[1] I. A. Deryugin, V. V. Zaporozhets, and G. A. Melkov, ZhETF Pis. Red. 5, 352 (1967) [JETP Lett 5, 292 (1967)].
[2] A. L. Mikaelyan, Teoriya i primenenie ferritov na svervysokikh chastotakh (Theory and Application of Ferrites at Microwave Frequencies), Gosenergoizdat, 1963.
[3] N. N. Tikhomirova and V. V. Voevodskii, Opt. Spektrosk. 7, 829 (1959).
[4] I. A. Deryugin, V. V. Zaporozhets, and P. S. Kuts, Issledovanie energeticheskogo spektra elektronov v metallakh (Investigation of the Energy Spectrum of Electrons in Metals), Naukova dumka, Kiev, p. 85, 1965.

INVESTIGATION OF THE REACTIONS $He^4(\gamma, p)H^3$ AND $He^4(\gamma, n)He^3$

A. N. Gorbunov
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 17 June 1968
ZhETF Pis. Red. 8, No. 3, 148 - 154 (5 August 1968)

An experimental investigation of the photodisintegration of He^4 is of considerable interest in connection with the problem of a consistent description of the static and dynamic properties of light nuclei, namely the binding energy, the nuclear radii, and the effective cross sections of the nuclear reactions.

We investigated the photodisintegration of the He^4 nucleus at energies up to 260 MeV with a cloud chamber in a magnetic field of 10.5 kG, operating in a synchrotron beam. The energy of the photon producing the reaction was determined from the emission angle and the momentum of one of the two particles emitted in the reaction. The absolute intensity of the synchrotron emission was measured accurate to approximately 6%.

The effective cross section of the (γ, p reaction), obtained by measuring 2920 events, is shown in Fig. 1 (histogram). It agrees well with the results of Perry and Bame [1] and of Gemmell and Jones [2] below 28 MeV (curve 1), results obtained by investigating the inverse reaction. An estimate of the total cross section of the (γ, p) reaction, obtained by multiplying the experimental cross section $(d\sigma/d\Omega)_{90^\circ}$ by a factor $8\pi/3$ under the assumption that the reaction is connected only with electric dipole transition, in accord with the data of Clerc et al. [3] (curve 2), is also in satisfactory agreement with our results. A similar estimate based on the data of Denisov and Kul'chitskii [4] (curve 3) agrees with our data if $E_\gamma > 30$ MeV.

The effective cross section of the (γ, n) reaction, obtained from measurements of 1980 events, is denoted in Fig. 1 by triangles. The circles designate the results obtained by Livesey and Main by an emulsion method.

It is seen from Fig. 1 that the effective cross sections of the reactions (γ, p) and (γ, n) reactions on He^4 agree within the limits of statistical errors. A similar conclusion is arrived at by comparison of the integral cross sections σ_0 and σ_{-1}, obtained in the energy region from the reaction threshold to 170 MeV:

	(γ, p)	(γ, n)
σ_0, MeV-mb:	40.1 ± 0.9	42.5 ± 1.1
σ_{-1}, mb:	1.13 ± 0.02	1.09 ± 0.03

The effective cross section of two-particle photodisintegration of the He^4 nucleus, calculated by Bransden et al. [6] with allowance for tensor forces with a variational wave function taken

