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On the (p, α) Direct-Reaction Mechanism in Light Nuclei.

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Summary. — Differential cross-sections for (p, α) reactions have been obtained at $E_p = 26.7$ MeV for ^{9}Be, ^{11}B, ^{19}F and at several proton energies between 25 and 45 MeV for ^{12}C and ^{16}O. For these two nuclei a marked variation with proton energy of both the shape of the angular distribution and the integrated cross-section is found. The present results, and the earlier ones at $E_p = 38$ MeV, have been compared with PWBA calculations for the four direct mechanisms (pick-up, knock-out, heavy-particle pick-up and heavy-particle knock-out) taking into account their interference terms.

1. – Introduction.

In a previous paper from this laboratory (1) a study of the (p, α) reaction in ^{9}Be, ^{11}B, ^{12}C, ^{16}O and ^{19}F at a proton bombarding energy of 38 MeV was reported. The main conclusion was that no single direct-reaction mechanism could satisfactorily account for the observed differential cross-sections at that energy: only for ^{19}F the hypothesis of a pure triton pick-up process seemed fairly compatible with the experimental results. While the above conclusion depended on a PWBA theoretical approach, it has been shown recently to remain valid also in a DWBA treatment (2).

(1) G. GAMBARINI, I. IORI, S. MICHELETTI, N. MOLHO, M. PIGNANELLI and G. TAGLIAFERRI: *Nucl. Phys.*, **126** A, 562 (1969).
(2) W. J. THOMPSON, S. EDWARDS, D. ROBSON and T. L. TALLEY: contribution in *International Conference on Clustering Phenomena in Nuclei* (Bochum, 1969).

The $^{19}F(p, \alpha)^{16}O$ differential cross-section exhibits a typical diffractionlike structure over the entire angular range. This reaction has been analysed at other energies, assuming a pure pick-up process, in the DWBA approach, by COLE *et al.* ([3]) and by HIRD and LI ([4]). These analyses reach a satisfactory agreement for the overall cross-section magnitude, but fail to give a detailed fit to the shape of the α-particle angular distribution. The experimental data for the reactions in ^{9}Be, ^{11}B, ^{12}C and ^{16}O, show in contrast prominent backward peaking ([1,5]) in the differential cross-sections, suggesting the presence of other mechanisms besides the pick-up.

We have now continued our study taking further data for the same reactions at different energies, and extending the PWBA analysis to take into account the four possible direct mechanisms and their interference terms. The procedure used to calculate the (p, α) differential cross-section is described in a separate report ([6]).

2. – Experimental results.

The measurements were performed with the external proton beam of the Milan AVF cyclotron. The experimental set-up and procedure were as described in ref. ([1]). Differential cross-sections $d\sigma/d\Omega$ at 26.7 MeV incident-proton energy have been obtained for the same nuclei already studied at 38 MeV and are shown in Fig. 1 to 5. In the case of the

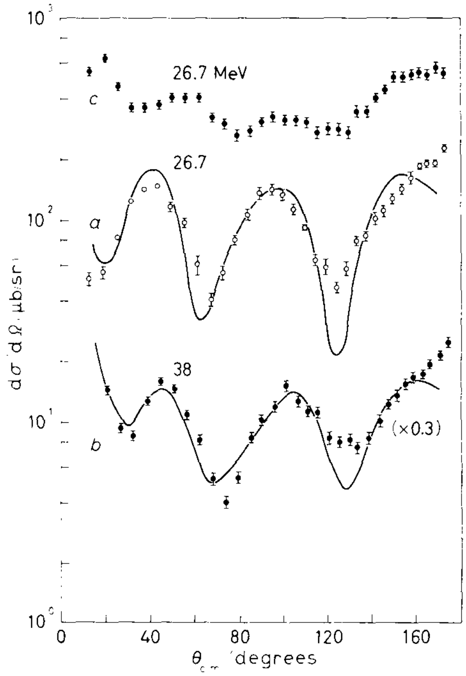

Fig. 1. – Angular distributions of α-particles for the reactions *a*), *b*) $^{9}Be(p, \alpha_0)^{6}Li$ at $E_p = 26.7$ and 38 MeV, and *c*) $^{9}Be(p, \alpha_1)^{6}Li$ at $E_p = 26.7$ MeV. The curves are the result of the four-mechanism PWBA calculation with the parameters given in Table I.

