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Excitation Functions of Deuteron Induced Reactions

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Excitation functions of reactions induced by deuterons on ^{142}Ce, ^{130}Te, ^{96}Zr, and ^{70}Ge were measured with the activation method up to 14.1 MeV deuteron energy. The observed reactions are (d, p), (d, n), (d, 2n) and/or (d, 3n), (d, α) reactions on each target. The results were well explained with a modified Peaslee theory on deuteron reactions, in which a new parameter, "entire absorption", was introduced.

Excitation functions of ^{142}Ce, ^{130}Te, and ^{96}Zr give the common values of variable parameters and a common pattern regarding relative contributions of neutron stripping, proton stripping and entire absorption processes. The situation is quite different for ^{70}Ge.

I. INTRODUCTION

It is well known that in the interaction of deuterons with a nucleus the neutron stripping process plays an important role because of the loosely bound structure of the deuteron.[3,4]

Recently, the cross sections of deuteron reactions other than (d, p) were measured, and by means of the statistical theory the following facts were disclosed about the contributions of the stripping process and the concurrent entire absorption process: (i) In the region of $Z \leq 30$ the evaporation probability of charged particles from the compound nucleus is quite large, and in the deuteron energies over the Coulomb barrier the contribution of the compound nucleus process is fairly large even in the (d, p) reaction.[5] In the region of $Z \leq 40$, (d, p) reaction can be regarded as a pure stripping process.[6,7] (ii) For the (d, n) reactions the contribution of the stripping process increases with the deuteron energy.[7] (iii) For the (d, 2n) reactions the entire absorption process seems to be predominant.[5-7]

Those facts suggest that the deuteron reaction must be interpreted not only with the stripping process but also with the entire absorption process. However, the discussions have been limited to the qualitative statements on the contributions of both processes, because the data so far obtained were frequently only fragmentary and all "Key" reactions necessary for the analysis could hardly be investigated radiochemically except in a few cases. Another reason lies in the analysing method.

In most investigations the excitation functions were analysed either with the statistical theory or with the direct interaction mechanisms as Peaslee[4] did, and the discrepancies between the experimental values and the calculated ones were attributed to the other process.

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In this work the deuteron induced reactions were investigated on several targets for which all the necessary key reactions could be measured. The results were analysed in terms of Peaslee's theory[4] of the deuteron reaction. A large discrepancy was found in the (d, 2n) reaction cross section due to the underestimation of the entire absorption process in the theory. Modifying Peaslee's theory, we tried to explain the experimental excitation functions and to estimate the relative contributions of the respective processes quantitatively.

II. MODIFICATION OF PEASLEE'S THEORY FOR DEUTERON REACTION

In the first part of this work we show experimental results of the deuteron reaction on ^{142}Ce and either the statistical theory or the Peaslee's theory can explain the results.

II-1. Experimental Procedures

The excitation functions of the reactions ^{142}Ce(d, p)^{143}Ce, ^{142}Ce(d, n)^{143}Pr, ^{142}Ce(d, 2n)^{142}Pr, and ^{142}Ce(d, α)^{140}La were measured radiochemically up to a deuteron energy of 14.2 MeV using cyclotrons of Osaka University and of Kyoto University. A thin layer of cerium oxide of natural isotopic abundance was deposited on an aluminium foil by electrophoresing its suspensions in acetone. The foils were stacked with aluminium foil for degrading the beam energies.

The target material together with the aluminium foil was dissolved in HCl, and the rare earth activities were separated by cation exchange chromatography using α-hydroxi-isobutyrate as an elutriant. The oxalate of each element was precipitated from the solution, mounted on a filter paper and used for the activity measurement. The chemical yields were varied from 20 to 80 %.

Cross sections of the four reactions were determined from the activities of three negatron emitters ^{140}La, ^{142}Pr, and ^{143}Pr. β-activities were measured with an anthracene scintillator and a 2π gas-flow counter. The activities of ^{142}Pr (19h) and ^{143}Pr (13d) in the praceodium sample were distinguished from each other by analysing the decay curve.

The cerium sample contains not only ^{143}Ce activities but also ^{141}Ce activities from the ^{140}Ce(d, P) reaction. After two weeks from the first chemical separation, when the activities of ^{143}Ce had completely decayed to ^{143}Pr, praceodium was again separated from cerium by the same ion exchange technique. The praceodium fraction thus obtained contained no other activities than those of ^{143}Pr, the daughter of ^{143}Ce. Corrections for counting efficiencies of each nuclei and for the decay and the build up of activities during bombardment and the first chemical separation were also taken into account for the calculation of the reaction cross sections.

II-2. Experimental Results

The observed cross sections are shown in Fig. 1. The errors were estimated from those of the target thickness mesurements, the counting statistics, the decay analyses, the half-lives used and the counting efficiency mesurements.

