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Abstract

We analyze the recent n + ^{232}Th TRIPLE data with an optical model potential that contains a parity non-conserving term. We account for the data on the analyzing power, with an effective PNC interaction that is three orders of magnitude larger than estimates based on standard meson - exchange models. Our findings not only support the recent ones by Koonin, Johnson and Vogel (KJV), but show that with an up-to-date OM potential, the KJV effect (enhanced PNC in the nuclear medium) is, in fact, ten times bigger.

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Recently there has been extensive work both theoretical[1] and experimental[2] on the question of parity conservation in low energy neutron-nucleus resonance reactions. It is expected that, due to the high density of states, parity mixing is enhanced in the compound nucleus. The usual approach based on the statistical theory, though clearly points to this enhancement, predicts a logitudinal analyzing power which exhibits no sign correlations, contrary to recent observations by the TRIPLE collaboration[3].

Several models for a possible coherent mechanism were suggested to account for the observed sign correlation[4-6]. No detailed calculations, however are available. Recently, Koonin, Johnson and Vogel[7] have taken the simple optical model picture to discuss the average properties of the cross section and analyzing power. Their conclusion is that with a standard Buck-Perey[8] strong potential, the PNC effective interaction that is needed to account for the average longitudinal analyzing power, comes up to be 100 times larger than estimates based on conventional meson-exchange models.

In this Letter, we point out that the optical-model analysis of PNC neutron scattering is strongly dependent on the background strong interaction. In fact our detailed calculation using an up-to-date optical model potential that represents very well the neutron scattering data in the actinide region shows that the effective PNC interaction comes out 10 times larger that the one obtained by KJV[7]. This, in turn, indicates that the effect of the nuclear medium on the PNC interaction is an order of magnitude larger than suggested by these authors.

The interaction of a neutron with a spin zero target of mass number A is taken to be the sum of a complex strong (parity conserving, PC) and weak (parity non-conserving, PNC) potential.

$$V = V_S(r) + V_{PNC} \tag{1}$$

$$V_S(r) = U(r) + V_{SO}(r)\ \vec{l}\cdot\vec{s} \tag{2}$$

$$V_{PNC} = \vec{\sigma}\cdot\vec{p}\ \nu(r) + \nu(r)\ \vec{\sigma}\cdot\vec{p} \tag{3}$$

The PNC interaction is spherically symmetric and time-reversal invariant ($\nu(r)$ is real). The potential $U(r)$ is complex and taken to be the Madland-Young optical potential[9] which describes very well neutron scattering from actinide nuclei at $E_n < 10$ MeV. It is given by

$$U(r) = -V_0 f_r(r) - iW_0 f_I'(r)$$

$$f_1(r) = \left[1 + \exp\frac{r - R_1}{a_1}\right]^{-1}$$

$$V_0 = 50.378 - 27.073\left(\frac{N-Z}{A}\right) - 0.354\, E_{Lab}\ \text{(MeV)}$$

$$R_r = 1.264\, A^{1/3}\ \text{fm},\quad a_r = 0.612\ \text{fm}$$

$$W_0 = 9.265 - 12.666\left(\frac{N-Z}{A}\right) - 0.232\, E_{Lab} + 0.003318\, E^2_{Lab}\ \text{(MeV)} \tag{4}$$

$$R_I = 1.256\, A^{1/3},\quad a_I = 0.553 + 0.0144\, E_{Lab}\ \text{(MeV)}$$

$$V_{so}(r) = \frac{\hbar}{m_\pi c^2}\, V^{(0)}_{so}\, \frac{1}{r}\, f'_{so}(r)$$

$$V^{(0)}_{so} = 6.2\ \text{MeV}$$

$$R_{so} = 1.01\, A^{1/3}\ \text{fm}$$

$$a_{so} = 0.75\ \text{fm}$$

To calculate the effect on the neutron scattering of the interaction V_{PNC}, we will first analyze the problem of elastic scattering due to the potential V_s. We will then use the DWBA to estimate the effect of V_{PNC}.

