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TRINUCLEON CHARGE FORM–FACTOR WITH THE INCLUSION OF MESON EXCHANGE CURRENT AND THREE–BODY FORCE

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We investigate the effect of meson exchange current (MEC) contribution to the charge form–factor (CFF) of ^{3}He and ^{3}H by hyper–spherical harmonics expansion method with the inclusion of three–body force (3BF). Results indicate that the combined effects of 3BF and MEC are substantial and modify the CFF of trinucleon in the right direction at high momentum transfer.

1. *Introduction*

Several theoretical attempts have been made using standard two–body forces (2BF) to study the bound state properties of trinucleon system, namely, binding energy (BE), charge form–factor (CFF), charge density etc., by the Faddeev method [1–6] or by the hyper–spherical harmonics expansion (HHE) method [7–9]. But in all the cases, it was observed that two–body force can not reproduce the experimental data for ^{3}H and ^{3}He. Theoretically calculated BE were generally less than experimental value by about $1.5 - 2.0$ MeV. Moreover one long standing problem is the disagreement between theory and experiment for the CFF (or equivalently the charge density) of ^{3}H and ^{3}He. The form–factor has a typical diffraction shape, as a function of q, the momentum transfer, falling rapidly through zero, becomes negative passing through a minimum and then gradually rising to be positive again. Experimentally [10–12] the first diffraction minimum (q^2_{min}) for the CFF of ^{3}He and ^{3}H occurs at $q^2 = 11.0 \pm 0.7$ fm^{-2} and 12.6 ± 0.5 fm^{-2}, respectively. The secondary maximum (F_{max}), in the magnitude of CFF, has a value of about 6.0×10^{-3} and 4.0×10^{-3} for ^{3}He and ^{3}H, respectively. The difficulty has been that the theoretical calculations have predicted too large a value of q^2_{min} (position of the dip) and too small a magnitude of the secondary maximum with the 2BF alone, even for the Reid soft core (RSC) [13] potential, which has a strong repulsive core. Some workers suggested that the discrepancy would be removed if three–body forces (3BF), which depends on the simultaneous coordinates of all three nucleons in an inseparable manner, were included in addition to the 2BF [14]. This follows from the argument that 3BF is attractive for an equilateral triangle configuration (ETC) of the trinucleon, whereas it is repulsive for the collinear configuration (CC). Thus inclusion of 3BF would prefer ETC over CC for which there will be a central depression in the charge density due to nucleon–nucleon repulsion at short separations, resulting in increased F_{max}. Actual calculations showed an additional binding of about 1 MeV with the inclusion of 3BF. But in most of the calculations including 3BF [15–19], the position of the dip moves to somewhat larger value of q^2. Also, all the two–body potentials fail, by at least a factor of 3, to predict the size of the secondary maximum observed between $14 - 20$ fm^{-2}. Previously, several authors have indicated that exchange contributions are important in calculations of ^{3}H and ^{3}He magnetic moments [20,21], magnetic form–factors [22] and CFF of ^{3}He [23] with a realistic 2BF.

In 1974, Kloet and Tjon [23] suggested that the discrepancy that exists between experimental data and theoretical calculations for the CFF of trinucleon arose partly due to the neglect of the exchange effects in which the photon interacts with a pion, which is exchanged between two nucleons. They included meson exchange current (MEC) contribution to the CFF of ^{3}He in a model calculation using standard 2BF and found that the inclusion of MEC moves q^2_{min} closer to the experimental value and improves the height of the secondary maximum to a value of about 2.5×10^{-3}. This demonstrated that MEC effect plays an important role at high momentum transfer. The pion-exchange contribution to the charge operator calculated by them was also applied later by Hadjimichael et al. [24] and an improved result was found. The current state of affairs is summarized by Gibson [25]. Although the details of the results depend on the choice of the potential, the general observation is that the BE increases due to the inclusion of the 3BF, but little improvement is seen in CFF [16].

