Drift Velocities of Electrons in Argon, Nitrogen, and Argon-Nitrogen Mixtures

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The drift velocities of electrons produced by polonium α-particles in a parallel-plate ionization chamber have been measured for pure argon, pure nitrogen, and argon-nitrogen mixtures. The argon data agree with the results of other investigators using the same method, but disagree with those obtained from the pulsed x-ray method. The nitrogen data agree with the results published by early investigators.

INTRODUCTION

BECAUSE of the increasing use of electron collection in ionization chambers, it is of interest to measure the drift velocities of electrons in the gases commonly employed in such chambers. Such measurements enable one to calculate the time of collection of electrons in a given ionization chamber. It is of practical importance to make this time of collection as short as possible, and it has been shown[1] that in certain gas mixtures one can obtain electron drift velocities which are higher than the drift velocity in either component of the mixture alone. It seemed of interest to repeat the measurement of the drift velocity in pure argon because of the discrepancies among the results obtained by various investigators.[1-3]

EXPERIMENTAL METHOD

The ionization chamber used in the present work consisted of two circular brass plates 5 in. in diameter and separated by 2.65 cm in a brass cylinder 6 in. in inside diameter. The chamber was sealed with a koroseal gasket, and a calcium-filled convection-current purifier whose volume was about 1/20 of that of the ionization chamber was used in obtaining the data for purified gases. The purifier was kept in operation, usually at 300°C, while the measurements were being made. Although calcium reacts with nitrogen rapidly at 400°C, the rate of reaction at 300° is low enough to enable one to remove the oxygen and water vapor from nitrogen by circulating it over calcium at this temperature.[4] In the present work, no appreciable pressure change occurred at 3 atmospheres of nitrogen in 24 hours with the purifier at 300°. A polonium α-particle source emitting about 3000 particles/min. was evaporated directly on the negative electrode.

The amplifier used was a "model 500," designed by W. C. Elmore,[5] and modified slightly so that one cathode follower output tube fed the voltage pulses from the chamber to trigger the sweep circuit of the oscilloscope and the other cathode follower fed the pulses from the first triplet feedback loop of the main
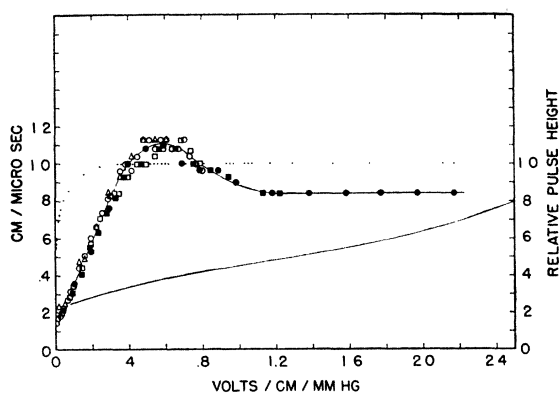

FIG. 1. Electron drift velocity curves obtained with pure argon. The open circles represent data obtained at a pressure of 3 atmos. and a purifier temperature of 160°C. The open triangles represent data at 3 atmos. and 300°C. The open squares, the solid squares, and the solid circles represent the data obtained at pressures of 2, 1, and ½ atmos., respectively. The dotted curve represents the relative pulse height and is referred to the scale at the right of the figure. The lower solid curve represents the data obtained by Nielsen (see reference 7) using the electrical shutter method.
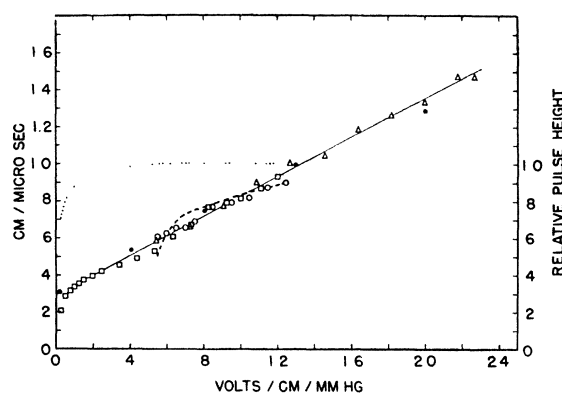

FIG. 2. Electron drift velocity curves for nitrogen. The open circles represent the data obtained with commercial water-pumped nitrogen at a pressure of 2 atmos. The open squares represent the data obtained at 2 atmos. after purification. The open triangles represent the data obtained at 1 atmos. with the purifier turned off after the gas had been purified. The dashed curve is the pulse height curve for the unpurified gas. The dotted curve is the pulse height curve for the purified gas. Several values of the drift velocity obtained from the published curves of Nielson (see reference 7) are indicated by the solid circles.