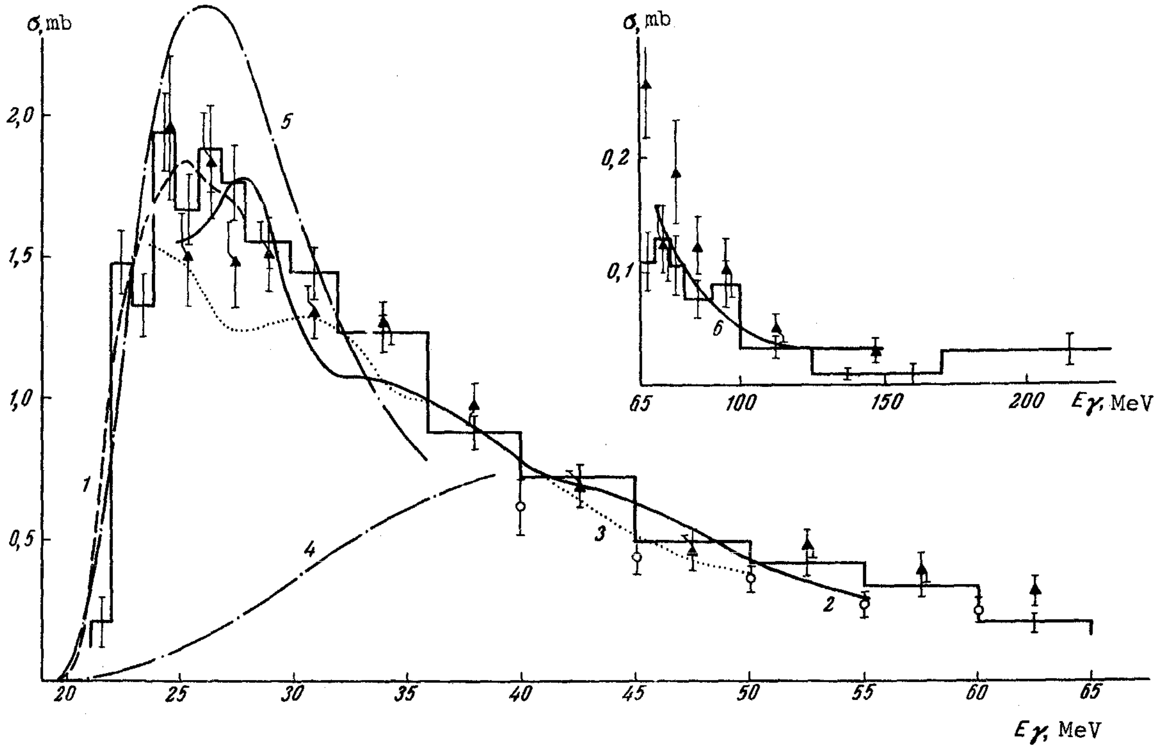


Fig. 1. Effective cross sections of the reactions $He^4(\gamma, p)H^3$ (histogram) and $He^4(\gamma, p)He^3$ (triangles)

in exponential form (curve 4), is in strong contradiction with experiment. Curve 5 is in better agreement with the experimental data, but corresponds to too large a radius of the He^4 nucleus, $\langle R^2 \rangle^{1/2} = 2.35$ F, and to too low a binding energy.

The calculation of Dzhibuti and Tagviashvili [7] (curve 6), based on the two-particle model, describes the observed cross section satisfactorily in the gamma-quantum energy from 70 to 150 MeV, but deviates strongly from experiment at lower energies. A calculation performed by Dzhibuti et al. [8] with allowance for the dependence of the single-particle potential on the velocity, with Irving's wave function, disagrees strongly with experiment at photon energies higher than 30 MeV.

The problem of simultaneously describing the binding energy and the radius of the He^4 nucleus, and also the form and the absolute magnitude of the effective cross section of the reactions $He^4(\gamma, p)H^3$ and $(\gamma, n)He^3$ thus remains unsolved.

The angular distributions of the protons and neutrons in the (γ, p) and (γ, n) reactions are shown in Figs. 2 and 3 respectively. The smooth curves on the diagrams have been calculated by least squares in a form corresponding to E1, E2, and M1 transitions

$$\frac{d\sigma}{d\Omega} = A(\sin^2\theta + \beta\sin^2\theta\cos\theta + \gamma\sin^2\theta\cos^2\theta + \delta). \qquad (1)$$

