ANGULAR CORRELATION BETWEEN GAMMA RAYS AND 14-MeV NEUTRONS SCATTERED INELASTICALLY BY CARBON

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The n′-γ angular correlation is investigated for 14-MeV neutrons scattered inelastically by carbon nuclei at angles $\vartheta_n = -24°$, 40°, and 135°.

1. INTRODUCTION

IN recent years many investigators have studied the angular correlation between inelastically scattered nucleons and de-excitation γ rays. It was the purpose of these investigations to elucidate the mechanism of inelastic interactions between nucleons and nuclei. In most instances fast protons were scattered by relatively light nuclei such as C, Mg, and Si.[1-5] Protons offer a number of methodological advantages over neutrons for these experimental studies. However, the utilization of neutrons is of decided interest.[6-10] A comparison of the inelastic scatterings of protons and neutrons having comparable energies furnishes additional information about the mechanism of the process. We therefore measured the n′-γ angular correlation in the inelastic scattering of 14-MeV neutrons by C^{12}, for which experimental data on inelastic proton scattering is available.[1-11] The use of a neutron beam, unlike protons, enables the study of inelastic scattering by all, including heavy, nuclei at relatively low energies. Measurements on C^{12} are also of methodological importance for determining the possibility of similar investigations in experimentally more complicated cases.

Data on the angular correlation between inelastically scattered nucleons and γ rays are frequently used to determine whether a process involves a compound nucleus or a direct nuclear interaction mechanism.[11-12] In the case of a compound nucleus an exact calculation requires that we know the specific contributions of the levels through which the reaction proceeds, but in most cases this is impossible. In practice therefore either a case involving a single level is studied or the existence of many levels is assumed whenever permissible.

Several authors have investigated angular correlations based on different hypotheses regarding the mechanism of direct nuclear interactions. All results are in qualitative agreement concerning the symmetry of the correlation function.[11,13,14] The agreement of the direct-interaction theory with experiment is usually regarded as a confirmation of this mechanism. The problem is actually more complicated, because it is not clear whether a compound-nucleus mechanism might not lead to the same relations in some instances. A more reliable conclusion is derived from the contrary: qualitative disagreement with direct-interaction theories can be regarded as an indication that the reaction takes place through a compound nucleus.

2. ANGULAR CORRELATION BETWEEN A NUCLEON AND A GAMMA RAY

We shall now consider the angular correlation in the case when as a result of scattering a 2^+ level is excited, after which a γ ray is emitted in a transition to an 0^+ ground state. This occurs in the C^{12} nucleus, which can be excited to a 2^+ state at 4.43 MeV. We shall consider the angular distribution in the reaction plane. Let the incident beam form the angle φ_1, while an inelastically scattered nucleon forms the angle φ_2, relative to an arbitrary axis lying in the reaction plane. The probability of photon emission at the angle θ_γ independently of the inelastic scattering mechanism is[2,15]

$$f(\theta_\gamma) = a + b\sin^2 2(\theta_\gamma - \theta_0) + c\sin^2(\theta_\gamma - \theta_0'). \qquad (2.1)$$

Here a, b, c, θ_0, and θ_0' depend, as a general rule, on the scattering angle ($\vartheta_n = \varphi_2 - \varphi_1$). The angular distribution will not change if the reference axis is rotated through an arbitrary angle α, i.e.,

θ_γ is replaced by $\theta_\gamma + \alpha$; hence

$$\theta_0(\varphi_1 + \alpha, \varphi_2 + \alpha) = \theta_0(\varphi_1, \varphi_2) + \alpha. \qquad (2.2)$$

From the foregoing we have

$$\theta_0(\varphi_1, \varphi_2) = -\theta_0(-\varphi_1, -\varphi_2) + n\pi/2, \qquad (2.3)$$

where n is an arbitrary integer (0, 1, ...). Since the period of the function $\sin^2 2(\theta_\gamma - \theta_0)$ is $\pi/2$, Eq. (2.3) reflects the obvious fact that when the signs of the angles φ_1 and φ_2 are reversed the sign of θ_0 is also reversed (up to a whole number of periods). The same applies to the angle θ_0', except that $n\pi/2$ must be replaced by $n\pi$. However, in accordance with experimental findings for the $(p, p'\gamma)$ reaction in carbon,[1] we shall assume that the third term in (2.1) can be neglected, i.e., that the coefficient c is small.

