surface and decreases almost linearly up to the range value.

[4]The following checks were performed: (i) changing the etching or cleaning procedure of the collector surface; (ii) changing the threshold energy of the electrons detected from 0 eV up to 15 eV by means of a properly biased control grid located between the collector and the Channeltron input, so as to detect preferentially the less deeply implanted ^{235m}U. No measurable difference in decay rate was found, while differences of up to 5% were found with unclean collectors, e.g., for Pt with traces of hydrocarbons on the surface: $\lambda(0\text{ eV}) = +2.583 \pm 0.006) \times 10^{-2}\text{ min}^{-1}$ and $\lambda(15\text{ eV}) = (2.445 \pm 0.029) \times 10^{-2}\text{ min}^{-1}$.

[5]J. Friedel, Ann. Phys. (Paris) 9, 158 (1954), and Nuovo Cimento, Suppl. 7, 287 (1958).

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[7]M. A. Blokhin, V. P. Satchenko, I. Y. Nikiforov, J. Phys. (Paris) 32, C4-211 (1972).

[8]It may be noticed that the relative variation of $\lambda(^{235m}\text{U})$ between the two extreme cases studied here, namely, Mn $[\lambda = (2.6613 \pm 0.0020) \times 10^{-2}\text{ min}^{-1}]$ and Pd $[\lambda = (2.5269 \pm 0.0030) \times 10^{-2}\text{ min}^{-1}]$ amounts to $(5.2 \pm 0.2)\%$.

[9]C. Kittel, *Quantum Theory of Solids* (Wiley, New York, 1963), p. 358.

^{4}He$(\gamma, p\pi^-)$ Cross Section Around $\Delta(1236)$

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The cross section of the reaction $^4\text{He} + \gamma \rightarrow p + \pi^- + (ppn)$ has been measured in the region of the first resonance for various values of the recoil momentum. An anomaly is observed for high values of this momentum and a tentative explanation is suggested.

The experiment described in this Letter was performed in order to understand how pion photoproduction on a quasifree nucleon in ^{4}He is affected by the proximity of the other nucleons, near the $\Delta(1236)$ resonance.[1]

The central idea of this experiment was to compare the photoproduction cross section

$$\gamma + {}^4\text{He} \rightarrow p + \pi^- + (ppn), \qquad (1)$$

for a given recoil momentum $\vec{\text{P}}_R$ of the residual (ppn) nucleus, to the elementary one $\gamma + n \rightarrow p + \pi^-$, because in these reactions we could easily detect the two emitted products.

For low values of P_R the probability of finding the neutron far enough from the $A-1$ other nucleons is large, and the nucleus may be described correctly by the independent-particle model. Thus, we may think that the impulse approximation is valid. In this model we have $-\vec{\text{P}}_R = \vec{\text{P}}_0$, where $\vec{\text{P}}_0$ is the momentum of the target neutron before the interaction. Then the cross section for the Reaction (1) as a function of the invariant mass Q of the proton-pion pair can be accurately predicted from the cross section for the elementary reaction and the nucleon momentum distribution $\mathcal{P}(P_0)$.

As we were interested in looking for a departure from the predictions of this model, we decided to study the photoproduction at high values of P_R.

Our experimental setup permitted us to determine Q and $\vec{\text{P}}_R$ by measuring the pion and the proton four-momenta in two magnetic spectrometers when the proton, the pion, and the photon lie in the same plane. The spectrometer for the pion could analyze a maximum momentum of 400 MeV/c and had a momentum acceptance of 6%. The corresponding figures for the proton spectrometer were 700 MeV/c and 12%. The particles were detected in each focal plane by a counter telescope consisting of two plastic scintillators. The particle identification was made by means of the energy losses and by the difference in time of flight. The target was 0.65-g/cm^2 liquid helium. The low counting rate of this coincidence experiment requires the use of a high-intensity photon beam with a duty cycle as high as possible: The Saclay linear accelerator facility offered us these conditions.[2] The bremsstrahlung beam intensity was measured by a Wilson-type gas quantameter. We estimate that the systematic error in absolute value is less than 10%.