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[1] J. S. Allen and Bruno Rossi, MDDC 448, p. 1.
[2] Pierre Herreng, Comptes Rendus 217, 75 (1943).
[3] Donald E. Hudson, MDDC 524.

[4] P. de Cori, IX Congr. intern. quim. pura aplicada (Madrid) 6, 225 (1934) (published in 1936).
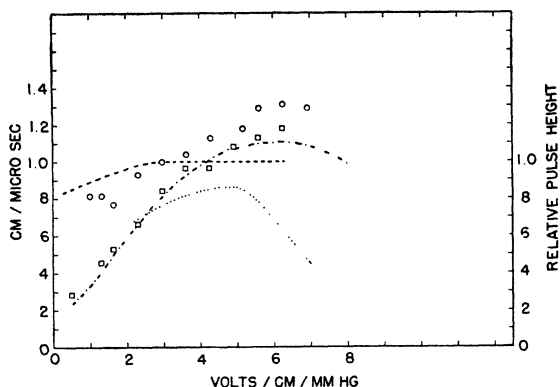[5] W. C. Elmore, LADC 89 and LADC 91.

Fig. 3. Electron drift velocity curve for 1 percent of oxygen in argon at 3 atmos. The open circles represent the data obtained with the unpurified mixture. The open squares represent the data obtained after the mixture was passed over hot calcium and the oxygen removed. The alternate dot and dash curve represents the data previously obtained with pure argon. The dotted curve is the pulse height curve of the mixture before purification; the dashed curve is the pulse height curve after purification.

amplifier through a 0.15 μsec. delay line to the amplifier of the oscilloscope. The rise time of the entire amplifying system, including the delay line, was 0.08 μsec., and the time constant determining the low frequency response (the "clipping time") was 50 μsec. From the decay of the pulses as observed on the oscilloscope screen, the effective "clipping time" was about 25 μsec. The signal-to-noise ratio at 3 atmospheres pressure was about 8 to 1 for the pulses of maximum height, corresponding to those α-particles coming off at small angles with respect to the surface of the negative electrode.[6]

The oscilloscope used was a Tektronix Model 511. The sweep speeds were calibrated by means of an oscillator and an accurate wave meter. It was found that the sweeps were slightly non-linear at their starts, and so the positions of the peaks of a known sine wave were determined accurately and a curve of time against distance along the sweep was obtained for each of the sweep speeds used in the experiments.

The output pulses of the amplifier were observed visually on the oscilloscope screen, and the time from the beginning of the sweep to the maximum height of the pulse was measured in each case. The entire pulse was not visible because the time necessary for the pulse to rise to the voltage required to trigger the sweep of the oscilloscope was longer than the delay introduced by the delay line. The pulses were extrapolated back to zero pulse height by means of a transparent straight edge, and the time corresponding to the extrapolation to zero pulse height was added to the time from the beginning of the sweep to the maximum pulse height, as discussed to obtain the total time of the voltage pulse from the chamber. Since the leading edges of the pulses were quite linear, this correction should

6 Rubby Sherr and Rolf Peterson, Rev. Sci. Inst. 18, 568 (1947).

not introduce a serious source of error. That this is the case was shown by observing the pulses obtained with a given set of experimental conditions in turn on each of two sweeps, the speeds of which varied by about a factor of three. The measurements made on the two sweeps agreed to within the uncertainty of observing the positions of the maxima of the pulses. This check was made each time the sweep speed was changed to accommodate for the change in the drift velocity as the field across the chamber was varied.