In this work we examine the role of exchange current on the CFF of ^{3}H and ^{3}He by the HHE approach. In the earlier work [23] the trinucleon wave function was obtained by the momentum space Faddeev calculation. However, such a calculation is not convenient for handling long–range interaction like the Coulomb force. Since a large number of partial waves contribute, the numerical calculations become extremely difficult. But in the HHE method, since the calculations are done in coordinate space, handling of long–range interactions is straightforward. Most of the previous calculations have used Faddeev method. To the best of our knowledge, no calculations with MEC to the CFF of trinucleon were done by HHE method. This provides our motivation for the present work. We also include various three–body forces (3BF) to the CFF of trinucleon and try to investigate the combined effect of 3BF and MEC on the CFF.

Here we adopt the HHE method to solve the trinucleon and, for simplicity, we consider the bound state to be a pure S-state. For this restriction we choose only S-projected central potentials for 2BF. Malfliet and Tjon MTV potential [26] and Afnan and Tang S3 potential [27], which are resonably realistic, although quite simple in structure, have been chosen to represent the 2BF. Among various 3BF's we choose (i) Fujita and Miyazawa (FM) [28] (ii) the Tucson-Melbourne (TM) [29] and (iii) the Brazilian (BR) [30] two pion-exchange three-nucleon force. The forces derived by Tucson and Melbourne (TM) and Brazilian (BR) groups are more realistic than the FM-3BF.

For the trinucleon form–factor, we take analytic form given by Das et al. [15] and then simply add the MEC contribution to the CFF. For MEC correction, we follow the Feynmann diagrams given by Kloet and Tjon [23].

The paper is organized as follows. We discuss the theory in Section 2 and results and conclusions are presented in Section 3.

2. *Theory*

Since the details of the HHE method is available in the literature [7], we present here only the rudiments of the method. In this method, the wave function is expanded in the complete basis of hyper–spherical harmonics (HH) spanning the hyper space

$$\psi(\vec{x},\vec{y}) = r^{-5/2} \sum \Phi_{K\alpha}(r)\ \mathcal{P}_{K\alpha}(\Omega). \tag{1}$$

Here r is the hyper–radial variable which is the invariant global length in a six–dimensional space and Ω represents a set of five hyper–angles. These are defined in terms of the particle coordinates r_i $(i = 1, 2, 3)$ through

$$\vec{x} = \vec{r}_2 - \vec{r}_1, \qquad \vec{y} = \sqrt{\frac{2}{3}}(\vec{r}_3 - \frac{1}{2}(\vec{r}_1 + \vec{r}_2)),$$

and

$$r = (x^2 + y^2)^{\frac{1}{2}}, \qquad \Omega = \{\hat{x}, \hat{y}, \phi\}, \tag{2}$$

where

$$\phi = \tan^{-1}(\frac{x}{y}).$$

The label $K\alpha$ stands for the five quantum numbers related to the five degrees of freedom in Ω. The complete orthonormal HH ($\mathcal{P}_{K\alpha}(\Omega)$) is the angular part of the homogeneous harmonic polynomial of degree K ($K = 0, 1, ..., \infty$) in the six–dimensional space and is given by,

$$\mathcal{P}_{K\alpha}(\Omega) = \sum_{m_x, m_y} \langle l_x l_y m_x m_y \mid LM \rangle \; Y_{l_x}^{m_x}(x) \; Y_{l_y}^{m_y}(y) \; {}^{(2)}P_{2K}^{l_y l_x}(\phi), \tag{3}$$

where

$${}^{(2)}P_{2K}^{l_y l_x}(\phi) = N_{2K}^{l_y l_x} \; (\sin\phi)^{l_x} \; (\cos\phi)^{l_y} \; P_n^{\alpha,\beta}(\cos 2\phi). \tag{4}$$

$P_n^{\alpha,\beta}(x)$ is Jacobi polynomial, $\alpha = l_x + \frac{1}{2}$ and $\beta = l_y + \frac{1}{2}$ and $n = (2K - l_x - l_y)/2$ is a non–negative integer.

