Possibility of observing weak neutral currents in light clustering nuclei

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A new mechanism for a weak interaction in light nuclei is proposed. This mechanism makes it possible link parity-breaking effects in few-nucleon systems with effects in light clustering nuclei. The reaction $^6\mathrm{Li}(\mathbf{n},\alpha)t$ is used as an example to propose a way to calculate the *P*-odd asymmetry $(\vec{\sigma}_n \mathbf{n}_t)$ from data on the process $nd \to t$. The cluster structure of the ^{6}Li and ^{7}Li nuclei is taken into account.

Parity-breaking effects in reactions of heavy and intermediate nuclei involving neutrons are associated with the formation of compound resonances of opposite parity.[1] Unfortunately, a complicated mechanism of this sort, which intensifies effects, does not allow one to extract the parameters of the weak nucleon-nucleon interaction from experimental data. On the other hand, when neutrons interact with simple few-nucleon systems, parity-breaking effects are amenable to a quantitative interpretation. An experimental study of these effects is exceedingly difficult for low-energy neutrons, however, because (in particular) of the small magnitude of these effects. In reactions of light nuclei, in cases in which these reactions can be described in a cluster model, there is another possibility for studying parity-breaking effects. This other method has some distinguishing features: First, such reactions can be interpreted theoretically in a relatively simple way, since in the cluster model the nuclei participating in a reaction consist of a small number of clusters, and the methods used in the analysis of few-nucleon systems can be used to analyze such models.[2–6] Second, one can expect that parity-breaking effects in light nuclei will not be as small as in the case of the interaction of few-nucleon systems with neutrons at very low energies. For these effects to appear, the excited nucleus need not necessarily have compound resonances of opposite parity.

As an example to illustrate this new possibility for studying parity-breaking effects, we will discuss an evaluation of the angular correlation between the spin of the polarized neutron incident on the nucleus and the direction in which the tritium is emitted [of the type $(\vec{\sigma}_n \mathbf{n}_t)$] in the reaction $^6\mathrm{Li}(\mathrm{n},\alpha)\mathrm{t}$, where $\vec{\sigma}_n$ specifies the neutron polarization, and $\mathbf{n}_t$ specifies the direction in which the tritium is emitted. This correlation is caused primarily by the weak neutral current, so a reaction of this sort with polarized neutrons is of particular interest. We will evaluate the magnitude of the parity-breaking effects in this process by introducing a weak-interaction Hamiltonian constructed in the one-boson-exchange approximation,[7] and we will use the constants of the weak nucleon-nucleon interaction which correspond to the exchange of π, ρ, and ω mesons.

A specific feature of this process is that the excited ^{6}Li and ^{7}Li nuclei participat-

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ing in the reaction can be represented in the following way[2,3] at excitation energies up to 20–25 MeV:

$$^6\mathrm{Li} \rightarrow \alpha + n + p \rightarrow \alpha + d'$$

$$^7\mathrm{Li} \rightarrow \alpha + 2n + p \rightarrow \alpha + t\,.$$

The theory, which gives a good description of essentially all of the experimental data, predicts a 70% degree of clustering of the ^{6}Li nucleus in the form of an α particle and a deuteron d', deformed in the field of the α particle, and a 100% degree of clustering of the ^{7}Li nucleus, in the form of an α particle and a tritium nucleus t. Accordingly, working in the cluster model we consider the process $^6\mathrm{Li}(n,\alpha)t$ in the following form:

$$n + \{\alpha d'\} \rightarrow \{nd\} + \alpha \rightarrow t + \alpha\,, \tag{1}$$

i.e., as a three-body pickup reaction.[8]

To evaluate the strong interactions among the deuteron, the neutron, and the α particle, we use the approximation of an infinitely large mass of the α particle, thereby reducing the problem to the case of a point interaction of a neutron and a deuteron in an external field. These approximations make it possible to solve the problem analytically, but they do not alter the main conclusion regarding the domination of the process by a weak neutral current. Another important feature of this problem is the anomalously small cross section for the capture process $nd \rightarrow t$. This circumstance suggests that the weak-interaction process in this reaction is dominated by the formation of tritium of positive parity, t^*, in the capture of a neutron by a deuteron in the field of an α particle:

$$\{d'\alpha\} + n \rightarrow \alpha + \{nd\}^* \rightarrow t^* + \alpha\,. \tag{1'}$$

In this approximation, an attempt to describe the collision of a neutron with a deuteron in one of the discrete levels of the external field of the α particle reduces to the problem of solving an equation of the type[8]

$$\tau^{nd}(p_t) = \hat{T}_{nd}\,\{\varphi_d \chi_n - \hat{G}\tau^{nd}\}\,, \tag{2}$$

where φ_d and χ_n are the wave functions of the deuteron and the neutron, respectively, $\hat{G}$ is the difference between (a) the three-body Green's function which corresponds to the Hamiltonian of the neutron and the deuteron which are interacting with the external field, but without their interaction with each other, and (b) the free Green's function G_0, and the operator $\hat{T}_{nd}$ represents the scattering of the neutron by the deuteron. The quantity $\tau^{nd}(p_t)$ is directly related to the probability amplitude for the process of interest here, so by solving Eq. (2) in the Padé approximation one can find the cross section for the process under consideration at thermal neutron energies. The comparatively small difference between the cross section found in this manner (about 700 b) and the experimental value ($\sim$900 b) raises the hope that this approach can take us toward a realistic estimate of the P-odd effect in which we are interested. In this case, the part of the function $\tau^{nd}(\bar{p}_t)$ which describes the weak interactions in the $\Delta\tau^{nd}$ system can be written in the form

$$\Delta\tau^{nd} = \Delta\hat{T}_{nd}\{\varphi_d\chi_n - \hat{G}\tau^{nd}\}$$
$$+ \hat{T}_{nd}\{\varphi_d\Delta\chi_n + \Delta\varphi_d\chi_n - \Delta\hat{G}\tau^{nd}\} + \hat{T}_{nd}\hat{G}\Delta\tau^{nd}. \qquad (3)$$

