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SCATTERING OF NEUTRONS BY α-PARTICLES AT 14.1 MeV.

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SCATTERING OF NEUTRONS BY α-PARTICLES AT 14.1 MeV[(x)].

Summary

The angular distribution of 14.1 MeV neutrons elastically scattered by α-particles has been measured by observing the α-recoils in a helium filled cloud chamber. The results are in satisfactory agreement with those previously obtained by other authors. Inspection of the small angle region of the measured distribution shows that phase shifts of orbital angular momentum higher than L = 1 are not negligible, although, according to the present experiment, quantitative information on D waves turns out to be somewhat elusive. The azimuthal angular distribution agrees well with the value P = 0.02 of the neutron beam polarization, as measured by Perkins.

Introduction

In the last few years there has been a revival of interest in the energy dependence of the neutron-alpha phase shifts, especially because helium has been used by many authors as neutron polarization analyzer. When this work has been undertaken, it was customary to calculate the helium analysing power using the n-α phase shifts obtained by Dodder and Gammel from p-α scattering experiments at 5.8 and 9.5 MeV and published by Seagrave[(1)] (DGS phase shifts). These phase shifts were found by Seagrave to be in agreement with n-α scattering experiments in the energy interval between 2.6 and 14.3 MeV, although a considerable uncertainty remained on the D wave effects, which are increasingly important at energies larger than about 10 MeV.

Further experimental results obtained at energies between 14 and 16 MeV, by Alston et al. [(2)], Smith[(3)] and Shaw[(4)], using helium cloud chambers were in reasonable agreement with the angular distribution calculated in terms of the DGS phase shifts. Some disagreement, present in the small angle results of Smith and Shaw, should be explicable in terms of the uncertainty of the adopted D wave phase shifts.

While this work was in progress, the n-α phase shifts have been re-examined by Austin, Barschall and Shamu[(5)], who measured 11 angular distribution between 2 and 23 MeV, by observing α recoils in a high pres-

(x) - This research has been performed under contract Euratom-CNEN, in the research program of the Laboratorio dell'Acceleratore di ioni di Legnaro.

sure helium gas scintillator. The agreement with the DGS phase shifts was found to be excellent up to 10 MeV and no attempts have been made to derive D waves at higher energies.

The main purpose of this work was to extend the measurement of the angular distribution in the neutron-alpha scattering at 14 MeV at smallest possible angles, where D effects ought to be detectable(x). A cloud chamber has been used which permitted contemporary measurement, in the small scattering angles region, of the angle of the alpha recoil and its range.

1. - Experimental method.

The experimental apparatus is shown in fig. 1. Neutrons of 14.1 ± 0.1 MeV were generated at 90^{o} by means of the reaction $T(d,n)He^{4}$; a thick tritium-zirconium target was bombarded with 200 KeV deuterons and the neutrons entered a cloud chamber from the rear, along its axis.

Collimation and shielding were obtained by a conical hole of 6^{o} aperture in a truncated iron cone 27 cm long followed by a 13 cm iron cube in a paraffin annulus 17 cm thick.

The cloud chamber was cylindrical, with a diameter of 25 cm and a depth of 12 cm, filled with commercial helium at a pressure of 70 cm Hg and satured water vapour at $15^{o}C$. The required illumination was obtained with linear flash lamps in a region limited by two planes 8 cm apart, parallel to the front glass of the chamber.

To avoid the presence of old diffused tracks, the deuteron beam was pulsed for 1/10 od second after each expansion of the chamber.

Stereoscopic photographs were taken with two lenses, 30 cm apart, at 90 cm from the center of the chamber.

The spacial reconstruction of the single scattering events was carried out according to the following procedure: both the images of each track were projected on a paper screen, where the tracks have been approximated by straight line segments. The drawing obtained in this way has been used for the analysis of each event: the coordinates of the end-points of the segments were read according to a reference system defined by the images of fiducial marks inscribed on the front glass and the following quantities calculated by means of an electronic computer:

a) the spacial coordinate (x, y, z) of the end-points of the track;
b) the angle ϑ_α between the direction of the recoil and the line of flight of the neutron supposed to come directly from the target; of the two ends of each track the one nearer to the target was assumed to be the origin;
c) the observed length R of the α recoil;
d) the distance L of the origin of the track from the chamber axis;
e) the energy $E = (16/25) \times 14.1 \cos^2\vartheta_\alpha$ of the α recoil calculated from the α scattering angle;
f) the cosine of the scattering angle in the center of mass system: $\cos\vartheta = 1 - 2\cos^2\vartheta_\alpha$;
g) the angle ϕ between the production plane of the neutron, defined by the line of flight of the deuteron and the produced neutron, and the scattering plane.