Full advantage of this method is taken by expanding the interaction potential also in a suitable HH basis,

$$V(r, \Omega) = \sum_{K'', \alpha''} V_{K''\alpha''}(r) \; \mathcal{P}_{K''\alpha''}(\Omega), \tag{5}$$

where $\{\mathcal{P}_{K''\alpha''}\}$ is the set consistent with the nature of the interaction.

Substitution of (1) into the three–body Schrödinger equation, and projection onto a particular HH, lead to a system of coupled differential equations [7]. Using uncoupled adiabatic approximation [31], the set of differential equation is approximately decoupled and solved numerically to obtain the BE and wave function. The CFF of the trinucleon is then calculated using the wave function thus obtained [15].

The exchange contribution for the CFF is given by [23]

$$F_{ch}^{ex}(q^2) = \frac{-g^2}{2(4\pi\sqrt{M})^3} \left[F_V(q^2) + G_V(q^2) + 3F_S(q^2) + 3G_S(q^2) \right] Q(q^2), \tag{6}$$

where the function $Q(q^2)$ is defined as

$$Q(q^2) = \int d\vec{p}_1 \; d\vec{p}_1' \; d\vec{q}_1 \; \phi_0(p_1, q_1) \; \phi_0(p_1', q_1') \times \frac{q^2 - 2(\vec{p}_1 - \vec{p}_1').\vec{q}\sqrt{M}}{\left[(\vec{p}_1 - \vec{p}_1')\sqrt{M} - \vec{q}/2 \right]^2 + \mu^2}, \tag{7}$$

where $\vec{q}_1' = \vec{q}_1 - \vec{q}/(2\sqrt{3M})$ and $\phi_0(p, q)$ is the momentum space wave function for the S-state of trinucleon and $\vec{p}_1, \vec{q}_1$ are relative momenta expressed in terms of particle momenta k_i ($i = 1, 2, 3$) by

$$\vec{p}_1 = \frac{1}{2\sqrt{M}}(\vec{k}_2 - \vec{k}_1),$$

$$\vec{q}_1 = \frac{1}{2\sqrt{3M}}(\vec{k}_2 + \vec{k}_3 - 2\vec{k}_1).$$

M and μ are the nucleon (939 MeV) and pion (139.6 MeV) masses, respectively. F_V and F_S are, respectively, the isovector and isoscalar charge form–factor of the nucleons, while G_V and G_S are its isovector and isoscalar magnetic form–factors and are given in Ref. 32.

Introducing angle θ between the vector $\vec{\Delta}$ and $\vec{q}$, where $\vec{\Delta} = (\vec{p}_1 - \vec{p}_1')\sqrt{M}$, we may write

$$Q(q^2) = \int d\vec{p}_1\, d\vec{p}_1'\, d\vec{q}_1\; \phi_0(p_1, q_1)\phi_0(p_1', q_1') \times \frac{q^2(1 - 2\Delta/q\cos\theta)}{(\Delta^2 + 1/4q^2 + \mu^2) - \Delta q\cos\theta}. \quad (8)$$

In the HHE method, the trinucleon wave function (in coordinate space) is given by [7]

$$\psi(\vec{x}, \vec{y}) = \sum_K \sum_{l_x l_y} \sum_{m_x m_y} \langle l_x l_y m_x m_y \mid LM\rangle\, Y_{l_x}^{m_x}(\theta_x, \phi_x)\, Y_{l_y}^{m_y}(\theta_y, \phi_y)$$

$$\mathcal{N}_K\, u_K(r)\, r^{-5/2}\, {}^{(2)}P_{2K}^{l_y l_x}(\phi), \quad (9)$$

where $\mathcal{N}_K = {}^0N_{2K}\, {}^0F_{2K}^{l_y l_x}(\phi)$ is taken from Ref. 7.

