ELASTIC SCATTERING OF PROTONS BY TRITIUM AT ENERGIES BELOW THE THRESHOLD OF THE (p, n) REACTION

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THE existence of a state of the He^4 nucleus with excitation energy near 20 MeV was pointed out in several papers[1-5]. The most direct method of investigating this state is to measure the differential cross section for the elastic scattering of protons by tritium at energies below the threshold of the (p, n) reaction (1020 keV). Until recently sufficiently complete data for the cross section of this process were available only in the energy region above 1 MeV[6,7]. In the present investigation we measured the cross section for elastic scattering of protons by tritium at energies from 300 to 990 keV. The maximum number of the noticeably different angles is eight (40—152° in c.m.s.).

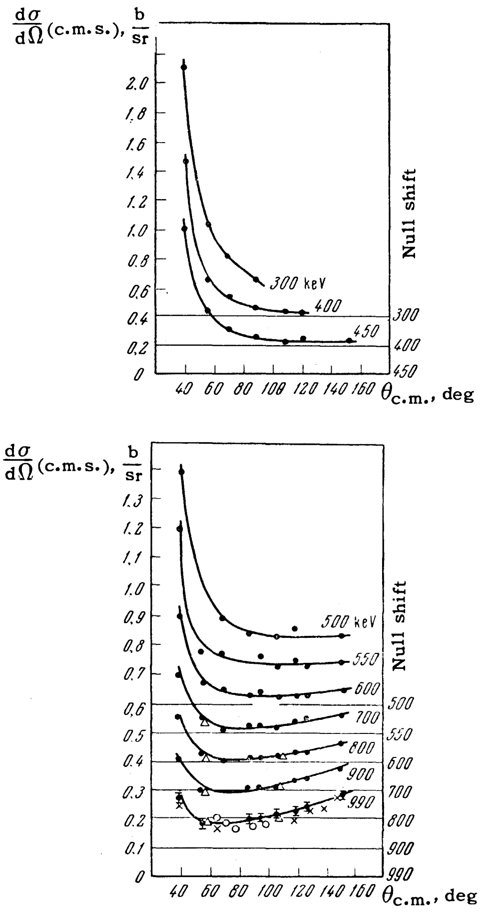

FIG. 1. Angular distribution of elastic pT scattering in the c.m.s. for different proton energies: ● – our data. △ – data of[19], × – [7], o – [6].

Figure 1 shows the obtained angular distributions in the c.m.s. and a comparison with the experimental data by others (a detailed description of the experiment and of the data reduction will be published in Izvestiya AN SSSR, ser. fiz.).

A phase shift analysis of the results of the measurements of the pT scattering was carried out by least squares with an electronic computer. For 120° and 300 and 350 keV, we used the data of the recently published paper by Jarmie et al.[5], which barely changes the phases, within the limits of error. In the analysis we made only two assumptions: inasmuch as the energies are sufficiently small, we took into account only the s and p waves, and, since it turned out that the accuracy of the experiment does not make it possible to determine more than 4 parameters, the analysis was carried out under the assumption that there is neither spin-orbit interaction nor a change in the spin of the channel. We have thus determined the phase shifts corresponding to the states ^1S, ^1P, ^2S, and ^3P. Four solutions were obtained. The corresponding sets of s and p phase shifts are shown in Fig. 2.

In addition to the phase shift analysis with the four parameters, we carried out an analysis with three parameters (the singlet p phase, the value of which is close to zero for solutions I and II, was assumed to be equal to zero) and with two parameters (the s phases only). The values of the phase shifts and the errors in the determination of the phase shifts, and also the data of [8] for 120 and 180 keV, are indicated in Figs. 3 and 4 for the first solution only, since, as will be shown below, this is the only solution with physical meaning. If only the s-phase shifts are used, the experimental curves can be obtained only for energies below 450 keV. An increase in the number of the parameters does not change essentially the average values of the phase shifts, and merely increases the limits of the errors.

To eliminate the ambiguity of the phase shift analysis, we used the condition of continuity of the energy variation of the phase shifts and the limita-

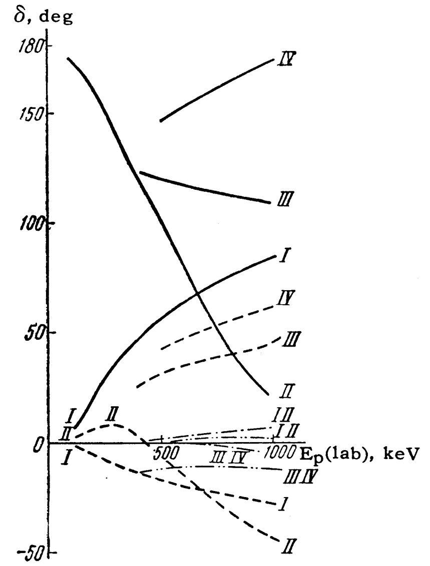

FIG. 2. Four solutions of the phase shift analysis of pT scattering. Solid curve – phase shift corresponding to the ^{1}S state, dashed – ^{3}S, dashed double dot – ^{1}P, dash dot dash – ^{3}P.

tions imposed on the scattering phase shift by the anomaly in the elastic scattering cross section near the threshold of the (p, n) reaction[9]. At energies below 450 keV, solutions III and IV cease to exist. One cannot likewise imagine that they go over into solutions I and II, for this would call for a jumplike change in the s and p phase shifts.