(x) - With the same purpose, an experiment of this kind has been recently carried out by G. Poiani using a different technique.

The only tracks measured were those originated inside a fiducial zone defined by two parallel planes $\beta\beta'$, 5.7 cm apart, well inside the illuminated region. The selection of tracks inside the fiducial zone was made during the scanning operation as the Z coordinate (distance from the front glass) was directly measurable on the projection screen.

2. - Experimental results.

The total number of tracks measured was 11.800 in about 7.000 photographs taken with the geometry shown in fig. 1; 1.525 tracks were obtained in 1.000 photographs taken with the collimation hole closed by iron, and were used to estimate the background. Out of the 11.800 tracks taken in "open" collimation conditions, 3.385 were found to be originated within the fiducial zone $\beta\beta'$ and ending outside it; the remaining 8.415 tracks were found to have both end-points inside the fiducial zone; the mean length of the first group of tracks was found to be considerably larger than that of the second group, as is seen from figs. 3 and 6. In the subsequent discussion the tracks belonging to the two groups will be called "long" and respectively "short" tracks.

The radial distribution of origins of long tracks per cm^2, originated in successive annular regions, centered at the chamber axis, is shown in fig. 2, which visualizes the "profile" of the intensity of the neutron beam impinging on the chamber. This "profile" form has suggested to construct the angular distribution only on the basis on the tracks characterized by $L < 35$ mm. The annulus 45 mm $< L <$ 80 mm was shielded from the neutron source by 43 cm of iron which correspond to about 7 times the mean free path of 14 MeV neutrons in iron. Thus, less than $1^{o}/oo$ of the neutrons coming directly from the target goes through the screen without interacting. The tracks in the annulus are therefore essentially due to spurious neutrons.

The distribution on the R, $\cos\vartheta$ plane of the 1.513 "long" tracks, having their origin in the central acceptance region ($L < 35$ mm), obtained with the collimator open, is shown in fig.3. The lenghts R turn out to be uniformely distributed between a maximum value defined by the kinematics of n-α scattering at 14 MeV and the thickness of the illuminated region; it should be pointed out that the minimum value of about 1 cm is connected with the fact that the illuminated region is larger than the fiducial one.

The angular distribution of the tracks reported in fig. 3 is shown in fig. 4, while fig. 5 exhibits the angular distribution of the 869 "long" tracks belonging to the annulus 45 mm $< L <$ 80 mm. It is seen that the latter angular distribution is practically isotropic, whereas the former is strongly anisotropic. This circumstance provides a further evidence that the tracks belonging to the annulus 45 mm $< L <$ 80 mm are to be ascribed to spurious neutrons only.

Consequently, the angular distribution shown in fig. 4 has been corrected for the background due to spurious neutrons by subtracting 230 tracks, isotropically distributed. The correction has been computed by multiplying the mean track density of 6.0 tracks per cm^2 on the annular region (45mm $< L <$ 80 mm) (see fig. 2) by the area of the central acceptance region.

The distribution on the R, $\cos\vartheta$ plane of the 2.630 "short" tracks, having their origin in the central acceptance region ($L < 35$ mm), is shown in fig. 6; the curve represents the range-energy relation for α particles[6] in the helium water vapour mixture contained in the cloud chamber. The energy E_α is given, in terms of $\cos\vartheta$, by:

$$E = (16/25)\,(14.1/2)\,(1 - \cos\vartheta).$$

In the $\cos\vartheta$ interval 0.6 - 0.3 one can distinguish, distributed on a strip symmetric around the energy-range curve, a population of events clearly separated in the assembly of the experimental points; such a population is obviously formed by "good" events; and, owing to the geometry of the chamber, it vanishes at $\cos\vartheta \cong 0.3$. The above strip has been extrapolated to lower angles where good and spurious events are mixed. The correction of the background present in the strip was calculated on the basis of the R, $\cos\vartheta$ distribution of "short" tracks obtained with the collimator closed and of those "short" tracks, taken with open collimator, which have L > 35 mm. These two distributions were found to be similar to each other and to the distribution concerning the spurious tracks, shown in fig. 6.