The function $Q(q^2)$ in (8) involves a nine–dimensional integral in momentum space. We have reduced it to a two–dimensional integral in coordinate space by taking appropriate Fourier transforms in the following way,

$$\phi_0(p_1, q_1) = (\frac{\sqrt{M}}{2\pi})^3 \int \psi(\vec{x}, \vec{y})\, e^{\imath\vec{x}\cdot\vec{p}_1\sqrt{M}}\, e^{\imath\vec{y}\cdot\vec{q}_1\sqrt{M}} d\vec{x}\, d\vec{y}, \quad (10)$$

$$\frac{(1 - 2\Delta/q\cos\theta)}{(\Delta^2 + 1/4q^2 + \mu^2) - \Delta q\cos\theta} = (\frac{1}{2\pi})^3 \int Y(x, q) e^{-\imath\vec{\Delta}\cdot\vec{x}} dx. \quad (11)$$

Using (10) and (11), $Q(q^2)$ takes the form

$$Q(q^2) = (\sqrt{M})^{-3} \int \psi(\vec{x}, \vec{y})\, \psi^*(\vec{x}, \vec{y})\, e^{\imath\vec{y}\cdot\vec{q}/2\sqrt{3}}\, Y(\vec{x}, \vec{q})\, d\vec{x}\, d\vec{y}. \quad (12)$$

For simplicity, in actual calculation, we have considered that the bound state is a pure S-state, for which L = M = 0 and $\psi(\vec{x}, \vec{y})$ is given by

$$\psi(\vec{x}, \vec{y}) = \frac{1}{4\pi} \sum_K {}^0N_{2K}\, {}^0F_{2K}^{00}(\frac{\pi}{2})\, r^{-5/2}\, u_K(r) {}^{(2)}P_{2K}^{00}(\phi). \quad (13)$$

Substituting (13) in (12), and doing the angular integration, one has

$$Q(q^2) = \frac{4\pi^2 q}{M^{3/2}} \int \sum_{KK'} \mathcal{N}_K \mathcal{N}_{K'}\, u_K(r)\, u_{K'}(r)\, r^{-5/2}\, {}^{(2)}P^{00}_{2K}(\phi)\ {}^{(2)}P^{00}_{2K'}(\phi) \times$$

$$\times j_0(\frac{qy}{2\sqrt{3}})\, j_1(\frac{xq}{2})\, \frac{\mathrm{e}^{-\mu x}}{x}\, x^2 y^2 \mathrm{d}x\, \mathrm{d}y \tag{14}$$

where $j_n(x)$ is the spherical Bessel function of order n. The function $Q(q^2)$ in (14) is now reduced analytically to a two–dimensional integral in coordinate space. It is then evaluated numerically using the hyper–radial wave functions $u_K(r)$, obtained by the HHE method.

3. *Results and discussions*

For the nucleon-nucleon 2BF, we have chosen two commonly used S-projected potentials, namely Afnan-Tang S3 potential and the Malfleit-Tjon MTV potential. Both these underbind the trinucleon in common with more realistic potentials like RSC potential. Most other calculated observables with S3 and MTV are also comparable with those with RSC potential. We performed the calculation for both ^{3}H and ^{3}He; for the latter, Coulomb repulsion between the two protons is included with the sum of the three two–body nuclear interactions, thus without resorting to perturbation approximation. The trinucleon wave function, including the effects of both 2BF and 3BF, can be obtained by introducing properly the three–body multipole in addition to the two–body multipoles, and solving the resulting coupled differential equation for the hyper–radial wave function. In the actual calculation, we have taken 12 hyper partial-waves including all the necessary multipoles of 2BF but two multipoles of 3BF. The 3BF being of much shorter range than the 2BF, only two multipoles of 3BF were found sufficient for the degree of precession achieved with 12 partial waves. Since the FM-3BF has a strong singularity (going as r^{-6} for $r \to 0$) and is attractive for the ETC of the trinucleon, a phenomenological cut–off parameter (x_0) is used [15] to regularize the very short–range behaviour of 3BF. For S3 potential, x_0 is chosen to be 0.34 fm as in Ref. 15. For MTV potential, we calculate the value of x_0 ($x_0 = 0.293$ fm) by a technique similar to that given by Das et al. [15], namely, x_0 is chosen such that no unphysical nodes appear in the hyper–radial wave function, but F_{max} has the largest value. The value of the parameter λ^2 (in the case of TM-3BF and BR-3BF) is taken as 17 and 25, as in Ref. 33.

