Role of Meson-Exchange Currents in the Charge Form Factor of ^{6}Li

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The meson-exchange currents and nucleon-nucleon short-range correlation have been invoked in the calculation of the charge form factor of ^{6}Li in the shell model with a harmonic-oscillator basis. The contribution from exchange current to the correlated form factor is not large for small momentum transfer but becomes significantly noticeable around the first minimum. A second minimum at $q^2 = 26.0$ fm^{-2} is predicted by correlation but the exchange-current contribution brings this to around $q^2 = 24.0$ fm^{-2}.

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It is obvious that at least for the lightest nuclei ($A \leqslant 4$) meson-exchange currents (MCE) have a large effect on the charge and magnetic form factors at relatively small momentum transfer ($q^2 \geqslant 10$ fm^{-2}).[1-7] The MEC presence was demonstrated first in the deuteron, triton, and helium nuclei successfully.[1-4] A significantly large contribution to the charge form factor of ^{2}H for $q^2 \geqslant 10$ fm^{-2} was noted in the electron scattering calculations.[1] By consideration of only the pair-current process for the trinucleon system the effect of the exchange currents on their charge form factors was shown to be large at high momentum transfer.[2] Similar behavior for the magnetic form factors for the same system was also shown explicitly.[3] A large contribution from MEC to the charge form factor of ^{4}He was noted particularly in the momentum-region around the first minimum and secondary maximum. However, it was shown that the pion-exchange current is "rather unimportant" in heavier nuclei such as ^{16}O and ^{40}Ca.[5-7] Nothing definite is known for nuclei between ^{4}He and ^{16}O. Of course, the role of MEC was examined in some p-shell nuclei only with respect to their transverse form factors.[8] It would, of course, be interesting to see how the charge form factor of a nucleus just next to ^{4}He behaves at a large momentum transfer when MEC are included in its wave function. We therefore explore here the influence of MEC on the charge form factor of ^{6}Li at large momentum transfer and invoke a Jastrow-type correlation[9] in its harmonic-oscillator wave function. Earlier in this model the elastic charge form factor has been analyzed with neglect of MEC.[10] These calculations will provide another independent test for the model of the nuclear structure of ^{6}Li used in this work from the presently available knowledge on the MEC of the simple type employed here.

The MEC contributions to the charge form factors of some doubly closed-shell nuclei, namely, ^{4}He, ^{16}O, and ^{40}Ca, were studied in the harmonic-oscillator model modified by Jastrow-type correlations[5] and with very sophisticated wave functions.[7] The results for the exchange-current contribution were found, not surprisingly, to be very similar in both of those cases. This demonstrates the relatively small sensitivity of the two-body matrix elements to the choice of the wave function.[6] Accordingly the results of this work (in which a harmonic-oscillator wave function with the Jastrow-type correlation is chosen) will not be significantly different from those of any realistic wave function.

The most common approach of invoking the short-range correlation (SRC) is to multiply the single-particle density by some type of SRC function which satisfies the requisite properties of the N-N interaction. This is related to the approach of Iwamoto and Yamada[11] in which only the first-order terms are kept in their cluster expansion.

To invoke the SRC effect in the harmonic-oscillator–type wave function of the nucleus the correlation function, denoted by $f(r)$, must satisfy the following properties:

$$\lim_{r\to 0} f(r) = 0, \quad \lim_{r\to\infty} f(r) = 1, \tag{1}$$

where $r = r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$. These properties can be satisfied by a variety of functions used in the literature. We choose $f(r)$ here of the form

$$f(r) = 1 - j_0(kr), \tag{2}$$

where $j_0(x)$ is the spherical Bessel function. The correlated charge density ρ is given by

$$\rho(\mathbf{r}_i) = N\int \Psi^*(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) \sum_{i=1}^{A} e\delta(\mathbf{r}-\mathbf{r}_i)\frac{1+\tau_i}{2}\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)\, d\mathbf{r}_1\, d\mathbf{r}_2 \cdots d\mathbf{r}_{i-1}\, d\mathbf{r}_{i+1} \cdots d\mathbf{r}_A, \tag{3}$$

where the correlated wave function ψ is given by

$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) = \psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A) \prod_{\substack{i=1 \\ j>i}} f(r_{ij}). \tag{4}$$

Here the uncorrelated wave function ψ, describing the ground state of the nucleus, can be obtained by the Slater determinant. According to the approach taken by Danos and Maximon[12] the correlation factor $f(r_{ij})$ is transformed to the center-of-mass system of the nucleus in which the uncorrelated wave function is being used.

