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THE EFFECT OF THE QUASIFREE SCATTERING PROCESS ON THE SHAPE OF KINEMATICALLY INCOMPLETE SPECTRA AT FORWARD ANGLES IN THE DEUTERON BREAKUP

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Abstract: In the deuteron breakup the quasifree scattering (QFS) process appears alongside the final state interaction process (FSI) even at low incident energies.

A preliminary calculation of the proton spectrum is presented taking into account only the n-p QFS in the D (n, p) 2n reaction for $\theta = 0°$. A simple impulse approximation has been used at this stage. The result shows a marked maximum at high proton energies. The importance of the QFS effect for the extraction of the n-n scattering length is discussed.

1. Introduction

Thus far experimental evidence has been reported for the existence of the quasifree scattering process (QFS) in the nucleon induced breakup of deuterons. The QFS appears alongside the final state interaction process (FSI) even at low incident energies[1]. However, experiments demonstrating the presence of the QFS process have been performed under such kinematically complete conditions where the QFS and FSI enhancements have been kinematically separated. There has been a number of calculations taking into account the overlap region of the FSI and the QFS as well as their interference[2]. The results of those calculations, except at energies higher than 150 MeV, have not considerably improved the fits to the experimental data.

In a very crude physical model one might expect the QFS and the FSI at low energies to be completely separated processes. The requirement for the QFS to occur is that the reduced wavelength of the incident particle be much smaller than the internucleon distance. For the FSI process the understanding is that the interacting pair of nucleons regardless of its relative energy, is

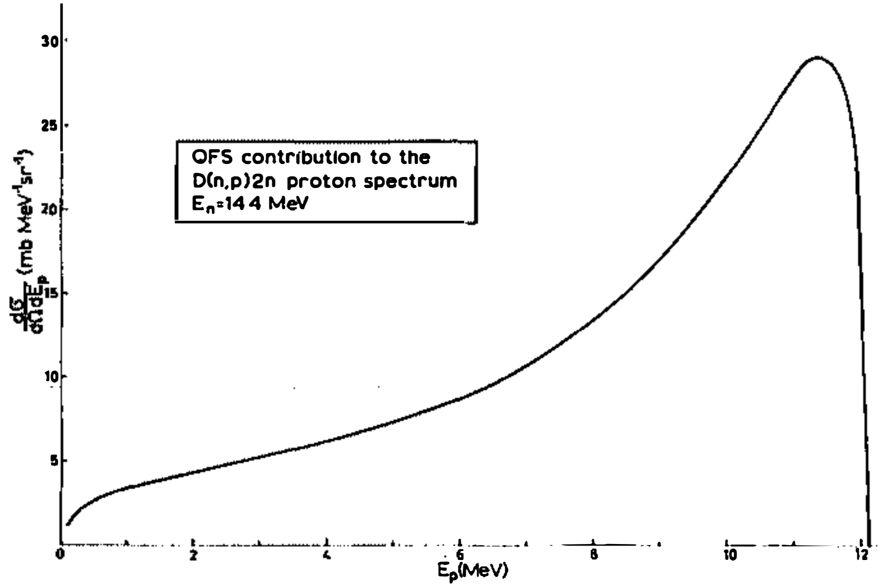

Fig. 1. The calculated proton spectrum for the QFS process.

within the range of nuclear forces. According to the above statements it follows that the contribution of the QFS in the nucleon induced breakup of a deuteron would have a different localization from the FSI with respect to the part of the deuteron wave function active for the respective processes.

2. *Calculation of the single counter proton spectrum*

In the framework of those considerations we calculated the shape of the n-p QFS contribution to the single counter proton spectrum of the D (n, p) 2n reaction at $E_n = 14.4$ MeV.

We calculated the QFS spectrum using a simple impulse approximation formula which can be derived from Fadeev-Lovelace equations[3]

$$U_{\beta\alpha} = \sum_{\delta \neq \alpha} V_\delta + \sum_{\gamma \neq \beta} t_\gamma G_0 U_{\gamma\alpha} . \qquad (1)$$

Here the Greek subscripts can take the values 0, 12, 32, 31 denoting the interacting pair of particles 1, 2, 3 (0 denotes free particles). $U_{\beta\alpha}$ is the operator of the scattering amplitude with an α-bound state in the incoming channel and a β-bound state in the outgoing channel. V_α is the two-body potential, $V_0 \equiv 0$. G_0 is the free Green operator and t_α is the two body scattering amplitude operator.