The total number N_1 of events on the strip in various angular intervals, the values N_2 of the background correction, the difference $N_S=N_1-N_2$ and the statistical error $\sqrt{N_1+N_2}$ of the difference are listed in table I.

TABLE I

$\cos\vartheta$	N_1	N_2	$N_S=N_1-N_2$	$\sqrt{N_1+N_2}$
0.8 - 0.7	238	80	158	17.8
0.7 - 0.6	127	16	111	12.4
0.6 - 0.5	91	0	0	9.5
0.5 - 0.4	58	0	0	7.6
0.4 - 0.3	23	0	0	4.8

The angular distribution has been experimentally restricted to $\cos\vartheta < 0.8$, because of the too large statistical errors at lower angles.

The events listed in table I have been added to those concerning the distribution shown in fig. 4 and corrected for background. The final angular distribution is given in table II and represented in fig. 7.

No correction has been made for the presence of n, p events, due to the water vapour in the chamber; this correction was found to be of the order of 2% and, therefore, negligible in comparison to the others.

The frequency distributions of the "long" tracks in the central region as a function of azimuthal angle ϕ for various intervals of $\cos\vartheta$ are shown in fig. 8; they are all isotropic within statistical errors, even in the intervals where the analysing power of helium to 14 MeV neutrons is high. This is consistent with the low polarization value, namely P = 0.02, of the (d, t) neutrons generated at 90° with 0.2 MeV deuterons, as measured by Perkins[7].

TABLE II

cos ϑ	N_L	C	N_S	$N=N_L-C+N_S$	ε
0. 8					
	52	11	158	199	19
0. 7					
	82	11	111	182	15
0. 6					
	102	11	91	182	14
0. 5					
	113	11	58	160	13
0. 4					
	144	11	23	156	13
0. 3					
	119	11	0	108	11
0. 2					
	86	11	0	75	9
0. 1					
	91	11	0	80	10
0					
	67	11	0	56	8
-0. 1					
	51	11	0	40	7
-0. 2					
	55	11	0	44	7
-0. 3					
	37	11	0	26	6
-0. 4					
	49	11	0	38	7
-0. 5					
	50	11	0	39	7
-0. 6					
	67	11	0	56	8
-0. 7					
	97	11	0	86	10
-0. 8					
	105	11	0	94	10
-0. 9					
	113	11	0	102	11
-1. 0					

N_L = long tracks with L < 35 mm ; C = correction to N_L ;
N_S = short tracks with L < 35 mm ; ε = statistical error of N.

Discussion.

The continuous curve, shown in fig. 7, represents the angular distribution calculated with the DGS phase shifts. The normalization has been carried out neglecting the last three points measured at small angles.

The agreement between the istogram and the curve is fairly good at intermediate angles: disagreement is apparent at high and particularly at small angles.

A comparison has been made with Austin's results at 14. 7 MeV and with the ones derived by the DGS phase shifts. The coefficients A_n of the measured angular distribution developed in powers of cos ϑ have been computed using the least square method. In order to understand the influence on the angular distribution coefficients of the measured small angle points deviating from the general trend of Seagrave's curve, the calculation has been carried out by considering all the 18 points of our istogram and neglecting in turn one, or two, or all three the apparently "anomalous" points at small angles.

The square sums of the residuals, measured in units of the statistical errors calculated for the two cases involving respectively 18 and 15 experimental points and relative to polynomials of degree 2, 3 and 4, are listed in table III.

TABLE III

degree	2	3	4
15 points	28	19	16
18 points	105	37	13

It is clear that a parabola is a sufficiently good fit if one excludes the three small angle points but is much worse than the fourth degree curve if one considers all points.

On the fig. 9 oblique crosses give the values of the coefficients A_0, A_1, A_2 and their errors obtained by fitting with a parabola the 15 points of our distribution having excluded the first three. The vertices of the continuous lines give the values of the coefficients of the fourth degree polynomial calculated excluding successively the first 3, 2, 1, 0 small angle points, with the errors relative to the two extreme (15 and 18 points) distributions. Dotted and broken lines give respectively the coefficients deduced from the Austin distribution at 14.7 MeV (fitted with a parabola) and of those calculated from the DGS phase shifts. Normalization between the four sets of coefficient has been done by equalizing our A_0's to the other two.

It is evident that the fluctuations of the values of the three first coefficients obtained in the present work are inside the statistical errors and consistent with the two sets of Austin and DGS. Disagreement is apparent for the last two coefficients.

