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n-n Scattering Length from the Photon Spectra of the Reactions $\pi^- d \rightarrow \gamma nn$ and $\pi^- p \rightarrow \gamma n$

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A high-statistics photon spectrum from the reaction $\pi^- d \rightarrow \gamma nn$, measured with a 0.72-meV–resolution pair spectrometer is compared with different theoretical spectra folded with the measured photon line from the reaction $\pi^- p \rightarrow \gamma n$. A value of $a_{nn} = -18.5 \pm 0.5$ fm (theoretical error included) is deduced assuming a fixed value of $r_{nn} = 2.8 \pm 0.1$ fm. The problem of extracting r_{nn} using the present theories is indicated.

The current value of the singlet $^1S_0$ scattering length a_{nn}, based on an average of selected experiments,[1] is -16.6 ± 0.6 fm. This is smaller in absolute value than a_{pp}(nuclear) $= -17.1 \pm 0.2$ fm deduced from low-energy p-p scattering after correction for the direct electromagnetic effects. However, a charge-symmetry breaking due to isospin mixing in the exchange of vector mesons (ρ-ω mixing) indicates[2] an absolute value of a_{nn} 0.9 fm larger than $|a_{pp}|$. This discrepancy could be explained by the model-dependent corrections of the direct electromagnetic effects[3] or an underestimate of the theoretical error in extracting a_{nn}. A remeasurement of a_{nn} with higher experimental accuracy using a reliable theory seems therefore necessary to clarify the situation.

$\pi^- d \rightarrow \gamma nn$ is one of the most suitable reactions to study the n-n final-state interaction because it involves no other hadron in the final state. The photon energy is uniquely related to the n-n relative momentum p. To be sensitive mainly to the scattering length and to minimize the theoretical uncertainties, a measurement should be restricted to $p < 35$ MeV$/c$; i.e., to photons with energies within the last MeV of the spectrum, which ends at 131.458 MeV. Thus, the spectrometer resolution is important. The limitation on p can be much more easily achieved by detecting the two neutrons. An experiment of this type by Salter *et al.*[4] yielded $a_{nn} = -16.7 \pm 1.3$ fm, not including the theoretical uncertainty of ~ 1 fm evaluated by Bander[5] for the extraction of a_{nn} with his theory. However, precision experiments with neutrons in the few-MeV energy range are notoriously difficult, which makes the simpler photon spectroscopy attractive.

Two recent calculations[6,7] demonstrate the possibility of extracting a_{nn} to an accuracy of 0.3 fm if $p < 35$ MeV$/c$. If this accuracy is to be reached in an experiment detecting only photons, a major difficulty arises. Since not only the shape of the photon spectrum but also the peak position is sensitive to a_{nn}, an energy calibration better than 3 keV at 130 MeV is needed to obtain a_{nn} with a similar experimental error. This difficulty, however, can be overcome if the 129.406-MeV calibration line from the $\pi^- p \rightarrow \gamma n$ reaction and the $\pi^- p \rightarrow \gamma nn$ spectrum are measured alternately. The position of the line may be defined to within 1 keV with 100 000 events and the 720-keV full width at half maximum resolution of our spectrometer. Since this calibration line also provides the response function, with which the theoretical spectrum has to be folded, the only critical requirement is a stable performance of the spectrometer during the measurement of the deuterium and hydrogen spectra.