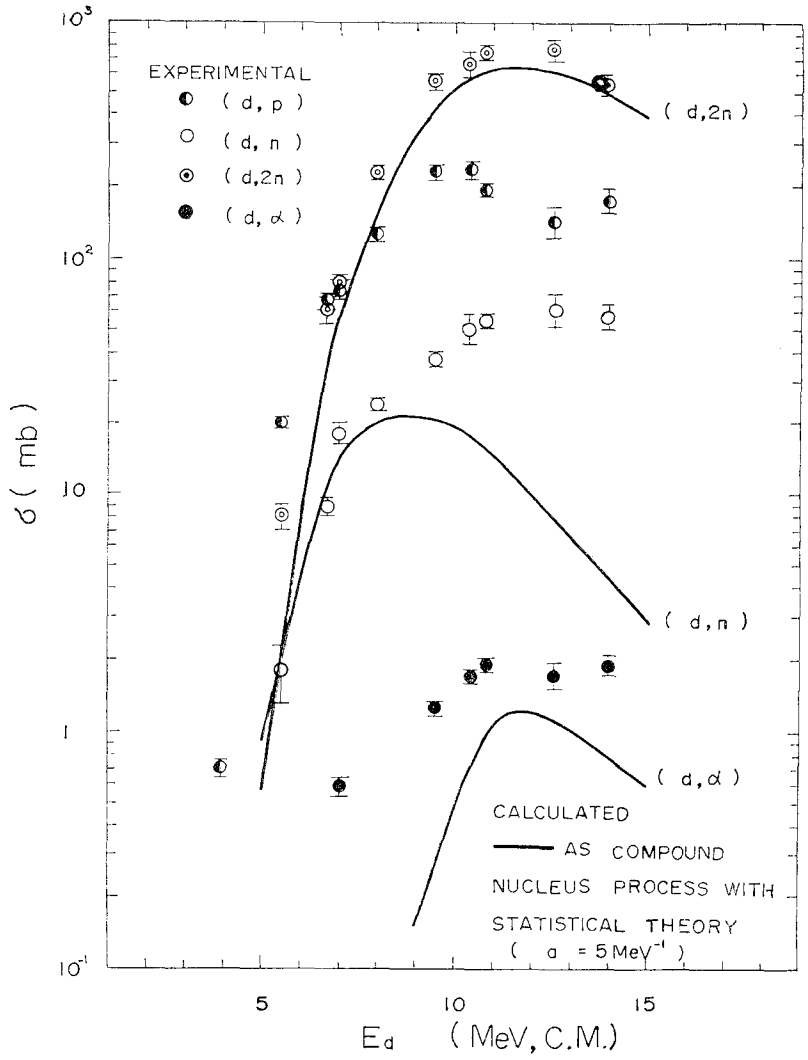

Fig. 1. Comparison between the cross sections calculated from the compound nucleus process with the statistical theory and the experimental ones.

The half-life of ^{142}Pr was determined from the decay data followed for more than two weeks of the praceodymium activities produced at 11.0, 9.6 and 8.1 MeV bombardments, and computed with the least-squares method by using the NEAC 2203 computer. The value of 19.14±0.05h, the weighted mean of three data, may be more accurate than the previously preported ones.

During the development of this work, Bock and Rudel[7] have measured the excitation functions for ^{142}Ce+d reaction up to 12 MeV. Their results agree well with ours for the (d, n) reaction, but are about 20% and more than 50% smaller than our's for the (d, p) and the (d, 2n) reactions, respectively. The reason for the discrepancies are not clear, because their method for radiation measurement are different from our's.

II-3. Discussion

3. a Calculation with the statistical theory The excitation functions of the $^{142}Ce+d$ reaction were calculated on the basis of compound nucleus processes using statistical theory. Procedures are reported previously.[8] Capture cross sections of deuterons were calculated following the method presented by Shapiro[9] with $r_0=1.5$ fm based on the square-well model. The expression $W(E)=const.\exp[2\{a(E-\delta)\}^{1/2}]$ was used for level density, and Cameron's pairing energies[10] were employed for the parameter δ. The inverse cross sections of the evaporated particles were calculated assuming the diffused surface optical potential model for neutrons[11] and for alpha particles,[12] and assuming the square-well potential model ($r_0=1.5$ fm) for protons.[9]

The calculated cross sections with $a=5\,MeV^{-1}$ are shown by the solid line in Fig. 1. The calculated (d, p) reaction cross section is too small to be shown in the figure. From the figure one can deduce: (1) the (d, p) reaction cannot be explained as the compound nucleus process, because the experimental values are larger than the calculated ones by a factor of more than 10^3. (2) The (d, 2n) reaction seems to be attributed largely to the compound process. (3) Discrepancies between the experimental cross sections and the calculated ones for the (d, n) reaction become obvious at high energies. (4) the (d, α) reaction can approximately be explained as the compound nucleus process.

3. b Calculation with Peaslee's theory The large discrepancies between the observed and the calculated cross section of the (d, p) reaction and of the (d, n) reaction above 10 MeV are due to the contribution of the stripping process. Thus, we tried to find parameter sets which explain the stripping part of the cross sections with Peaslee's theory. The calculating procedures were the same as described in the literature,[4] correcting some omissions in the original expressions. The same parameters as in the literature concerning the deuteron itself were used in the calculation, but the reduction factors for n-stripping and p-stripping reactions were recalculated using the neutron separation energy for each residual nucleus.

The stripping reaction cross sections were calculated for some values of r_0 from 1.5 to 1.8 fm and fitted to the experimental values by choosing adequate values of ξ. Table I gives the sets of parameters thus obtained.