Here $\Delta\hat{T}_{nd}$ incorporates the contribution of weak effects in the nd interaction, so the first term on the right side of Eq. (3) corresponds to the P-odd part of the nd scattering amplitude. The second term on the right side of Eq. (3), which describes the P-odd correlation which arises in nα and dα interactions, can be ignored, since the contribution of the nα interaction to the P-odd part is small,[7] while the dα interaction contributes nothing to the correlation of interest here in the case of an unpolarized ^{6}Li nucleus. Consequently, an estimate of the probability amplitude for the production of tritium of the opposite parity in the process $^6\text{Li}(n,\alpha)t$ reduces to the solution of the equation

$$\Delta\tau^{nd} = \Delta\hat{T}_{nd}\{\varphi_d\chi_n - \hat{G}\tau^{nd}\}. \qquad (4)$$

The structure of this equation can be explained in the following way. When rescattering effects are taken into account, the weak-interaction event occurs at the end of a chain of multiple interactions, as was shown in Ref. 5 for the case of the nd system. If we instead consider the weak interaction in some system other than the *nd* system, we find that the result contains the anomalously small amplitude of the process $nd \rightarrow t$. We thus acquire an additional small factor. Accordingly, we can find a realistic estimate of the effect of interest here by solving Eq. (4) in the Fermi approximation (incorporating the term $\Delta\hat{T}_{nd}\varphi_d\chi_n$, and we can show that the P-odd correlation coefficient $(\bar{\sigma}_n\bar{p}_t)$ can be written with the help of the amplitude for the scattering of a nucleon by a deuteron which is at rest in a state with $J = 1/2$, as follows[5]:

$$\alpha \approx \left(2f_\pi - \frac{4}{15}h_\rho^0\right)\frac{|K_n^2|^{1/2}}{M}, \qquad (5)$$

where f_π and h_ρ^0 are the weak-interaction constants which correspond to the exchange of a π meson and a ρ meson without a change in isospin ($\Delta T = 0$), and M is the mass of a nucleon. Even if we abandon the Fermi approximation (and incorporate terms $\Delta\hat{T}_{nd}\hat{G}\tau^{nd}$ in Eq. (4), we still have a situation in which the result contains the weak amplitude for the process $nd \rightarrow t$, which occurs in the field of the α particle. Incorporating rescattering effects and also recoil effects, without a change in the form of expression (5), can reduce α by a factor of no more than two. An important circumstance reflecting the increase in the effect is the dependence of α on the mean square momentum of the neutron in the nucleus, $|\bar{K}_n^2|^{1/2}$. To estimate this momentum, we can use the harmonic-oscillator model, $\bar{K}_n^2 = 2M(5/2)\hbar\omega$, where $\hbar\omega = B_N = 7.6$ MeV. Using the cluster model of a nucleus, we can also estimate the mean square momentum of a deuteron in the nucleus[2]: $\bar{K}_d^2 \approx 0.04\ \text{fm}^{-2}$. Consequently, the effect of interest here is dominated by the interaction of a fairly energetic neutron, with a momentum on the order of 25–30 MeV, with a deuteron which is essentially at rest in the field of an α particle. The fact that the contribution of the neutral current is dominant in (5) remains in force for all versions of nuclear forces which are presently being used to evaluate the weak forms of the one-boson-exchange factors. An increase in the energy of the neutron in the nucleus, which leads to an increase in the effect, has essentially no effect on the relations among the contributions due to the exchange of π, ρ, and ω mesons. These relations are in fact determined by the magnitude of the weak form factors of one-boson exchange, which are essentially independent of the energy of the neutron. In the standard weak-interaction model we can choose $f_\pi = 12$ and $h_\rho^0 = -30$ (in units of 10^{-8}). We find the following estimate:

$$\alpha \approx (-0.06\, h_\rho^2 + 0.45 f_\pi) \sim 3\times10^{-7}.$$

Accordingly, in a case in which the momentum of a neutron interacting in a nucleus is not small, the effect increases, even in reactions with thermal neutrons. The observation of an effect at this level would make it possible to find a first reliable estimate of the contribution of a weak neutral current associated with the exchange of a π meson, i.e., the constant f_π There is a long list of light nuclei which, again up to an excitation energy of 20–25 MeV, can be represented in a clustered form[2,3]:

$$^9\mathrm{Be} \to 2\alpha + N, \quad ^{10}\mathrm{B} \to 2\alpha + 2\mathrm{N}, \quad ^{11}\mathrm{B} \to 2\alpha + 3N \to \alpha + {}^7\mathrm{Li} \text{ etc.}$$

For these nuclei, we can use the same cluster model of the nucleus in evaluating the weak-interaction effects. For the reasons discussed above, we can hope that these effects will not be anomalously small. In such a case it will become possible to determine a complete set of constants of the weak nucleon-nucleon interaction in a common series of experiments on light clustering nuclei.

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