It is important to notice that in the small angle region systematic errors, which are difficult to evaluate, may be introduced by the normalizations in the background correction and by errors in the measurement of the recoil angle, due to the fact that the tracks are shorter and more distorted by the Coulomb scattering. The small angle points must therefore be weighted less than would be indicated by statistical errors alone. The above reasons tend to reduce the meaning of the discrepancy of the higher order coefficients.

Conclusions.

The present work confirms the value of the S and P waves phase shifts given by Seagrave; the small angle distribution, although affected by the above mentioned uncertainties, suggests that phase shifts of orbital angular momentum higher than L = 1 should not be negligible. Quantitative information on D wave turns out to be somewhat elusive.

The experimental difficulty in making precise angular distribution measurements in the small angle region, together with the fact that polarization in n-α scattering, as pointed out by Austin et al.[5], is strongly dependent on higher order phase shifts, suggests that an improvement in the knowledge of the n-α phase shifts, particularly in the higher energy region, may be better achieved by direct polarization measurements.

Acknowledgements.

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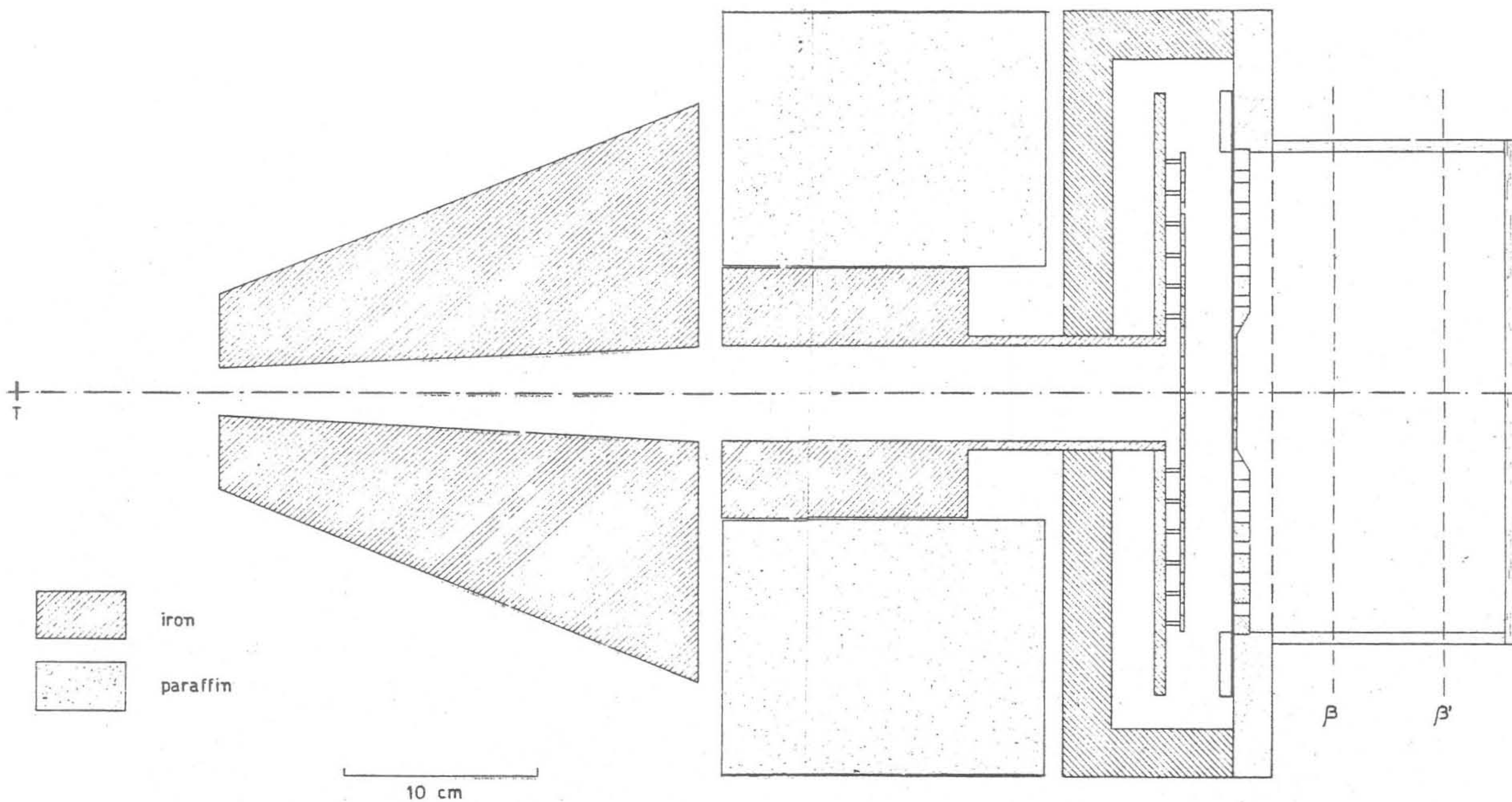