Error may be introduced by the observed effective "clipping time" owing to its distortion of the linear leading edge of a pulse from the ionization chamber. This possibility was considered by plotting to the same scale as that of the oscilloscope screen the effect of the observed time constant on a pulse rising linearly to the saturation value in 5 μsec. It was found that the position of the maximum pulse height was still well defined for this case and that no appreciable error in the measurement of the rise time resulted. Since the rise time of the entire amplifying system was about 7 percent of the minimum electron collection time, the effect of this on the observed shapes of the pulses was considered to be negligible in comparison with the errors resulting from the time measurements on the scope screen. The largest pulses were always used for the measurements since for this case the slope of the expected voltage pulse should be accurately constant until the maximum, and then the amplitude should decay with the effective "clipping time" of the amplifier. The drift velocity of the electrons is then given by the distance between the plates of the ionization chamber
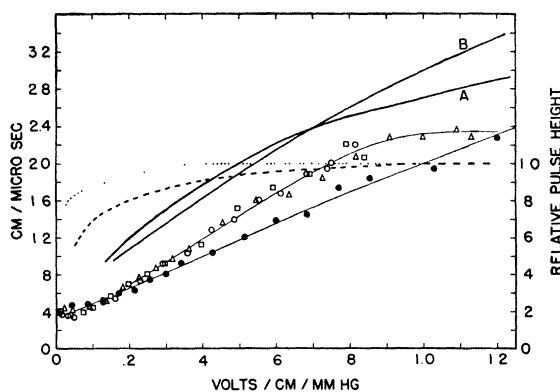

Fig. 4. Electron drift velocity curves for mixtures of nitrogen and argon. The open circles represent data obtained for the purified 1 percent mixture of nitrogen in argon at 3 atmos. The open squares represent data for the purified 1 percent mixture at 2 atmos. The open triangles represent data for the purified 1 percent mixture at 1 atmos. The solid circles represent data for the unpurified 10 percent mixture of nitrogen and argon at 1 atmos. These data extend linearly to a value of 2.76 cm/microsec. at 1.5 volts/cm/mm of Hg. The dotted curve is the pulse height curve for the purified 1 percent mixture. The dashed curve is the pulse height curve for the unpurified 10 percent mixture. The solid curve A is a computed electron drift velocity curve for 1 percent of nitrogen in argon based on the data for argon and nitrogen given by Townsend (see reference 11). The solid curve B is a similarly computed curve for 10 percent of nitrogen in argon.

divided by the observed total time to the maximum of the voltage pulse from the chamber. The relative accuracy of the drift velocity measurements was estimated to be ±5 percent.

RESULTS

The argon used in this experiment was 99.6 percent pure according to the manufacturer. The drift velocities of electrons in purified argon were measured at pressures of $\frac{1}{2}$, 1, 2, and 3 atmospheres, and the results are given in Fig. 1. The drift velocity in cm/μsec. is plotted against the field strength per unit pressure in volts/cm/mm of mercury. For the case of a pressure of 3 atmospheres, it was found necessary to outgas the calcium in the purifier at a temperature higher than that used for purifying the gas in order to get a reproducible drift velocity curve. When this was done, the data obtained at a purifier temperature of 160°C agreed with those obtained at a purifier temperature of 300°. The dotted curve is the plot of the relative pulse height as a function of the field strength per unit pressure. One sees that at values of E/p greater than 0.3 all the electrons produced by the α-particles are collected.

The data obtained with nitrogen are shown in Fig. 2. The nitrogen used was the water-pumped grade sold commercially in metal cylinders. It is seen that one obtains the same drift velocity curve with tank as with pure nitrogen. However, the saturation properties of the gas improve markedly with purification. The data at 1 atmosphere were obtained with the purifier having been turned off for 2 hours after having been on for about 24 hours. The drift velocity curve obtained for nitrogen agrees with the data of Nielsen.[7]

The effect of introducing 1 percent of commercial tank oxygen into argon at 3 atmospheres pressure is shown in Fig. 3. The drift velocity of the electrons is increased because their average energy is decreased, and the pulse height is decreased because of capture of electrons by oxygen molecules to form negative ions. It is seen that above $E/p=0.5$, as the field strength is increased, the pulse height decreases because the electrons increasingly excite the electronic excitation level of the oxygen molecule at 1.62 electron volts.[8] The fact that the oxygen was removed by the purifier is shown by the agreement of the observed points with the curve obtained for pure argon.