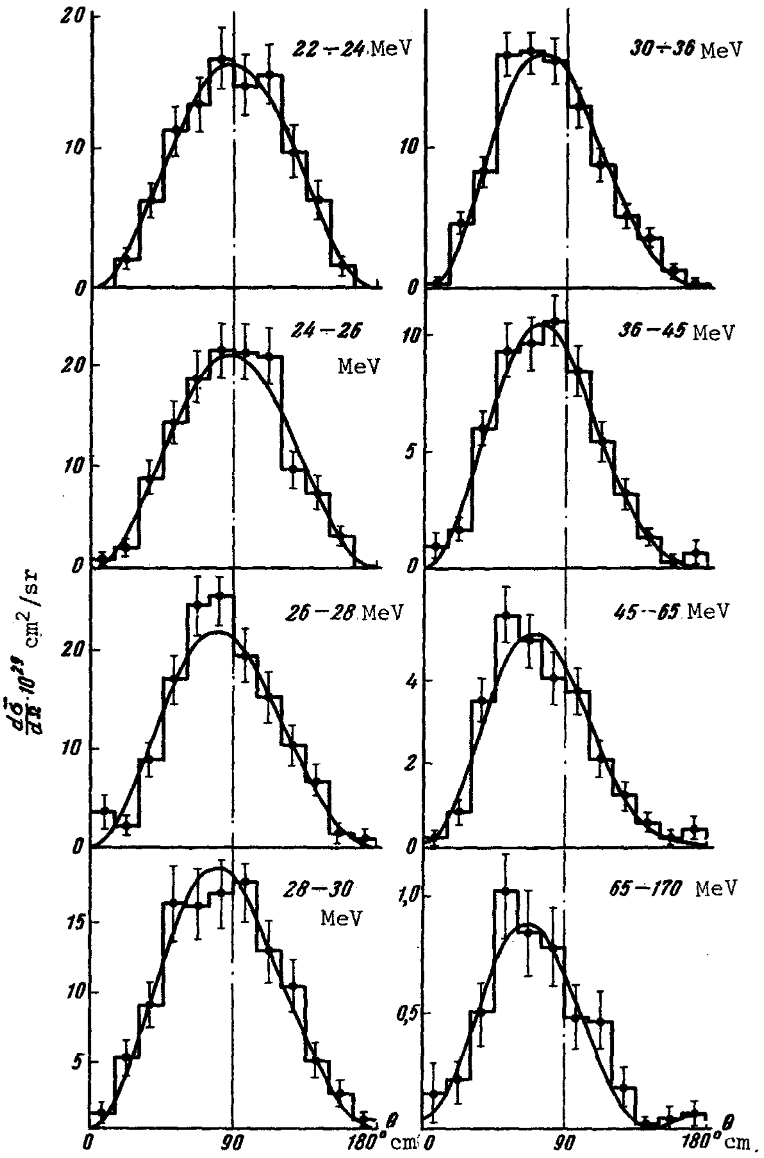
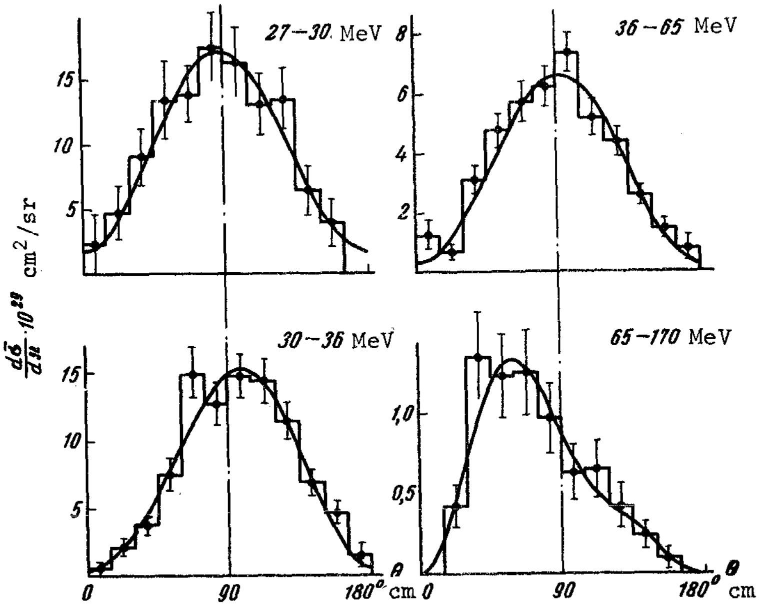


Fig. 2. Angular distributions of the protons in the reaction He^4(γ, p)H^3.

The calculations were also performed with other variants of formula (1), in which one or several parameters were set equal to zero. The table lists the best sets of parameters. The last column of the table gives the probability P of obtaining, at the given form of the angular distribution, a larger value of χ^2 than was obtained in the present experiment.

It is seen from Figs. 2 and 3 and from the table that at low values of the γ-quantum energies the angular distributions of the protons and neutrons agree, within the limits of errors, with a distribution of the $\sin^2\theta$ type. At larger energies, an asymmetry appears in the front part of the angular distribution of the protons, and increases monotonically with increasing γ-quantum energy. A characteristic feature of the neutron angular distributions is the change of the sign of the asymmetry coefficient β_n with change of energy. In the photon energy range E_γ = 30 - 36 MeV, in which a particularly fast increase of the front asymmetry of the proton angular distribution is observed in the (γ, p) reaction, the asymmetry

Fig. 3. Angular distributions of the neutrons in the reaction $He^4(\gamma, n)He^3$.



Angular distributions of protons and neutrons in the reactions $He^4(\gamma, p)H^3$ and $He^4(\gamma, n)He^3$ (in the c.m.s.)

E_γ, MeV	A, μb/sr	β	γ	δ	P,%
		Protons			
22 – 24	165 ± 9	0.04 ± 0.11	–	–	93
24 – 26	210 ± 11	0.07 ± 0.10	–	–	47
26 – 28	213 ± 11	0.33 ± 0.10	–	–	10
28 – 30	184 ± 11	0.34 ± 0,11	–	–	79
30 – 36	155 ± 6	0.66 ± 0,07	–	–	14
36 – 45	93 ± 4	0,79 ± 0,07	–	–	55
45 – 65	43 ± 3	0,98 ± 0,10	–	0,03 ± 0,02	22
65 – 170	6,1 ± 0.9	1.48 ± 0,22	–	0.08 ± 0.06	75
		Neutrons			
27 – 30	152 ± 19	0,10 ± 0.18	–	0,12 ± 0,08	89
30 – 36	142 ± 9	–0,36 ± 0,09	–	0,04 ± 0.03	30
36 – 65	68 ± 4	–0,03 ± 0.08	–	0.04 ± 0.03	4
65 – 170	8,7 ± 1,2	1,43 ± 0,32	1,5 ± 0,6	–	87
30 – 170	44 ± 2	0,05 ± 0,07	–	0.13 ± 0,02	81