In Tables 1 and 2, we present the values of q^2_{min} and F_{max} for both 2BF and various combinations of 2BF, 3BF and MEC. From the fifth column, we see that q^2_{min} moves further out for both 2BF with the inclusion of 3BF alone, in agreement with calculation by other authors [15–19]. Effects of MEC on q^2_{min} is presented in the sixth column, which shows that q^2_{min} shifted towards the experimental value with the inclusion of MEC. The amount of shift for both 2BF and various combination of 3BF varies from 2.5 to 5.9 fm^{-2} for ^{3}He and from 0.3 to 0.46 fm^{-2} for ^{3}H. Last two columns show calculated values of F_{max} for the cases when no exchange effects are taken and when exchange current contributions are included. Inclusion of 3BF

TABLE 1.
CFF for ^{3}He *calculated up to* $q^2 = 25$ fm^{-2}.

$2BF$	$3BF$	λ^2/x_0	BE MeV	q^2_{min} fm^{-2}	q^{2*}_{min} fm^{-2}	F_{max} $\times 10^3$	F^*_{max} $\times 10^3$
S3	-		5.7887	15.92	13.40	1.06	2.24
	FM	0.340	6.9218	16.40	13.61	1.39	2.99
	TM	17	6.4171	16.41	13.84	1.13	2.51
		25	6.7123	16.68	14.28	1.15	2.78
	BR	17	6.4270	16.47	13.63	1.13	2.50
		25	6.7296	16.72	13.82	1.14	2.55
MTV	-		7.3688	18.43	14.38	0.62	1.85
	FM	0.293	8.3605	19.50	14.77	0.70	2.37
	TM	17	8.1650	19.89	15.02		1.98
		25	8.6268	20.27	15.48		2.13
	BR	17	8.3249	20.55	15.24		2.11
		25	8.8227	21.65	15.71		2.20
Exp			7.718	11.0 ± 0.7		5.9 ± 0.3	

* indicates the corresponding values with MEC.

increases F_{max} slightly for both ^{3}H and ^{3}He and also for both 2BF. These increments are more or less equal for TM and BR 3BF's. From the fifth column, one notices that the amount of shift in q^2_{min} with the inclusion of 3BF changes only by small amounts for the FM, TM and BR three–body forces. Thus the choice of x_0, needed in the case of FM-3BF only, will not have too much effect on the present investigation. Although the value of secondary maximum (F_{max}) does not change appreciably with the inclusion of various 3BF only, the inclusion of MEC contribution with 2BF alone increases F_{max} by an appreciable amount. In the case of

2BF plus 3BF including MEC contribution, F_{max} also increases to a value of about (2 to 3) $\times 10^{-3}$ in the case of ^{3}He and (1.8 to 2.2) $\times 10^{-3}$ in the case of ^{3}H. From Table 2, it is clear that the effect of MEC on q^2_{min} and F_{max} for ^{3}H is very small in comparison with that of ^{3}He. The CFF for ^{3}He, calculated with 2BF alone, 2BF plus MEC contribution, 2BF plus 3BF and 2BF plus 3BF plus MEC contribution is plotted against q^2 in Fig. 1 (for S3 potential) and Fig. 2 (for MTV potential). Some of the experimental values together with their error bars is shown in Fig. 1. For comparison, we also include the CFF calculated by Hadjimichael et al. [24], including all the effects (the data were estimated from Fig. 10 of Ref. 24 and hence are not very accurate). One can notice that q^2_{min} moves appreciably to a smaller value and the amount of shift depends on the 2BF. However, inclusion of 3BF has a negligible effect on both q^2_{min} and F_{max}. Although F_{max} increases with the inclusion of MEC contribution (the increment again depends on the choice of 2BF), the value of F_{max}, including both 3BF and MEC, is still short of the experimental value.