The results obtained with mixtures of argon and nitrogen are shown in Fig. 4. The data for the mixture of 1 percent of nitrogen in argon were limited by the fact that a discharge in the gas occurred at a field strength of 1280 volts/cm at a pressure of 2 atmospheres and at a field strength of 940 volts/cm at a pressure of 1 atmosphere. When the chamber was filled with the 10 percent mixture of nitrogen in argon at 1 atmosphere,

a field strength of 1360 volts/cm was reached before breakdown occurred.

One sees that at low values of E/p the electron drift velocity is higher for the 1 percent mixture than for the 10 percent mixture. However, the fact that one can reach higher values of E/p before breakdown with the 10 percent mixture enables one to reach higher values of drift velocity with it than with the 1 percent mixture. The data for the 10 percent mixture shown in Fig. 4 were extended, and the drift velocity continues to increase linearly with E/p to a value of 2.76 cm/μsec. at $E/p=1.5$ volts/cm/mm of mercury.

The Drift Velocity of Electrons in Mixtures of Gases

As mentioned earlier, Allen and Rossi[1] have developed a procedure for the calculation of the drift velocity of electrons in mixtures of two or more gases when the appropriate data for the individual gases are available. A short description of this method has been given by Healey and Reed,[9] and a more detailed discussion has been given by Staub and Rossi.[10] Since this method has proved to be extremely valuable when used to predict the behavior of an ionization chamber, the predicted values of the drift velocity were compared with the observed values for the argon-nitrogen mixtures in order to indicate the accuracy of this method.

For convenience a summary of the method developed by Allen and Rossi[1] will be presented here using the same notation. Consider a gas such as argon in which the probability of negative ion formation is extremely small. When an electric field E volts/cm is applied, a drift velocity W is superimposed upon the irregular thermal motion of any free electrons present in the gas and their average energy is increased above the thermal value. Let $K(3/2kT)$ be the new value of this average energy.

The values of K and W are determined by an equilibrium condition between the energy and momentum imparted by the electric field to the electrons and the energy and momentum transferred by the electrons to the gas molecules through collisions. These two equilibrium conditions may be expressed by the following equations:

$$eEW = p\epsilon(K) \qquad (1)$$

$$eE = pW\pi(K) \qquad (2)$$

where e is the electronic charge, p is the pressure of the gas in mm of Hg, $\epsilon(K)$ is the average energy transfer per second for $p=1$ mm of Hg and $\pi(K)$ is the average momentum loss per second for $W=1$ and $p=1$ mm of Hg. In general, ϵ and π are functions of K.

For a mixture of n gases with partial pressures p_1, p_2

[7] R. A. Nielsen, Phys. Rev. **50**, 950 (1936).

[8] Leonard B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley & Sons, Inc., New York, 1939), p. 190.

[9] Healey and Reed, *The Behavior of Slow Electrons in Gases* (Iliffe and Sons, Ltd., London, 1941).

[10] H. H. Staub and B. Rossi, National Nuclear Energy Series, Los Alamos Project (McGraw-Hill Book Company, Inc., New York, 1949), Vol. 2.

$\cdots p_n$ and total pressure p, the quantities $p\epsilon(K)$ and $p\pi(K)$ of Eqs. (1) and (2) may be written as

$$p\epsilon(K)=p_1\epsilon_1(K)+p_2\epsilon_2(K)+\cdots p_n\epsilon_n(K), \quad (3)$$

and

$$p\pi(K)=p_1\pi_1(K)+p_2\pi_2(K)+\cdots+p_n\pi_n(K), \quad (4)$$

where ϵ and π now refer to the mixture. In the present experiment the drift velocities were computed for mixtures of 1 percent and 10 percent of nitrogen in argon. The procedure was as follows:

A. $\epsilon_1/e=W_1E_1/p_1$ and $\pi_1/e=E_1/p_1W_1$ were plotted as functions of K for argon, and corresponding curves were plotted for nitrogen. The values of W as functions of E/p and K for the two gases were obtained from tables published by Townsend.[11]

B. Curves showing ϵ and π as functions of K were obtained after substitution of the appropriate values of ϵ_1, ϵ_2, π_1 and π_2 in Eqs. (3) and (4).

C. The curve for ϵ obtained in step B was replotted as a function of E/p, using the relation $\pi/e\times\epsilon/e=(E/p)^2$ for a given value of K.