The form of the MEC operator chosen for this work is the lowest-order relativistic correction to the adiabatic limit of the pion photoproduction current. In the pseudoscalar pion-nucleon coupling model it is obtained by consideration of the adiabatic limit of the pair current diagram only. The charge component of the two-nucleon pion-exchange current is thus chosen to be of the form

$$J_0(\mathbf{k}_1,\mathbf{k}_2)=\frac{g^2}{8m^2}G_m^s(q^2)\boldsymbol{\tau}^1\cdot\boldsymbol{\tau}^2\left[\frac{\boldsymbol{\sigma}^2\cdot\mathbf{k}_2\boldsymbol{\sigma}^1\cdot\mathbf{q}}{\mu^2+k_2^2}+\frac{\boldsymbol{\sigma}^1\cdot\mathbf{k}_1\boldsymbol{\sigma}^2\cdot\mathbf{q}}{\mu^2+k_1^2}\right]. \tag{5}$$

In this expression g is the pseudoscalar pion-nucleon coupling constant $(g^2/4\pi\simeq 14.5)$, m is the nucleon mass, μ is the pion mass, and G_m^s is the isoscalar nucleon magnetic form factor $[G_m^s(0)=0.88]$. The isospin and spin matrices of the two nucleons involved are respectively denoted by $\boldsymbol{\tau}^1$, $\boldsymbol{\tau}^2$ and $\boldsymbol{\sigma}^1$, $\boldsymbol{\sigma}^2$. The momentum delivered to the first of the two participating nucleons is k_1, and k_2 is the same to the second one. The total momentum transfer is $\mathbf{q}=\mathbf{k}_1+\mathbf{k}_2$.

We assume that other pion-exchange currents are of much less importance than the one we consider here for the form factors.[2,4,13]

In the first Born approximation the elastic charge form factor F of a nucleus including the contribution due to a two-body current is given by

$$F(q^2)=\frac{A(A-1)}{2Z(2\pi)^6}\int\int\int e^{i\mathbf{k}_1\cdot\mathbf{r}_1}e^{i\mathbf{k}_2\cdot\mathbf{r}_2}d^3k_1\,d^3k_2\,\Psi^\dagger(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A)$$
$$\times\Psi(\mathbf{r}_1,\mathbf{r}_2,\ldots,\mathbf{r}_A)(2\pi)^3\delta(\mathbf{q}-\mathbf{k}_1-\mathbf{k}_2)J_0(\mathbf{k}_1,\mathbf{k}_2)\,d^3r_1\,d^3r_2\cdots d^3r_A. \tag{6}$$

The integrals involved in Eq. (6) are laborious but can be done analytically because of the harmonic-oscillator basis. First the integrals are performed over k_1 and k_2 and then in the coordinate space of all nucleons. The details of the calculations will be presented elsewhere. We present here just the results in Fig. 1. The elastic charge form factor of ^{6}Li has been evaluated with the harmonic-oscillator parameters for s and p nucleons as $\alpha_s=0.582$ fm^{-1} and $\alpha_p=0.467$ fm^{-1}, respectively,[14] and the correlation parameter $k=2.1$ fm^{-1}.[10] The pure harmonic-oscillator shell-model wave function does not produce any diffraction minimum as expected. It falls off much more sharply as the momentum transfer increases than the experimental data.[15] The steepness of the form factor is removed for large momentum transfer by invoking either SRC or MEC or both. Just the inclusion of MEC produces the first minimum and second maximum qualitatively but not quite in agreement with the data. The form factor with SRC, F_c, agrees with the experiment reasonably including the first minimum and second maximum. It also predicts a pronounced second diffraction minimum around $q^2\simeq 26$ fm^{-2} and a third maximum at $q^2\simeq 28$ fm^{-2}. There is no third minimum or fourth maximum produced with this SRC at least as far as $q^2=50$ fm^{-2}. Unfortunately, observed data for the ^{6}Li form factor are not available for large momentum transfer beyond $q^2\simeq 13$ fm^{-2} around the second maximum, and those too have rather large errors in that vicinity. One finds, however, on close examination that this correlated form factor F_c prossesses a more steepening trend than that observed in the data around $q^2\simeq 10$ fm^{-2}. With this trend the predicted second minimum and third maximum could be in error at that large momentum transfer. In the region of large momentum transfer the role of the MEC is known to be important. The contribution to the charge form