([3]) R. K. COLE, R. DITTMAN, H. S. SANDHU and C. N. WADDEL: *Nucl. Phys.*, **91** A, 665 (1967).

([4]) B. HIRD and T. Y. LI: *Can. Journ. Phys.*, **46**, 1237 (1968).

([5]) R. M. CRAIG, B. HIRD, C. J. KOST and T. Y. LI: *Nucl. Phys.*, **96** A, 367 (1967).

([6]) G. GAMBARINI, I. IORI and N. MOLHO: Rep. INFN/BE-69/4 (1969).

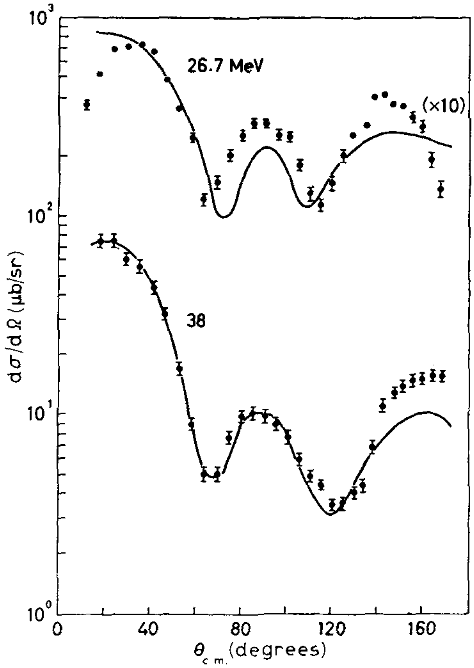

Fig. 2. – Angular distributions of α-particles from the reactions $^{11}B(p, \alpha_0)^8Be$ at $E_p = 26.7$ and 38 MeV. The curves are the result of the four-mechanism PWBA calculation with the parameters given in Table I.

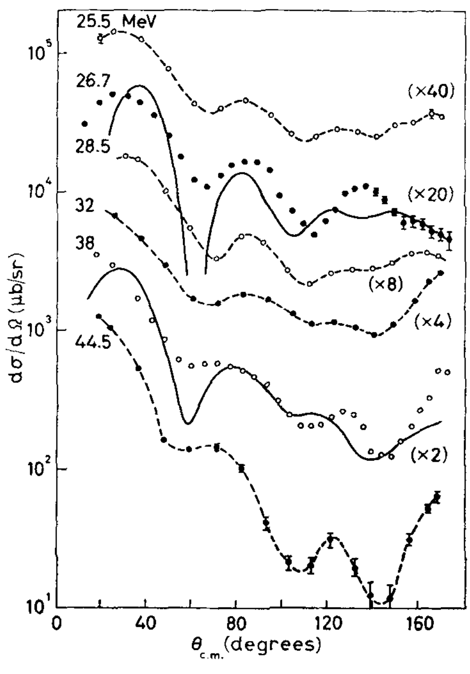

Fig. 3. – Angular distributions of α-particles from the reactions $^{12}C(p, \alpha_0)^9B$ at several proton energies. The full curves are the result of the four-mechanism PWBA calculation with the parameters given in Table I. The dashed curves are guides to the eye. Where not drawn, the statistical error bars are smaller than the size of the points.

reactions on carbon and oxygen the angular distributions exhibit a marked change when the proton energy is lowered to 26.7 MeV.

For this reason the differential cross-sections for these two nuclei have been measured at a number of other energies, as reported in Fig. 3 and 4. As is evident from the curves shown in these Figures the shapes change strongly, especially for the reaction on ^{16}O. A marked energy dependence is also present for the cross-section integrated from 12.5° to 167.5°.