D. The drift velocity W as a function of E/p was computed for each mixture using the curve obtained in step C and the relation

$$W=\epsilon/e\times p/E \quad (\text{Eq. (1)}).$$

The computed values of the drift velocity in mixtures of $0.01N_2+0.99A$ and $0.10N_2+0.90A$ are shown by curves A and B of Fig. 4. Although the computed values of W are considerably higher than the experimental data, the two sets of curves show the same general shape and indicate that the drift velocities in either of the mixtures are approximately twice the values in either A or N_2 at the same E/p. The physical reason for this increase in the drift velocities can be understood from an analysis of the behavior of electrons in A and in N_2. The curves of ϵ against K show that the energy loss in A is very small until K reaches a value of about 270 (which corresponds to 10 ev) and then starts rising abruptly, while in N_2 the energy loss increases rapidly above $K=30$. This is due to the fact that in A no inelastic collisions occur unless the electrons have an energy larger than the first excitation potential of 11.6 ev. In N_2 however, inelastic collisions occur at much smaller energies because of the vibrational excitation levels of the molecule beginning at about 1 ev. The effect of the addition of N_2 to A is to reduce the average energy of the electrons from about 10 ev for A at $E/p=1$ to about 1 ev for the mixture at the same value of E/p.

The curves of π as a function of K for either of the two mixtures show that the average momentum loss of the electrons is only slightly greater than that in pure argon because of the small proportion of nitrogen. Hence, we can say that the main effect of the addition of a small amount of N_2 to A is to bring the average

[11] J. Townsend, *Electrons in Gases* (Hutchinson's Scientific Publications, London, 1947), pp. 72, 73.

energy of the electrons from a high value, for which π is large, to a low value, for which π is small. Since the electron drift velocity is inversely proportional to π, this will result in an increased value of the drift velocity.

Since it was necessary to use the values of W and K given by Townsend,[11] a close agreement between the computed and experimental curves was not expected. However, the agreement is sufficiently close to indicate that this method can be used to estimate the behavior of ion chambers containing a mixture of two gases such as argon-nitrogen or argon-carbon dioxide.

CONCLUSIONS

As mentioned in the introduction, large discrepancies exist between the data published by various investigators for the drift velocity of electrons in argon. Since the drift velocity in this gas is extremely sensitive to small amounts of impurities, the values of W and also of K obtained by Townsend[11] probably are not representative of a pure gas. In recent years, discrepancies have appeared among the results obtained with modern vacuum techniques, but with different methods of drift measurement. The values of W obtained in the present experiment and shown in Fig. 1 are considerably above the curve representing the work of Nielsen[7] for values of E/p less than 2.6. The two sets of data apparently agree at $E/p=2.6$. Nielsen used the electrical shutter method with a thermionic source of electrons. The purity of the argon was stated to be 99.8 percent and the gas was introduced in to the apparatus through a liquid air trap.

The data of Nielsen are in close agreement with those obtained by Herreng.[2] In this latter experiment the electrons were produced by a narrow beam of x-rays parallel to the surface of the upper plate of the ionization chamber. No information regarding the purity of the gas has been published. Hudson[3] has measured the drift velocity of electrons in argon using the pulsed x-ray method. In his experiment, the entire sensitive volume of the ionization chamber was irradiated by the x-ray beam. The gas was purified by the same type of purifier used in the present experiment. He obtained a curve for W as a function of E/p which agrees with our data for low values of E/p, but rises to a maximum of $W=2.1$ cm/μsec. at $E/p=1.0$. This is about twice the maximum value of W observed in our experiment and occurs at about twice the value of E/p.

An obvious explanation for the discrepancies which still exist between the values of the drift velocity of electrons in argon as reported by various investigators is that the methods of purification used at present do not result in the degree of purity required for consistent results. In the present experiment, reproducible drift velocity curves were obtained when the calcium purifier had been evacuated and outgassed prior to the circulation of the gas through the system. The curves of Fig. 3 indicate that the purifier will remove relatively large amounts of oxygen from argon. Since the argon was

allowed to circulate continuously through the purifier during the experiment, all impurities other than inert gases should have been removed. It is possible that impurities were present in the gas used by Nielsen[7] or by Herreng[2] since continuous purification was not used in these experiments.