The elastic scattering amplitude owing to V_s is written as

$$F_o(\theta) = f(\hat{k}.\hat{k}') + i\vec{\sigma}.\hat{k} \times \hat{k}' g(\hat{k}.\hat{k}') \tag{5}$$

$$f(\hat{k}.\hat{k}') = \frac{1}{k}\sum\left[(\ell+1)\, t_\ell^{\,j=\ell+1/2} + \ell\, t_\ell^{\,j=\ell-1/2}\right] P_\ell(\hat{k}.\hat{k}') \tag{6}$$

$$g(\hat{k}.\hat{k}') = \frac{1}{k}\sum_\ell^\ell \left[t_\ell^{\,j=\ell+1/2} - t_\ell^{\,j=\ell-1/2}\right] P'_\ell(\hat{k}.\hat{k}') \tag{7}$$

where t^j_ℓ is the t-matrix element.In order to calculate, with DWBA, the effect of V_{PNC}, we need, aside from the outgoing wave whose partial wave expansion is

$$\psi^{(+)}_{\vec{k}}(\vec{r}) = 4\pi \sum_{j\ell\nu} (i)^\ell\, F^{(+)}_{\ell j}(r) < \hat{r} \mid \ell\, \tfrac{1}{2}\, j\nu > < \ell \tfrac{1}{2}\, j\nu \mid \hat{k} > \tag{8}$$

and asymptotic form is

$$\psi^{(+)}_{k}(\vec{r}) \xrightarrow[r\to\infty]{} e^{i\vec{k}.\vec{r}} + F_o(\theta)\,\frac{e^{ikr}}{r}\,, \tag{9}$$

the adjoint incoming-wave solution

$$\tilde{\psi}^{(-)*}_{\vec{k}}(\vec{r}) = \left(\theta\ \psi^{(+)}_{\vec{k}}(\vec{r})\right)^{+} = 4\pi\sum_{j\ell\nu}(i)^{-\ell}\, F^{(+)}_{\ell j}(r) < \hat{r} \mid \ell\, \tfrac{1}{2}\, j\nu > < \ell\, \tfrac{1}{2}\, j\nu \mid \hat{k} > \tag{10}$$

The resulting DWBA correction to the scattering, can be calculated from

$$\delta F = -\frac{1}{4\pi}\frac{2M}{\hbar^2} < \tilde{\psi}^{(-)}_{\hat{k}'} \mid V_{PNC} \mid \psi^{(+)}_{\hat{k}} > \tag{11}$$

Thus

$$\delta F(\theta,\phi) = -\vec{\sigma}.(\hat{k}+\hat{k}')\, h(\hat{k}',\hat{k}) \tag{12}$$

with

$$h(\hat{k}',\hat{k}) = \frac{1}{k}\,\frac{1}{1+\hat{k}'.\hat{k}}\,\sum_j \left(\frac{2j+1}{2}\right) t^j_{\ell+1,\ell}\left[P_\ell(k'.k) + P_{\ell+1}(k'.k)\right] \tag{13}$$

where the t-matrix is taken to be of the general form

$$t^J = \begin{pmatrix} t^J_{\ell,\ell} & t^J_{\ell,\ell+1} \\ t^J_{\ell,\ell+1} & t^J_{\ell+1,\ell+1} \end{pmatrix} \quad (14)$$

The diagonal terms $t^J_{\ell,\ell}$ and $t^J_{\ell+1,\ell+1\ell}$ enter in the definition of $F_o(\theta)$, Eqs.5,6 and 7.

The elastic scattering angular distribution is then givem by

$$\frac{d\sigma}{dr} = \frac{1}{2}\,\mathrm{Tr}\,(FF^+) \quad (15)$$

while the polarization is

$$P(\theta,\phi) = \frac{\mathrm{Tr}F\,\vec{\sigma}\,F^+}{\mathrm{Tr}\,FF^+} \quad (16)$$

with

$$F = F_o(\theta) + \delta F(\theta,\phi) \quad (17)$$

We thus obtain

$$\frac{d\sigma}{d\Omega} = |f(\cos\theta)|^2 + \sin^2\theta\,|g(\cos\theta)|^2 + 2(1+\cos\theta)\,|h(\cos\theta)|^2 \quad (18)$$

and

$$P(\theta,\phi) = \frac{2\left[(\hat{k}x\hat{k}')\ \mathrm{Im}\left(f(\cos\theta)g^*(\cos\theta\right) - (\hat{k}+\hat{k}')\ \mathrm{Re}\left(f(\cos\theta)h^*(\cos\theta)\right)\right]}{\frac{d\sigma}{d\Omega}} \quad (19)$$

