously described,[8] we have found 86 γ-resonances in the voltage region from 500 to 2150 kev. (See Fig. 1.) A few of the strongest of these peaks have also been detected with targets of separated chlorine prepared by Dr. J. Koch and Mr. K. O. Nielsen by the methods previously used for neon and argon.[9,10] These peaks are: Cl^{35}: 858, 888, 1102, 1258, 1484, and 1510 kev; Cl^{37}: 1090 kev.

Neutrons have been searched for with boron-filled proportional counters surrounded by paraffin wax. In the voltage region from 1600 to 2300 kev, 47 neutron-emitting levels have been found, the lowest situated at 1637 kev in fair agreement with the threshold found by Richards *et al.*

Six of these resonances, i.e., 1928, 1974, 2014, 2028, 2079, and 2108 kev, have been detected in Cl^{37} targets, whereas none was found in Cl^{35}. This is in accordance with the highly negative Q-value calculated from accepted mass values for the $Cl^{35}(p, n)A^{35}$ process.

α-particles have been looked for (at a right angle to the proton beam) with a proportional counter, magnetic deflection being used to separate α-particles from scattered protons. In the interval from 1450 to 2040 kev, 10 resonances giving rise to α-emission have been found. The energy of the α-particles has been estimated from pulse size and gives a Q-value of 3.2 Mev. As the Q-value for the process $S^{32}(\alpha, p)Cl^{35}$ is known to be -2.1 Mev,[11,12] the α-particles are ascribed to the process $Cl^{37}(p, \alpha)S^{34}$.

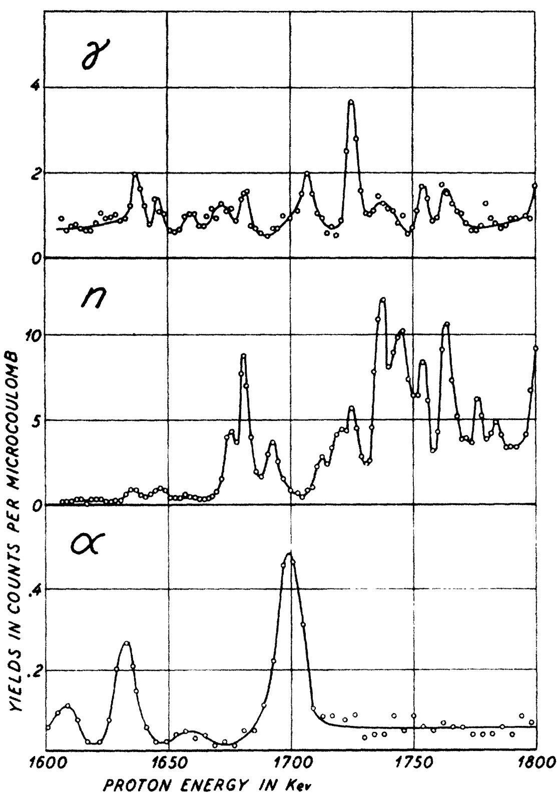

FIG. 1. Section of α-, n-, and γ-yield curves of a $PbCl_2$-target of about 4-kev stopping power.

At most resonance voltages more than one sort of radiation has been observed, e.g., at 1838 kev, 1928 kev, and at 1974 kev we have found conspicuous peaks in both the α-, γ- and n-curves, but a few strong peaks (e.g., the n-peak at 1693, the γ-peak at 1707, and the α-peak at 1699 kev) show up only in one of the yield curves.

In order to decrease the effect of voltage uncertainties, measurements were always made either of the n- and γ-yields simultaneously or of the n- and α-yields simultaneously.

In the whole voltage region the resonance widths are smaller than the experimental widths, which are for γ- and neutron peak 6–8 kev and for α-peaks 15 kev.

The average distance between the observed neutron peaks is about 14 kev. For the γ-peaks the distance is the same in the interval from 800 to 1500 kev whereas it is 25 kev from 1500 to 2150 kev. From this, however, it cannot be inferred that the density of γ-levels decreases with increasing energy, as the number of small peaks which are concealed by the background rises markedly with voltage. This is not the case with the neutron curve, where the background is much smaller. A more detailed account of the experiments and a closer discussion of the results will shortly appear in the Communications of the Copenhagen Academy (Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd.).

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A Note on the Theory of Directional Correlation

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As a general formula for the correlation of 2 successive emissions of any nuclear particles, Falkoff and Uhlenbeck[1] found

$$W(\vartheta)=\Sigma_{M_aM_bM_c}P_{M_aM_b}(0)P_{M_bM_c}(\vartheta)=Q+R\cos^2\vartheta+S\cos^4\vartheta+\cdots, \quad (1)$$

where M_a, M_b, M_c are the magnetic quantum numbers of the 3 energy levels A, B, C. $P_{M_aM_b}$ is the relative probability for the transition $M_a\rightarrow M_b$ in the notation of F.U. In a more natural way $W(\vartheta)$ can be expanded in Legendre polynomials:

$$W(\vartheta)=\Sigma a_kP_k(\cos\vartheta). \quad (2)$$

Here a_k is a product of 2 factors I_k and II_k, which are dependent only upon the first and upon the second of the two transitions, respectively,

$$a_k=\mathrm{I}_k\mathrm{II}_k. \quad (3)$$

For pure transitions

$$\mathrm{I}_k=\{\Sigma_mC_{LmL-m}{}^{k0}(-1)^mF_L{}^M(0)\}W(I_BI_AkL|LI_C), \quad (4)$$

and the same formula holds for II_k with I_C replacing I_A. $W(I_BI_AkL|LI_B)$ is the Racah coefficient,[2] $C_{LmL-m}{}^{k0}$ the Clebsch-Gordon coefficient as used, for example, in the paper of Gardner.[3] If the influence of the magnetic field of the electronic shells on the angular correlation has to be taken into account, the general formula is

$$a_k=\mathrm{I}_k\mathrm{II}_kG_k, \quad (5)$$

where G_k is an attenuation factor, given by

$$G_k=\sum_{FF'}\frac{(2F+1)(2F'+1)|W(I_BJkF|F'I_B)|^2}{1+(\nu_{FF'}|2\gamma)^2}. \quad (6)$$

Following Goertzel,[4] J denotes the electronic angular momentum, F the total angular momentum, $\nu_{FF'}$ the hyperfine splitting, and $4\pi\gamma$ the total transition probability of the intermediate nuclear state B. G_k is completely independent of multipole order and of the spins of initial and final state. G_k can be split up into a part $F=F'$ and into interference terms $F\neq F'$. The latter are negligible when the interaction is strong $\nu_{FF'}\gg 2\gamma$. We are left then with a minimum correlation.

$$(G_k)_{\min}=\Sigma_F(2F+1)^2|W(I_BJkF|FI_B)|^2.$$

The case $J=\frac{1}{2}$ can be easily discussed. The sum of the Racah