arrangement, to lead to the total matrix element

$$M=(ie/m)(2\pi/k)^{\frac{1}{2}}\sum c^{(\lambda)}\langle T_{\mu}{}^{(\lambda)}\rangle$$

$$\times\int(\bar{\chi}(0)T_{\mu}{}^{(\lambda)}\mathcal{G}_{E_n-k}(0,\mathbf{r})$$

$$\times e^{-i\mathbf{k}\cdot\mathbf{r}}\mathbf{e}_{\eta}(\partial_{\eta}-\tfrac{1}{2}\sigma_{\eta\rho}k_{\rho})\psi_n(\mathbf{r}))d\tau, \quad (3)$$

in which $\sigma_{\eta\rho}=(i/2)[\gamma_{\eta},\gamma_{\rho}]$ and $k_{\rho}=(\mathbf{k},k)$. The function $\mathcal{G}_{E_n-k}(0,\mathbf{r})$, which is a Green's function for the second order Dirac equation, implicitly embodies the summation over intermediate states. It is quite adequately approximated in the present context, by the simpler nonrelativistic Green's function for the propagation of an electron with energy E_n-k in a Coulomb field. The latter function is defined in terms of Coulomb wave functions $\varphi_j(\mathbf{r})$ as

$$G_{E_n-k}(0,\mathbf{r})=\sum_j\frac{\varphi_j(0)\varphi_j{}^*(\mathbf{r})}{E_j-E_n+k}. \quad (4)$$

Since this expression has spherical symmetry about the origin, it is easily evaluated by solving the appropriate radial Schrödinger equation. The occurrence of a particularly tractable form for the Coulomb Green's function stems from the fact that electron capture necessarily takes place at the center of force. The solution is found to contain a Whittaker function and has integral representation,

$$G_{E_n-k}(0,\mathbf{r})=(m\beta/\pi)e^{-\beta r}\int_0^{\infty}e^{-2\beta ru}\left(\frac{1+u}{u}\right)^{Z/\beta a_0}du, \quad (5)$$

for $k-E_n>Z^2$ Rydbergs, where $\beta=[2m(k-E_n)]^{\frac{1}{2}}$, and a_0 is the Bohr radius.

With the expression (5), the integrations required to find the matrix element (3) may be carried out analytically. The resulting γ-ray spectra for capture from the various significant electron shells have been calculated for Fe^{55} which has an energy release[1] of 220 kev. They are shown in Fig. 1. The spectra for capture from S states, aside from their slightly different maximum energies, have the general shape $x(1-x)^2$. The P-state spectra are by comparison quite weak at high energies and extremely intense near the characteristic x-ray lines. The processes responsible for the intensity peaks are ones in which capture of an S electron is followed by a radiative transition from a higher P state. They differ from the normal and highly probable course of electron capture and subsequent emission of characteristic x-rays only by relaxation of the requirement of energy conservation in the intermediate state. The P state spectra of Fig. 1 may, in fact, be thought of as representing the extreme wings of the characteristic x-ray lines.

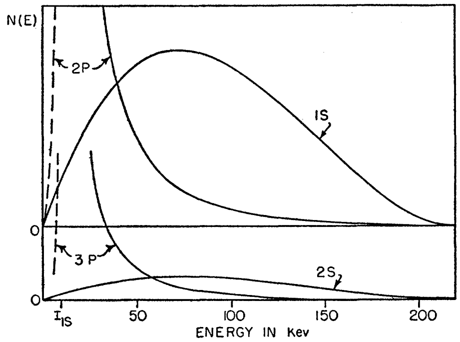

FIG. 1. Gamma-ray spectra for radiative capture from various electron shells of Fe^{55}. The characteristic x-ray region lies below I_{1S}, the K-shell ionization energy.

For a given energy release, the intensities of the P-state spectra increase relative to those of the S states roughly as the square of the nuclear charge. Hence for Ge^{71} and Cs^{131} the P-state contributions should dominate all save the upper ends of the spectra. The shapes observed[2] corroborate this. Screening of the Coulomb field will act to reduce somewhat the intensities of spectra from the $n=2$ and 3 shells and will be taken into account in seeking quantitative agreement with experiment.

The analysis described may be applied equally well to forbidden transitions which will be characterized in general by differing spectrum shapes. The capture in Fe^{55} for which log ft equals 6.1, is evidently allowed, but quite unfavored, a fact which might be anticipated from the shell model since $\Delta l=2$. A detailed account of the techniques employed including an examination of the effects of screening is in preparation. We wish to thank Dr. T. Berlin for calling this problem to our attention.

[1] L. Madansky and F. Rasetti, Phys. Rev. **94**, 407 (1954).

[2] B. Saraf, Phys. Rev. **94**, 642 (1954); also work on Ge^{71} [B. Saraf, Phys. Rev. **95**, 97 (1954)].

[3] Emmerich, Singer, and Kurbatov, Phys. Rev. **94**, 113 (1954).

[4] P. Morrison and L. I. Schiff, Phys. Rev. **58**, 24 (1940).

[5] We employ units in which $\hbar=1$, $c=1$.