It is now a simple matter to calculate the shape elastic cross-section, σ_E ,the absorption (compound) cross section, σ_{ABS}, and the total cross-section, σ_T. For this purpose, we introduce the partial S-matrix, defined by

$$S^J_{\ell,\ell'} = \delta_{\ell,\ell'} + 2it^J_{\ell,\ell'} \quad (20)$$

We find

$$\sigma_E = \frac{\pi}{k^2}\sum\frac{2j+1}{2}\left[|S^1_{\ell,\ell}-1|^2 + |S^J_{\ell,\ell+1}|^2 + |S^J_{\ell+1,\ell+1}|^2 + |S^J_{\ell,\ell+1}|^2\right]$$
$$-\frac{\pi}{k^2}\ \vec{\sigma}.\hat{k}\sum\frac{2j+1}{2}\ 2\ \mathrm{Re}\left[S^{J*}_{\ell\ \ell+1}\left(S^J_{\ell\ \ell} - 1 + S^J_{\ell+1,\ell+1} + 1\right)\right] \quad (21)$$

$$\sigma_{ABS} = \frac{\pi}{k^2}\sum_J\frac{2j+1}{2}\left[1 - \left|S^J_{\ell,\ell}\right|^2 - \left|S^J_{\ell,\ell+1}\right|^2 + 1 - \left|S^J_{\ell+1,\ell+1}\right|^2\right.$$
$$\left. + \left|S^J_{\ell,\ell+1}\right|^2\right] + \frac{\pi}{k^2}\ \vec{\sigma}.\hat{k}\sum\frac{2j+1}{2}\ 2\ \mathrm{Re}\left(S^{J*}_{\ell,\ell+1}\left(S^J_{\ell,\ell} + S^J_{\ell+1,\ell+1}\right)\right) \quad (22)$$

$$\sigma_T = \sigma_E + \sigma_{ABS} = \frac{2\pi}{k^2}\sum\frac{2j+1}{2}\left[1 - \mathrm{Re}\,S^J_{\ell,\ell+1} + 1 - \mathrm{Re}\,S^J_{\ell+1,\ell+1}\right]$$
$$+\frac{2\pi}{k^2}\ \vec{\sigma}.\hat{k}\sum\frac{2j+1}{2}\ 2\mathrm{Re}\left(S^J_{\ell,\ell+1}\right) \quad (23)$$

The spin-averaged total cross-section is

$$\bar{\sigma}_T = \frac{2\pi}{k^2}\sum_J\frac{2j+1}{2}\left[1 - \mathrm{Re}\,S^J_{\ell,\ell} + 1 - \mathrm{Re}\,S^J_{\ell+1,\ell+1}\right] \quad (24)$$

Finally, the longitudinal asymmetry coefficient, ε, defined from Eq.(23), as

$$\varepsilon = \frac{\sigma_{T+} - \sigma_{T-}}{\sigma_{T+} + \sigma_{T-}} \quad (25)$$

is found to be

$$\varepsilon = \frac{\frac{2\pi}{k^2}\sum_J\left(2j+1\right)\ \mathrm{Re}\,S^J_{\ell,\ell+1}}{\bar{\sigma}_T} \quad (26)$$

We have calculated, σ_E , σ_{ABS}, σ_T, and ε for n + ^{232}Th in energy region 10^{-5}MeV < E < 10 Mev, using the Madland-Young[8] (M-Y) optical potential and a PNC potential, Eq.(3), with a form factor $\nu(r)$ given by

$$\nu(r) = \frac{1}{2}\, \varepsilon_7\, \hbar c\ 10^{-7} \left[1 + \exp\left(\frac{r - r_0 A^{1/3}}{a}\right)\right]^{-1} . \qquad (5)$$

r_0 = 1.25 fm, a = 0.6 fm.