Table I Parameters Used in the Calculation with Peaslee's Theory.

r_0 (fm)	ξ_n	ξ_p
1.8	0.32	0.34
1.7	0.35	0.45
1.6	0.49	0.55
1.5	0.60	0.72

The shape of the excitation function calculated fits better with the experimental one when r_0 is larger. Figure 2 shows an example of the fitting of the excitation functions calculated with $r_0=1.7$ fm. Peaslee's theory for deuteron reaction can

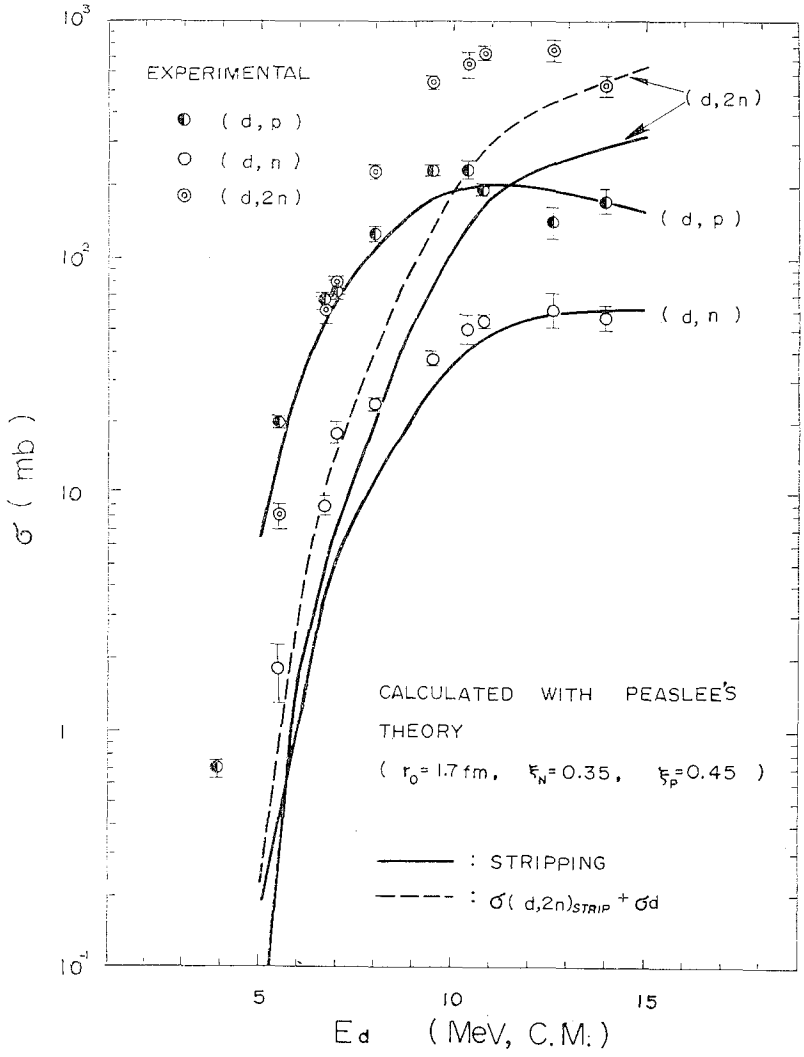

Fig. 2. An example of the fitting of the excitation functions calculated with Peaslee's theory to the experimental ones.

reproduce the experimental excitation functions for (d, p) and (d, n) reactions, in which the stripping process is dominant, with a proper set of parameters.

In the figure the stripping cross sections calculated for the (d, 2n) reaction, which are the differences between the cross sections calculated for the p-stripping process and the ones for the (d, n) reaction, are also shown. As seen in the figure, the stripping cross sections calculated for the (d, 2n) reaction are much smaller than the experimental ones, and the differences between those two cross sections would be attributed to the entire absorption process.

According to the Peaslee's theory, the entire absorption cross section, σ_d, can be calculated. The sum of the calculated σ_d and the stripping cross section for the (d, 2n) reaction would be the upper limit of the cross section for the

(d, 2n) reaction with a given parameter set, because most of the σ_d would be observed as the cross section of the (d, 2n) reaction. The limit was also shown in Fig. 2 with a broken line, and is again much smaller than the experimental value. Peaslee's theory cannot reproduce the (d, 2n) reaction cross section with the same parameter set which gives good fitting for the (d, n) and the (d, p) reaction, because of the underestimation of the entire absorption process.

3. c **Improvement of the Peaslee's theory** In order to explain the experimental results based on the stripping process and the entire absorption process in a unified style, it was attempted to introduce a new "entire absorption parameter" ρ increasing the entire absorption process. Peaslee assumes that in the stripping of either nucleon from the deuteron, the other nucleon which happens to exist outside the target nucleus surface escapes experiencing no nuclear force.

