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-

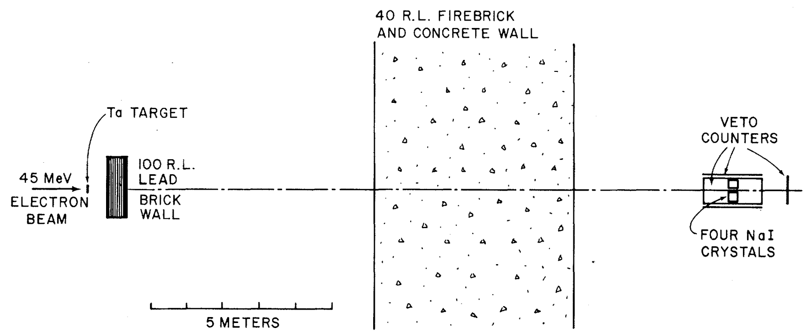

FIG. 1. Layout of the experiment.

stream, by a 40-radiation-length firebrick and concrete wall. The 140 radiation lengths were necessary to reduce the ordinary bremsstrahlung radiation seen by our detector. The concrete wall was followed by a 4.4-m drift space in which axions might decay, and then by the detector.

The detector consisted of four large NaI crystals, averaging 22.5 cm in diameter and 25 cm in length, aligned with their axes parallel to the beam line. The crystal centers were located at the corners of a rectangle 25 cm across and 36 cm high, with the center of the rectangle 46 cm above the beam line. The crystal array was covered, above, below, on both sides, and behind, but not in front, by 160-cm$\times$69-cm plastic scintillation counters used to veto cosmic rays. This was further surrounded on both sides and above and below by at least 2.5 radiation lengths of lead or of steel-loaded concrete to reduce the ambient room radiation level at the crystals from 10 to 0.2 mrem (the room in which our detector was situated is the exposure room of a nuclear reactor).

We calibrated the crystals with ^{60}Co sources before and after the experiment. During the experiment we used the 1.8-MeV γ from ^{26}Al and the 0.511-MeV annihilation γ, both of which originated in the walls of the detector room, to check for drifts in pulse height.

The electron beam was pulsed at 60 cps in 5-μsec-long, 0.36-A pulses. Our electronics was gated on during these 5-μsec pulses. Our electronics was also gated on for a 20-μsec interval between the beam pulses in order to study the cosmic-ray and room-radiation backgrounds at 4 times the statistics of the beam-time data. A high-low triggering scheme was used to prevent time slewing and resultant distortion of our energy scale. A trigger was generated whenever 4 MeV or more was deposited anywhere within the NaI crystals during the two gates described above, and was not vetoed by any of the scintillation counters. The pulses from each crystal were integrated in fast analog-to-digital converters. The output of the crystals 3.5 μsec after a trigger was also integrated and digitized to determine whether there was a steady low-energy background which might statistically pile up above threshold to give us triggers. No such background was found.

Figure 2 shows the energy spectra of the events during the in-time (beam time) and out-of-time gates. The events below 10 MeV are due to the room radioactivity, while the peak at about 30 MeV is due to electrons from the decay of cosmic-ray muons which stop within our detector and decay after the end of the cosmic-ray veto gate. This veto gate was 5 μsec long if a veto pulse was coincident with above-threshold energy deposited within the crystals, or 160 nsec long if a veto counter gave a noncoincident pulse. The Michel spectrum is distorted since high-energy showers not aimed parallel to the crystal axis would exit from the crystal and veto the event,

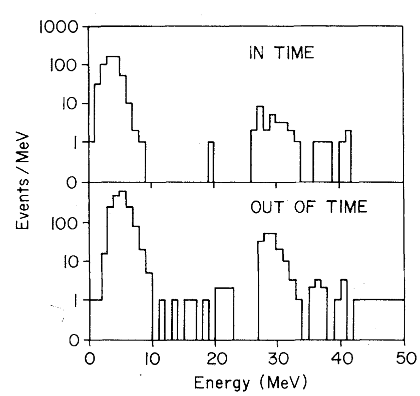

FIG. 2. In-time and out-of-time singles spectra.

or else would not leave all their energy within the crystals even if not vetoed. Eleven events are found between 10 and 25 MeV in the out-of-time spectrum and only one event is found within the same limits in the in-time spectrum. This sets a 90%-confidence-level upper limit of 2.9 events in the in-time run inside the 10- to 25-MeV energy cuts which could be due to axions.

Since we digitized the pulses in the four crystals separately, we also looked for two-crystal coincidence events. No such events were found either in the in-time or out-of-time runs where any two crystals had at least 5 MeV deposited in each with a total deposition in both crystals less than 45.3 MeV. This gives a 90%-confidence-level upper limit of 2.3 events in the coincidences which could be due to axions. The resulting limit on axion production, however, because of solid-angle considerations, is less stringent than the singles limit.