The kinematics of (1) are governed, in the lab frame, by the following equations:

$$\vec{\nu} = \vec{\text{P}}_p + \vec{\text{P}}_\pi + \vec{\text{P}}_R, \qquad (2)$$

$$\nu^0 + M_{^4\text{He}} = P_p{}^0 + P_\pi{}^0 + M_{^3\text{He}} + T_R + E_R, \qquad (3)$$

where $M_{^4\text{He}}$ and $M_{^3\text{He}}$ are the ground-state masses of ^{4}He and ^{3}He; $(\vec{\nu}, \nu^0)$, $(\vec{\text{P}}_\pi, P_\pi{}^0)$, and $(\vec{\text{P}}_p,$

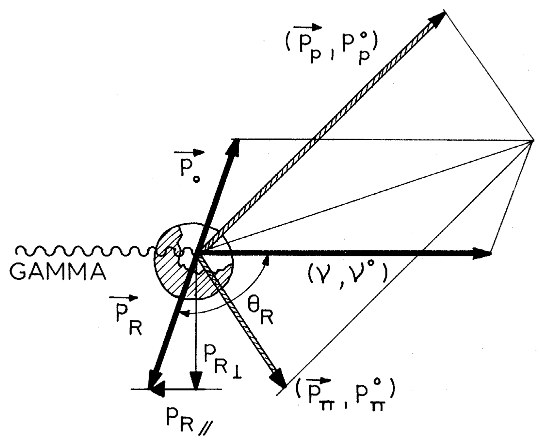

FIG. 1. Kinematics of the reaction $\gamma + {}^4\mathrm{He} \to p + \pi^- + (npp)$ in the lab frame. $(\vec{\nu}, \nu^0)$, $(\vec{P}_\pi, p_\pi^{\,0})$, $(\vec{P}_p, p_p^{\,0})$ are the four-momenta of the photon, the pion, and the proton. $\vec{P}_R$ is the recoil momentum of the (ppn) residue. θ_R is the angle between $\vec{P}_R$ and the photon. In the impulse approximation, the initial nucleon momentum $\vec{P}_0 = -\vec{P}_R$.

$P_p^{\,0}$) are the four-momenta of the photon, pion, and proton. T_R, E_R, and $\vec{P}_R$ are, respectively, the kinetic energy, excitation energy, and recoil momentum of the three-nucleon system (Fig. 1).

There are five unmeasured quantities, i.e., $\vec{P}_R$, E_R, and ν^0, which are coupled by the four equations (2) and (3); hence, one of them remains undetermined. The recoil-momentum component perpendicular to the photon direction, $P_{R\perp}$, is well known. For the two other quantities determined experimentally, one can choose $\nu^0 - P_{R\parallel}$ and $\nu^0 - E_R - T_R$, where $P_{R\parallel}$ is the component of $\vec{P}_R$ parallel to the photon beam. The uncertainty in $P_{R\parallel}$ does not strongly affect P_R—which is the quantity of interest—provided that the direction of $\vec{P}_R$ is judiciously chosen. Assuming $E_R = 0$ and making a choice of $\vec{P}_R$, Q, and ω (the angle between the pion and the photon in the pion-nucleon c.m. frame), we determine the corresponding values of $\vec{P}_\pi$ and $\vec{P}_p$. For one set of $\vec{P}_\pi$ and $\vec{P}_p$, if E_R is different from zero, Q, ω, and $\vec{P}_{R\perp}$ remain the same; then changes in $P_{R\parallel}$ and ν^0 are given by

$$\delta_{P_{R\parallel}} = \delta\nu^0 \simeq \frac{E_R(1 + E_R/2M_{^3\mathrm{He}})}{1 + P_{R\parallel}/M_{^3\mathrm{He}}}. \tag{4}$$