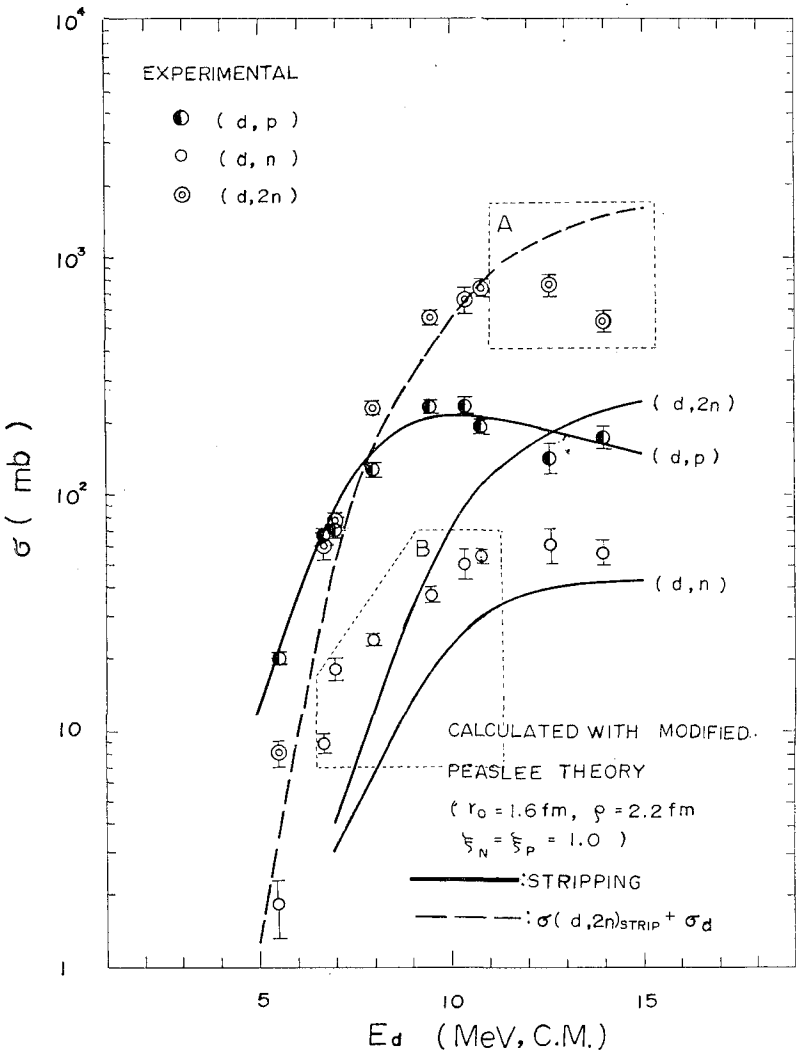

Fig. 3. Preliminary fitting with the modified Peaslee calculation.

We assumed, however, that the other nucleon within the distance ρ from the nuclear surface is absorbed into the nucleus, and results in an entire absorption process.

Analogous fittings as in Fig. 2 were performed for two selected ρ values of 1.1 and 2.2 fm and for r_0 values of 1.5−1.8 fm, and proper ξ values were chosen for each set of r_0 and ρ. A good fitting was obtained with a parameter set of $r_0=1.6$ fm, $\rho=2.2$ fm and $\xi_n=\xi_p=1.0$, and is shown in Fig. 3.

The stripping cross sections for the (d, p) and the (d, n) reaction by the modified theory agree with the experimental ones in a similar manner as in Fig. 2 based on Peaslee's theory ($\rho=0$), and upper limit of the cross section for the (d, 2n) reaction approaches the experimental value. However, some portions of σ_d must naturally be observed as the (d, 3n) and the (d, n) reactions in the

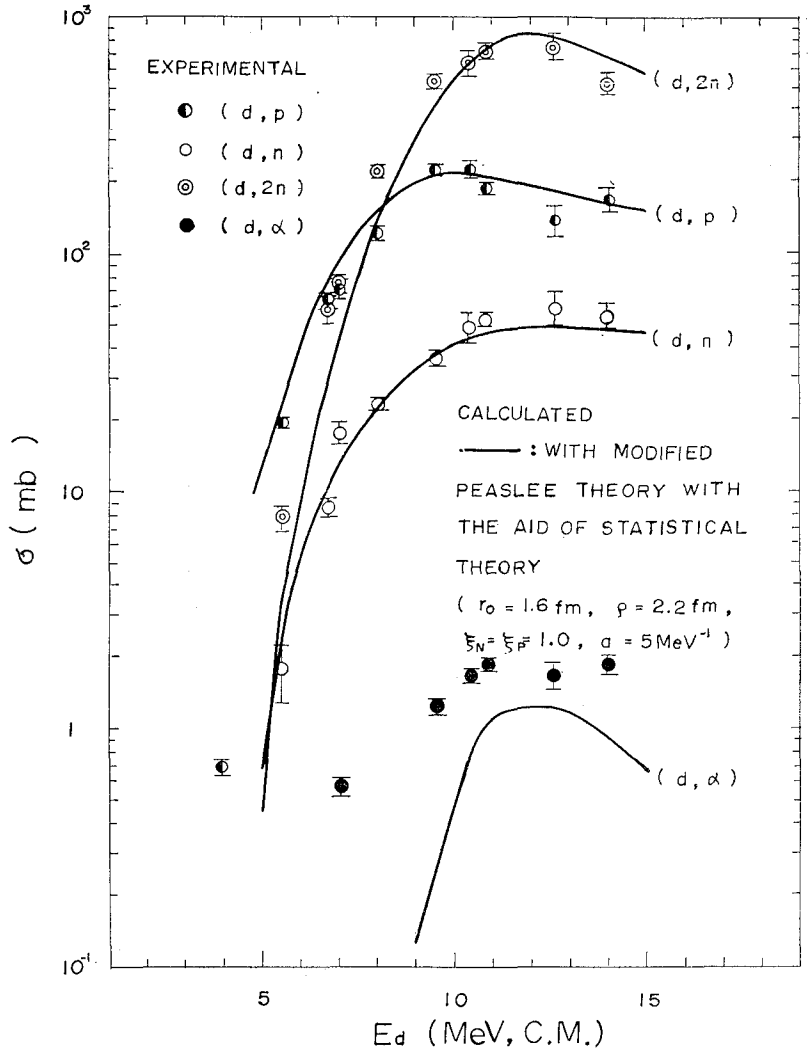

Fig. 4. Best fitting of the modified Peaslee theory with the aid of the statistical theory to the experimental cross sections.

high and the low energy region, respectively. This is the reason that the discrepancies appear in the region A and B in Fig. 3.

