DETERMINATION OF THE NEUTRON-NEUTRON SCATTERING LENGTH FROM THE REACTION $\pi^- + d \rightarrow 2n + \gamma$

P. G. Butler, N. Cohen, A. N. James, and J. P. Nicholson
Nuclear Physics Research Laboratory, University of Liverpool, Liverpool, England
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The photon energy spectrum from the reaction $\pi^- + d \rightarrow 2n + \gamma$ at zero energy has been measured by a pair spectrometer using acoustic spark chambers to locate the pair-electron tracks. From the shape of the spectrum the neutron-neutron scattering length was determined to be $a_{nn} = 13.1^{-3.4}_{+2.4}$. The probability of existence of a bound state of two neutrons was calculated to be less than 5×10^{-9}.

Recent interest in the neutron-neutron interaction[1-10] has been primarily direction towards checking the charge dependence of nuclear forces. The concept of charge symmetry may be directly verified by a comparison of the ${}^1S_0$ neutron-neutron scattering length, a_{nn} with the nuclear part of the proton-proton scattering length $(a_{pp})_n$. The latter quantity has been calculated by Schwinger[11] who, using a value of $a_{pp} = -7.67$ F for the measured proton-proton scattering length, obtained values for $(a_{pp})_n$ of -16.4 and -18.3 F assuming rectangular and Yukawa nuclear-potential-well shapes, respectively. More recent results by Heller, Signell, and Yoder[1] using more accurate data and improved calculations lead to the results that $(a_{pp})_n$ is probably within the range -16.6 to -16.9 F. The more stringent charge-independence hypothesis is more difficult to check, as the neutron-proton scattering length, $a_{np} = -23.68 \pm 0.03$ F,[2] may be influenced by charged- and neutral-pion mass differences, and by electromagnetic and vacuum-polarization potentials.[1]

Previous determinations of a_{nn} have either used reactions such as D$(n,p)2n$, T$(n,d)2n$, or T$(d,\mathrm{He}^3)2n$[3-5] or have investigated the reaction $\pi^- + d \rightarrow 2n + \gamma$.[8-10] The latter method has the advantage that theoretical analysis is facilitated by the presence of only two strongly interacting particles, the two neutrons, in the final state. In the case where the photon rather than the neutron energies are determined, as in the present work, a further advantage is that the sign of a_{nn} may be determined.

A schematic diagram of the apparatus is shown in Fig. 1. Negative pions, produced by the Liverpool 156-in. cyclotron, passed through the monitor counters 1, 2, the Cherenkov counter C, and the carbon moderator before being brought to rest in the deuterium target. The purpose of the Cherenkov counter was to veto electrons in the beam, which would have produced a background of bremsstrahlung radiation. The coincidence sequence $123\overline{4}\overline{C}$ (bars indicating vetoes) thus notified the occurrence of stopped pions.

By measuring the diameters of the orbits of the electron and positron, created by a γ photon in a thin lead foil in a uniform magnetic field, the γ-photon energy could be found. This was achieved by locating the points at which the electron and

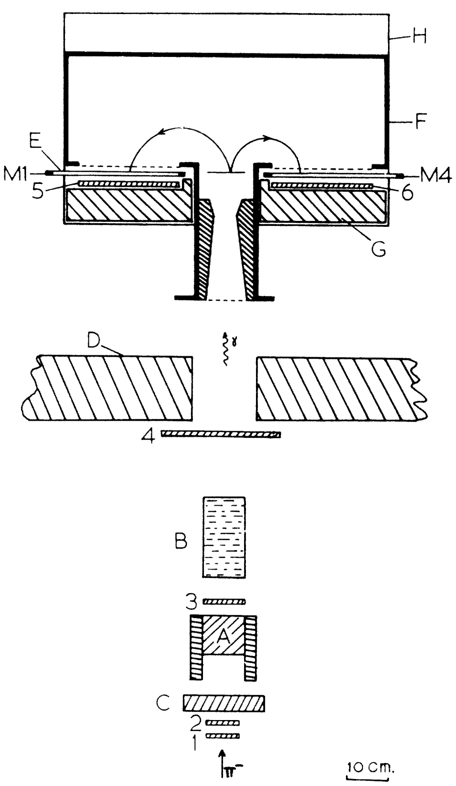

FIG. 1. Apparatus for measurement of photon energies from radiative capture of zero-energy pions. Key to diagram: A, carbon moderator and collimator; B, deuterium target; C, Cherenkov counter; D, yoke of pair-spectrometer magnet; E, spark chamber for evaluation of pair-electron trajectories; F, vacuum tank; G, lead shielding against direct particles from the beam; H, region of pair-spectrometer field; $M1$, $M4$, microphones 1 and 4, respectively; 1, 2, 3, 4, pion counter telescopes; 5, 6, pair-electron counters.

positron recrossed the plane of the lead foil by the use of two acoustic spark chambers. Only the co-ordinate perpendicular to the magnetic field direction was measured; two linear microphones per chamber monitored the correct operation of the acoustic timing system.

Denoting the times recorded by the timing unit to be t_1, t_2, t_3, t_4 (the subscripts refer to the microphones numbered from left to right in Fig. 1), the sum of the diameters of the pair-electron trajectories D is given to a first approximation by

$$D = \frac{t_2}{t_1+t_2}S_1 + \frac{t_3}{t_3+t_4}S_2 + A, \tag{1}$$

where S_1, S_2, and A are the distances between microphones 1 and 2, 3 and 4, and 2 and 3, respectively.