The requirements (2.2) and (2.3) will be satisfied if

$$\theta_0(\varphi_1, \varphi_2) = n\pi/4 + a_1\varphi_2 + (1 - a_1)\varphi_1$$
$$+ a_3(\varphi_2 - \varphi_1)^3 + a_5(\varphi_2 - \varphi_1)^5 + \ldots \qquad (2.4)$$

We shall assume that when θ_0 is expanded in powers of the nucleon scattering angle $\vartheta_n = \varphi_2 - \varphi_1$, the third and higher powers can be neglected. Then, if the direction of the incident particle is taken as the reference axis (i.e., $\varphi_1 = 0$),

$$\theta_0 = n\pi/4 + a_1\vartheta_n. \qquad (2.5)$$

In this case a_1 is not entirely arbitrary. Indeed, both $\vartheta_n = \pi$ and $\vartheta_n = -\pi$ represent the same case of nucleon scattering backward. Therefore the condition

$$a_1\pi = -a_1\pi + m\pi/2 \quad \text{or} \quad a_1 = m/4, \qquad (2.6)$$

must be satisfied, where m is a positive or negative integer. Thus, if θ_0 is a linear function of the scattering angle, we can represent it by a simple formula that can be tested experimentally:

$$\theta_0 = \frac{n\pi + m\vartheta_n}{4}. \qquad (2.7)$$

The linear dependence of θ_0 on ϑ_n cannot be regarded as theoretically justified; therefore (2.7) must be tested experimentally. If (2.7) is assumed, additional limitations on the magnitude of m can be obtained by making some assumptions regarding the mechanism of the process. Let us assume that in an inelastic process the nucleon spin is unimportant and that the nucleus has zero spin in the ground state. We also assume that at the instant of interaction the system consisting of a nucleon and a nucleus has a completely definite orbital angular momentum l. In the c.m. system this in-

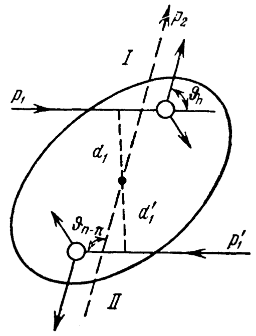

FIG. 1

termediate state is not affected if the momentum of the incident particle is reversed (p_1 becomes p_1' in Fig. 1). These cases will be equivalent classically if the collision parameter d_1 is replaced by d_1' (Fig. 1).

If it is assumed that the direction of the inelastically scattered nucleon p_2 is given, we arrive at the following two conclusions:

(a) The scattering angle is ϑ_n or $\vartheta_n - \pi$ with equal probability (Fig. 1).

(b) The angular distribution of γ rays should not depend on whether the scattering angle is ϑ_n or $\vartheta_n - \pi$.

It is important that (b) follows from (a), although the converse would be false. It follows directly from (b) that m in (2.7) must be an even number.

Let us now consider the special cases of correlation for m = 0, 2, and 4. We then obtain

$$\sin^2 2(\theta_\gamma - n\pi/4), \quad \text{if} \quad m = 0; \qquad (2.8)$$
$$\sin^2 2(\theta_\gamma - \vartheta_n/2 - n\pi/4), \quad \text{if} \quad m = 2; \qquad (2.9)$$
$$\sin^2 2(\theta_\gamma - \vartheta_n - n\pi/4), \quad \text{if} \quad m = 4. \qquad (2.10)$$

In the first case the angular distribution of γ radiation is obviously given completely by the direction of the incident particle (symmetry about 90°; maximum or minimum intensity at the angle $\pi/2$ for n = 0 and n = 1, respectively). In the third case (m = 4) the analogous picture is not related to the direction of the emitted nucleon.

For intermediate values of m the θ_0 axis is determined by the directions of the incident and scattered particles, the angle ϑ_n being divided in a definite ratio. Thus for m = 2 the angular distribution of γ rays is symmetric about $\vartheta_n/2$. This relation is regarded as characteristic of direct nuclear interactions. Indeed, in this case the angular distribution is given by the direction of transferred momentum. If only a small fraction of the primary-particle energy is expended in nuclear excitation, its direction forms the angle

$\vartheta_0 = (\vartheta_n - \pi)/2$; addition or subtraction of $\pi/2$ in this case does not change the angular distribution.[1)] The theory of direct nuclear interactions in the so-called adiabatic approximation[14] gives, as we know, $\theta_0 = (\pi - \theta_n)/2$.[2)] This is well verified, in particular, by the inelastic scattering of protons from C^{12} excited to the 2^+ level.