On the other hand, some portions of the stripping cross section calculated for the (d, 2n) reaction over the threshold energy of (d, 3n) reaction (9.5 MeV) must be observed as the (d, 3n) reaction. This stripping cross section of the (d, 3n) reaction, which contributes to the discrepancy in the region A to some extent, can be estimated from the probability that a residual nucleus of an excitation energy produced by p-stripping process emits two successive neutrons. This branching ratio of evaporation is calculated by the statistical theory. The net stripping cross section for the (d, 2n) reaction could thus be obtained. The entire absorption cross sections for the respective reactions were calculated by multiplying σ_d by the branching ratios obtained from the statistical theory.

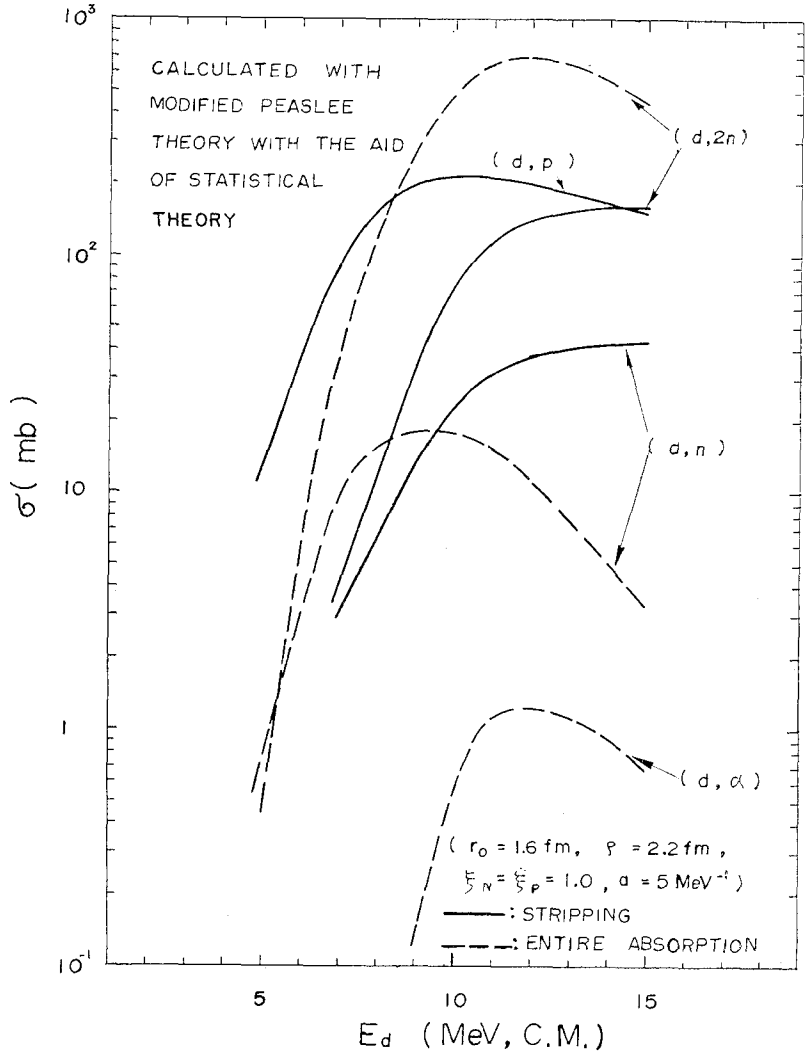

Fig. 5. Estimated cross sections attributed to the stripping and the entire absorption processes for the various reactions.

The sum of the calculated cross sections from both processes is compared with the experimental cross sections for the respective reactions in Fig. 4. In the figure those for the (d, α) reaction, which was assumed to proceed through only the entire absorption process, are also included. As shown in the figure, the modified Peaslee's theory reproduces the experimental excitation functions quite well with the parameter set $r_0=1.6$ fm, $\rho=2.2$ fm and $\xi_n=\xi_p=1.0$, by the aid of the statistical theory with $a=5$ MeV^{-1}.