Fig. 1 - Experimental apparatus. T is the target. The planes β, β' define the fiducial region.

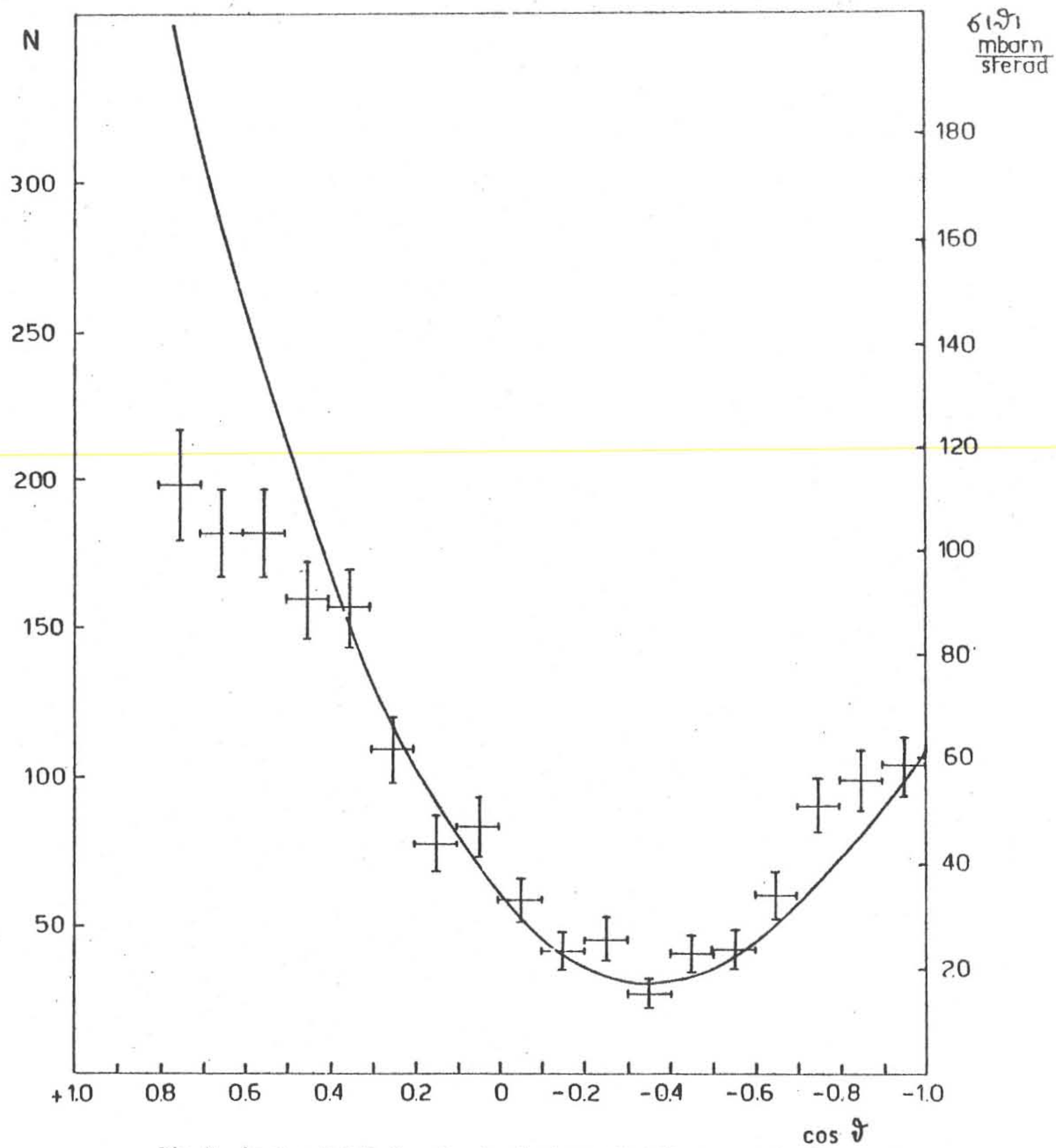

Fig. 7 - Angular distribution of n-α scattering at 14.1 MeV. Continuous curve is the angular distribution calculated with the phase shifts given by Seagrave.