The Schweizerisches Institut für Nuklearforschung $\pi E1$ pion beam is stopped in a 60-mm-diam 80-mm-long Mylar cell which can be filled alternatively with liquid hydrogen or deuterium. Photons are detected with a pair spectrometer, described elsewhere.[8] To fulfill the stability requirement, the magnetic field at a reference point is measured within 5 μT whenever a photon is detected. In addition the pressure and the temperature, which affect the density of the multiwire-proportional-chamber (MWPC) gas and hence the e^+e^- energy losses, are monitored throughout the experiment. The photon energy is corrected accordingly. During a four-day run, 428 000 photons from radiative capture in deuterium and 129 000 from radiative capture in hydrogen were registered. The upper part of the two spectra are displayed in Fig. 1 after background subtraction. The only background above 125 MeV comes from the hydrogen content in the deuterium and the Mylar container. A small fraction of the measured H spectrum is subtracted from the D spectrum. This fraction is deduced from the charge-exchange photons from hydrogen ($\pi^- p \to \pi^0 n, \pi^0 \to \gamma\gamma$), observed between 55 and 83 MeV in the deuterium spectrum. In-flight capture is negligible.

For the analysis we used three calculations (Fig. 2). All are based on the impulse approximation, which is acceptable since the resulting error on a_{nn} has been estimated[9] to be 0.04 fm. The transition operator is limited to the $\vec{\sigma}\cdot\vec{\epsilon}$ term, and equivalent descriptions of the deuteron with 7% D state are used. Bander[5] and de Têramond[7] treat the final-state interaction by a dispersion relation method. Bander's spectrum corresponds to the first-order solution without higher partial waves, which limits its validity to $p < 25$ MeV/c. De Têramond gives an exact solution of the dispersion relation and includes unshifted higher partial waves. Gibbs, Gibson, and Stephenson[6] use a phenomenological wave function for the n-n final state and a distorted pion wave function to describe the pion rescattering from the neutron.

When Bander's and de Têramond's spectra are compared for $p < 25$ MeV/c (Fig. 2), the former yields an a_{nn} absolute value larger by 0.3 fm. The results of the complete experiment of Salter *et al.*[4] obtained with Bander's theory would probably yield a value around -16.4 fm if analyzed with more recent models.

The uncertainties have been evaluated from modified theoretical photon spectra folded with the spectrometer response. The effect of each parameter on the error (for example, the percentage of deuteron D state) has been evaluated by allowing this parameter to vary and recording the value of a_{nn} resulting from a fit to the modified spectrum. The statistical error of the comparison is deduced from the width of the χ^2 curve.

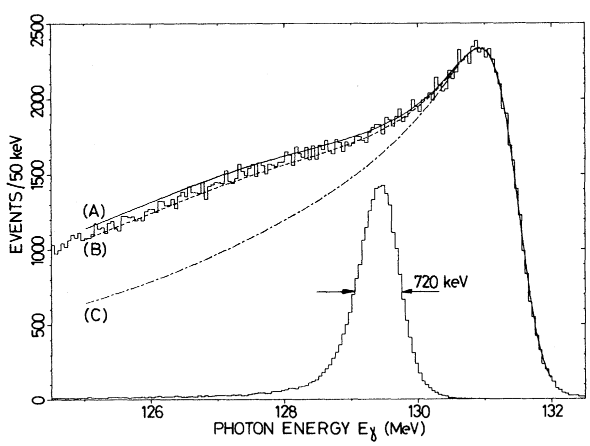

FIG. 1. Photon spectra from pion capture on H and D. Folded theoretical spectra from curve A, de Têramond; curve B, Gibbs, Gibson, and Stephenson; and curve C, Bander for $a_{nn} = -18.5$ fm and $r_{nn} = 2.8$ fm. The spectra are normalized to the number of events between 130.5 and 132 MeV.