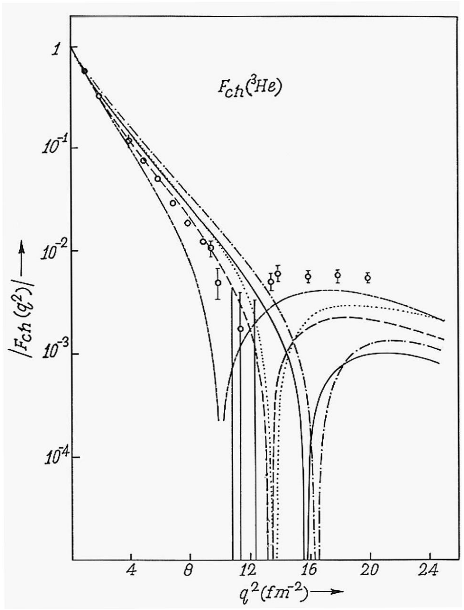
TABLE 2.
CFF for ^3H calculated up to $q^2 = 25$ fm^{-2}.

2BF	*3BF*	λ^2/x_0	BE MeV	q^2_{min} fm^{-2}	q^{2*}_{min} fm^{-2}	F_{max} $\times 10^3$	F^*_{max} $\times 10^3$
	-		6.4915	15.96	15.48	1.49	1.72
	FM	0.340	7.6262	16.45	16.03	1.85	2.16
		17	7.1308	16.31	16.06	1.59	1.83
S3	TM	25	7.4382	16.75	16.33	1.62	1.87
		17	7.1485	16.53	16.18	1.58	1.89
	BR	25	7.4603	16.78	16.35	1.61	1.92
	-		8.0990	18.52	17.84	0.89	1.10
	FM	0.293	8.9231	19.53	15.47		
		17	8.9642	19.91	19.02		
MTV	TM	25	9.3987	20.84	19.76		
		17	9.0678	20.58	19.42		
	BR	25	9.6225	21.52	20.24		
Exp			8.482	12.6 ± 0.5		3.95 ± 0.4	

* indicates the corresponding values with MEC.

In Figs. 3 and 4, we plot the same quantities of ^{3}H, for the two 2BF potentials

(S3 and MTV, respectively). Once again, we show some of the experimental points with their error bars. In this case the shift in q^2_{min} is smaller.



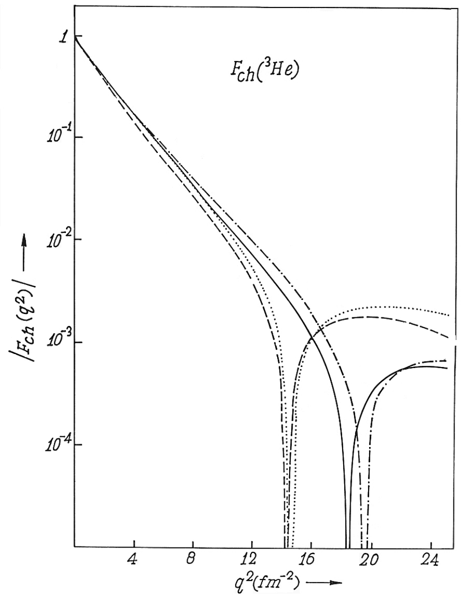
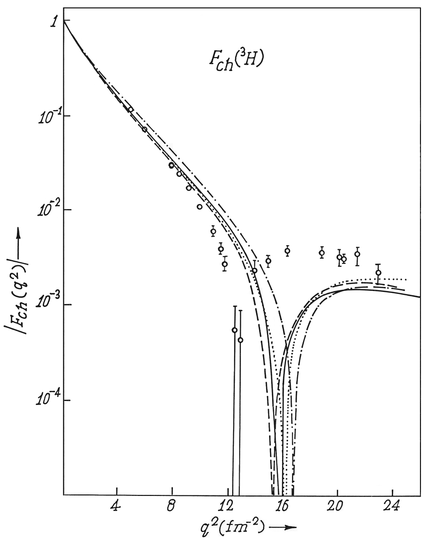


Fig. 1. Plot of $F_{ch}(q^2)$ as a function of q^2 for ^{3}He for 2BF alone (continuous), 2BF plus MEC (dashed), 2BF plus 3BF (dash–dot) and 2BF plus 3BF plus MEC (dotted). Experimental points are from Ref. 16. The dash-dot-dot-dot curve is drawn from the data of Ref. 24 and includes all the effects. The 2BF is chosen as S3 potential.