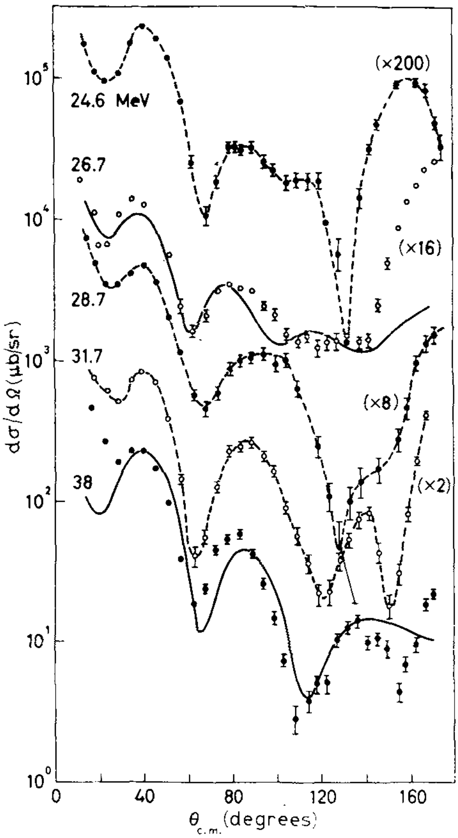

Fig. 4. – Angular distributions of α-particles from the reactions $^{16}O(p, \alpha_0)^{13}N$ at several proton energies. The full curves are the result of the four-mechanism PWBA calculation with the parameters given in Table I. The dashed curves are guides to the eye. Where not drawn, the statistical error bars are smaller than the size of the points.

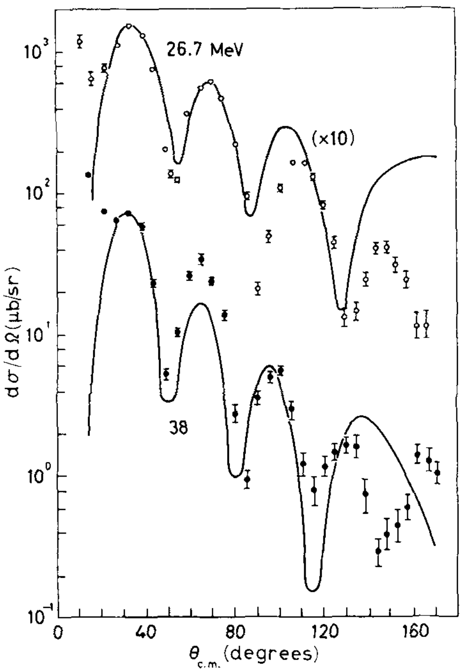

Fig. 5. – Angular distributions of α-particles from the reactions $^{19}F(p, \alpha_0)^{16}O$ at $E_p = 26.7$ and 38 MeV. The curves are the result of a PWBA calculation assuming only the PU mechanism with the parameters given in Table I.

3. – Analysis.

3·1. *The* PWBA *calculation*. – The (p, α) reaction cross-sections have been analysed in terms of a PWBA calculation with zero-range interaction. The use of the PWBA in place of the more refined distorted-wave treatment may be justified as far as the shape of the angular distributions is concerned. This point has been discussed in ref. (1), and in more detail in ref. (6) where the results of PW and DW calculations for the $^{19}F(p, \alpha)^{16}O$ reaction have been compared and found practically equivalent: an outcome which is not surprising, in view of the drastic approximations needed at present in both methods. Part of these reflect a lack of knowledge of fundamental physical quantities, others are made only to overcome technical difficulties in the calculations. The use of approximate wave functions and interactions is an example of the former type, that of zero-range interaction of the latter.

In the case of DWBA a further cause of uncertainties derives from the choice of optical-model potentials. Analogously in PWBA calculations an additional indetermination is introduced by the choice of cut-off radii.

The difficulties encountered in the DWBA approach have been pointed out very recently also by KOST and HIRD (7).