In the case of the breakup we obtain from (1) the following equation

$$U_{0\alpha} = \sum_{\gamma \neq \alpha} [t_{\gamma} + U_{0\gamma} G_0 t_{\gamma}]. \tag{2}$$

Taking into account only the first term in the iterated form of (2)

$$U_{0,23} = t_{12} + t_{31} + \sum_{\beta \neq 31} t_{\beta} G_0 t_{31} + \sum_{\beta \neq 12} t_{\beta} G_0 t_{12} + \dots, \tag{3}$$

one obtains the expression for the cross section

$$\frac{d\sigma}{d\Omega_4\, d\Omega_3\, dE_3} = \frac{4\sqrt{2}}{\pi^2} \frac{E_3}{E_1} \sqrt{E_a E_b} (\sqrt{E_a} + \sqrt{E_b})^3 \cdot$$

$$\cdot \sum_{i=1}^{2} \frac{E_4^{(i)} \left(\frac{d\sigma_{34}}{d\Omega}\right)_i}{|2\sqrt{E_4^{(i)}} - \sqrt{E_1}\cos\theta_4 + \sqrt{E_3}\cos\theta_{34}|} \cdot \frac{1}{[(E_a + 2E_5^{(i)})(E_b + 2E_5^{(i)})]^2} =$$

$$= C(E_1 E_3) \sum_{i=1}^{2} A_i (\theta_3, \theta_4, \varphi_3, \varphi_4, E_1, E_3). \tag{4}$$

Kuckes and Wilson[4] derived the same formula from somewhat less general considerations. It should be noted that in expression (4) the off-energy-shell two-body matrix element is taken on the shell, since there is evidence that the off-energy-shell effects are small[5].

In expression (4) the subscripts 1 and 2 denote the incident and the target particle, respectively; 3, 4, 5 apply to the particles in the final state. $E_4^{(i)}$ ($i = 1, 2$) represents the solutions of the equation

$$E_4 + \sqrt{E_4}(\sqrt{E_3}\cos\theta_{34}) - \sqrt{E_1}\cos\theta_4) - \sqrt{E_1 E_3}\cos\theta_3 + E_3 - \frac{1}{2} Q = 0, \tag{5}$$

obtained from the conservation laws. $E_5^{(i)} = E_1 + Q - E_3 - E_4^{(i)}$. $E_a = 59.8$ MeV, $E_b = 2.226$ MeV. θ_3 and θ_4 are the scattering angles of particles 3 and 4, and θ_{34} is the angle between them. $\left(\frac{d\sigma_{34}}{d\Omega}\right)_i$ is the differential cross section for the scattering of particles 3 and 4 in the CM system (the superscript i is related to the energy $E_4^{(i)}$). From the derivation of (4) it follows that the term A_i appears only if the solution $E_4^{(i)}$ is positive.