The missing-mass spectrum obtained in ${}^4\mathrm{He}(p, 2p)$ reactions[3] does not extend above 30 MeV. As a result, for a value of $P_R = 50$ MeV/c, $P_{R\parallel} = 0$, and changing E_R from 0 to 30 MeV increases P_R by only 8 MeV/c. The experimental resolution also introduces uncertainties into the kinematical quantities; and for $P_R = 50$ MeV/c and $Q = 1206$ MeV, we have $\Delta P_R = 15$ MeV/c and $\Delta Q = 7$ MeV. The measured cross section must be compared for the same set of final states of the residual nucleus. For this purpose, the end-point energy of the bremsstrahlung spectrum was always set at 100 MeV above the photon energy $E_{\gamma 0}$ calculated with $E_R = 0$. The $E_{\gamma 0}$ values are indicated in Table I.

If we assume the impulse approximation and the independent particle model, as represented in Fig. 2(a), and neglect all rescattering phenomena,

TABLE I. The experimental conditions and the measured cross sections.

p_R MeV/c	θ_R	Q (MeV)	$Q_{NN\pi}-2m$ (MeV) a	E_{γ_0} (MeV) b	$\frac{d\sigma(Q,\omega,p_R,\theta_R)}{d\Omega_\omega d\Omega_R p_R^2 dp_R}$ (μb fm^3 sr^{-2}) c
50	90	1136	212	246	15.5 ± 2.3
		1147	223	259	19.3 ± 2.7
		1156	233	271	18.6 ± 2.6
		1171	250	290	17.6 ± 2.9
		1176	256	297	25.4 ± 2.9
		1186	267	309	20.6 ± 2.8
		1206	289	335	20.6 ± 1.9
		1236	324	376	16.1 ± 1.2
		1256	346	403	12.3 ± 1.7
		1286	380	449	12.5 ± 0.7
		1306	404	473	8.7 ± 0.9
125	90	1206	302	346	7.4 ± 1.5
200	90	1146	260	288	1.4 ± 0.7
		1156	270	300	3.8 ± 1.9
		1161	276	306	3.2 ± 0.7
		1169	285	317	3.1 ± 0.6
		1176	292	326	3.5 ± 0.5
		1191	309	346	2.1 ± 0.5
		1206	325	365	2.1 ± 0.4
		1226	348	392	1.9 ± 0.4
		1246	370	419	1.8 ± 0.3
		1266	393	447	0.7 ± 0.3
		1286	416	475	0.6 ± 0.3
275	90	1206	360	394	0.4 ± 0.5
300	50	1186	299	314	1 ± 0.5
		1206	318	336	0.2 ± 0.5
		1246	357	383	0.2 ± 0.4

[a] $Q_{NN\pi}$ is the invariant mass of the three-particle system: the pion, the proton, and an unobserved nucleon with a momentum equal to $\vec{P}_R$ (m is the nucleon mass).
[b] $E_{\gamma 0}$ is the energy of the photon inducing the reaction when $E_R = 0$. The end-point energy of the bremsstrahlung spectrum was chosen about 100 MeV above $E_{\gamma 0}$.
[c] Experimental cross sections.

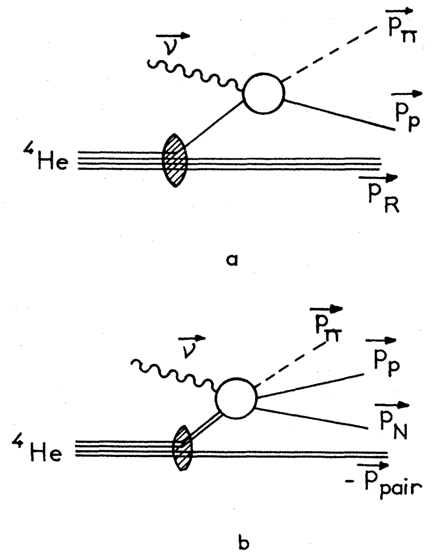

FIG. 2. Diagrams for the $(\gamma, p\pi^-)$ reaction. (a) One-nucleon process; (b) two-nucleon process. $\vec{P}_{pair}$ is the initial momentum of the pair involved in the photoproduction process, and $\vec{P}_N$ is the momentum of the detected nucleon.