Equation (2.9) does not contain the assumption of direct nuclear interaction. Equations (2.8)—(2.10) were derived assuming that the intermediate state has a definite orbital angular momentum l (which occurs in reality if a definite compound-nucleus level is excited). The same result is obviously obtained if the intermediate state is a superposition of states of given parity. However, if the parity of the intermediate state is not given, the result is not clear beforehand. We shall consider qualitatively the simplest scheme of direct nuclear interaction. Let us assume that an incident nucleon interacts with only a certain region within a nucleus. If the energy transferred by the interaction comprises only a small fraction of the initial nucleon energy the direction of the transferred momentum forms the angle $(\vartheta_n - \pi)/2$, as already mentioned. The direct-interaction process results in a state of definite parity (2^+ in the considered case); therefore cases I and II in Fig. 1 must lead to an identical angular distribution of γ rays. We must therefore have symmetry about the direction $(\vartheta_n - \pi)/2$; consequently, the simplest scheme of direct nuclear interaction leads to (2.9).

3. EXPERIMENT AND RESULTS

The n'-γ angular correlation in the reaction $C^{12}(n, n'\gamma)C^{12}$ was measured with the geometry shown in Fig. 2. The D + T reaction was the source of 14.2-MeV neutrons, which were emitted from the zirconium-tritium target perpendicular to the beam of 150-keV deuterons bombarding the target.

Figure 3 is a block diagram of the apparatus. Scintillation counters were used to register the coincidences of 4.43-MeV γ rays (from the $2^+ - 0^+$ transition in C^{12}) with neutrons scattered at given angles. The γ rays were registered by a 40×40-mm NaI(Tl) crystal.

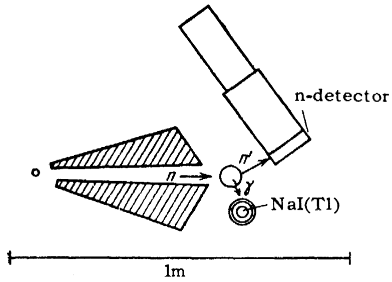

FIG. 2. Diagram of apparatus for measuring n'-γ angular correlations.

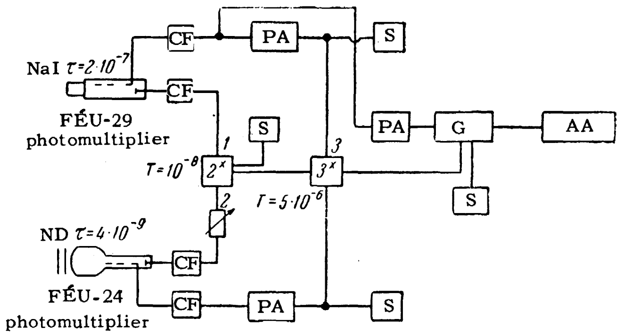

FIG. 3. Block diagram of apparatus for registering n'-γ coincidences. CF – cathode followers, 1 – fast (double) coincidence circuit, 2 – variable delay line, PA – proportional amplifiers (with pulse shaping at output), 3 – triple coincidence circuit, G – gate, AA – amplitude analyzer, S – scaler, ND – neutron detector.

The neutron detector had to satisfy the following requirements. Low sensitivity to γ rays was needed along with sufficient sensitivity to neutrons to permit at least a rough analysis of the fast-neutron spectrum. The detector was to be used in a fast coincidence circuit. These requirements were satisfied by a layered scintillation detector[7] consisting of three round plates, 3.3 mm thick and 85 mm in diameter, made of an organic scintillator. The plates were separated by Plexiglas layers 6 mm thick. This detector, in which the scintillator fills one-third of the volume, is 7% efficient for 14-MeV neutrons. Its amplitude resolution for 6—14-MeV neutrons is about 15%, while the average size of pulses due to electrons generated by hard γ rays is reduced to a very small fraction. When confined to the registration of pulses representing 6—14-MeV protons the probability of registering 4.4-MeV photons is reduced by a factor of about 100.