The ρ value of 2.2 fm is equal to the average n-p distance in the deuteron, and is a reasonable range in which the deuteron acts as one nuclear particle near the nuclear surface. Furthermore, it must be remembered that the capture cross section for protons is explained in terms of the parameter set $r_0=1.5$ fm and $\xi_p=1.0$ in the square-well potential.[9]

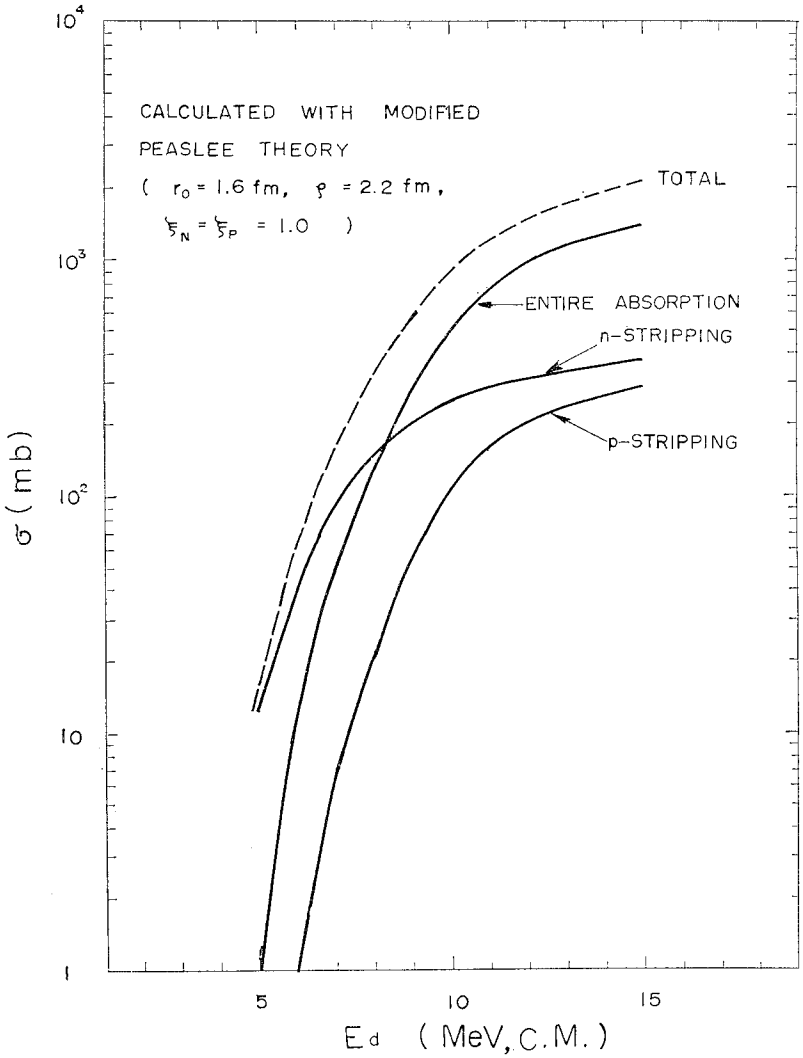

Fig. 6. Estimated cross sections for the entire absorption, the n-stripping and the p-stripping processes and their total sum.

3. d Contributions of each process In Fig. 5 the cross sections of both processes for each reactions are plotted. Those results are consistent with the qualitative expressions obtained by Bock and Rudel for the same reaction, and those obtained by other authors for the reactions on other targets.[5,6]

The estimated cross sections for the entire absorption, the n-stripping and the p-stripping processes, and also their total sum are plotted in Fig. 6. It is interesting to note here that the estimated cross sections for the entire absorption process approximate the capture cross sections for deuterons calculated by Shapiro as described in ref. 1).

III. APPLICATION OF MODIFIED PEASLEE'S THEORY TO SEVERAL DEUTERON INDUCED REACTIONS

In the previous part a unified explanation of the deuteron reaction with Peaslee's theory modified by introducing the entire absorption parameter was presented. In this part the applicability of this method and the universality of the adopted parameter values were tested for some other target nuclei.

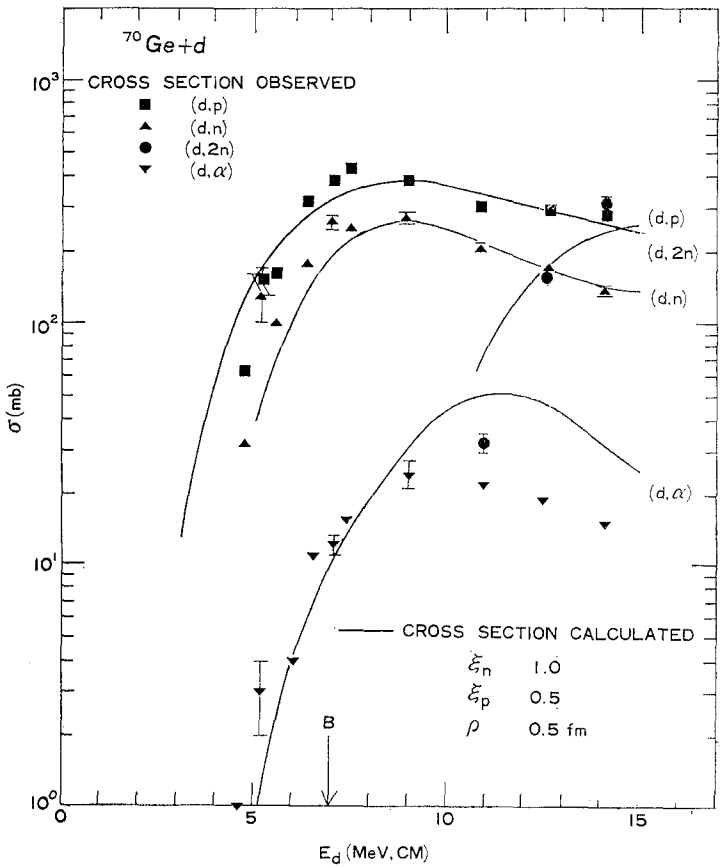

Fig. 7. Excitation functions for the ^{70}Ge+d reactions. Symbol B denotes Coulomb barrier (7.0 MeV).