The γ-photon energy E in MeV is given to first approximation by

$$E = 0.149\,895BD, \tag{2}$$

where the magnetic induction B is in kG and D in cm.

Two effects invalidate Eq. (2): (a) nonhomogeneity of the magnetic field of the pair-spectrometer magnet and (b) nonconstancy of the velocity of sound in the chambers, arising from shock-wave effects.[12] The latter effect has been shown by Maglič et al.[13] to contribute a correction of about 3.5 mm to the calculated distance for 0.05-J sparks. Since only photon energies within a narrow range were considered, the range of variation of D was also small. The correction ϵ due to both effects above therefore is a function of the position of just one pair-electron track to a good approximation. The expression for E now becomes

$$E = 0.149\,895B[D - \epsilon(x)], \tag{3}$$

where $x = t_1/(t_1+t_2)$ is the fractional coordinate of one of the pair electrons.

The function $\epsilon(x)$ was determined empirically by using the reaction $\pi^- + p \to n + \gamma$ which produces monoenergetic photons of energy 129.38 MeV, i.e., photons in the required energy region. An experimental run with hydrogen in the target was performed, and for each event, values of D [from Eq. (1)], x, and hence ϵ were calculated by setting $E = 129.38$ MeV in Eq. (3). The correction $\epsilon(x)$ was then obtained by fitting a polynomial to a plot of ϵ against x.

Equation (3) was then used to calculate E for each event for both the hydrogen and deuterium runs. Any errors in $\epsilon(x)$ are unimportant as they merely contribute to the shape of the resolution function which is determined experimentally from the hydrogen data. The histrograms of the spectra are shown in Fig. 2.

Theoretical spectra derived by Bander[7] were folded with the resolution function and fitted by χ^2 test to the background-corrected deuterium data over the energy ranges 120-131.5 and 125-131.5 MeV. The results for the scattering length are compared in Table I with previous determinations. The result for the energy range 120-131.5 MeV must be considered doubtful as this energy range is well outside the range of validity of the theory[7]; disagreement with the results by Haddock et al. and Baumgartner et al. is by about two probable errors. The result for the higher energy range, however, is in agreement with the latter determinations and also with charge-symmetry predictions (−16.9 to 16.6 F[1]) within experimental error. Uncertainties in the effective range approximation may also produce a further unknown error of ~1 F.[7]

Fits for positive values of a_{nn} were also attempted. In this use a monoenergetic line, separated from the continuous spectrum by the binding energy of the hypothetical dineutron, would also be present. The expected intensity of the monoenergetic component was calculated from an expression due to McVoy[6] using Hulthén-type wave functions for both deuteron and dineutron.

It was found that a fit for positive a_{nn} was not possible, although fits could be obtained with the monoenergetic component excluded. The proba-

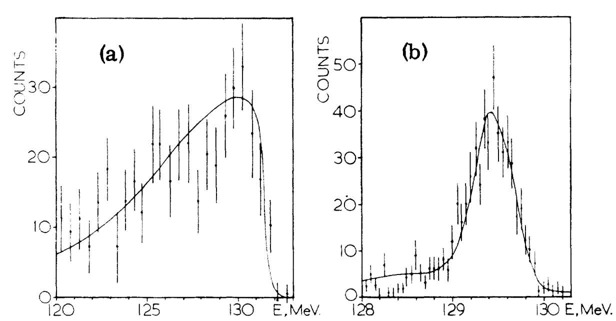

FIG. 2. (a) γ-photon spectrum from the reaction $\pi^- + d \to 2n + \gamma$ in units of counts per 0.5-MeV interval. The smooth curve is the folded theoretical spectrum for $a_{nn} = -9.0$ F, the best fit over the region $E = 120$-131.5 MeV. (b) Spectrum from the reaction $\pi^- + p \to n + \gamma$ in units of counts per 0.05-MeV interval. The fitted curve is a modified Gaussian function and is the resolution function used in the folding procedure. The rms deviation of the resolution function is ~300 keV.

Table I. Measurements of a_{nn}.

Reference	a_{nn} (F)	Probable error (F)	Standard deviation (F)
Phillips and Crowe[a]	−15.9	+7.4, −∞	
Cerineo et al.[b]	−21.7		±2
Ryan[c] (E = 120-131.5 MeV)	−15.2	+2.6, −3.6	
(E = 122-131.5 MeV)	−18.8	+3.6, −5.9	
(E = 124-131.5 MeV)	−18.8	+4.0, −6.8	
(E = 126-131.5 MeV)	−16.9	+4.4, −7.8	
Sloan[d]	−12		±5
Haddock et al.[e]	−16.4		±1.9
Baumgartner et al.[f]	−16.1		±1.0
Present work (E = 120-131.5 MeV)	−11.2	+1.9, −2.6	
(E = 125-131.5 MeV)	−13.1	+2.4, −3.4	

[a]R. Phillips and K. Crowe, Phys. Rev. 96, 484 (1954).
[b]Ref. 3.
[c]Ref. 10.
[d]Ref. 9.
[e]Ref. 8.
[f]Ref. 5.

bility that the poor fit was due to statistical chance alone was calculated from the χ^2 values to be less than 5×10^{-9}. Modification of the values of β (the Hulthén wave-function core parameter) for both bound wave functions by up to 50% failed to make the fit significantly more probable. On the basis of this experiment alone therefore the existence of a bound state of two neutrons seems highly unlikely and the sign of a_{nn} is negative. This conclusion also seems to be supported by other work.[10,14,15,16]

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