The specific purpose of the present PWBA calculation was to see the effect of taking into account at the same time the four direct mechanisms: pick-up (PU), knock-out (KO), heavy-particle pick-up (HPPU) and heavy-particle knock-out (HPKO). The differential cross-section can be written as follows:

$$\frac{d\sigma}{d\Omega} = K \sum_{\nu_p m_T m_R} |N_1(T^{PU}_{\nu_p m_T m_R} + T^{HPKO}_{\nu_p m_T m_R}) + N_2(T^{KO}_{\nu_p m_T m_R} + T^{HPPU}_{\nu_p m_T m_R})|^2 . \tag{1}$$

The factor K contains the dependence on kinematics, and statistical factors. The quantities T are the transition matrix elements for the single mechanisms and their expressions can be found in ref. (1), or more explicitly in ref. (6). The matrix elements are calculated in plane-wave zero-range approximation with a cut-off radius. The p-t system is described with a Yukawa-type wave function.

The sum in (1) is performed over the z-component of proton, target and residual nucleus intrinsic spin. The coefficients N_1 and N_2 are related to tritonlike and alphalike structures in target nuclei, being proportional to $\theta_{1t}O_t$ and $\theta_{1p}\theta_{1\alpha}O_\alpha$ respectively. The θ_1 are the reduced widths and O_t, O_α are overlap integrals. The latter give the degree of overlap between the internal wave function of the transferred group of nucleons when bound in the target nucleus and in the α-particle.

A single l-value has been used for each bound systems. This limitation however, because of the spin and parity conservation, does not give rise to

(7) C. J. KOST and B. HIRD: *Nucl. Phys.*, **132** A, 611 (1969).

ambiguity in almost all our cases. This is true also for KO and HPPU mechanisms if one assumes the core in the ground state.

When interference effects between the four mechanisms are calculated it is important that the absolute values of the single amplitudes be evaluated with the same degree of accuracy. The above requirement is assumed to be satisfied by the present calculations since the same type of approximations have been used for the various amplitudes. However this point cannot be proved.

The sign of the interference term is essentially given by Clebsch-Gordan coefficients. We have constructed these coefficients for t-core and α-core systems in a symmetric way.

The approximations introduced, although important, do not limit the possibility of extracting an indication of the role played by the four mechanisms if consistent relative values at different energies are obtained.

3'2. *Comparison with the experimental data.* – The experimental angular distributions at 26.7 MeV and 38 MeV have been compared with the PWBA predictions with a best-fit procedure. Because of the long computing time required for the calculation of each curve, the time allowed for the best-fit search does not assure that the best possible result has been obtained in each case. The choice of the cut-off radii has been limited by the requirement that they should decrease with increasing energy, in agreement with the deeper

TABLE I. – *Values of the cut-off radii and of the coefficients N_1 and N_2 of eq.* (1) *obtained from the best-fit procedure.*

Target	E_p (MeV)	R (PU) (fm)	R (HPKO)	R (KO)	R (HPPU)	N_1	N_2	N_1/N_2
^{9}Be	26.7	6.8	4.8	6.8	5.4	0.25	0.423	0.59
	38	5.6	4	5.4	4.6	0.174	0.263	0.66
^{11}B	26.7	3.8	4	5.6	4	0.228	0.277	0.82
	38	3.2	3.4	4.3	3.4	0.269	0.25	1.07
^{12}C	26.7	5.2	6.2	6.0	5.2	0.477	0.273	1.75
	38	4.2	3.2	5.8	3.6	0.875	0.193	4.50
^{16}O	26.7	4.8	5.8	3.2	5.2	0.643	0.177	3.60
	38	3.6	4.6	2.4	4	0.386	0.05	7.70
^{19}F	26.7	6.1				0.48		
	38	5.5				0.38		

penetration in the nucleus of the more energetic particles. Table I reports the values of the cut-off radii and of the coefficients N_1 and N_2.