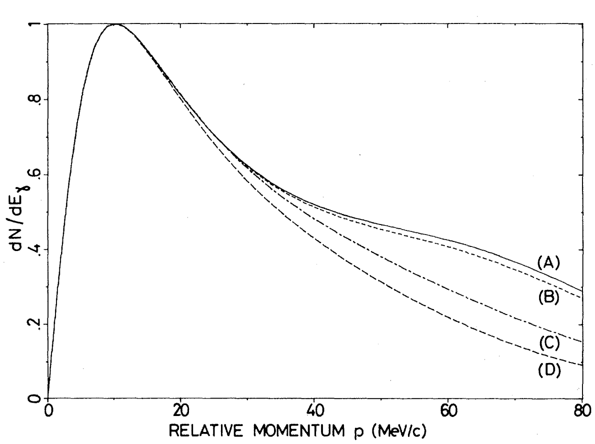

FIG. 2. Photon energy spectra as a function of the n-n relative momentum p. Curve A, de Têramond; curve B, Gibbs, Gibson, and Stephenson; curve C, Bander; and curve D, de Têramond, S wave only. All curves are calculated with $r_{nn} = 2.8$ fm and $a_{nn} = -18.0$ fm, except Bander's where $a_{nn} = -18.3$ fm.

The contributions to the theoretical or experimental error vary with the energy range of the comparison. Typical values, calculated for a fit between 130 and 132 MeV with r_{nn} fixed are given in Table I.

The spectrometer acceptance is known to be constant within 0.2% per MeV in the region of interest. The uncertainty in the mass and the atomic binding energy of the pion have almost the same effect on the theoretical energy position of the H and D spectra and cancel out. The remaining experimental errors can be associated with an uncertainty in the relative energy position of the folded theoretical spectrum and the measured one. A 10-keV relative shift would result in a difference of 1 fm in a_{nn} in the range 130 to 132 MeV. As already mentioned, the statistical accuracy of the position of the H line is 1 keV. The linearity of the spectrometer has been verified within 0.05% from the positions of the H line and the high-energy edge of the charge-exchange photon spectrum. Finally a 2.1-keV energy stability of the spectrometer has been evaluated from three contributions: 5 μT uncertainty in the monitored magnetic field, 1% uncertainty in the measured MWPC gas density and a 5% fluctuation of the isobutane to argon concentration in the MWPC gas.

As a check of the spectrometer stability we fitted a_{nn} using all D data and different sections of the H data. The 0.22-fm dispersion of the a_{nn} values thus obtained agrees with the calculated stability of the spectrometer.

TABLE I. Uncertainties in a_{nn} extracted from the folded photon spectrum between 130 and 132 MeV, r_{nn} being fixed.

	Ref. 7 (fm)	Ref. 6 (fm)
Final-state interaction	0.10	0.25
Pion rescattering	0.25	0.10
Transition operator	0.07	0.07
Deuteron D state (±2%)	0.05	0.08
Effective range (±0.1 fm)	0.12	0.06
Theoretical uncertainty	0.30	0.30
Background subtraction (±80 events)		0.01
Relative acceptance (±0.2%/MeV)		0.08
Energy calibration (±1 keV)		0.10
Spectrometer linearity (±0.05%)		0.10
Spectrometer stability (±2.1 keV)		0.21
Statistical uncertainty		0.34
Experimental uncertainty		0.43

Figure 3 shows the results of the fit as a function of the lower limit of the energy range. For this, r_{nn} was fixed at 2.8 fm as deduced from r_{pp}. The expected charge-symmetry-breaking effects should not modify the effective range[2,3] by more than 0.1 fm. The most reliable value of a_{nn}, -18.5 fm, is derived from the fits of the spectrum with a lower energy limit around 130 MeV. When one raises this energy limit, the statistical error and the effect of the energy calibration and stability rapidly increase, whereas for a more extended energy range the theoretical uncertainties and the sensitivity to r_{nn} become larger. The relative stability of the results reflects the capability of the two most recent theories to reproduce the shape of the spectrum over a large range. (The χ^2 per degree of freedom stays around 0.9.)

Nevertheless the effects of approximations in the different theories manifest themselves clearly at large relative momenta (Figs. 1 and 3). The fast decrease of $|a_{nn}|$ in Bander's theory arises from neglecting higher partial waves. It explains why our preliminary value[10] obtained with Bander's theory and a resolution of 910 keV was $a_{nn} = -17.5$ fm.