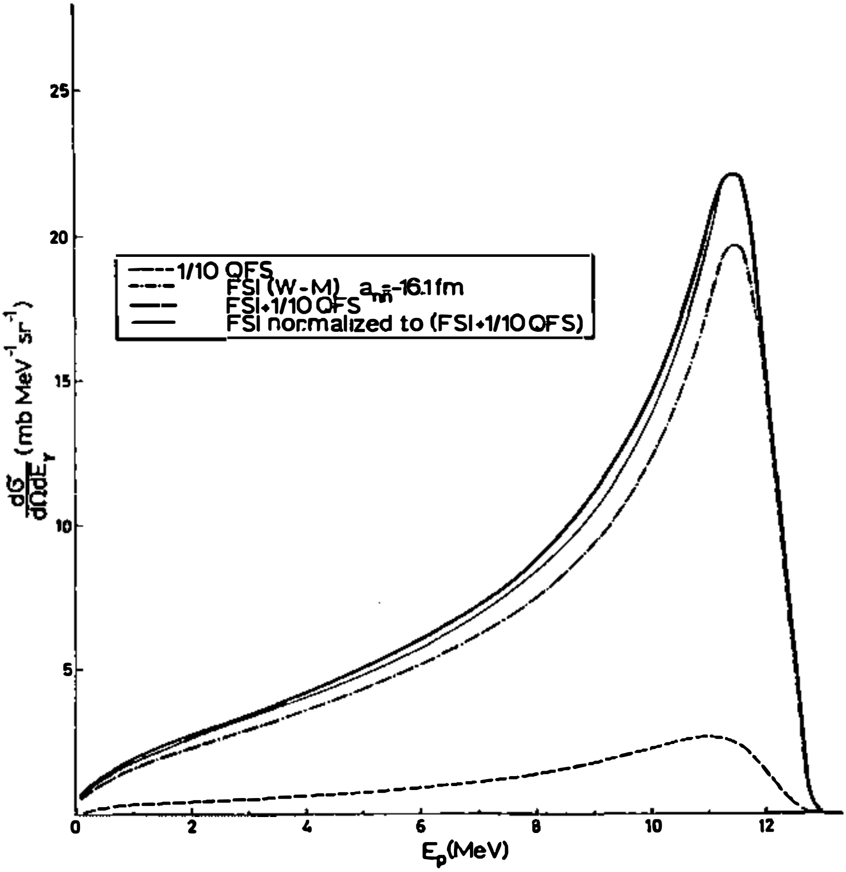

Fig. 2. Contributions to the proton spectrum from the FSI and the QFS and the resulting spectrum with $a_{nn} = -16.1$ fm. The results are smeared for an experimental resolution of 0.5 MeV FWHM.

If relation (4) is integrated over $d\Omega_4$, we obtain the kinematically incomplete spectrum of particle 3 at the angle θ_3. We consider the proton spectrum in the D (n, p) 2n reaction at forward angles and at relatively low incident neutron energies, so that $\frac{d\sigma_{34}}{d\Omega} \equiv \frac{d\sigma_{np}}{d\Omega}$ is nearly constant. The kinematics of the process determines the boundaries of integration. We obtain three integrals for the kinematically allowed region of proton energy E_3

$$S_1(E_1, E_3) = 2\pi C \int_0^{\pi} A_1(\theta_4, E_1, E_3) \sin\theta_4 \, d\theta_4, \qquad E_3 \in (\varepsilon_2, \varepsilon_1),$$

