Deuteron form factors and the tensor force

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Abstract. Results of a non-relativistic calculation of deuteron form factors are presented for separable potentials with and without tensor force. The tensor term in triplet state is added in such a way as to keep the values of deuteron binding energy, \( a \), and \( r_0 \) unaltered, so that the difference in the form factors can be regarded as the effect of tensor force only. The calculation has been performed for two different shapes of separable potentials and for three different \( D \)-state probabilities to study their comparative effect.

Keywords. Electromagnetic form factors; separable potentials; tensor force; deuteron.

1. Introduction

The electromagnetic form factors of deuteron provide a convenient probe of the nucleon-nucleon (\( NN \)) interaction. The \( NN \) interaction is fairly complicated and is well-known to have an attractive central, repulsive core, tensor and \( L\cdot S \) components. Many phenomenological forms for \( NN \) interaction have been proposed and studied in the literature over the past two decades. The parameters of the various components are first obtained from a comparison of two-body data—scattering in singlet and triplet states at various energies, properties of deuteron, including binding energy, quadrupole moment, magnetic moment, etc. These forces are then used in studying various more complicated systems—three-body bound state and scattering systems, electromagnetic form factors of \( 3N \) systems, few-body reactions and so on. Since most of these calculations are forbiddingly difficult, requiring solution of many-dimensional integral equations, eigen value problems and quadratures, which in turn require large computing times and programming and calculational skills, one often includes only those terms which are likely to make a reasonable contribution to the quantity under calculation.

In the triplet state the most important term after the attractive central term, is the tensor term. (The effect of the repulsive core (in the triplet state) and the \( L\cdot S \) term can usually be ignored for many calculations; there are situations however where these terms could be crucial). One measure of the tensor term is the deuteron \( D \)-state probability \( P_0 \). It is usually taken to be anywhere between 3\% and 7\%, though it is not amenable to direct experimental measurement (Amado 1981). Another, and perhaps more reliable, measure of the tensor force is the asymptotic \( D/S \) ratio, \( \eta \). This quantity has been estimated both theoretically and experimentally. Till recently its average value was quoted as \( \eta = (0.0264 \pm 0.0004) \) which agreed rather well with the theoretical
estimate of Ericson and Rosa-Clot (1982). However two more recent measurements have both given a somewhat higher value for $\eta$. Borbély et al (1982) quote a value $\eta = 0.0272 \pm 0.0004$ and Goddard et al (1982) $\eta = 0.0271 \pm 0.0008$, which are consistent with the theoretical estimate $\eta = 0.0271 \pm 0.0007$ by Klarsfeld et al (1981). This has pushed up the average $\eta$ value to $0.0271 \pm 0.0004$ (Ericson and Rosa-Clot 1983). Therefore, for the present even this quantity remains somewhat uncertain.

The deuteron and triton form factors, most properties of $^3\text{H}$ and $^3\text{He}$ and of scattering state have been calculated with extremely elaborate potentials containing a large number of terms. Many four-body, $n$-body ($n > 4$) ground-state calculations and many few-body calculations of vertex functions are too complicated to be handled with the complete potential; in the first instance such calculations are carried out with the simplest of potentials including only the central term hoping that the effect of the tensor term will be small. Nevertheless, it is important to have an estimate of the contribution of tensor term on various quantities of interest. In the three-body bound state problem its contribution is well documented; the addition of tensor force alters the binding energy by $\sim 10\%$ at best (Kharchenko et al 1968; Schrenk and Mitra 1967; Schrenk et al 1970). The $n-d$ doublet scattering length is a more sensitive parameter, whose experimental value (van Oers and Seagrave 1967; Dilg et al 1971) is still not agreed upon with absolute certainty and therefore is not particularly suited for estimating the contribution of tensor term. The 2-body and 3-body radii and form factors are usually believed to be quite sensitive to the tensor term. One expects the radii to be reduced by a few percent and the form factors at high momentum transfer to be reduced quite significantly. Though there are quite a few calculations of the form factors with tensor term present, a clear-cut comparison of the form factors with and without the tensor term is lacking. Further, the contribution of tensor force to a particular quantity could be different for different central potentials. Kharchenko et al (KPS) (1968) developed a series of separable potentials with shapes of the type $(p^2 + \beta^2)^{-n}$, $n = 1, 2, \ldots$, which could be fitted to give the same two-body low energy data but differed in their off-shell behaviour. In a series of calculations (Mehdi and Gupta 1974, 1976, 1979, 1980) using these potentials for $n = 1, 2$ we found that the $n = 2$ potential gave better fit to the triton form factors and $^3\text{H}-^3\text{He}$ binding energy difference. The effect of addition of a tensor term to each of these potentials on the triton binding energy and the $n-d$ doublet scattering length reduces as $n$ is increased progressively (Kharchenko et al 1968). It is therefore likely that the effect will reduce progressively with increasing $n$ even for other quantities of interest, such as the 2-body and 3-body form factors, $^3\text{H}-^3\text{He}$ binding energy difference etc. For the deuteron form factors this can be seen most clearly because analytic expressions for these form factors can be written down.

In this paper we report results of such a calculation of the electromagnetic form factors of deuteron for potentials with and without a tensor term. The tensor term is added in such a way as to keep the values of binding energy ($\text{BE}$), $a_0$ and $r_0$, unaltered, so that the difference in the form factors can be regarded as the "true" effect of tensor force. Though deuteron form factor calculations with tensor force have been reported earlier (Gourdin 1964, 1965; Mehrotra and Gupta 1970), no such comparative study exists in the literature to the best of our knowledge. We have performed the calculation with potentials $(p^2 + \beta^2)^{-n}$ corresponding to $n = 1$ and $n = 2$ to study their comparative effect.

In §2, we present the well-known formalism of deuteron form factors. We also give the exact analytic expressions for the form factors for $n = 1$ and 2 potential shapes. In