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Abstract

The $^{10}B(t,p)$ ground state angular distribution has been quoted as one of the clearest indications of a two-step reaction mechanism. As, however, no DWBA calculations were performed, one might doubt, whether the unusual angular distribution was not due to coincidental peculiarities lost in the plane wave description. Our DWBA calculation indicates, that the basis for ruling out a one-step mechanism is weakened when distorted waves are introduced, but that there is still room left for components of various two-step mechanisms.

The simplest reaction mechanisms for the $^{10}B(t,p)$ reaction are sketched in fig. 1. The one-step process fig. 1a can only proceed with $\ell=2$. The process in fig. 1b, where the two neutrons are transferred one-by-one, was proposed for this reaction by Shapiro and Timashev [16] and by J. Bang et al.[1], who estimated from a plane wave calculation, that this mechanism would yield an angular distribution peaked at $\theta=0°$, whereas the one-step process in the

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[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

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same approximation has an angular distribution with a broad maximum around $\theta=50°$. In addition, it seems as important to include another two-step mechanism [2], namely the one shown in fig. 1c, where the triton is inelastically scattered before inducing the reaction. The dominant levels in this type of process will be ones which have strongly enhanced $BE\lambda$ values to the ground state of ^{10}B and which overlap well with the ^{12}B ground state. Before making serious attempts to calculate the two-step mechanisms, it is reasonable to study the one-step process in further detail, as we will try to do in the following by examining the optical model parameters as well as the nuclear structure dependence entering into a DWBA calculation along the lines indicated by Glendenning [3].

We fix the proton optical parameters [4] and study the triton parameters, starting with a set labelled I in table 1 derived from elastic scattering of tritons on ^{10}Be [5]. This triton potential which, however, corresponds to 1.5 MeV tritons whereas the reaction $^{10}B(t,p)$ has been studied at 5.5 MeV [6] and 10 MeV [7] incident energy, is rather unusual in the extremely large difference between the real and imaginary radii, and by having on the other hand almost the same diffusenesses. In addition, the imaginary potential is extremely small compared with standard triton parameters [8].

The cross-sections and angular distributions are calculated by the method described by Glendenning [3], thus writing the differential cross-section

$$\sigma(\theta) = \sum_L \left| \sum_N G_N \rho_{NL} (R,\theta) \right|^2 ,$$

where the radial part of ρ_{NL} is that of a harmonic oscillator wave function matched with a Hankel function of correct asymptotic behavior. If the two neutrons go into shell model states belonging to the p-shell, only $G_{N=0}$ is non-zero, so the angular distribution is independent of the detailed correlations. If the ^{10}B and ^{12}B ground states are pure (jj-coupling) shell model states, the neutrons transferred have to be $(p_{1/2}, p_{3/2})$, in which case $G_0 = 0.569$ [9].

Figure 2 shows the angular distributions for 10 MeV incident energy calculated with the optical model parameters of table 1. The set I cannot fit the forward peaked experimental data [7], whereas an increase in the imaginary potential (set II and III) does give some forward peaking. For set II the positions of maxima and minima at larger angles are wrong, but a decrease in the imaginary radius (set III) to a more conventional magnitude makes it possible to reproduce the behavior at angles larger than 100°, whereas the minimum at 60° is not reproduced.

The nuclear structure can affect the angular distributions only if ground state correlations are present which go beyond the p-shell. Considering the magnitudes of interaction matrix element evaluated by Kuo and Brown for the Hamada-Johnson potential [10], it seems reasonable to quote an upper limit of 15% of s-d shell neutron admixtures. This implies that G_1 is different from zero, ranging in magnitude from roughly -0.1 to +0.1. We have repeated the calculations with these limiting values, obtaining only improved results with respect to the first minimum for the case of coherent phases. The values

$$G_0 = 0.6, \quad G_1 = -0.1$$

have been used with the parameter sets II and III, as also shown in fig. 2.