III-1. Experimental Procedures

The three target nuclei, ^{70}Ge, ^{96}Zr and ^{130}Te, which produce radioactive products by the three important key reactions (d, p) (d, n) and (d, 2n), were used as targets. All the target materials are enriched isotopes obtained from ORNL.

Most of the experimental procedures are similar to those described in Section II, but a few words seem to be necessary to explain the experimental details. Stacked targets were irradiated by the 14.4 MeV deuteron from the cyclotron of Kyoto University. The initial energy and its spread were determined by the aluminium absorption method.[13] The spread of initial energy was about 0.1 MeV, and the maximum variation of initial energy from day to day was 0.2 MeV.

After chemical separation, the radioactivities produced were measured by γ-ray and/or x-ray spectroscopy with calibrated NaI (Tl) detectors.

III-2. Experimental Results

The excitation functions obtained are shown in Figs. 7-9. Errors shown in the figures are the 90 % confidence intervals estimated from repeated experiments.

Bock[6] has measured the excitation functions for the ^{96}Zr(d p), (d, n) and (d,

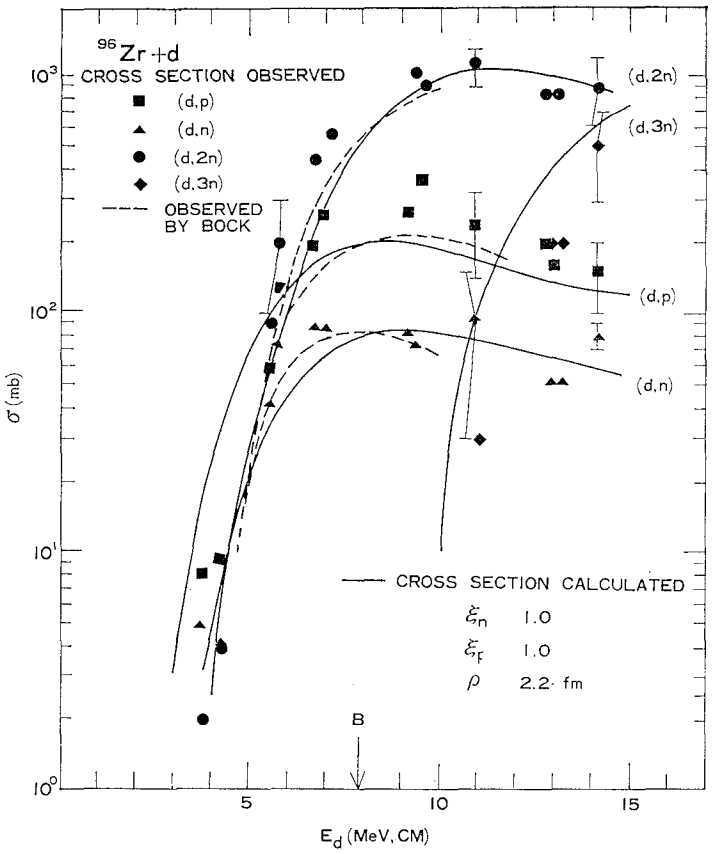

Fig. 8. Excitation functions for the ^{96}Zr+d reactions. Symbol B denotes Coulomb barrier (7.9 MeV).

2n) reactions, which are also shown in Fig. 8. Pement and Wolke[14] have studied ^{130}Te(d, 2n) reaction. The present results agree well with their data in spite of the different methods of radioactivity measurements.

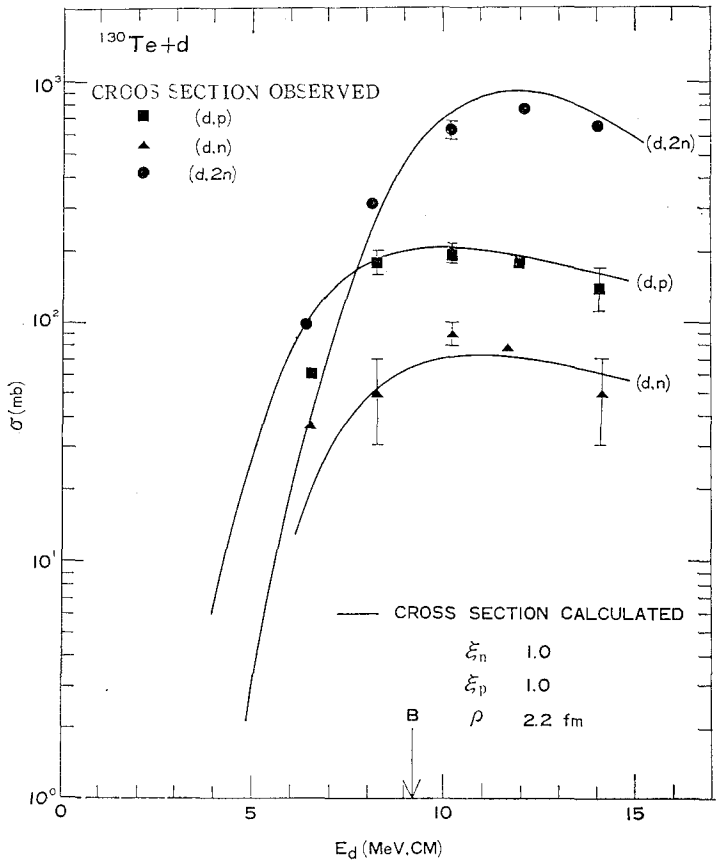

Fig. 9. Excitation functions for the ^{130}Te+d reactions. Symbol B denotes Coulomb barrier (9.2 MeV).