where

$$\varepsilon_{1,2} = \frac{1}{2}(E_1 + Q \pm \sqrt{E_1^2 - 2E_1 Q});$$

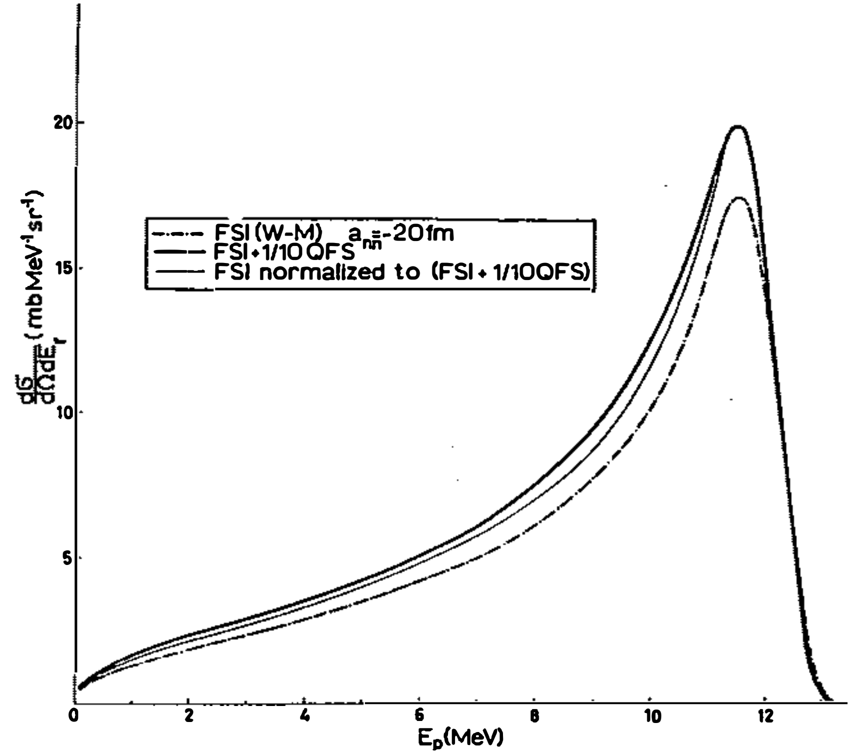

Fig. 3. Contributions to the proton spectrum from the FSI and the QFS and the resulting spectrum with $a_{nn} = -20$ fm. The results are smeared for an experimental resolution of 0.5 MeV FWHM.

$$S_i(E_1, E_3) = 2\pi C \int_0^{\pi/2} A_i(\theta_4, E_1, \varepsilon_i) \sin\theta_4 \, d\theta_4, \qquad i = 1,2;$$

$$S_2(E_1, E_3) = 2\pi C \int_0^{a} \sum_{i=1}^{2} A_i(\theta_4, E_1, E_3) \sin\theta_4 \, d\theta_4, \quad E_3 \varepsilon (\varepsilon_2, \eta_1).$$

Here

$$a = \arc\cos \frac{\sqrt{2(2E_3 - 2\sqrt{E_1 E_3} - Q)}}{\sqrt{E_1} - \sqrt{E_3}}$$