Although no perfect fit to the data has been achieved, it may be concluded, that the DWBA can provide a description, which in contrast to the plane wave description [7,1] does not immediately call for the introduction of more complex reaction mechanisms. However, the remaining discrepancy and the fact that the best fits are obtained with rather a large imaginary triton potential, appears consistent with the claim, that two-step mechanisms do play some role. The absorption implied by the imaginary part of the optical potential, which formally is supposed to represent a large number of channels associated with large energies, may in this specific reaction also provide a gross description of the effects associated with the two-step processes.

The fact that an increase in G_1/G_0 implies a better fit to the rapidly decreasing cross section at forward angles may contain a hint of the type of two-step mechanism responsible for the anomali. A large G_1 can only be achieved by assuming large s-d shell (or higher) admixtures in the ground state. Now there is reason to believe, that the two-step process involving inelastic scattering (fig. 1c) may affect the cross section in a way which can be grossly described by adding components of the levels reached by the inelastic scattering process to the ground state wave function.* Hence the

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*Several quanta of such excitations may have to be coupled in order to give the ground state spin and parity.

success of employing unrealistic high G_1 values seems primarily to point at the type of two-step mechanism involving inelastic scattering. However, most of the levels in either target or final nucleus, which are strongly excited in inelastic processes, are the positive parity levels of the same nature as the ground state which we assumed did not have large s-d shell admixtures. Yet there are 2- states, of which the lowest one in ^{10}B (at 5.11 MeV) has an enhanced E1 transition to the ground state, which may serve the purpose.

As a further test of the appropriateness of the DWBA description in conjunction with the triton optical parameters given by set III of table 1, we have calculated cross sections for the excited states observed in the E_t = 10 MeV experiment [7]. This is done without reference to any detailed knowledge of the wave-functions of the various states, which can be done because of the little freedom in choosing the G_N-coefficient, which on the other hand constitute all that is needed for the reaction model. The shell model states expected in ^{12}B is a 2+ close to the ground state and a set 0+ to 3+ (of which the 0+ cannot be seen by t,p), all of which have p-shell configurations as main components. These states we have associated with the levels observed below 4 MeV. Their position seems to indicate the appropriateness of intermediate coupling [13], but our estimate of the G_N's is rather independent of the particular coupling scheme, unless $\Delta N = 2$ admixtures become important, and we have allowed no larger admixtures of higher shells than for the ground states (i.e., $G_0/G_1 \geq 6$, $G_2 = 0$). The positive parity states observed at higher excitation energy may be of the same type but with higher isospin. All these states are reached by $\ell=0$ or 2 transfer. In one case (the 5.0 MeV level) the excitation of two particles to the s-d shell allows the addition of a possible $\ell=4$ component if the 1+ assignment is correct. Further, a number of negative parity levels are observed, at much lower energies than the pure shell model states. For these we have assumed no higher configurations than p to s-d shells, implying $G_1 = 0$ for $\ell=3$ and any ratio G_1/G_0 for $\ell=1$, since the contributions to G_0 and G_1 from single shell model configurations vary in signs and magnitude [9]. When more than one ℓ value is assumed, they have to add coherently. The ℓ values and (G_0,G_1) assumed for each level are listed in table 2 together with earlier spin assignments. The G-coefficients have been adjusted in absolute magnitude to reproduce the magnitude of cross section at $\theta = 0°$, and the resulting angular distributions are shown in fig. 3. Besides the best ℓ-values are shown distributions for the ℓ value corresponding to firm spin assignments by Ajzenberg-Selove and Lauritsen [11] whenever different. Most of the fits are comparable to that for the ground state, showing some anomali, often in the same region of angles (40°-90°). There remains the 2.62 MeV level, which cannot be fit by any ℓ value. All the angular distributions for levels around 3 MeV have a peculiar peak at 180° and somewhat unusual shapes at forward angles. Such a behavior at specific Q-values is well known in transfer reactions on light nuclei and is similar to the effects appearing when the energy dependence of a transfer leading to a definite final state is considered (cf. $^{12}C(t,p)^{14}C_{gr.st.}$, ref. [12]). Since these effects, which usually occur at low incident energy or low Q-value, cannot be reproduced by the DWBA treatment of the one-step mechanism, they are usually attributed to two-step processes or compound mechanisms. Our spin assignments of the 2.72 MeV and 3.39 MeV levels are based on the following reasoning. These two levels are supposed to be the 1+ and 3+ members of the triplet including the known 2+ level at 3.76 MeV with main neutron configuration $(p^3_{3/2}, p^2_{1/2})$. Since the 3.39 MeV level has a shoulder on the angular distribution around $\theta=25^\circ$, which is characteristic of a mixed $\ell=0$ and 2 distribution, we think that this level is the 3+. We do disagree with the assignment by ref. [11] of $J=2$ for the 5.61 MeV level. The angular distribution is indeed fit very well by $\ell=0$, but the extremely high value of the G_N's indicate that the configuration mixing must be extremely large. There is of course the possibility of a doublet, as also in the other cases of disagreement (e.g., the 2.62 MeV level).