Proton-Neutron Coincidences in the High-Energy Photodisintegration of Lithium*

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WHEN photons with energies of several hundred Mev interact with complex nuclei, they eject high-energy protons and neutrons in greater numbers than compound nucleus formation can explain. The cross sections and angular distributions of such reactions indicate a direct interaction between the photons and individual nucleons. Of the various models proposed to explain these results, perhaps the most appealing is the "pseudodeuteron" model discussed by Levinger.[1] Several experiments have tended to confirm this theory,[2] but the clearest proof would seem to be the observation of the simultaneous ejection of a proton and a neutron in the photodisintegration of a complex element. We have recently observed coincident protons and neutrons from lithium irradiated with 265-Mev bremsstrahlung from the University of Illinois betatron.

In our experiment a proton counter consisting of a series of five organic scintillators was set at 76.5° to the x-ray beam. Pulse heights photographed from an oscillograph in three of the organic scintillators allowed an almost unambiguous identification of the particle and its energy. Protons in the energy range 65 Mev to about 200 Mev were observed in the same betatron run. When this counter was run by itself, electrons, mesons, meson stars, and protons were all clearly distinguished. This counter is more adequately described in the accompanying letter on the photodisintegration of deuterium.

In order to observe coincident protons and neutrons a counter 4 inches in diameter by 10 inches long filled with terphenyl in phenylcyclohexane was placed behind 2 inches of lead on the side of the beam opposite the proton counter. A coincidence between this counter and the proton telescope triggered the sweep of the oscillograph used for photographing the pulse heights. The pulse height distribution in the proton telescope clearly indicated that only protons were in coincidence with neutrons on the other side of the beam.

A further check on the two-body nature of such interactions was made by swinging the neutron counter in angle. Figure 1 shows the number of coincidences from a lithium target as a function of the neutron counter angle. A definite angular correlation is observed. The angular correlation from deuterium is shown for comparison. The equality of the peak angles gives striking confirmation of the two-body nature of the interaction. The broadening of the lithium curve is about what would be expected from the internal momentum distribution of the "pseudodeuteron" in the nucleus.

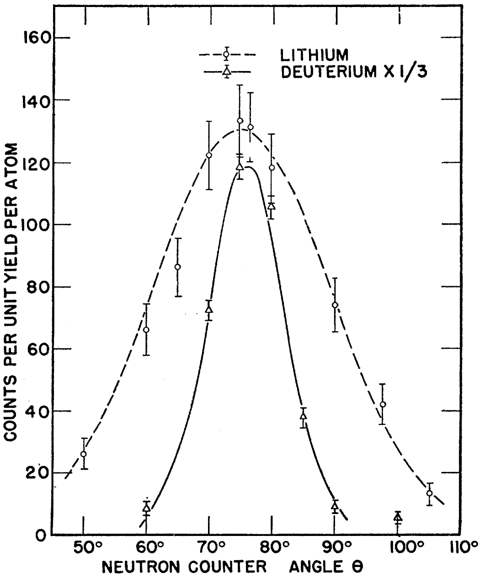

FIG. 1. Neutron-proton coincidences as a function of the angle of the neutron counter. The proton counter is fixed at 76.5°. The lithium ordinate is in most cases the actual number of counts observed. The deuterium curve has been normalized for number of atoms in the beam and reduced by a factor of three to facilitate comparison.

In a supplementary experiment with A. O. Hanson and T. Yamagata described in an accompanying letter, the liquid deuterium target was used to measure the efficiency of our neutron counter as 6.8 percent. We can then estimate that 53 percent of all photoprotons from lithium have a correlated neutron. If the probability of subsequent interactions in the nucleus is taken into account, the possibility remains that all photoprotons in this energy range are produced in such a two-body process.

We have observed this effect qualitatively in beryllium, carbon, boron, nitrogen, and oxygen targets.

The data presented in this letter are at best preliminary, and quantitative conclusions are subject to considerable uncertainty. However, the qualitative existence of correlated protons and neutrons in the high-energy photoeffect leaves little doubt of the basic correctness of the "pseudodeuteron" model for at least a large fraction of the interactions.

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[1] J. S. Levinger, Phys. Rev. 84, 43 (1951).

[2] J. W. Weil and B. D. McDaniel, Phys. Rev. 92, 391 (1953). See this paper for other references.

Photodisintegration of Deuterium by 265-Mev Bremsstrahlung

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We have measured the differential cross section of the photodisintegration of deuterium at 45°, 75°, and 120° in laboratory coordinates.

Figure 1 shows the schematics of our experimental arrangement. The liquid deuterium target[1] was placed in the x-ray beam from the University of Illinois betatron. The proton counter telescope consisted of five organic scintillators. Two of them, viewed by 931-A phototubes, supplied pulses for a coincidence circuit which triggered the sweep of an oscilloscope. The other three crystals were viewed by 5819 phototubes. Their outputs were suitably delayed, put in a mixing and integrating circuit, and displayed on the oscilloscope. 35-mm photographs of the individual traces were later projected and the pulse heights measured.

In most cases, pulses from protons, mesons, and electrons are readily distinguishable, since particles differing