The additional conditions imposed on the scattering phase shifts by the anomaly in the cross section for the elastic scattering of protons by tritium near the threshold of the $T(p, n)He^3$ reaction (E_p = 1.02 MeV)[10] were considered in [11] 1).

It turns out that solution I agrees best with the threshold anomaly, and at the same time the ratio of the cross sections of the reaction in the states ^{3}S and ^{1}S can assume values $^3\sigma_r/^1\sigma_r$ = 0.3–5. In order for solution II to satisfy the threshold anomaly, the triplet channel should make the main contribution to the reaction, whereas Bergman and Shapiro[1] have observed that the reaction proceeds essentially via the 0^+ state. Thus, the foregoing considerations enable us to discard all the solutions except the first.

If spin-orbit splitting exists, it can change the values of the phase shifts noticeably. However, since the freedom in the variation of the phase shift is limited by the data for the threshold anomaly, the spin-orbit splitting cannot change the

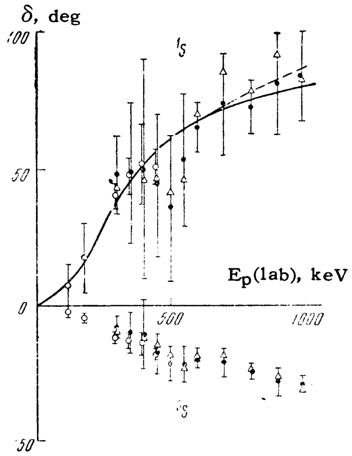

FIG. 3. Dependence of s-phases on the energy for solution I, which has physical meaning. The circles denote the results of the phase shift analysis with s-phases only, dots – with s-phases and the triplet p-phase, triangles – with four parameters (^{1}S, ^{3}S, ^{1}P, ^{3}P). The solid curve has been calculated with resonance parameters in the c.m.s.: E_λ = 0.30 MeV, γ_p^2 = 3.0 MeV, γ_n^2 = 0, a = 3 F; dashed – with allowance for the reaction, E_λ = – 0.45 MeV, γ_p^2 = 5.2 MeV, γ_n^2 = 2.1 MeV, a = 3 F.

qualitative conclusion concerning the presence of resonance in the state $^1S_0$.

The resonant variation of the singlet s-phase was compared with the resonance formula in the one-level approximation. At a radius a = 3 × 10^{-13} cm, it is impossible to describe satisfactorily the energy dependence of the phase shift, by assuming that the proton and neutron reduced widths are equal. The parameters were obtained under the condition that the sum of the widths is smaller than the Wigner limit, and their ratio differs as little as possible from unity: E_λ = – 0.45 MeV, γ_p^2 = 5.2 MeV, γ_n^2 = 2.1 MeV, and a = 3 F. In addition, for comparison with the results of [2,4], we found the resonance parameters with the reaction for a = 3 F neglected, and the energy E_0 corre-

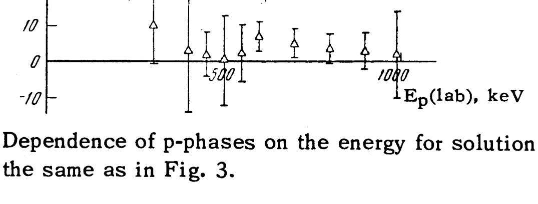

FIG. 4. Dependence of p-phases on the energy for solution I. Notation the same as in Fig. 3.

1)It is necessary to replace the erroneous values of the coordinates X and Y given in[11] by X = (–0.25 ± 0.5) × 10^{-25} and Y = (–0.8 ± 0.5) × 10^{-25}.

sponding to the boundary conditions of [4]: $E_\lambda = 0.30$ MeV ($E_0 = 0.55$ MeV) and $\gamma_p^2 = 3.0$ MeV. A comparison with the results of Frank and Gammel[2] on pT scattering above the threshold of the reaction ($E_\lambda = 0.63$ MeV, ($E_0 = 0.78$ MeV), $\gamma_p^2 = 2.1$ MeV) and the results of Werntz[4], who studied the breakup of the deuteron and tritium[4] ($E_0 = 0.40$ MeV, $\gamma_p^2 = 1.4$ MeV), shows that the resonant energies are in satisfactory agreement. Taking into account the assumptions made in [2,4], we can hardly expect good agreement between the values of the reduced widths.

Using the resonance parameters obtained in the present work, we calculated the cross section of the He^3(n, p) reaction for thermal neutrons and the deviation of the energy variation of the reaction from the 1/v law at a neutron energy 30 keV. The corresponding values amount to 3100 b and 15%. The experimental value of the thermal cross section is 5400 b, and according to Bergman and Shapiro[1] the deviation amounts to ~ 30%. An allowance for the contribution of the other channel can reconcile the absolute values of the thermal cross section, but it will increase the discrepancy observed in the energy dependence of the (n, p) reaction.

An excited He^4 level thus appears in elastic scattering of protons by tritium. An analogous conclusion was arrived at in the investigations of the reactions He^3(n, p) T and T(d, n) pT. The lack of evidence for the presence of this state in the reaction He^3(d, p) pT[12] in inelastic scattering of protons by helium[13] can be attributed to the insufficient accuracy of these experiments.

The resonance parameters determined from the different interactions are in poor agreement with one another. Consequently the question of the values of the resonance parameters and the nature of the level cannot be regarded as completely explained.

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277