The parameter ε_7 is properly adjusted to account for the experimental value of the longitudinal asymmetry ε(P1/2). The expressions for the cross-section, polarization and asymmetry are well known and can be found e.g. in Ref. 7).

The potential, Eq.(1) gives for the s- and p- wave strength function S_0 , S_1 in ^{232}Th the values (at E_n = 1 eV).

$$S_0 = \frac{T\ (S1/2)}{2\pi \sqrt{E_{Lab}(ev)}} = 1.2 \times 10^{-4} \qquad (6)$$

$$S_1 = \left[\frac{1}{3}\,\frac{T\ (P1/2)}{2\pi \sqrt{E_{Lab}(ev)}} + \frac{2}{3}\,\frac{T\ (P3/2)}{2\pi \sqrt{E_{Lab}(ev)}}\right] \Big/ \left(\frac{k^2 R^2}{1+k^2R^2}\right) = 2.0\text{x}10^{-4} \qquad (7)$$

In Eqs.(28) and (29) T refers to the transmission coefficient and R in Eq. (29) in taken to be 1.25 fm. The above values of S_0 and S_1 are in reasonable agreement with the experimental ones given, respectively, by 0.84 ± 0.07x10^{-4} and 1.48 ± 0.07x10^{-4}. The value of S_1obtained in Ref. 7) with the Perey-Buck potential[9], or equivalently the Wilmore-Hodgson potential[10] is 5.29x10^{-4}. The difference between the Wilmore-Hodgson or Perey-Buck potential and the Madland-Young potential is clearly exhibited in Fig.1, which shows the corresponding strength functions vs. the mass number

We have also calculated the longitudinal asymmetry coefficient ε(P1/2) for ε_7 = 1, for the two potentials and the results are shown in Fig.2. We see clearly that where as for A<100 the two potentials give practically equal asymmetries, in

the heavy targets region there is an appreciable difference. For A = 232, we have for the Perey-Buck potential the value quoted by Koonin et al[7], ε(P1/2) = 2.7x10^{-3} (E_n = 1 eV, ε_7 = 1). The value we obtain with the Madland-Young potential is ε(P1/2) = 6.7x10^{-4} (E_n 1eV, ε_7 = 1).

The compound nucleus resonances in the n + ^{232}Th system start at a neutron Lab. energy of 8 eV. Therefore we have to know the value ε(P1/2)/ε_7 at this energy. In Fig.3 we show ε(P1/2)/ε_7 as a function of E_n and conclude that it exhibits an $E_n^{-1/2}$ dependence as observed by the TRIPLE people[4]. At E_n= 8 eV we get ε(P1/2) = 2.37x10^{-4} (E_n = 8 eV, ε_7 = 1). Thus to account for the experimental value of ε(P1/2) in the resonance region (E_n > 8 eV), which is 8±6% we have to take for ε_7= 307 ± 240. This is more than 10 times bigger than the value obtained by Koonin et al.[7]

The conclusions we draw from the above is that the effective PNC interaction is more than three orders of magnitude bigger than estimates based on standard meson-exchange models. We are thus in agreement with the conclusions of Ref.7 that the nuclear medium greatly enhances the PNC interaction. The enhancement we obtain is, however, ten times bigger than theirs. Full details of the calculation reported here will appear elsewere[11].

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Figure Captions

Fig.1: The singlet, S_0(1a), and triplet, S_1(1b) strength functions vs the mass number A. The full curve is obtained with the Wilmore-Hodgson (Perey-Buck) potential while the dashed curve is obtained with the Madland-Young potential. The neutron Lab. energy is $E_n = 1$ eV.

Fig.2: The asymmetry coeficient ε(P1/2) for $\varepsilon_7 = 1$, $E_n = 1$ eV vs. A. Details of curves are the same as in Fig.1.

Fig.3: The asymmetry coefficient ε(P1/2) for $\varepsilon_7 = 1$, A = 232, vs. the neutron Lab. energy.Details of curves are the same as in Fig.1.