and

$$\eta_1 = \frac{1}{9}[5E_1 + 6Q + 2\sqrt{2E_1(2E_1 + 3Q)}].$$

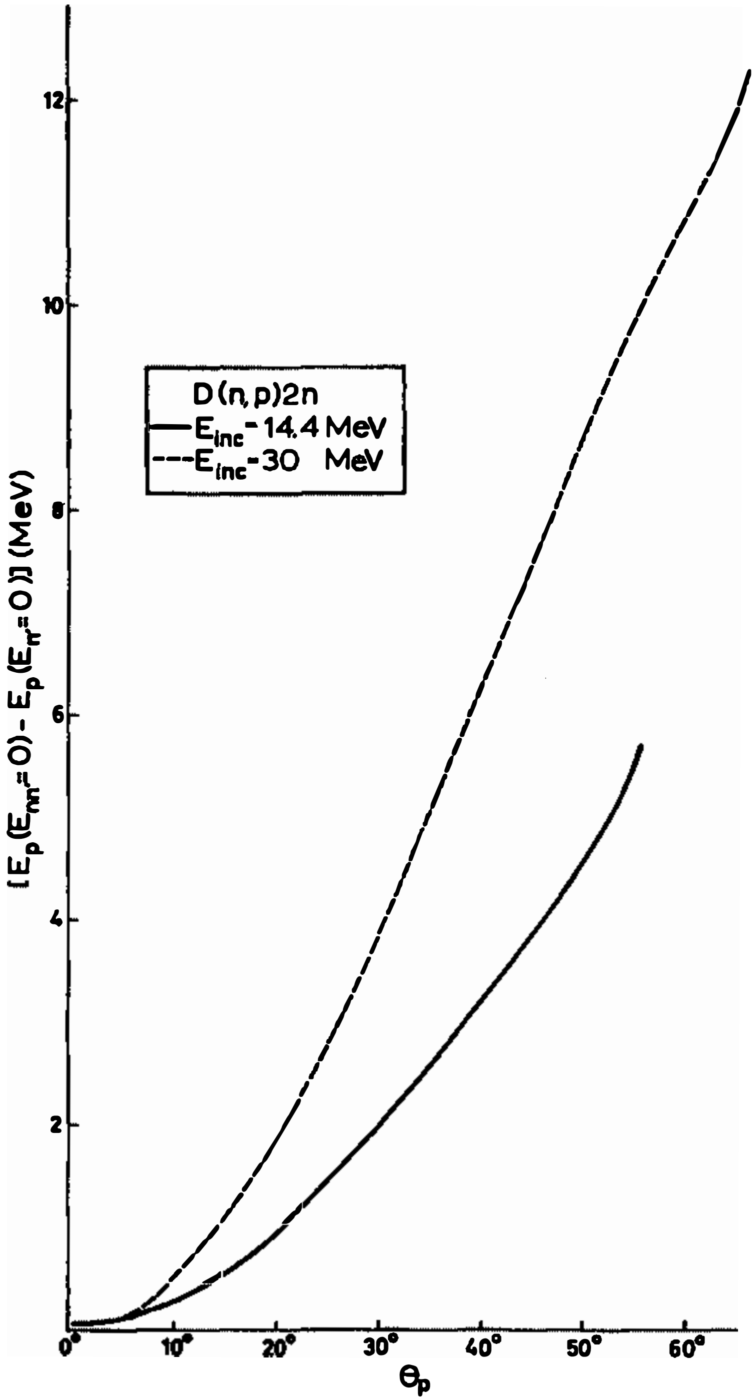

Fig. 4. Difference between the location of the minimum spectator energy from the kinematic end point of the proton spectrum at E_{inc} = 14.4 MeV and 30 MeV.

Each of these integrals can be exactly calculated. We obtain the kinematically incomplete proton spectrum $\frac{d\sigma}{dE_3\,d\Omega_3}$ which is a smooth and continuous function of $E_3\,\varepsilon\,[\varepsilon_2, \eta_1]$.

The result obtained using $\frac{d\sigma_{np}}{d\Omega}$ = 55 mb/sr is shown in Fig. 1.

Figs. 2 and 3 show the influence of the QFS addition to the FSI proton spectrum as calculated using the Watson-Migdal formula. According to the indication of experiments we took the QFS contribution to be 1/10 of the one obtained theoretically. The incoherent addition of the QFS contribution to the FSI contribution resulted in a broadening of the summed curve as compared with the Watson-Migdal contribution alone. It is interesting to note that the Watson-Migdal curve for $a_{nn} = -16.1$ fm falls exactly on the top of summed curve using the 1/10 QFS + (FSI) ($a_{nn} = -20$ fm).

3. *Conclusion*

From the present calculation it is possible to draw some conclusions. The QFS contribution to the FSI spectrum gives rise to a change in shape. In the present calculation it broadens the spectrum but a more sophisticated theory might alter the shape given in Fig. 1 in such a way as to give a narrower final spectral shape for the QFS + FSI. There is also a slight change in the position of the maximum. In our case it amounts to $\sim$ 50 keV.

The present calculation has been performed for $\theta_p = 0°$ but the contribution of the QFS process will be felt in a wide range of forward angles, since at 14 MeV the kinematic location of the spectator energy $E_n' = 0$ is only 0.56 MeV removed from the end point of the spectrum corresponding to $E_{nn}' = 0$, at $\theta_p = 15°$, as visible from Fig. 4.

Thus the QFS contribution should be taken into account when applying simple theories. Especially, the effects described here should be considered when extracting the low-energy scattering parameters.

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UTJECAJ KVAZI-SLOBODNOG RASPRŠENJA NA OBLIK KINEMATIČKI NEKOMPLETNOG SPEKTRA ZA PREDNJE KUTEVE U RASCJEPU DEUTERONA

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Sadržaj

Izračunat je doprinos *n-p* kvazi-slobodnog raspršenja u kinematički nekompletnom spektru protona u rascjepu deuterona $D(n, p) 2n$. Račun je proveden pomoću Kuckes-Wilsonove formule (jednostavna impulsna aproksimacija) i to za prednji kut $\theta_p = 0°$ kod kojeg je integracija izvršena egzaktno.

Dobiveni doprinos ima izraženi vrh kod 11.4 MeV. Taj doprinos je uporeden s doprinosom procesa interakcije u konačnom stanju i diskutiran je njegov utjecaj na oblik spektra kao i na ekstrakciju *n-n* dužine rapsršenja.