In contrast to the results for argon the curves shown in Fig. 2 indicate that, in the case of nitrogen, there is a close agreement between the drift velocity data of the present method and those of Nielsen.[7] Apparently, the drift velocity in this gas is less sensitive to the purity of the gas than in the case of argon.

On a New Theory of Nuclear Forces*

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A new theory of nuclear forces is based on the result established in an earlier paper that if the matrix α^0 in the field equations $(\alpha^k p_k + \chi)\psi = 0$ satisfies the minimal equation $\{(\alpha^0)^2 - 1\}^2 (\alpha^0)^s = 0$, any integer, then every component of the field ψ satisfies the iterated generalized wave equation $(\Box + \chi^2)^2 \psi = 0$ of the fourth order. The static potential between two nucleons is then a sum of the interaction (29) between two point charges and the dipole-dipole interaction (30) multiplied by numerical coefficients and isotopic spin factors. This interaction, unlike the usual one based on the Yukawa theory, allows an exact solution of the deuteron problem. The potentials based on more complicated fields satisfying the n times iterated generalized wave equation are also given.

1. INTRODUCTION

THE present theories of nuclear forces are all essentially based on Yukawa's original idea that the force between two nucleons results from the interaction of the nucleons with a field which satisfies the generalized second-order wave equation. For brevity we call this the meson field. All such theories lead in essence to a static potential between two point charges at a distance r of the form**

$$e^{-\chi r}/r, \tag{1}$$

and a static potential between two dipoles of the form

$$e^{-\chi r}\left[\left(\frac{\chi}{r^2}+\frac{1}{r^3}\right)(\sigma^{(1)}\cdot\sigma^{(2)})\right.$$
$$\left.-\left(\frac{\chi^2}{r}+\frac{3\chi}{r^2}+\frac{3}{r^3}\right)\left(\sigma^{(1)}\cdot\frac{r}{r}\right)\left(\sigma^{(2)}\cdot\frac{r}{r}\right)\right]. \tag{2}$$

χ is the constant associated with the field and equal to

the meson mass in suitable units. Here $\sigma^{(1)}$ and $\sigma^{(2)}$ stand for two three component vectors representing the directions of the moments of the two dipoles. The potentials (1) and (2) may be multiplied by isotopic spin factors depending on whether the meson field is neutral or charged or both. The potential between two nucleons is essentially a sum of these two potentials multiplied by numerical factors, the sign and magnitude of the factors depending on the spin of the meson field and the type of coupling assumed between the nucleons and the meson field. All such theories have proved unsatisfactory, not only because of the inability of any of them to describe the properties of the deuteron and the scattering of nucleons correctly, but because of the fundamental difficulty that the potential (2) between two nucleons becomes so singular as their mutual distance r diminishes, that no rigorous quantum mechanical solution of the deuteron problem exists.

Both the classical and quantum theories agree in giving the same potentials (1) and (2) between two nucleons, with the typical r^{-3} singularity in the interaction of two dipoles. This singularity is the same as that for the potential between two dipoles interacting through the electromagnetic field, and is unaffected by letting $\chi \to 0$ in (2). Since this very singular potential means that the kinetic energy of the two nucleons must become very large at close distances, one might for a moment suppose that a relativistic calculation of the potential taking into account the reaction of the emitted mesons might diminish the order of the singularity. This is however extremely unlikely, in my opinion, since every component of the meson field satisfies the

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** x^k, $k=0$, 1, 2, 3, are the four coordinates, and the metric tensor is taken in the form $g^{00}=-g^{11}=-g^{22}=-g^{33}=1$, $g^{kl}=0$ for $k \neq l$. A summation from 0 to 3 is understood over every index occurring both above and below. A letter in heavy type, for example r, denotes a space-vector with three components r_1, r_2, and r_3, and absolute length $r=+\{\sum_{k=1}^{3}(r_k)^2\}^{\frac{1}{2}}$. We use the vector product notation $(\mathbf{a}\cdot\mathbf{b})=\sum_{k=1}^{3}a_k b_k$. The four coordinates of a nucleon are denoted by z^k and the suffices (1) and (2) in brackets are used to identify variables belonging to the two nucleons. $r_k = z_k^{(1)} - z_k^{(2)}$, for $k=1$, 2, 3.