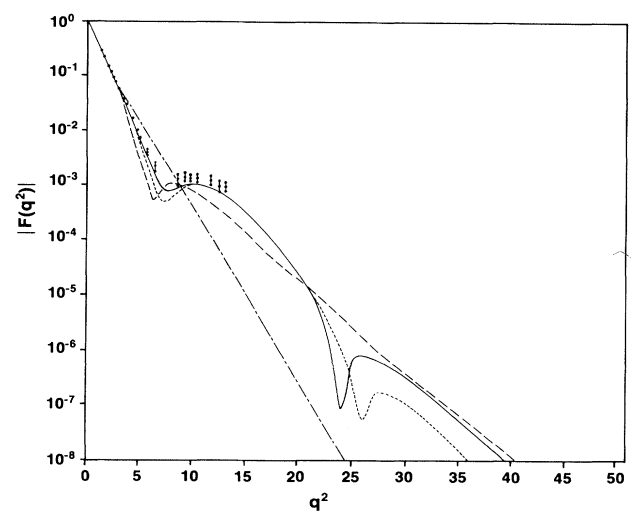

FIG. 1. The elastic charge form factors of ^{6}Li are represented by the dot-dashed curve F_0 calculated from the pure harmonic oscillator, the dotted curve F_c calculated with SRC, the dashed curve F_e calculated with MEC, and the solid curve F_{ec} calculated with MEC and SRC. The experimental data are taken from Ref. 15. The units of q^2 are inverse femtometers squared.

factor of ^{6}Li due to the MEC is small but may be significant enough to account for the discrepancy noted between F_c and the data for momentum transfer beyond $q^2 = 13$ fm^{-2}. The curve for the charge form factor of ^{6}Li, F_{ec}, calculated with SRC and MEC agrees with the data in general. It reproduces, well within error bars, the first minimum and the second maximum. A second mininum and a third maximum are predicted at around $q^2 \simeq 24.0$ fm^{-2} and 25.5 fm^{-2}, respectively. From this analysis we observe that the nuclear structure model of ^{6}Li assumed in Eq. (4) however *ad hoc* it may be, is a reasonable one. We also note that the contribution due to the MEC to the charge form factor of ^{6}Li (a relatively heavier nucleus than a deuteron or alpha particle) is small but conjecture that it could be significant enough to account for any discrepancy which SRC alone could not resolve at large momentum transfer, should the data be available. This conclusion is supported in a way by other works on ^{4}He, ^{16}O, and ^{40}Ca.[5-7] Obviously, the MEC's contribution to the charge form factor of ^{6}Li even at large momentum transfer is small relative to the SRC's contribution, but it is significantly large relative to the uncorrelated shell model. However, the MEC's contribution could be "rather important" enough to account for the discrepancy between the calculations and the experiment, which might not be removed by SRC or otherwise for the data if taken at momentum transfer larger than the current one.

Before concluding this paper it seems appropriate for us to make an important remark on this work and those of others regarding the MEC—that there is a degree of uncertainty in the form of the pion-exchange charge operator.[5,16] The isovector nature of the pion produces large isovector exchange currents of order $1/m$. In addition there are pion-exchange contributions of orders $1/m^2$ and $1/m^3$ to the isoscalar charge and current operators. The former topic has been the subject of considerable interest.[1-7,16-19] However, less complete treatments of the isoscalar current have been made in several of these works. Because there are a number of natural unitary equivalences which arise in deriving the nonstatic nucleon-nucleon potential from meson exchanges, there are corresponding ambiguities in the nuclear charge and current operators. These nonstatic potentials are relativistic corrections of order $(v/c)^2$ to the local nonrelativistic potential.

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