In conclusion there appears to be definite anomalies in the angular distributions of the $^{10}B(t,p)$ process, which do attach considerable interest to the performance of reliable calculations of the influence of two-step mechanisms. On the other hand we think we have pointed out the danger in jumping to the introduction of new mechanisms on the basis of plane wave calculations. This reminder may also apply to the DWBA method, which do involve approximations other than the neglect of two-step mechanisms. A method for treating the process in fig. 1c through the introduction of a source term in the coupled equations for inelastic scattering has been developed by Ascuitto and Glendenning [14]. This method is from a computational point of view promising compared to more direct methods of coupling the reaction and scattering channels, and it can be modified to apply also to the type of process shown in fig. 1b.

The author wishes to thank Dr. Glendenning for permission to use his DWBA program, and for valuable discussions.

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Table 1

Optical model parameters. The nomenclature of the parametrization follows Satchler [15].

	V	W	W_D	r_v	r_w	r_c	a_v	a_w
proton[a)]	49.2	0	11.5	1.25	1.25	1.25	.65	.47
triton I[b)]	138.0	4.0	0.	0.85	2.0	1.4	0.704	0.722
triton II	138.0	40.0	0.	0.85	2.0	1.4	0.7	0.9
triton III	138.0	40.0	0.	0.85	1.5	1.4	0.4	1.1

[a)] Ref. [4].

[b)] Ref. [5], which in addition has a spin-orbit term.

Table 2

Structure ceofficients and assumed ℓ-values.

E	J a)	ℓ b)	J b)	ℓ c)	J c)	G_0 c)	G_1 c)
0	1+			2	1+	0.6	-0.1
0.95	2+	0	3+	2	2+	0.3	-0.05
1.67	2-			1/3 1	2- 2-	0.36/0.36 0.078	0/0 -0.065
2.62	1-	0	3+	3	1-	0.36	0
2.72	1,2,3+	(0)	(3+)	2	1+	0.06	-0.01
3.39	1,2,3+	0	3+	0/2	3+	0.23/0.32	-0.04/-0.05
3.76	2+	1	2,3,4-	2	2+	0.28	-0.05
4.30	(1-)			1/3 3	2- 1-	0.01/0.06 0.12	0.01/0 0
4.54	3-	1	2,3,4-	1	3-	0.15	-0.13
5.00	1(+)			3 2/4	1- 1+	0.11 0.04/0.02	0 -0.007/0
5.61	2	0	3+	0	3+	5.4	-0.9
5.71	3	0	3+	0	3+	1.25	-0.2

a) Ajzenberg-Selove and Lauritsen [11].

b) Middleton and Pullen [7].

c) Present calculation.

Figure Captions

Fig. 1. Various mechanisms for the $^{10}B(t,p)$ reaction.