Fig. 2. Same as Fig.1 for MTV potential. Experimental points and comparison with Ref. 24 are omitted (right).

Both q^2_{min} and F_{max} are worse compared to experimental values for MTV potential than for S3 potentials. But there is a substantial enhancement in F_{max} due to the exchange effect for ^{3}He nucleus. Shifts in the position of the first diffraction minimum are greater for MTV than for S3, when effects of exchange currents are included. The CFF with 2BF alone is far worse for MTV (although BE is closer to the experimental value); hence CFF including exchange currents are better for the S3 potential. Since the MTV potential is more strongly repulsive at very short separations (< 0.6) compared to S3 potential, these observations indicate that the effects of the exchange currents are more pronounced for potential with very strong repulsive core. But the CFF without exchange current effects is closer to observed values for potentials which are less attractive at intermediate separations, like the S3, which, by virtue of the fact that at very short separations it is less repulsive than MTV, is less attractive at intermediate separations compared to MTV, in order that the BE of the deuteron has the correct value. Hence, our simple model calculation indicates that the inclusion of exchange current effects with a realistic potential like RSC is likely to produce a CFF close to the experimental one. For the RSC, the effective potential for the S-state has a very strong short separation repulsion and a rather shallow attraction at intermediate separations — a large part of the BE coming from the S-D states coupling, mediated through the tensor interaction.

In conclusion we state that the inclusion of 3BF moves q^2_{min} in general outwards and increases F_{max} slightly, thus making the overall agreement of CFF with experiment worse. The inclusion of MEC moves q^2_{min} inwards substantially and enhances F_{max} by an appreciable amount. The combined effects of 3BF and MEC are substantial and modify the CFF of trinucleon in the correct direction, however these do not fully reproduce experimental results.



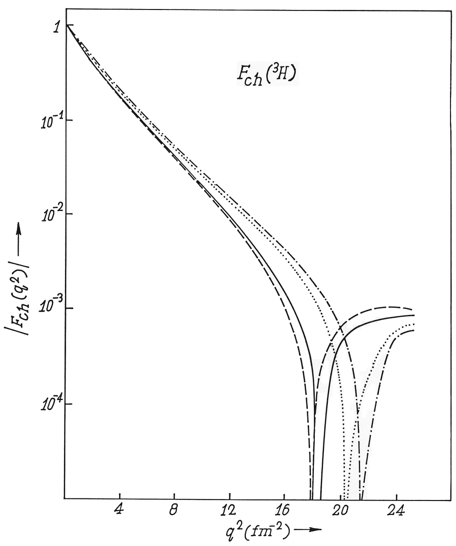


Fig. 3. Same as Fig.1 for ^{3}H *with S3 as the 2BF. No comparison is included.*

Fig. 4. Same as Fig. 2 for ^3H *with MTV potential (right).*

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TRONUKLEONSKI NABOJSKI FAKTOR OBLIKA S UKLJUČENJEM MEZONSKE SILE IZMJENE I SILE TRI TIJELA

Istražili smo učinak doprinosa stanja izmjene mezona nabojskom faktoru oblika (formfaktoru) ^{3}He i ^{3}H, primjenom metode razvoja po hipersferičnim harmonicima, uz uključenje tročestične sile. Dobiveni rezultati ukazuju da je zajednički učinak tročestične sile i mezonskih izmjena važan i da bitno mijenja nabojski faktor oblika prema rezultatima mjerenja.