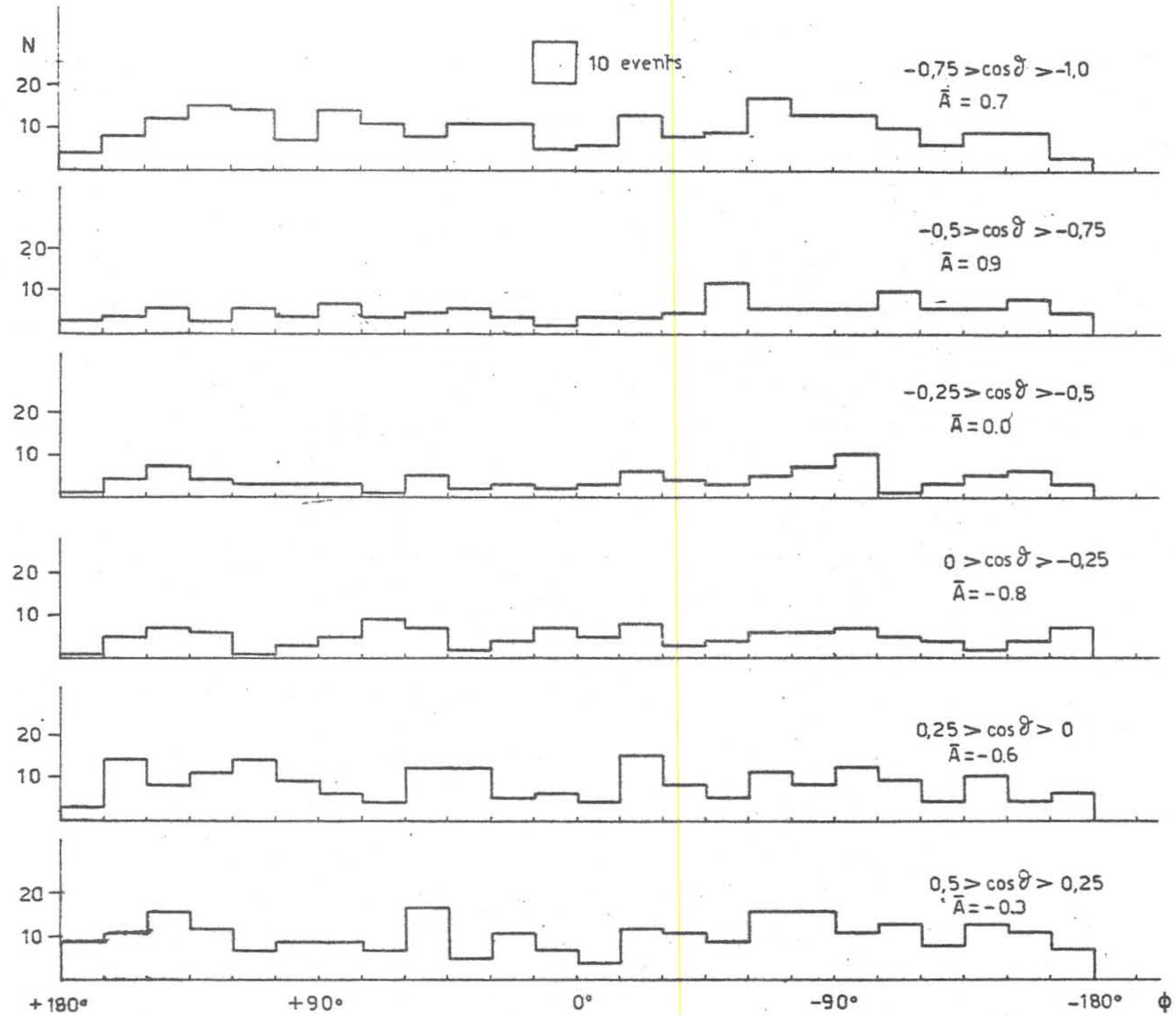

Fig. 8 - Distribution of "long" tracks with L < 35 mm, as a function of azimuthal angle ϕ. A is the mean analysing power of helium to 14 MeV neutron as given in ref. (8).