Fig. 2. Ground state angular distributions. The theoretical cross-section at $\theta=0$ has been adjusted to the experimental. The triton optical parameters used are given in table 1, curve a uses set I, curve b set II and curves c and d set III. For curves a-c $G_1 = 0$ whereas $G_0/G_1 = -6$ for curve d.

Fig. 3. Angular distribution for excited states. The triton optical parameters were set III, other parameters are listed in table 2.

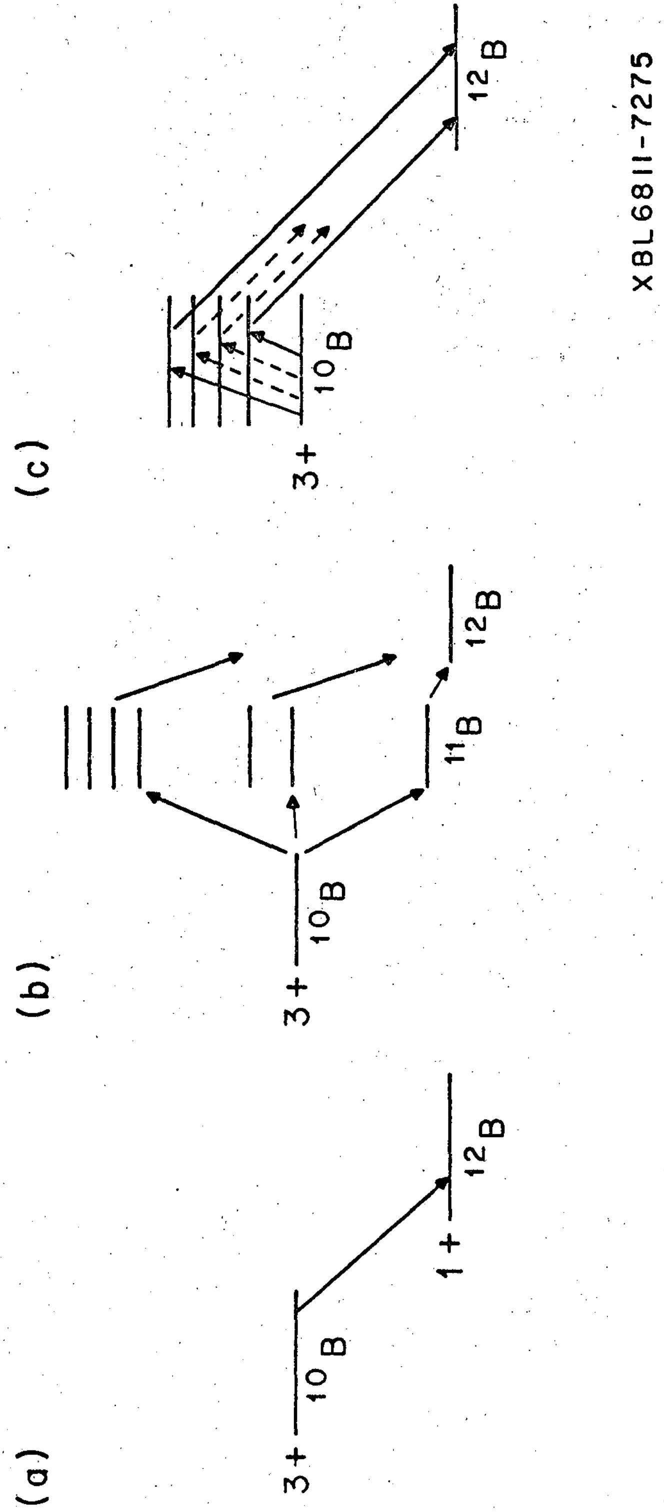

