Cross Sections and Angular Distributions for the $B^{10}(\alpha, d)C^{12}$ Reaction from 3.2 Mev to 3.8 Mev

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(Received July 29, 1959)

In order to investigate the possibility of direct interactions in (α,d) reactions, the $B^{10}(\alpha,d)C^{12}$ reaction has been studied for alpha-particle bombarding energies from 3.1 to 3.7 Mev. The yield curves are rather flat and show no typical resonance structures. The angular distributions show a peak at about $\theta_{c.m.}=70°$ and an increase of intensity in the backward direction over the entire alpha-particle energy range. These results indicate that the $B^{10}(\alpha,d)C^{12}$ reaction proceeds mostly by direct processes, probably both stripping (or knock on) and heavy-particle stripping ones.

IN order to investigate the possibility of direct interactions in (α,d) reactions, the excitation functions and the angular distributions of the deuterons from $B^{10}(\alpha,d)C^{12}$ have been measured at incident alpha-particle energies from 3.2 Mev to 3.8 Mev.

The alpha particles were supplied from the 16-inch variable-energy cyclotron.[1] The beam has an energy spread of about 0.6%. The targets were prepared by depositing B_2O_3 (enriched to 96% in B^{10}) on a thin gold foil or a thick Be plate (for measurements at backward angles). They were within an equivalent thickness of 40 kev for 5.3-Mev polonium alpha particles. The outgoing particles were detected by a thin CsI(Tl) crystal. The resulting pulses were sorted by a seventy-channel pulse-height analyzer. The main background reactions are $B^{10}(\alpha,p)C^{13*}$ ($Q=0.981$ Mev, $Q=0.391$ Mev, and $Q=0.211$ Mev), $B^{11}(\alpha,p)C^{14}{}_{\text{ground}}$ ($Q=0.781$), and $Au(\alpha,\alpha)Au$. Because there is a fairly remarkable difference between the range-energy relations of deuterons and protons and that of alpha particles, most of the particles were resolved with a silver absorber of adequate thickness placed in front of the detector. However, this simple method is not effective in distinguishing deuterons from protons having slightly lower energy, for example, in the case of the deuterons and the protons from $B^{10}(\alpha,p)C^{13*}$ ($Q=0.391$ Mev, and $Q=0.211$ Mev) emitted at large angles. Therefore, at $\theta_{c.m.}>90°$, the resolution was poor and errors were large.

The yields at $\theta_{c.m.}=0°$ and $\theta_{c.m.}=55°$ are shown in Fig. 1. Although there are small peaks or slow variations, the curves show remarkable differences from those of reactions involving a compound-nucleus mechanism. For example, the yield curves of $B^{11}(\alpha,p)C^{14}$, $Al^{27}(\alpha,p)Si^{30}$, and $P^{31}(\alpha,p)S^{34}$ obtained by us[2] at the same bombarding energy show typical resonance structures and the peak-to-valley ratio is very large.

The angular distributions have also been measured at alpha-particle energies of 3.80 Mev, 3.61 Mev, 3.52 Mev, 3.38 Mev, and 3.27 Mev. All of them are similar and show a peak at about $\theta_{c.m.}=70°$ and may also show an increase of intensity in the backward direction. Except for the measurement at $E_\alpha=3.80$ Mev shown in Fig. 2 which has been taken with the energy resolution of the detector system as high as possible,

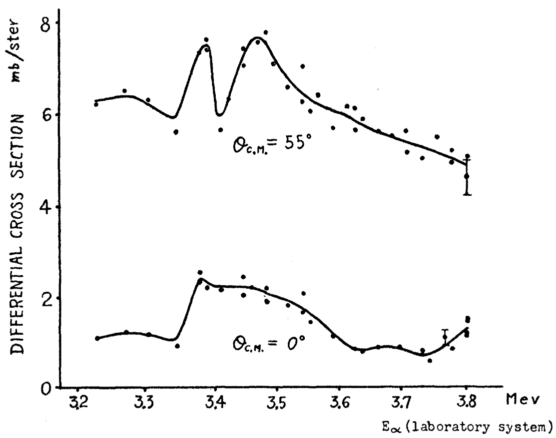

FIG. 1. Excitation functions, in the center-of-mass system, of deuterons from the ground-state transition in $B^{10}(\alpha,d)C^{12}$ at angles of 0° and 55° (center-of-mass system).

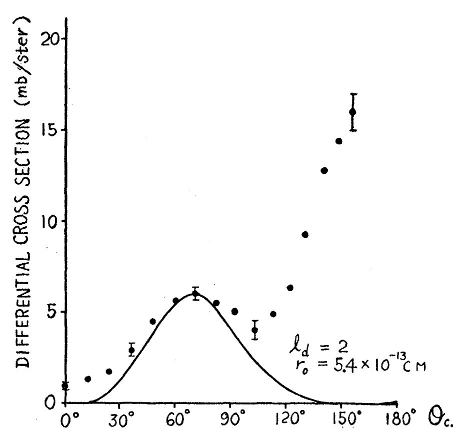

FIG. 2. Angular distribution, in the center-of-mass system, of deuterons from the ground-state transition in $B^{10}(\alpha,d)C^{12}$ at an alpha-particle energy (laboratory system) of 3.80 Mev, fitted by $|j_2(KR)|^2$ with $R=5.4\times10^{-13}$ cm.