coefficient of the angular distribution of the neutrons becomes negative. In the energy region 36 - 65 MeV the neutron angular distribution becomes almost symmetrical, and at photon energies above 65 MeV its maximum shifts abruptly forward, and the asymmetry coefficient β_n becomes equal, within the limits of errors, to the asymmetry coefficient β_p of the angular distribution of the protons in the reaction (γ, p).

The forward asymmetry of the angular distributions of the photoneutrons was observe also earlier for other nuclei [9 - 12]. Thus, in the reaction $O^{16}(\gamma, n)O^{15}$ at photon energies higher than 30 MeV, the maximum of the anvular distribution of the neutrons shifts forward just as strongly as in the angular distribution of the protons in the reaction $O^{16}(\gamma, p)N^{15}$ [11]. The variation in the sign of the asymmetry coefficients of the angular distributions of the neutrons in the $He^4(\gamma, n)He^3$ reaction was reported recently also by Arkatov et al. [13]. Shevchenko et al. [14], Fujii and Sugimoto [15], and Balashov et al. [16], in analyzing the question of the quadrupole giant resonance within the framework of the shell model, have shown that the change in the sign of the asymmetry of the angular distributions of the neutrons with change in energy may be connected with the splitting of the quadrupole resonance into two groups of states having greatly differing energies (with T = 0 and T = 1), owing to the particle-hole interaction. The calculation of Fujii and Sugimoto [15] describes qualitatively the change in the asymmetry of the neutron angular distribution as observed in the present experiment.

In conclusion, the author is deeply grateful to V. V. Balashov and V. N. Fetisov for a discussion of the work, and also to V. A. Dubrovina, G. V. Sokolenko, and G. G. Taran for taking part in the reduction of the experimental results.

[1] J. E. Perry and S. Bame, Phys. Rev. 99, 1368 (1955).
[2] D. S. Gemmell and G. A. Jones, Nucl. Phys. 33, 102 (1962).
[3] H. G. Clerc, J. R. Stewart, and R. C. Morrison, Phys. Lett. 18, 316 (1965).
[4] V. P. Denisov and L. A. Kul'chitskii, Yad. Fiz. 6, 437 (1967) [Sov. J. Nuc. Phys. 6, 318 (1968)].
[5] D. L. Livesey and I. G. Main, Nuovo Cimento 10, 590 (1958).
[6] B. H. Bransden, A. C. Douglas, and H. H. Robertson, Phil. Mag. 2, 1211 (1957).
[7] R. I. Dzhibuti and A. V. Tagviashvili, Zh. Eksp. Teor. Fiz. 39, 1756 (1960) [Sov. Phys.-JETP 12, 1225 (1961)].
[8] R. I. Dzhibuti, V. I. Mamasakhlisov, and T. S. Macharadze, Yad. Fiz. 2, 59 (1965) [Sov. J. Nuc. Phys. 2, 40 (1966)].
[9] L. A. Kul'chitskii and V. Presperin, Zh. Eksp. Teor. Fiz. 39, 1001 (1960) [Sov. Phys.-JETP 12, 696 (1961)].
[10] G. C. Reinhardt and W. D. Whitehead, Nucl. Phys. 30, 201 (1962).
[11] A. N. Gorbunov and V. A. Osipova, Zh. Eksp. Teor. Fiz. 43, 40 (1963) [Sov. Phys.-JETP 16, 27 (1963)].
[12] F. R. Allum, T. W. Quirk, and B. M. Spicer, Nucl. Phys. 53, 545 (1964).
[13] Yu. M. Arkatov, P. I. Vatset, V. I. Voloshuk, A. P. Klyucharev, V. L. Marchenko, and A. F. Khodyachikh, Program and Abstracts of Papers of XVIII Annual Conference on Nuclear Spectroscopy and Structure of the Atomic Nucleus, Nauka, 1968, p. 230.
[14] V. G. Shevchenko, N. P. Yudin, and B. A. Yur'ev, Zh. Eksp. Teor. Fiz. 45, 180 (1963) [Sov. Phys.-JETP 18, 128 (1964)].
[15] S. Fujii and O. Sugimoto, Nucl. Phys. 56, 73 (1964).
[16] V. V. Balashov, P. Doleshal, G. Ya. Korenman, V. L. Korotkikh, and V. N. Fetisov, Yad. Fiz. 2, 643 (1965) [Sov. J. Nuc. Phys. 2, 461 (1966)].