In all the cases where the four-mechanism analysis has been applied, the shapes given by pick-up and knock-out processes are practically indistinguishable when appropriate cut-off radii are chosen. The best-fit procedure is then often determined by the heavy-particle processes.

Interference terms are generally important; an example of their effect is given in Fig. 6 for the case of the reaction $^{11}B(p, \alpha_0)^8Be$ at 38 MeV.

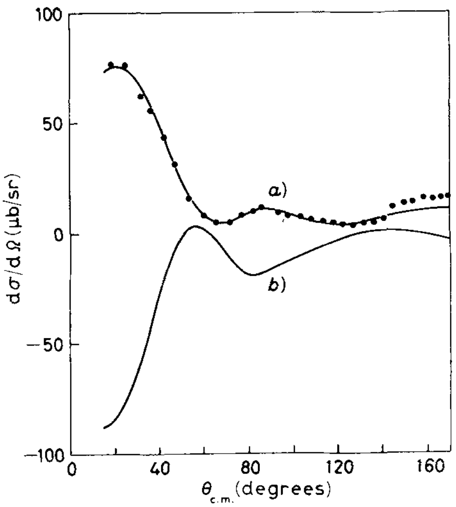

Fig. 6. – Contribution of the interference terms to the cross-section calculated with the four-mechanism PWBA approach. The case shown is that of the $^{11}B(p, \alpha_0)^8Be$ reaction at $E_p = 38$ MeV. *a*) PWBA cross-section with interference terms; *b*) interference terms.

3·3. *Discussion of specific reactions.*

3·3.1. The $^9Be(p, \alpha)^6Li$ and $^{11}B(p, \alpha)^8Be$ reactions. The experimental angular distributions do not vary markedly between the two energies. The PWBA fits given in Fig. 1 and 2 are satisfactory and certainly better than those obtained with only one mechanism and reported in ref. [1]. In Fig. 1 the experimental results for the transition to the 2.184 MeV first excited state of ^6Li are also given. No four-mechanism PWBA analysis has been carried out in this case because of the longer computing time required by the high-spin value.

3·3.2. The $^{12}C(p, \alpha)^9B$ reaction. Changes in the shape of the experimental angular distribution are seen when the energy is lowered from 38 to 26.7 MeV. Since the main change is the disappearance of the backward peak at large angles, it is not suprising that the general trend of the experimental distribution at 26.7 MeV can be reproduced using only the PU process (or the KO which gives a similar pattern provided the cut-off radius is readjusted). The 38 MeV data, instead, cannot be fitted with only one mechanism. The results of the four-mechanism calculation are given in Fig. 3 for both energies.

3'3.3. The $^{16}O(p, \alpha)^{13}N$ reaction. Again there are here noticeable changes with energy in the angular distribution, but this time the size of the backward peak is greater at the lower energy (Fig. 4).

The shape of the 26.7 experimental curve shows also less pronounced oscillations. The strong backward peaking requires at least one heavy-particle mechanism. It is apparent anyway that in this case not even the four-mechanism calculation can account for the behaviour at large angles.

We have found however that calculations with HPPU alone reproduce this peaking when one allows the two cut-off radii to vary independently. In the four-mechanism analysis the two radii have been given the same value for computational convenience.

A negative conclusion is also reached in attempts to reproduce, without drastic changes (8) in the value of the parameters, the strong energy dependence of the shape of the angular distributions.

3'3.4. The $^{19}F(p, \alpha)^{16}O$ reaction. The angular distributions present a typical diffractionlike structure which, apart from an angular displacement of diffraction oscillations, does not change substantially with energy, as shown in Fig. 5. The curves given in the Figure are calculated using only the pick-up mechanism as suggested by the structure of ^{19}F, which is well described as a ^{16}O core plus three nucleons in an (sd) cluster.

No four-mechanism analysis has been attempted for this reason, and also because our best-fit procedure fails in case of strongly oscillating distributions. The pick-up curve reproduces the position of the first three maxima but not the behaviour at small and large angles.

4. – Conclusion.