[1] Kumagai, Ôno, Hayashi, Shôno, and Kuroda, J. Phys. Soc. Japan 14, 1 (1959).

[2] K. Ôno and K. Kuroda (to be published).

the deuterons from $B^{10}(\alpha,d)C^{12}$ and the protons from $B^{10}(\alpha,p)C^{12*}$ ($Q=0.981$ Mev and $Q=0.391$ Mev) were hardly resolved in the backward direction, $\theta_{c.m.}>90°$. In Fig. 2 the theoretical angular distributions calculated from a simple stripping equation derived by Bhatia *et al.*[3] are compared with the experiment, the theory being assumed to be applicable to the (α,d) reaction. We have calculated only $|j_2(KR)|^2$, considering the form factor nearly constant. In order to fit the calculated functions to the experiment, it is necessary to assume $l_d=2$, $R=5.4\times10^{-13}$ cm. The value required for R is a reasonable one that is used for interpreting the (d,p) stripping reaction.[4] The fact that good agreement is found between the calculated distribution and the experimental one in the forward direction provides strong support for a direct process. The increase of intensity in the backward direction suggests that heavy-particle stripping may exist. Although the absolute differential cross-section measurements are not highly precise, it is to be noted that their magnitudes are fairly large and comparable with the largest values in $B^{10}(\alpha,p)C^{12}$ reactions.

The angular distribution of the inverse reaction, $C^{12}(d,\alpha)B^{10}$, has been measured at $\theta<60°$ by El Bedewi and Hussein[5] at relatively high-deuteron bombarding energy of 8.9 Mev. The forward peak can approximately be fitted to $|j_2(KR)|^2$ with $R\simeq8\times10^{-13}$ cm, which is somewhat larger than the value employed for the $B^{10}(\alpha,d)C^{12}$ reaction. The difference in the values of R between the two reactions may be due to the difference in the bombarding energies employed and to incompleteness of the calculation.

In conclusion, the results obtained in the present work indicate that the $B^{10}(\alpha,d)C^{12}$ reaction at our relatively low bombarding energy proceeds mostly by a direct process as in the case of (α,p) and (α,α') reactions at high bombarding energy. The results also suggest that the probabilities of finding a deuteron and an alpha particle at the nuclear radii in B^{10} and C^{12}, respectively, are fairly large. These features are very interesting in terms of a nuclear model, especially a cluster model in a light nucleus.

A more detailed report is in preparation and will be published in the *Journal of the Physical Society of Japan.*

ACKNOWLEDGMENTS

The authors wish to thank Professor T. Muto and his co-workers for many valuable discussions.

[3] Bhatia, Huang, Huby, and Newns, Phil. Mag. **43**, 485 (1953).

[4] R. Huby, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Academic Press, New York, 1953), Vol. 3, p. 206.

[5] F. A. El Bedewi and I. Hussein, Proc. Phys. Soc. (London) **A70**, 233 (1957).

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Stability of the Adiabatic Motion of Charged Particles in the Earth's Field*

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(Received July 20, 1959)

The motion of charged particles in a magnetic field such as that of the earth or that of a magnetic mirror machine is discussed. It is shown that during the motion and drift of a relativistic particle, not only the magnetic moment, but also a longitudinal invariant and an additional flux invariant are adiabatically conserved. These conservation laws lead to retention of the particles in the field. The derivation of the adiabatic invariants leads to a set of equations of motion which describe the average drift of the particles from one force line to the other, and which also describe the changes that occur in the energies and periods associated with the motion. In the absence of scattering, loss of particles from the magnetic field will be due to the violation of the adiabatic laws.

I. THE PROBLEM

MOTION of charged particles outside the atmosphere in the geomagnetic field has received recently increased attention because of the discovery of the Van Allen radiation belts and also because of the artificial temporary generation of exceedingly low intensity belts of this kind by small nuclear explosions.[1] It follows from the simplest considerations of the motion of particles in magnetic fields that many charged particles will oscillate between the north and south polar regions along magnetic lines and that they will be reflected by the mirrors formed by the stronger magnetic fields in high latitudes. It is also well known that due to the inhomogeneity of the earth's magnetic field electrons will drift from west to east and positive ions from east to west, giving rise in this manner to a corpuscular radiation belt.

* Work was performed under auspices of the U. S. Atomic Energy Commission.

[1] These experiments have become known under the code name, Argus. For description and results see, for example: N. C. Christofilos, University of California Radiation Laboratory Report UCRL-5548 (to be published). Also, see the Proceedings of the Argus Symposium held at the National Academy of Sciences, April 29, 1959 (to be published).