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Letters to the Editor

POSSIBLE OCCURRENCE OF A SECOND-ORDER PROCESS IN INELASTIC SCATTERING OF DEUTERONS BY NUCLEI

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IN many papers, in calculating cross sections for various "direct" nuclear reactions at low and medium energies, the authors use perturbation theory, the applicability of which is not justified (because of the absence of a small parameter). However the results of the computations appear to be in good agreement with the experimental data (for inelastic scattering of protons,[1] and for the stripping reaction), probably because in these reactions higher-order processes do not produce any special features in the angular distribution. Nevertheless, the study of processes associated with the appearance of "higher-order effects" is of fundamental interest.

Apparently the most favorable reaction for studying the role of second-order effects should be the inelastic scattering of deuterons. In this case, the first-order process is process a, as a result of which the neutron or the proton in the deuteron interacts with the nuclear surface and transfers part of its energy to it.[2,3] According to Huby and Newns,[2] at low and medium energies the maximum in the angular distribution, for $l \geq 2$ (where l is the angular momentum transferred by the deuteron to the nucleus), occurs at medium angles. But because of the low binding energy of the deuteron, one of the second order processes, the process b of "double stripping" (for example d—p—d′) should give a maximum in the angular distribution at zero degrees, if the orbital angular momenta of the neutrons which are transferred from the deuteron to the nucleus (l_i) and back (l_f) are small.

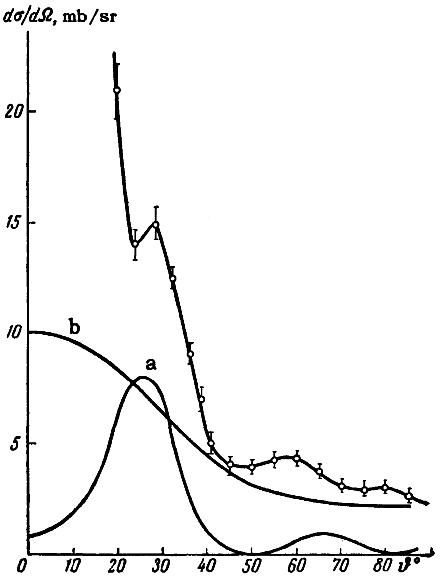
In many cases the experimental angular distributions show, in addition to the maximum associated with the first order process, a maximum at an angle close to zero.[4] A maximum at zero degrees cannot be explained by the "focusing" properties of the nucleus[5] (since the transparency for deuterons is much less than for protons,[6] and the angular distribution has a shape different from that given by the "focusing" properties of the nucleus), or by the effect of Coulomb excitation of the nucleus, since at these energies the angular distribution from Coulomb excitation is practically isotropic (for low energy transfer) and the cross section is many times less than that observed in experiment.

Process b was first treated theoretically by Fairbairn,[7] using the method of "matching" the wave functions at the nuclear boundary. However, no direct comparison of the formula with experiment could be made. In the present work, to calculate the differential cross section $d\sigma/d\Omega$ for inelastic scattering (process b), we use the results of the general theory of scattering.[8] In the Born approximation, the reaction cross section is given by the square of the matrix element of the transition:

$$I \sim \int \Psi^{*}_{k'd}(\mathbf{r}_p\mathbf{r}_n)\Psi^{*}_{f}(\xi)\,V_{np}(\mathbf{r}_p\mathbf{r}_n)\left\{\int g\,(\mathbf{r}_p\mathbf{r}'_p;\ \mathbf{r}_n\mathbf{r}'_n;\xi,\xi')\,V_{np}(\mathbf{r}'_p\mathbf{r}'_n)\right.$$
$$\left.\times\exp\left[i\mathbf{k}_d(\mathbf{r}'_p+\mathbf{r}'_n)/2\right]\chi\,(|\mathbf{r}'_p-\mathbf{r}'_n|\;\Psi_i(\xi)\,d\mathbf{r}'_n d\mathbf{r}'_p d\xi'\right\} d\mathbf{r}_p d\mathbf{r}_n\,d\xi, \tag{1}$$