A graphite cylinder 6.5 cm in diameter and 15 cm long was bombarded. Protons having energies < 5 MeV were cut off in the coincidence measurements in order to eliminate any contribution from inelastic neutron scattering with C^{12} excitation to

[1)]Eqs. (2.8)-(2.10) were obtained assuming that θ_0 is represented by (2.5). If the more general formula (2.4) is used for θ_0, the sines in (2.8)-(2.10) must include the additional function $f(\vartheta_n)$, which is an odd periodic function of ϑ_n of a degree higher than the first; for example,

$$f(\vartheta_n) = \Sigma c_{mn} \sin^{2m+1} 2n\vartheta_n.$$

[2)]The replacement of $\vartheta_0 = (\vartheta - \pi)/2$ by $\theta_0 = (\pi - \vartheta)/2$ is insignificant if the sign of θ_γ is reversed at the same time, negative θ_γ being replaced by the positive value.

Neutron scattering angle ϑ_n in (n, n′γ) reaction, deg	θ_0, deg	$\frac{b}{1+b/2}$	Proton scattering* angle ϑ_p in (p, p′γ) reaction, deg	θ_0, deg	$\frac{b}{1+b/2}$	$(\pi-\vartheta)/2$, deg
−24	100±13	1.40±0.50				102
30	70 **		30	75	1.55	75
40	82±10	0.65±0.15				70
45			45	63	0.73	67.5
110			110	36	1.00	35
125			125	29		27.5
135		$0.10^{+0.30}_{-0.10}$	135			22.5
150			150	14	1.33	15

*p′-γ correlation data for up to 16-MeV protons in [1].
**Measured in [8]

levels above the first level.[3)] For obtuse angles of neutron scattering the energy threshold was set somewhat lower, at 3.5—4.5 MeV. The background was determined from the coincidence count in the absence of the graphite cylinder and comprised 40—50% of the total coincidence count.

The angular distribution of γ rays was measured in a plane determined by the n and n′ directions for fixed neutron scattering angles of 40° and 135°. Measurements for a −24° scattering angle had been performed with annular geometry in earlier work;[7] all results are shown in Figs. 4—6. The experimental data were compared with the formula

$$f(\theta_\gamma) = 1 + b\sin^2 2(\theta_\gamma - \theta_0). \quad (3.1)$$

The values of b and θ_0 computed by least squares are given in the table along with the theoretical values of $\theta_0 = (\pi - \vartheta_n)/2$ and the data of [1] on the inelastic scattering of 16-MeV protons. It is seen that for acute nucleon scattering angles the values of b and θ_0 measured for inelastic proton and neutron scattering coincide within experimental error. For neutrons we also have the data in [8]; here for 14-MeV neutrons scattered by carbon at 30°, $\theta_0 = 70$ (see the table).

We know that the angular distributions of both inelastically scattered neutrons [6,17] and protons

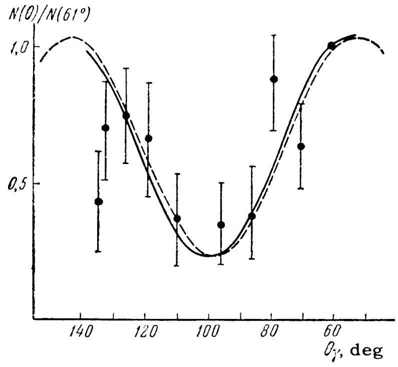

FIG. 4. Angular distribution of 4.4-MeV γ-rays in the reaction $C^{12}(n,n')C^{12}$ for neutron scattering at the angle $\vartheta_n = -24°$. The continuous curve represents the experimental formula (3.1); the dashed curve follows from the theory of direct interactions.[11]

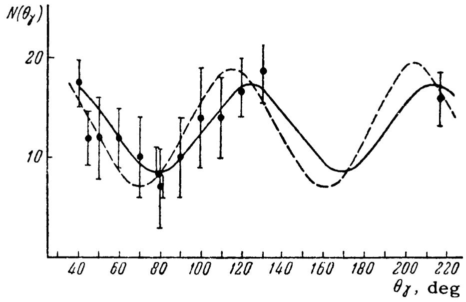

FIG. 5. Angular distribution of 4.4-MeV γ-rays in the reaction $C^{12}(n,n'\gamma)C^{12}$ for neutron scattering at the angle $\vartheta_n = 40°$. The continuous curve represents the experimental formula (3.1); the dashed curve follows from the theory of direct interactions.[11]

