ADIABATIC TREATMENT OF ELASTIC DEUTERON–NUCLEUS SCATTERING

Hirotaka AMAKAWA and Shuhei YAMAJI
Cyclotron Laboratory, Institute of Physical and Chemical Research, Wako-shi, Saitama, 351 Japan

Akihiko MORI
Numazu Technical College, Numazu-shi, Shizuoka, 410 Japan

and

Koichi YAZAKI
Department of Physics, University of Tokyo, Tokyo, 113 Japan

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We calculate the elastic deuteron–^{58}Ni scattering at 80 MeV, 52 MeV and 21.6 MeV in the framework of the three-body model with the adiabatic approximation. The contribution from the s-wave and d-wave breakup channels is quite important and that from the g-wave breakup channel is very small. The calculation including these effects is found to give a good account of the elastic d–^{58}Ni scattering at 80 MeV. The agreement between the calculated and the observed cross sections is fairly good at 52 MeV, but becomes poor at 21.6 MeV.

The effect of the deuteron breakup on the elastic deuteron–nucleus scattering is important, since the deuteron is a loosely bound system. Investigations of the elastic deuteron–nucleus scattering including the breakup effect have been performed by many authors [1–4]. Although the straightforward coupled-channel approach has been found applicable to the breakup effect, it requires a large amount of numerical work and the convergence in the actual calculations is not quite clear. This is especially the case if the effect of the d-wave breakup channel which has been pointed out to be important is taken into account [2,3]. In this paper, we will treat the effect of the d-wave and g-wave breakup channels as well as the s-wave breakup channel in a much simpler way than the previous investigations by using the adiabatic approximation [5] ‡1.

In the three-body model, a deuteron–nucleus scattering system is assumed to consist of a proton, a neutron and an inert target nucleus. The three-body wave function $\Psi(\boldsymbol{r}, \boldsymbol{R})$ satisfies the Schrödinger equation

‡1 We are grateful to Professor R.C. Johnson for informing us of this reference.

$$(T_R + H_{\mathrm{pn}} + V(\boldsymbol{r}, \boldsymbol{R}) - E)\Psi(\boldsymbol{r}, \boldsymbol{R}) = 0\,, \tag{1}$$

where $\boldsymbol{r}$ and $\boldsymbol{R}$ are the relative and the center of mass coordinates of the p–n system with respect to the target, $H_{\mathrm{pn}} = T_r + V_{\mathrm{pn}}$ is the hamiltonian of the p–n relative motion, T_R is the kinetic energy operator of the center of mass motion and $V(\boldsymbol{r}, \boldsymbol{R})$ is given by the sum of the proton–target and the neutron–target potentials evaluated at half the incident energy of the deuteron. The spin–orbit potential is neglected to simplify the calculation, and its effect will be briefly discussed later. If the deuteron incident energy is sufficiently high, the p–n relative motion is slow compared with the p–n center of mass motion. The adiabatic approximation consists of neglecting the excitation energy of the p–n relative motion, and eq. (1) becomes

$$(T_R + V(\boldsymbol{r}, \boldsymbol{R}) + \epsilon_{\mathrm{d}} - E)\Psi(\boldsymbol{r}, \boldsymbol{R}) = 0\,, \tag{2}$$

where H_{pn} has been replaced by a constant ϵ_{d}, which is the binding energy of the deuteron. The interaction $V(\boldsymbol{r}, \boldsymbol{R})$ can be expanded,

$$V(\boldsymbol{r}, \boldsymbol{R}) = 4\pi \sum_{\lambda} V_{\lambda}(r, R)(Y_{\lambda}(\hat{r}) \cdot Y_{\lambda}(\hat{R}))\,. \tag{3}$$

The total wave function $\Psi(\boldsymbol{r}, \boldsymbol{R})$ is written as

$$\Psi(\boldsymbol{r}, \boldsymbol{R}) = \sum_{lLJ} \chi_{lLJ}(r, R)[Y_l(\hat{r}), Y_L(\hat{R})]_J \,. \qquad (4)$$

We solve the coupled equations for χ_{lLJ} with a fixed r and J, and obtain the r-dependent t-matrix $T^J_{l'L',lL}(r)$. The deuteron wave function contains an intrinsic d-state as well as the s-state. In the absence of the spin–orbit potential, however, the additional effects due to the intrinsic d-state contribute only incoherently and are expected to give minor corrections. We therefore consider only the intrinsic s-state. Then, the elastic t-matrix T including the breakup effect in the intermediate stage is given by [5],

$$T = \int T(r)|\phi_d(r)|^2 r^2 \mathrm{d}r \,,$$

$$T(r) = \sum_L (2L+1) T^L_{0L,0L}(r) P_L(\cos\theta) \,, \qquad (5)$$

where ϕ_d is the ground state deuteron wave function. The numerical calculation can easily be performed by using the conventional coupled-channel program with a slight modification. We calculate the elastic deuteron scattering from the ^{58}Ni target. The optical potential parameters of nucleon–^{58}Ni are taken from refs. [6] and [7], which were obtained by a systematic search. For the coupled potential of eq. (3), $V_0(r,R)$, $V_2(r,R)$ and $V_4(r,R)$ are included. The coupled equations are solved with the d-wave ($l = 2$) and g-wave ($l = 4$) breakup channels as well as the s-wave ($l = 0$) breakup channel by using the coupled-channel code CCSEARCH [8] [‡2] with a minor modification. The t-matrix is calculated using eq. (5) where the Hulthén wave function is used for $\phi_d(r)$.