where $\Psi_{k'd}$ is the wave function of the initial deuteron wave, $\Psi_i(\xi)$ and $\Psi_f(\xi)$ are the wave functions of the ground state and final state of the nucleus, $V_{np} = V_0\delta(\mathbf{r}_p - \mathbf{r}_n)$ is the neutron-proton interaction potential, $\chi(|\mathbf{r}_p - \mathbf{r}_n|)$ is the internal wave function of the deuteron, $g(\mathbf{r}_p\mathbf{r}'_p;\ \mathbf{r}_n\mathbf{r}'_n;\ \xi,\ \xi')$ is the Green's function for the (d, p) reaction. Writing the wave functions of the intermediate system as a product of the wave function of the initial (even-even) nucleus and the wave function of the captured nucleon, we perform an expansion of the plane waves into spherical partial waves and sum the resulting expressions over the magnetic quantum numbers of the initial and final state, using Levinson's method.[9]

The computation was carried out for the reaction Mg^{24}(d, d′)Mg^{24*} (with $\Delta E = 1.37$ Mev, $E_0 = 15$ Mev). The summation over states of the intermediate nuclei (I_N) was limited to the lowest levels of Mg^{25} and Al^{25}, having spins of $5/2^+$, $1/2^+$, and $3/2^+$. The transitions $I_i \rightarrow I_N$ occur via the transfer of an s-nucleon or via the transfer of an s- or d-nucleon; the transitions $I_N \rightarrow I_f$ involve the transfer by the nucleus to the free nucleon of an s-nucleon or a d-nucleon. The results of the computation are shown in the figure together with the experimental data[4] and the value of $d\sigma/d\Omega$ for process a. By normalizing curves a and b, we can apparently explain the experimental angular distribution.



The maximum value $(d\sigma/d\Omega)_{\max}$ for process a depends weakly on E_d. With increasing E_d, the first maximum shifts toward smaller ϑ, but does not go beyond zero, since $m_d = m_{d'}$ and $|\mathbf{k}_d - \mathbf{k}'_d| \rightarrow 0$ for increasing E_d. According to Eq. (1), for process b the dependence of $(d\sigma/d\Omega)_{\max}$ on E_d should be stronger, since even for ordinary stripping $(d\sigma/d\Omega)_{\max}$ depends on E_d approximately as E_d^{-2}, while the first maximum in the angular distribution is shifted, for large E_d, to the left of zero angle (since $|\mathbf{k}_p - \mathbf{k}_d|$ for a given ϑ varies approximately as $E_d^{1/2}$). Apparently these qualitative conclusions are in agreement with the presently available experimental data on excitation of first excited levels by inelastic scattering of deuterons on Mg^{24} (references 4 and 10), Be^9 (references 4 and 11), and Mg^{24} with excitation of the 4^+ level.[10] In the last case, the absence of a maximum at $\vartheta \sim 0$ is explained by the fact that to excite the level it is necessary that l_i and l_f be large (for example, $l_i = l_f = 2$). With increasing l_i and l_f, the reaction amplitude drops if E_d is not very large, while the peak in the angular distribution is shifted toward large scattering angles.

In the scattering of deuterons by nuclei with different external shells, different intermediate states give the main contribution to process b. Thus, in the scattering of deuterons by C^{12}, apparently the 1p-state is most important, for Mg^{24} the main contribution is from the 1d+2s states, and possibly the 2p states, for Ca^{40}, the 2p states.

In conclusion the authors express their gratitude to G. S. Tyurikov for aid in carrying out the numerical computations.

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COMPETITION BETWEEN NEUTRON EVAPORATION AND FISSION IN THE REACTIONS OF MULTIPLY CHARGED IONS WITH HEAVY NUCLEI

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In this work we use certain experimental results[1-3] to estimate the relative importance of two competing processes — neutron evaporation and fission — in the de-activation of the compound nuclei formed when heavy elements are bombarded by multiply charged ions.

As is well known, the reaction cross section σ_{xn} for the evaporation of x neutrons when a particle interacts with a nucleus can be written

$$\sigma_{xn}(E) = \sigma_c(E)\,\bar{G}_n^x P(E, x).$$

We used this relation to approximate the experimental values of the cross section for neutron evaporation. $\sigma_c(E)$ is the cross section for formation of the compound nucleus and was calculated