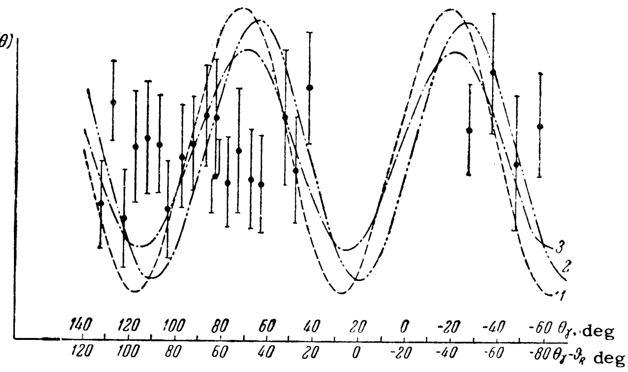

FIG. 6. Angular distribution of 4.4-MeV γ-rays in the reaction $C^{12}(n,n')C^{12}$ for neutron scattering at the angle $\vartheta_n = 135°$. Curve 1 – predicted by direct-interaction theory;[11] curves 2 and 3 – γ-ray distribution in the reaction $C^{12}(p,p'\gamma)C^{12}$ for $\vartheta_p = 150°$ and 110°,[11] respectively. γ-ray directions are measured from the direction ϑ_R of the recoil nucleus.

3)The inelastically scattered neutrons could include a certain number accompanying the excitation of C^{12} to 7.6 MeV. However, the excitation of this level is unlikely and does not lead to γ-ray emission,[16,17] so that the n′-γ coincidences are not affected.

[18] are peaked sharply forward and are identical within experimental errors.[6] Because of this directivity the γ-ray angular distribution for an unfixed direction of neutron emission is determined mainly by the neutrons scattered within a narrow cone. Indeed, this angular distribution[6,19] is given by (3.1) with the parameter $\theta_0 = 90°$ corresponding to zero effective scattering angle. This agreement between small-angle inelastic proton and neutron scattering indicates that the scattering mechanisms are identical. The data for inelastic proton scattering by carbon are in good agreement with the direct-interaction hypothesis,[11,13] which would not lead us to expect any appreciable difference between proton and neutron scattering; therefore the results obtained here serve as an additional proof that this mechanism plays a fundamental part for scattering angles $\vartheta_n < \pi/2$.

The situation differs in the case of neutron scattering at 135°. Figure 6 and the table show that the γ-ray distribution is practically isotropic for neutron scattering. For protons (see the table) the quantity b is in any event of the order of unity for both acute scattering angles and angles $> \pi/2$. It was impossible to ascertain beforehand that some unmonitorable background did not mask an anisotropic part of the γ-ray angular distribution in our measurements. In order to estimate the possible error associated with such a background we obtained the ratio of scattering cross sections at 135° and 40° from the γ-ray angular distributions. The ratio $\sigma(40°)/\sigma(135°) = 1.8 \pm 0.4$ is in good agreement with [6].

We cannot likewise assume, apparently, that in the case of neutrons the direct process is supplemented simply by another scattering mechanism (e.g., via a compound mechanism) giving an approximately isotropic angular distribution of γ rays. The relative contribution of this additional process would have to be especially great for large scattering angles. However, the angular distribution for inelastic neutron scattering would be considerably more isotropic than that of protons; this does not occur. It is not clear from a theoretical point of view why in [9] isotropy of the azimuthal n'-γ correlation was found in a plane perpendicular to the beam when 14-MeV protons were scattered in carbon. Thus the problem of determining the scattering mechanism requires additional experimental and theoretical study.

4. CONCLUSIONS

Our data for the inelastic scattering of 14-MeV neutrons in carbon and a comparison with similar data for protons show that for scattering at acute angles the mechanism depends very little, in any event, on the kind of nucleon. In the case of large angles the results for neutrons and protons exhibit a difference which must be studied further to determine its cause.

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