The introduction of the four direct mechanisms leads to fits which generally reproduce at least the overall behaviour of the experimental data and represent an improvement over those obtained when only the pick-up or knock-out is used.

This improvement could be ascribed simply to the increased number of degrees of freedom; the use of more than one mechanism, however, is required by the physical situation in light-mass target nuclei, and is well justified if reasonable values are assigned to the additional parameters. The best-fit values found in the present analysis for the cut-off radii are in fact near those expected, and their energy dependence is reasonable.

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(8) R. L. WARSH and S. EDWARDS: *Nuovo Cimento*, **55 B**, 443 (1968).

The absolute values of the coefficients N_1 and N_2 which are connected to nuclear properties are not significant as derived from this type of analysis. Their ratio, however, and its energy dependence might allow some speculation on the role of possible tritonlike or alphalike structures in the target nuclei.

In this connection it should be noticed that their choice, operated by the best-fit procedure, is mainly determined by the fit of the heavy-particle processes as discussed in Subsect. **3**˙2.

From the data of Table I it is seen that for ^{9}Be and ^{11}B the ratio N_1/N_2 is approximately the same at the two energies, and that its value is not far from 1 (and in fact quite close to this figure for the second nucleus). These N_1/N_2 ratios and the satisfactory fit obtained for the angular distributions indicate, within the precision of the method, important contributions from alphalike structures.

A different situation is found in the case of ^{12}C, and ^{16}O. The coefficient N_1 is always larger than N_2, and their ratio shows a large increase with incident energy. This predominance seems in contrast with an alphalike structure such as has been hypothesized for these two nuclei. It is however possible that the KO mechanism on a nucleus with alphalike cluster structure is hindered by the presence of a strong (p, pα) reaction that does not require capture in the residual nucleus of the incoming proton, which is rather weakly bound in ^{9}B and ^{13}N.

Moreover the experimental situation for ^{12}C and ^{16}O nuclei is more complex than previously envisaged, as borne out by the strong energy variation of the differential cross-sections with proton energy. This behaviour cannot be reproduced by direct mechanisms unless the parameters are allowed wide variations.

It is therefore difficult to extract any definite information on clusterlike structure of these two nuclei from our analysis.

This situation invites further experimental study of the (p, α) reaction energy dependence and suggests that, at least in the case of ^{12}C and ^{16}O, the above analysis is inadequate. Some progress in directions other than simply adding several direct mechanisms is needed.

RIASSUNTO

Sono state misurate le sezioni d'urto differenziali per reazioni (p, α) indotte da protoni di 26.7 MeV di energia sui nuclei di ^{9}Be, ^{11}B, ^{12}C, ^{16}O e ^{19}F. Per il ^{12}C e il ^{16}O le misure sono state estese anche ad altre energie comprese tra 25 e 45 MeV, e per questi due nuclei si sono osservate al variare dell'energia notevoli cambiamenti sia nella forma delle distribuzioni angolari che nel valore delle sezioni d'urto integrate. I risultati sperimentali riportati nel presente lavoro, unitamente ad altri dati ottenuti precedentemente ad $E_p = 38$ MeV, sono stati analizzati nell'approssimazione delle onde piane, tenendo conto dei quattro possibili meccanismi diretti di reazione, e dei loro termini di interferenza.

О механизме прямой реакции (p, α) на легких ядрах.

Резюме (*). — Были получены дифференциальные поперечные сечения для реакций (p, α) при E_p=26.7 МэВ на ^{9}Be, ^{11}B, ^{19}F и при некоторых энергиях протона между 25 и 45 МэВ на ^{12}C и ^{16}O. Для этих двух ядер обнаружено заметное изменение и формы углового распределения и проинтегрированного поперечного сечения с энергией протона. Полученные результаты и более ранние результаты при E_p=38 МэВ сравнивались с PWBA вычислениями для четырех прямых механизмов (захват, выбивание, захват тяжелых частиц и выбивание тяжелых частиц), с учетом их интерференционных членов.

(*) *Переведено редакцией.*