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Fig. 1

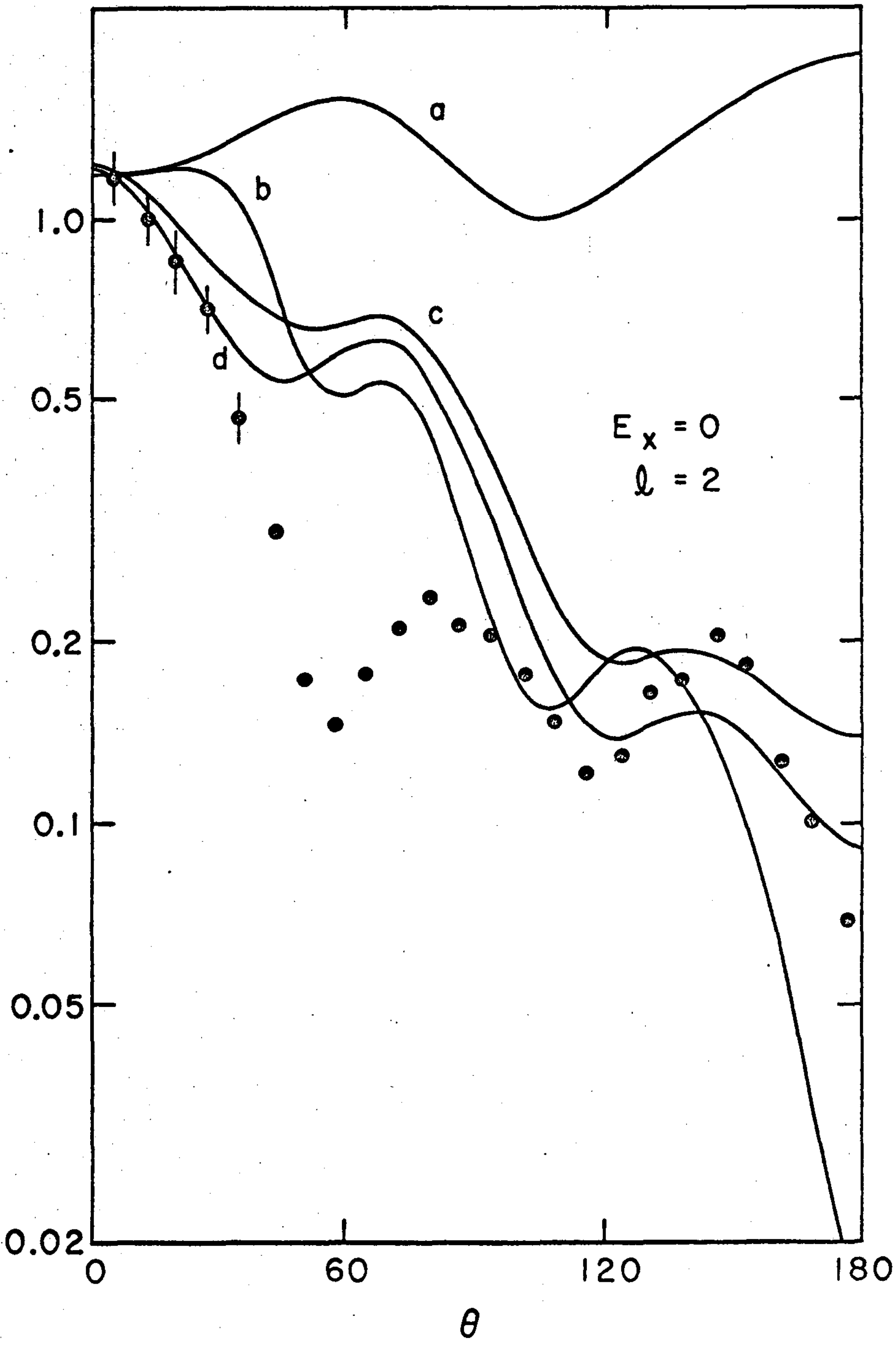

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Fig. 2

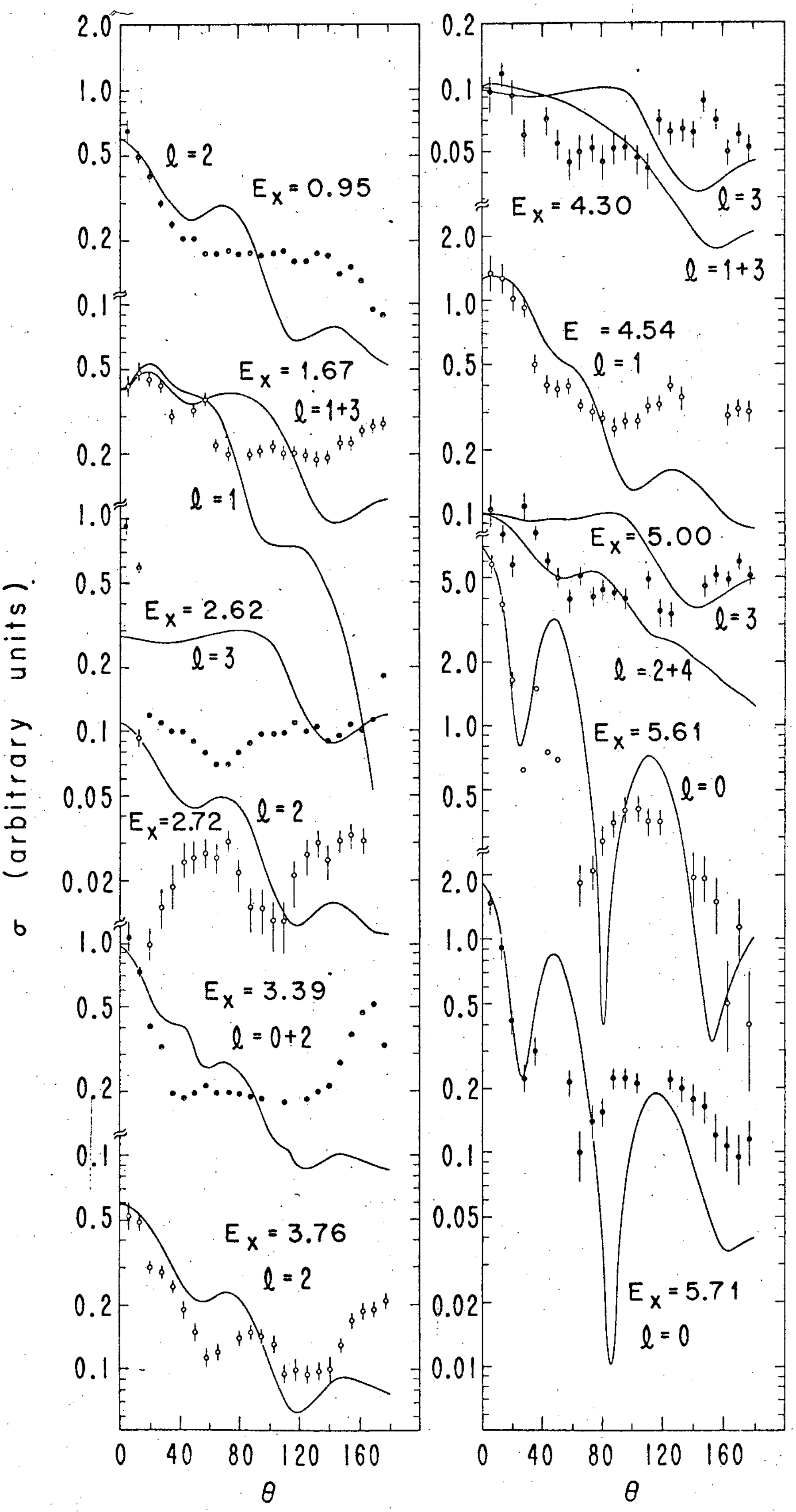

Fig. 3

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