We have performed Monte Carlo studies to determine the number of axion events we should have observed. These simulations include the angular broadening and energy degradation of the electron beam in our target,[11] the angular and energy dependence of the axion production cross section,[9,12] and the self-vetoing of $a \to e^+e^-$ decay events if one of the electrons goes through a veto counter. We have carried out these calculations for the models of Bardeen, Tye, and Vermaseren[9] and for the model of Wilczek.[5] Both models begin with the same Lagrangian, and therefore have the same axion production cross section,[13] but while Wilczek uses the axion mass and X (or $\tan\lambda$), the ratio of the vacuum expectation values of the two Higgs doublets, as two separate parameters of the theory, Bardeen and Tye find that

$$M_a = 0.025N(X + 1/X)\ \mathrm{MeV}/c^2$$

with $N = 3$, the number of left-handed quark (and lepton) doublets. Their theory thus depends on only one parameter. We use $2^{1/4} G_W^{1/2} M_a / X$ as the coupling of axions to electrons. Bardeen and Tye also give[6] the mixing of axions with pions, which allows us to calculate the probability that axions interact hadronically in our detector.

Figure 3 is a graph showing our results for the Wilczek model. We rule out the shaded area at a confidence level of 90% or higher, based on the predicted axion decay rate into either e^+e^- or $\gamma\gamma$. The curve AB represents the value of X for which an axion of a given mass has a maximum lifetime.

Our results for the model of Bardeen, Tye,

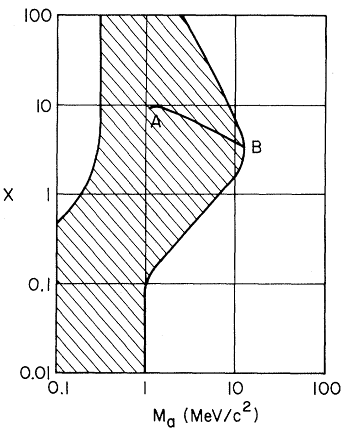

FIG. 3. Results for the Wilczek model. The shaded area is ruled out by this experiment.

and Vermaseren, based on the predicted axion decay rate, rule out two bands of X values at the 90% confidence level: $0.074 \leq X \leq 0.42$ and $9.2 \leq X \leq 70$. The values $0.42 \leq X \leq 1.2$ are additionally ruled out by pion-axion mixing if the first Higgs doublet couples to the three charge-$\frac{2}{3}$ quarks. If, however, this doublet couples to the charge-$(-\frac{1}{3})$ quarks, then the values $0.42 \leq X \leq 9.2$ are ruled out.

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Atomic Electron Correlation in the *M* Capture of ^{37}Ar

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The first experimental evidence for electron correlation in nuclear electron-capture ratios is reported. The measured M/L capture ratio of ^{37}Ar, 0.073 ± 0.007, is inconsistent with Hartree-Fock calculations, but can be explained by final-state correlation, if the disputed $3s3p^6$ assignment in Cl I is adopted. The discrepancy in the experimental $K\beta/K\alpha$ x-ray intensity ratio of Cl is removed, and the designation of L_{23} x-ray and $3s$ photoemission satellites in Cl is revised.

The inclusion of the atomic electrons in the calculation of nuclear electron-capture (EC) probabilities leads to exchange-overlap factors.[1] Recently, EC ratios were recalculated according to the independent-particle approaches of Bahcall[2] and Vatai,[3] and, for M/L ratios (P_M/P_L), fair agreement was stated between experiment and Vatai's approach, which neglects shakeup and shakeoff.[1] More recently, a first calculation that took correlations into account[4] gave an ^{37}Ar M/L ratio of 0.102 (Bahcall, 0.129; Vatai, 0.115),[1] which was in excellent agreement with experiment[5] ($0.104^{+0.006}_{-0.003}$).

This Letter reports on a new experiment which yields 0.073 ± 0.007 in strong contrast to this result. It is shown that the independent-particle model breaks down in ^{37}Ar M capture and that the measured spectra have been drastically misinterpreted. Moreover, the previous experimental value[5] turns out to be spurious, so that agreement with theory[4] can only be fortuitous. The observed correlation effect corresponds to correlation in the optical spectrum[6,7] of Cl I and in atomic processes[8-12] leading to the same final state as ^{37}Ar M capture.

Both experiments were performed with proportional counters.[5,13] The spectra are dominated by two overlapping pulse distributions, the L-capture peak and a single-electron spectrum[14] (Fig. 1). Renier *et al.*[5] identified the latter with M capture on assuming that each M event entailed the

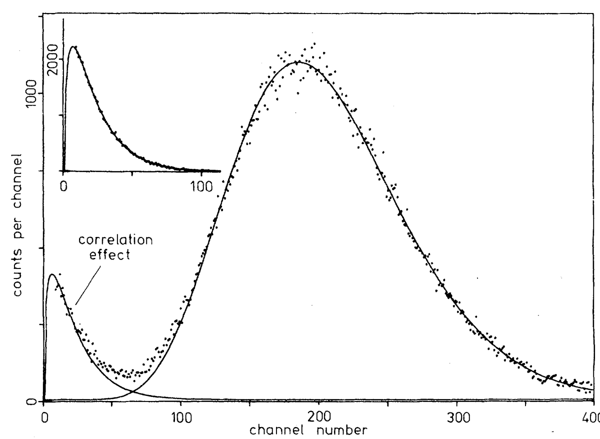

FIG. 1. M-L spectrum of ^{37}Ar (pressure: 4 bars), background subtracted. The extrapolated K degradation tail is drawn in as pedestal of the fitting curves. L degradation is not marked for clarity. The L peak is fitted by a Γ (Ref. 15), the M peak by a Polya distribution (Ref. 14); the latter was determined from a single-electron spectrum (inset) due to photoelectrons released in the counter by uv irradiation (the peaked shape was confirmed at higher sensitivity).