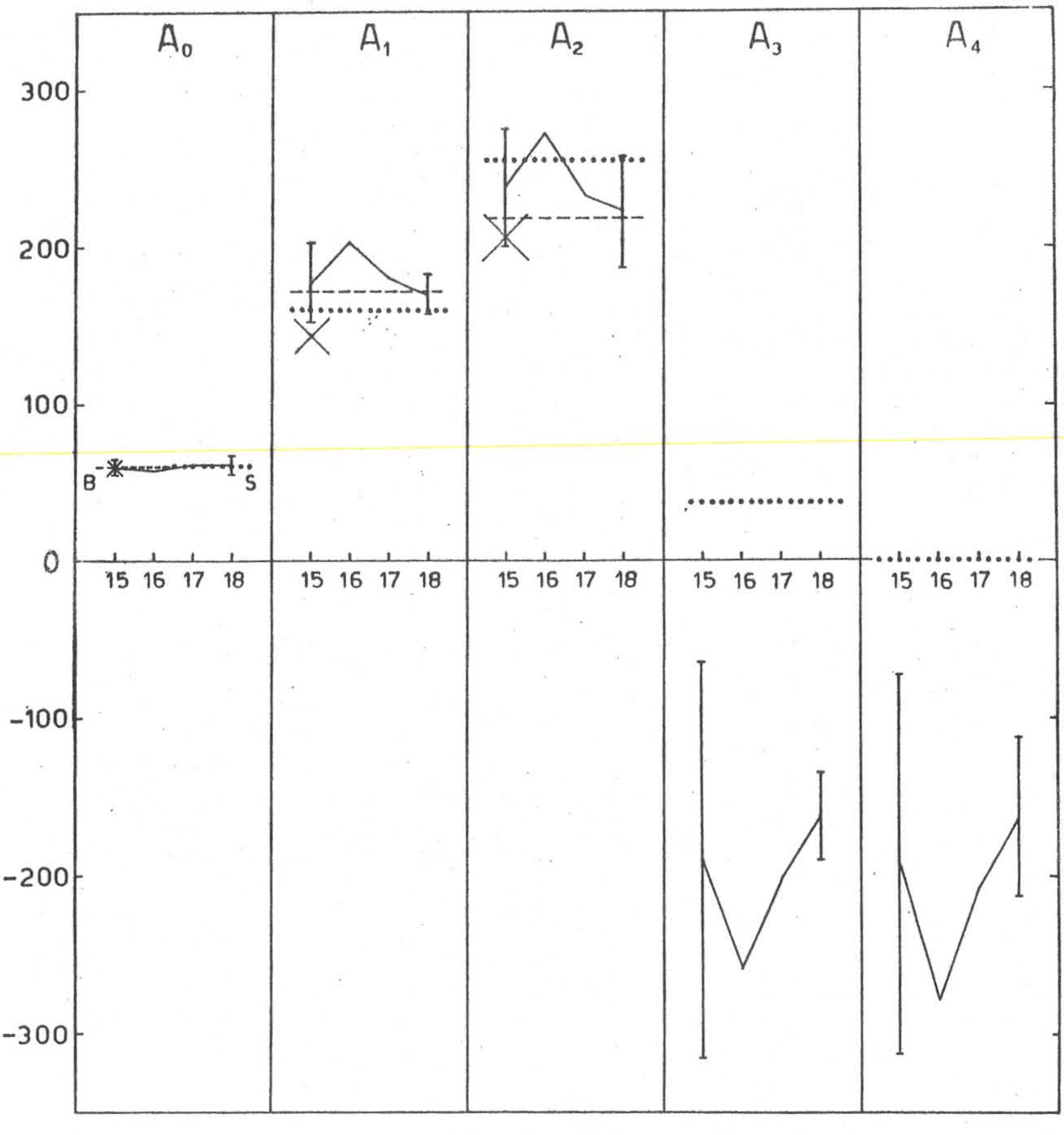

Fig. 9 - Comparison between the coefficients A_n of the angular distri butions developed in terms of power of cos ϑ.
X: present work, 15 points fitted with a parabola. Vertices of the continuous lines: present work, 15, 16, 17 and 18 points fitted with 4th degree curves.
– – – – – – : Austin results fitted with a parabola.
·············· : DGS results, SPD waves.