IV. DISCUSSION

IV-1. Calculating procedures

Experimental excitation functions were analysed by the modified Peaslee's theory with the aid of statistical theory. The same values of parameters as in the Peaslee's calculation were used on the deuteron itself. The value of 1.6 fm was used throughout for r_0. As the level density parameter a, which is necessary for the evaporation calculation, the values 3.3 and 5 MeV^{-1} were used for ^{70}Ge, ^{96}Zr and ^{130}Te, respectively. Calculated excitation functions were fitted to experimental ones by varying the three parameters ξ_n, ξ_p, and ρ using a computor NEAC 2203. The values 0.2, 0.4, 0.6, 0.8 and 1.0 were chosen for ξ_n and ξ_p, and the values 2.2, 1.1, 0.5 and 0 fm for ρ.

IV-2. Comparison with experiments

The final calculated results are shown in Figs. 7–9 together with the experimental ones. The values of variable parameter sets used are shown in Table II.

Table II Adopted Values of Variable Parameters.

Target	ξ_n	ξ_p	ρ (fm)
^{70}Ge	1.0	0.5	0.5
^{96}Zr	1.0	1.0	2.2
^{130}Te	1.0	1.0	2.2
^{142}Ce	1.0	1.0	2.2

In these figures it is seen that the calculated excitation functions reproduce the experimental ones quite well. Thus, the modified Peaslee's theory has a wide range of applicability. It is noticeable here, however, that the best-fit values of the variable parameter ξ_n, ξ_p and ρ on ^{96}Zr, ^{130}Te and ^{142}Ce are the same, but the smaller values of ξ_p and ρ are necessary in the case of ^{70}Ge. The reason why the different parameter set should be used for the reproduction of excitation functions of the neutron-defficient nucleus, ^{70}Ge, needs further investigation.

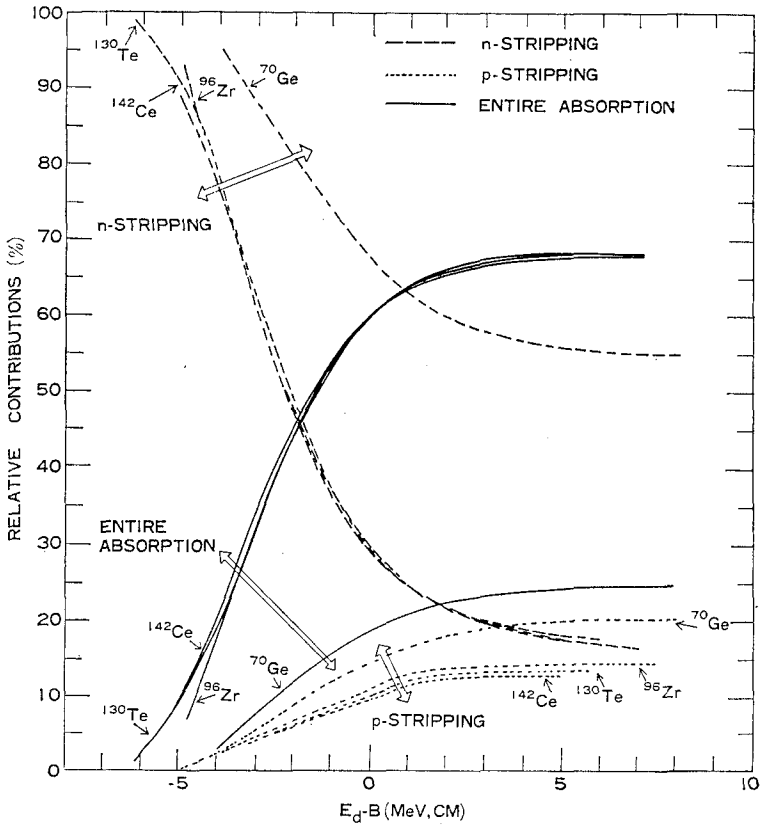

Fig. 10. Relative contributions of the three processes to the total reaction cross section. Symbol B denotes Coulomb barriers of respective reactions.

It is of interest to see how the dependence on deuteron energy of the cross sections of n-stripping, p-stripping and entire absorption processes vary with the atomic number. In Fig. 10 the relative contributions of the three processes to the total reaction cross section are plotted versus the energy which amounts to the Coulomb barrier for the respective target nucleus subtracted from the incident deuteron energy. In the reaction system, whose cross section are reproduced with the same parameter set, the relative contributions of the three processes are expressed with the same manner.

The remarkable enhancement of n-stripping process and the depression of the entire absorption process are seen in the case of ^{70}Ge and correspond to the smaller values of ξ_p and ρ. We are now trying to explain this interesting difference.

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