Figs. 1, 2 and 3 show the calculated and observed elastic cross sections of the deuteron scattered from ^{58}Ni at 80 MeV, 52 MeV and 21.6 MeV, respectively. In all cases, it is found that the cross sections obtained by the present adiabatic method are appreciably different from those for the Watanabe potential [9] (folding potential) which does not contain the effect of deuteron breakup. The effect of the d-wave breakup channel is found to be fairly large. On the other hand, the effect of the g-wave breakup channel which

‡2 This program is a version of JUPITOR-I written by T. Tamura modified to make automatic parameter search.

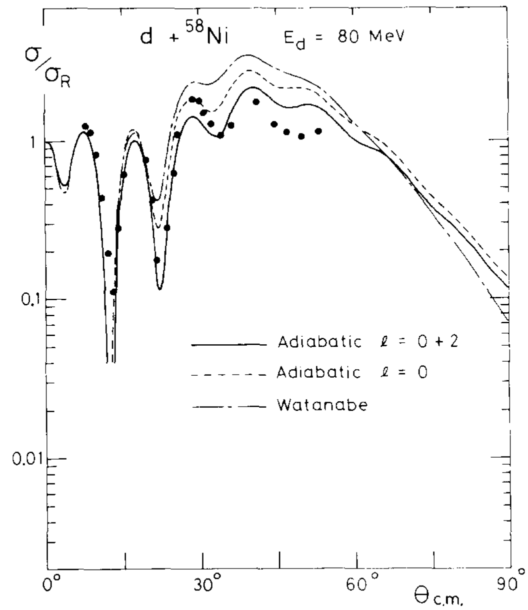

Fig.1. Elastic cross sections of deuteron scattered from ^{58}Ni at 80 MeV. Solid and dashed lines show, respectively, the cross sections obtained by the adiabatic method with the s-wave and d-wave breakup channels and with the s-wave breakup channel only. The dash–dot line illustrates the cross section for the Watanabe potential. The experimental data are taken from ref. [10].

is not illustrated in the figures is very small. In the case of $E_d = 80$ MeV, the cross section calculated by the adiabatic method with s-wave and d-wave breakup channels (solid line) is found to be in good agreement with the experimental data [10]. The cross section obtained by the Watanabe potential (dashed–dot line) is too large except in the forward angle region. Adding the breakup channels changes the cross section towards the experimental data very nicely. Fig. 4 shows the elastic scattering matrices at 80 MeV. One finds from this figure that the absorption increases as the breakup channels are added and that the effect of the d-wave breakup channel is small in the inner region ($L \leqslant 12$), while it is appreciable in the surface region ($14 \leqslant L \leqslant 22$). These features of the S-matrices are intuitively reasonable. In the surface region ($14 \leqslant L \leqslant 22$), which is the most important region in determining the cross section, inclusion of the breakup channels changes the S-matrix towards the values calculated by the phenomenological optical potential (serie 1 of ref. [10]), which reproduces the experimental cross section quite well.

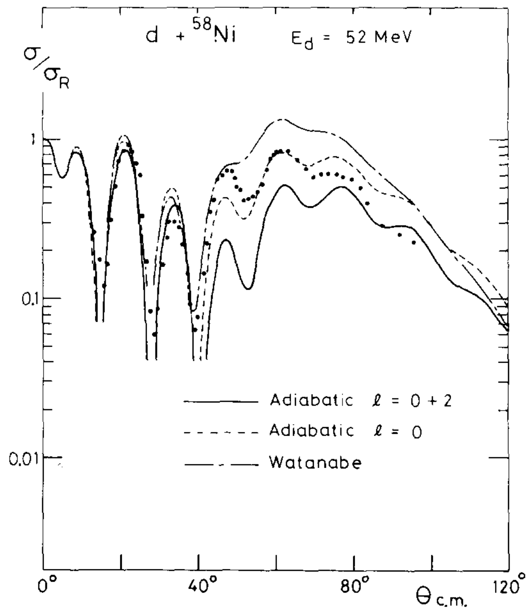

Fig. 2. Elastic cross sections of deuteron scattered from ^{58}Ni at 52 MeV. The experimental data are taken from ref. [11]. See the caption to fig. 1.