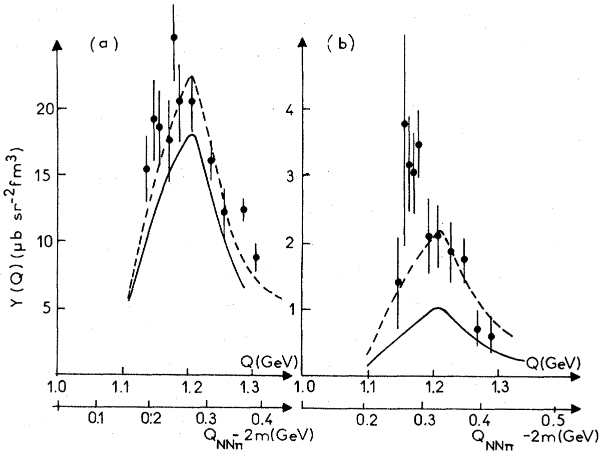

FIG. 3. The differential cross-section values $Y(Q) = d\sigma/d\Omega_R d\Omega_\omega P_R^2 dP_R$ of the reaction ${}^4\mathrm{He}(\gamma, p\pi^-)$ for $\theta_R = 90°$ and $\omega = 90°$. (This means that the recoil $\vec{P}_R$ vector occurs on the same side of the photon beam as the emitted pion.) The solid lines correspond to the calculation outlined in Sect. 3.1 of Ref. 1 (a realistic single-particle wave function and optical-parameter set III were used). The dashed curves are obtained by multiplying by the normalization factors 1.25 for $P_R = 50$ MeV/c in (a), and 2.1 for $P_R = 200$ MeV/c in (b).

the cross section may be written

$$\frac{d\sigma(Q, \omega, P_R, \theta_R)}{d\Omega_\omega d\Omega_R P_R^2 dP_R} = \frac{d\sigma(Q, \omega)}{d\Omega_\omega} \mathcal{P}(P_0), \qquad (5)$$

where θ_R is the angle of the recoiling three-nucleon system in the laboratory frame, and $d\sigma(Q, \omega)/d\Omega_\omega$ is the cross section for the elementary reaction.[4] To take into account the distortion effects of the nuclear potential on the pion and proton waves, we must replace $\mathcal{P}(P_0)$ in formula (5) by the distorted momentum distribution $\mathcal{P}'(\vec{P}_0, Q, \omega)$, calculated in a manner described in Ref. 1. We must point out that for a given value of P_0 the function $\mathcal{P}'(\vec{P}_0, Q, \omega)$ varies slowly versus Q. Consequently, the maximum of the cross section will be practically located at the value for photoproduction on free nucleons, $Q = 1206$,[4] and the width of the bump will have the same order of magnitude, about 120 MeV.

The prediction of this calculation and the experimental points are shown in Fig. 3 as a function of the invariant mass of the pion-proton system for two different values of P_R (50 and 200 MeV/c). All our results are summarized in Table I. It appears that for $P_R = 50$ MeV/c the experimental points are well fitted by the theoretical cross section apart from a normalization factor of 1.25 (dashed curve). This factor can be easily explained by uncertainties in parameters used for the calculation. This confirms that the impulse approximation adequately describes this phenomenon at low values of neutron momentum.

On the other hand, for $P_R = 200$ MeV/c the theoretical cross section even when normalized is not able to reproduce the experimental results. A structure appears for $Q = 1165$ MeV corresponding to a photon energy of 315 MeV (for $E_R = 0$).