When r_{nn} is fixed at 3.05 fm in Gibbs, Gibson, and Stephenson's and 2.68 fm in de Téramond's theory, a very stable value (-18.5 fm) for a_{nn} is obtained with both theories, independent of the relative momentum range. In this case the ex-

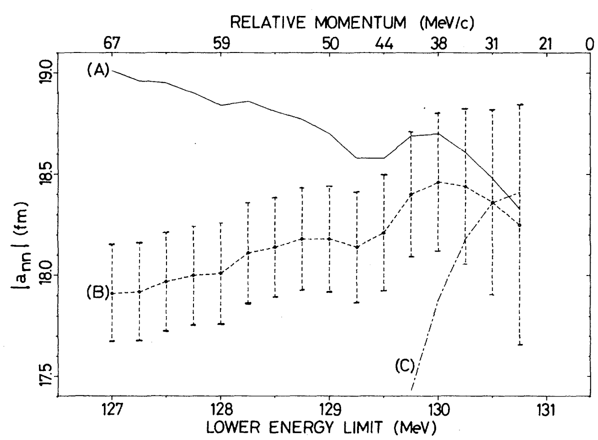

FIG. 3. Extracted values of a_{nn} with $r_{nn} = 2.8$ fm for fits of the D spectrum between the lower limit given in abscissa and 132 MeV. Corresponding mean n-n momenta are also indicated. Curve A, de Téramond; curve B, Gibbs, Gibson, and Stephenson; curve C, Bander. The statistical errors of the fits, which are not independent, are plotted for curve B.

perimental spectrum is extremely and indistinguishably well reproduced by both theories. In fact, for photon energies above 123 MeV, the χ^2 per degree of freedom is 0.86. Apparently, adjusting r_{nn} can compensate for deficiencies of both theories over a wide relative momentum range.

Our final value for a_{nn} is -18.5 ± 0.5 fm, including the theoretical uncertainty. This result is 4 standard deviations lower than the average of previous experiments,[1] but is in agreement with the value derived from a_{pp}. The binding-energy difference for the $A=3$ mirror nuclei[2] also indicates $|a_{nn}|>|a_{pp}|$. Improved theories would permit us to fully exploit the potential accuracy of this experiment, and in particular to determine r_{nn} to ± 0.08 fm by fitting the spectrum over a range of n-n momenta up to 80 MeV/c.

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Search for Axion Production in Low-Energy Electron Bremsstrahlung

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We present results of an experiment to detect axions produced by bremsstrahlung of 45-MeV electrons. No signal is found. We interpret our upper limits in terms of two models.

The instanton solution of quantum chromodynamics violates P and T invariance.[1] These effects may be avoided by having one of the quark masses equal zero, at the cost of disagreement with current-algebra quark-mass estimates.[2] Peccei and Quinn show[3] that imposing a chiral U(1) symmetry on the Lagrangian will restore P and T invariance. If one identifies this symmetry with a new Higgs doublet in a unified theory of weak and electromagnetic interactions, the spontaneous breaking of this symmetry then leads to the appearance of a light pseudoscalar particle, the axion[4,5] or Higglet.[6]

Several authors[4,7,8] have analyzed different experiments to search for axions. However, other authors[8-10] point out that many of these analyses depend on uncertain theoretical assumptions. Bardeen, Tye, and Vermaseren point out[9] that the calculation of axion production in electron bremsstrahlung, and the subsequent decay of axions into either $\gamma\gamma$ or e^+e^-, is free of such theoretical uncertainties. We have performed this experiment.

Figure 1 is a drawing of the experimental layout. Our target, 11.8 g/cm^2 of tantalum, was exposed, during the live time, to 8.5 C of 45.3-MeV electrons produced by the linac at the Armed Forces Radiobiology Research Institute, Bethesda, Md. The target was followed by a 100-radiation-length lead brick wall, and, about 7 m down-