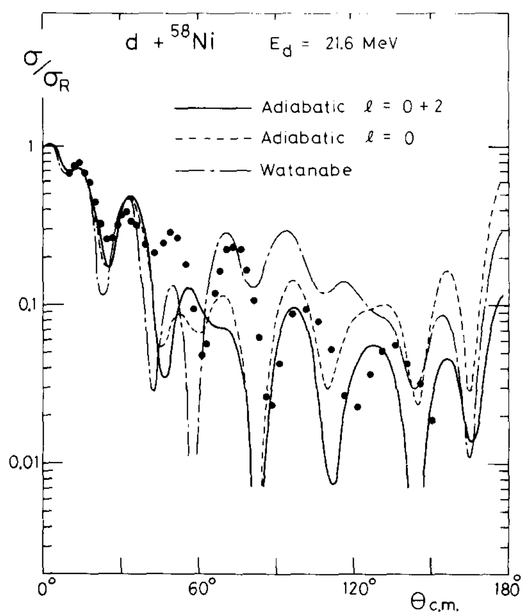

Fig. 3. Elastic cross sections of deuteron scattered from ^{58}Ni at 21.6 MeV. The experimental data are taken from ref. [12]. See the caption to fig. 1.

In the case of E_d = 52 MeV, the cross section obtained by the adiabatic method with s-wave and d-wave breakup channels gives better agreement with the experimental data [11] than that with the Watanabe potential in the forward angle region, but gives poorer agreement in the large angle region. The cross section obtained by the adiabatic method with the s-wave breakup channel only, reproduces well the experimental data in the large angle region, while the inclusion of the d-wave breakup channel gives too much reduction of the cross section around $\theta = 60°$. This seems to suggest that already at this energy the adiabatic approximation overestimates the absorption due to the breakup effect for the partial wave contributing to the scattering angle $40° \lesssim \theta \lesssim 80°$.

Similar features prevail at lower energy. The cross section at 21.6 MeV obtained by the adiabatic method

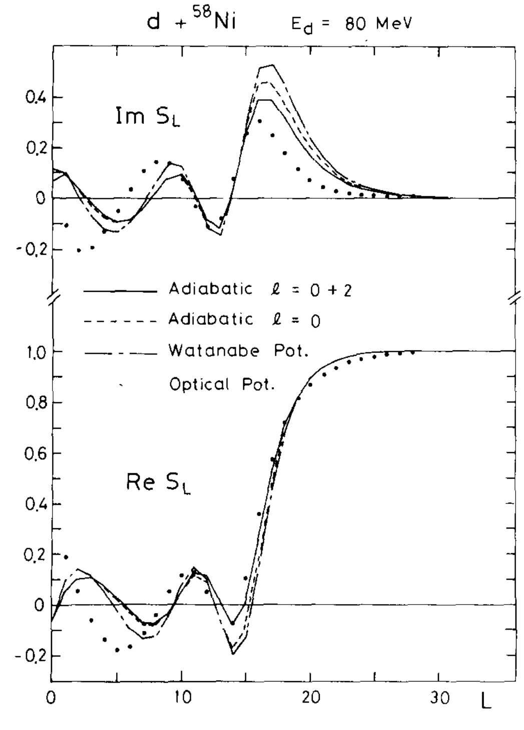

Fig. 4. Elastic S-matrices of deuteron scattered from ^{58}Ni at 80 MeV. Solid and dashed lines show, respectively, the S-matrices obtained by the adiabatic method with the s-wave and d-wave breakup channels and with the s-wave channel only. Dash–dot line and full circles illustrate the S-matrices for the Watanabe potential and the phenomenological optical potential of ref. [10] (serie 1), respectively.

gives a fairly good account of the experimental data [12] in the forward ($10^\circ \leqslant \theta \leqslant 40^\circ$) and backward ($90^\circ \leqslant \theta \leqslant 140^\circ$) angle regions but deviates largely from the data in the region $40^\circ \leqslant \theta \leqslant 90^\circ$. The results of other approaches are available at this energy. The work by Johnson and Soper [1] seems closest in spirit to ours. They used the adiabatic approximation only for small values of r, for which $V_{pn}(r)$ was appreciable, and used the so-called factorization approximation for the transition potential between the ground state and the continuum states of the p–n relative motion. Their result on the effect of the deuteron breakup is qualitatively similar to ours but a detailed comparison is not possible, since they used a different set of parameters for the neutron–^{58}Ni potential [13]. This is also the case for the coupled-channel calculation by Rawitscher [2]. A direct comparison is possible between a similar calculation by Anders and Lindner [3] and the present one. Their result obtained without the adiabatic approximation gives larger cross sections in the region $40^\circ \leqslant \theta \leqslant 90^\circ$ in better agreement with the data, although the qualitative features of the breakup effect are similar to those of the present work. This again suggests that the adiabatic approximation tends to overestimate the breakup effect.

All of the above results are obtained by neglecting the spin–orbit potential. We include the spin–orbit potential into the Watanabe potential to examine its effect. The inclusion of the spin–orbit potential at 80 MeV is found to change the cross section only slightly in the forward angle region, while the effect seems to become more important at large angles. We therefore expect that the effect of the spin–orbit potential will not be very important in the forward angle region in the present adiabatic treatment.

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