As a guide for our investigation, we are tempted to attribute this anomaly found at high recoil momentum to a resonant process with two or more nucleons or even the whole nucleus. The simplest process of this kind involves only a $\Delta(1236)$ and a nucleon and is given in Fig. 2(b). In this case the resonant system is characterized by its invariant mass $Q_{NN\pi}$. Assuming that the nucleon pair is quasifree and has an initial momentum $\vec{P}_{pair}$, we obtain approximately

$$Q_{NN\pi} - 2m \simeq Q - m + \frac{m+Q}{2Q}\left|\vec{P}_R - \frac{m}{m+Q}\vec{\nu} + \frac{Q}{m+Q}\vec{P}_{pair}\right|, \qquad (6)$$

where m is the rest mass of the proton. $Q_{NN\tau}$ values for $P_{pair} = 0$ are given in Table I.

The contribution of this process to the differential cross section should not vary rapidly with P_R because the phase-space variations are small in our experimental conditions. It cannot be seen at 50 MeV/c because the single-nucleon contribution is too large. At $P_R = 300$ MeV/c (see Table I) preliminary experimental values are in good agreement with the 200 MeV/c one, while the impulse approximation predictions[1] are smaller by an order of magnitude.

The observed width of the structure ($\simeq 35$ MeV) is determined by the convolution of the natural width with that due to the motion of the nucleon pairs, as shown by Eq. (6). A rough evaluation of the latter gives about 40 MeV, showing that the natural width must be smaller than this value.

In relation to this narrow width we have considered possible selection rules inhibiting the decay. We note that on the deuteron (isospin $T=0$), the photon can produce only $T=1$ excited states, whereas in ^{4}He a pair of nucleons can be found in a $T=1$ state and, thus, the photon can excite this pair to a $T=2$ state. To investigate the isospin dependence we asked Piazza, Rossi, and Susinno to reanalyze their data on the reaction $\gamma + d \rightarrow \pi^- + p + p$. Since they did not find any corresponding anomaly, it is tempting to attribute our phenomenon to the excitation of $T=2$ states which cannot decay into two nucleons and therefore have a much longer lifetime than those observed in similar two-baryon $T=1$ systems such as occur, for example, in reactions $\pi^+ + d \rightarrow p + p$ and $\gamma + d \rightarrow p + n$.

We are indebted to A. Bloch and C. Lopata, who built all the electronics used in this experiment, to G. Thetu and A. Godin for the liquid-helium target, and to all the technical groups of the Département de Physique Nucléaire et Hautes Energies. We also want to thank the machine crew who provided a good electron beam during these measurements. Finally, we wish to acknowledge helpful discussions with C. Tzara during this experiment.

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γ-Neutrino Angular Correlations in Muon Capture*

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Doppler-broadened γ-ray transitions have been observed for the first time in the reaction $\mu^- + (Z,A) \rightarrow (Z-1,A) + \nu_\mu$, which are suitable for analysis in terms of angular correlations between the neutrino and a de-excitation nuclear γ-ray. The observed transitions are interpreted in terms of γ-ν correlation coefficients which are functions of the weak-interaction coupling constants.

Experimental determinations of the weak-interaction coupling constants in muon capture have principally involved measurements of capture rates to specific final states.[1] The values of the coupling constants extracted from these experiments are very sensitive to the choice of initial- and final-state nuclear wave functions. In a series of recent articles, Popov and co-workers[2-8] and Oziewicz and Pikulski[9] have made theoretical studies of the angular correlations between the emitted neutrino and the de-excitation γ ray which occurs following muon capture to specific excited nuclear states. They find that the correlations in certain allowed transitions are sensitive to the induced pseudoscalar coupling C_P and, to a precision of 10%, should be independent of the nuclear wave functions involved. Grenacs *et al.*[10] have proposed a method to observe these correlations in terms of Doppler broadening of the transition γ ray due to the recoil of the nucleus upon neutrino emission. Using a high-resolution Ge(Li) spectrometer, we have observed several Doppler-broadened transitions in ^{28}Al excited by muon capture in ^{28}Si. Several of the transitions, the first such reported, are suitable for analysis in terms of γ-ν correlations.

The correlation function W^N for Nth forbidden muon capture can be written[9] in terms of the