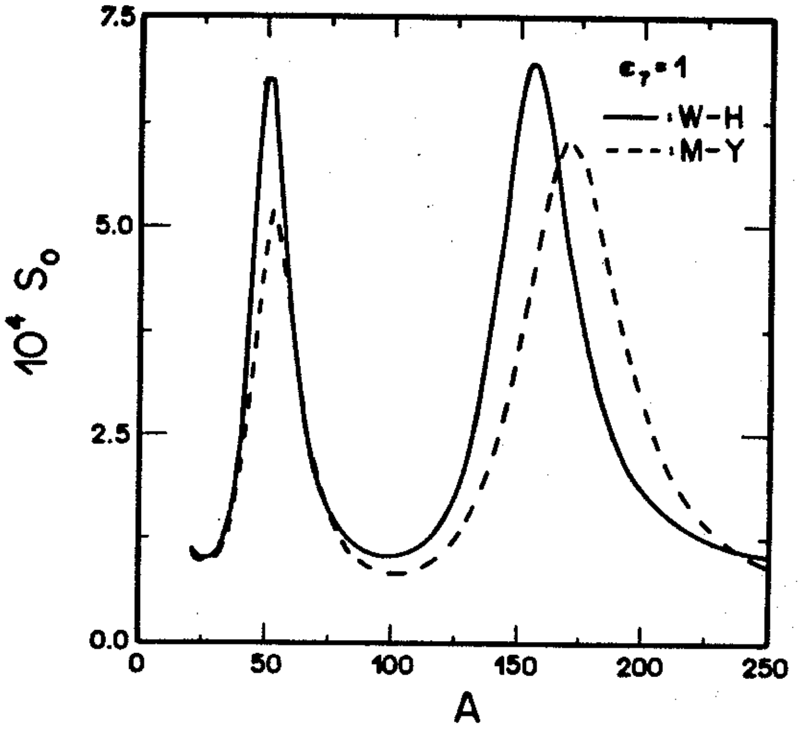

7.5
5.0
2.5
0.0
0
50
100
150
200
250
A
$10^4\ S_0$
$\epsilon_\gamma = 1$
W-H
M-Y

Fig. 1a

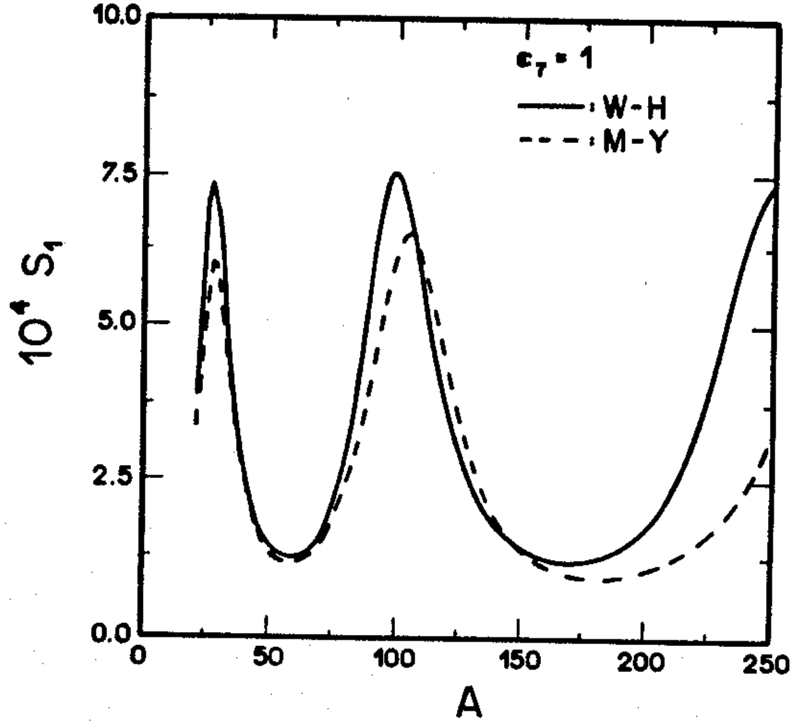
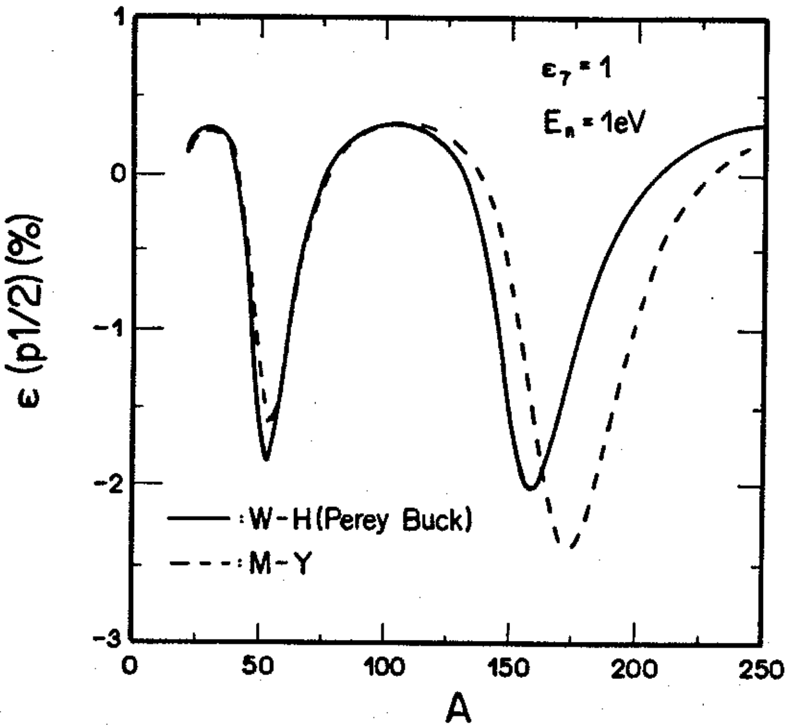
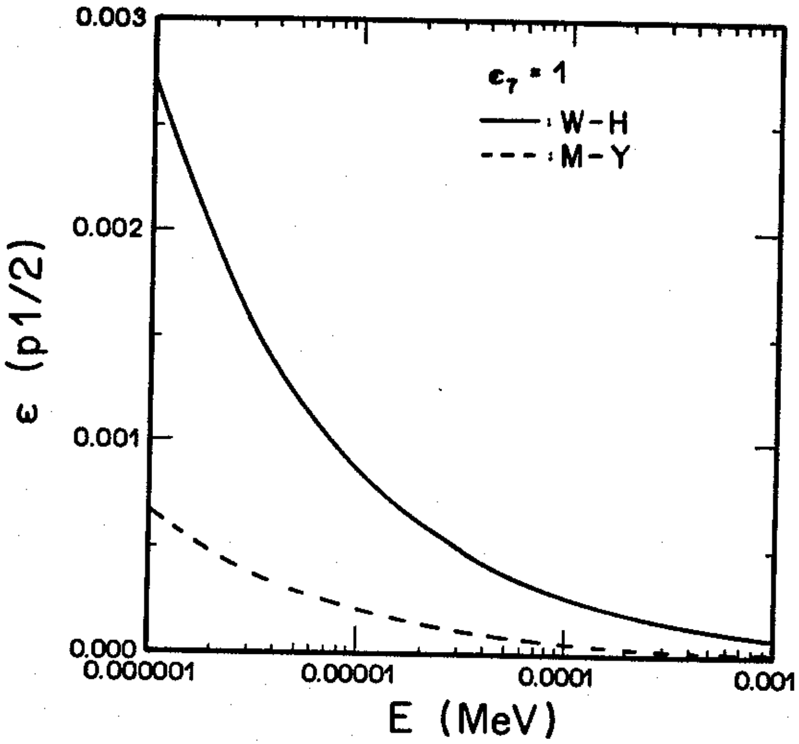

10.0
7.5
5.0
2.5
0.0
0
50
100
150
200
250
A
$10^4\ S_1$
$\epsilon_\gamma = 1$
W-H
M-Y

Fig. 1b



ε (p1/2) (%)
A
1
0
-1
-2
-3
0
50
100
150
200
250
$\varepsilon_\gamma = 1$
$E_n = 1eV$
—— : W-H (Perey Buck)
- - - : M-Y

Fig. 2



ε (p1/2)
E (MeV)
0.003
0.002
0.001
0.000
0.000001
0.00001
0.0001
0.001
$\varepsilon_\gamma = 1$
—— : W-H
- - - : M-Y

Fig. 3