Restrictions on a 1.7-MeV Axion from Nuclear Pair Transitions

A. L. Hallin, F. P. Calaprice, R. W. Dunford, and A. B. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 11 August 1986)

We analyze nuclear internal-pair-transition experiments for evidence of a possible 1.7-MeV axion and find that the conventional axion and the new axions described by the theories of Krauss and Wilczek and of Peccei, Wu, and Yanagida are inconsistent with these data. The results are independent of nuclear models.

PACS numbers: 14.80.Gt, 23.20.En

Recent experiments on superheavy-ion collisions have shown evidence of coincident positron and electron monoenergetic lines with energies of about 370 keV.[1] One possible explanation of these results is the formation and subsequent decay into an e^+e^- pair of a particle with a mass of 1.7 MeV.[2,3] A logical candidate for this object is the pseudoscalar particle called the axion.[4,5] Several searches have already been made for the axion and no evidence has been found for its existence. In particular, a 1.7-MeV axion would have produced a very large signal in experiments looking for the decay of the J/ψ or Y into an axion and a gamma ray.[2,3,6]

Mukhopadhyay and Zehnder[6] have stressed that experiments on *nuclear* systems do not rule out a 1.7-MeV axion. The interaction of the standard axion with quarks and leptons is determined by one parameter X, the ratio of the vacuum expectation values of the two Higgs fields in the theory. A conventional 1.7-MeV axion would have $X = 0.044$ and would decay to an e^+e^- pair with the lifetime of 4.5×10^{-12} s. To avoid conflict with experiments on the J/ψ and Y decays, Peccei, Wu, and Yanagida,[7] and independently Krauss and Wilczek[8] have suggested a modified axion model in which the coupling of the axion to the charm and bottom quarks is weakened while maintaining its coupling strength to the light up and down quarks and the leptons. These new theories allow axions to be produced in nuclear processes, and predict a lifetime for pair decay so short that a previous nuclear search for axions[9] emitted in the decay of the 15.1-MeV state of ^{12}C and beam dump experiments would not be sensitive.

In this note we show that a 1.7-MeV axion with the standard coupling to nucleons and electrons determined by $X = 0.044$ is in conflict with published data on nuclear internal-pair transitions. The new axion models mentioned above are also inconsistent with these data.

The emission of e^+e^- pairs in the decay of excited states of nuclei has been used extensively as a spectroscopic tool to determine the multipolarity of electromagnetic transitions.[10] One can calculate that the rate for pair emission and the rate for axion emission are both roughly 10^{-4} of the gamma rate. However, for isoscalar transitions the small magnetic dipole moment of the nucleon leads to a suppression factor of approximately 100 in electromagnetic isoscalar $M1$ transitions but does not affect the axion emission rate. For example, for a pure 3.6-MeV isoscalar $M1$ transition, the ratio of the emission rate for conventional axions to that for gammas is expected to be $\Gamma_a/\Gamma_\gamma = 0.32$ and $\Gamma_a/\Gamma_\pi \approx 500$.

We have analyzed in detail the nuclear pair experiments of Warburton and co-workers[10] for the $M1$ transitions illustrated in Fig. 1. The transitions in ^{14}N and ^{10}B are isoscalar and the one in ^6Li is isovector. The apparatus used in Ref. 10 consisted of a magnetic pair spectrometer, which was sensitive to pairs with an opening angle of less than 90°. A baffle arrangement could also be introduced to block any pairs with opening angle less than 50°. The ratio R_{120} of pairs with

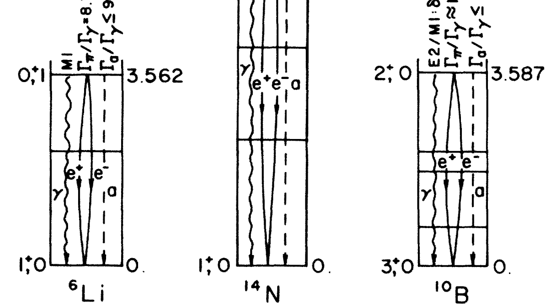

FIG. 1. The nuclear level diagrams for the transitions of interest, showing the $M1$ gamma branching ratio, the nuclear pair branching ratio, and the limits set on a 1.7-MeV axion.

the baffle in to those with the baffle out is sensitive to the multipolarity of the transition, because the angular correlation between the e^+ and the e^- depends on the multipolarity. The measured ratio has been used to establish the multipolarity of several transitions.[10] We show that it is also sensitive to pairs from axions decaying near the target and can be used to set limits on axion emission for transitions of known multipolarity.

The kinematics of axion decay, with the spectrometer constraint that the electron and positron have the same energy, leads to pairs with a well defined opening angle, which is less than 50° for all the cases we considered. Including the pairs due to axions, one finds that the baffle-in to baffle-out ratio is

$$R'_{120}=\frac{R_{120}+R_{120a}(\epsilon_a/\epsilon_\pi)(\Gamma_a/\Gamma_\pi)}{1+(\epsilon_a/\epsilon_\pi)(\Gamma_a/\Gamma_\pi)}, \qquad (1)$$

where $\epsilon_{a,\pi}$ are the axion and internal-pair spectrometer efficiencies, R_{120} is the calculated baffle in/out ratio for internal pairs, and R_{120a} is the ratio for pairs from axions alone. In the cases we have analyzed, $R_{120a}=0.0$, that is, all axion pairs are blocked by the baffle. To set a limit on Γ_a/Γ_π from the measured R'_{120} one must calculate ϵ_a/ϵ_π and R_{120}. The calculation of R_{120} depends upon the Born-approximation calculations of Rose[11] for the angular correlation between the e^+ and e^-; the error introduced by the use of the Born approximation has been shown to be less than 1%.[12] The ratio ϵ_a/ϵ_π depends on the spectrometer geometry, but is independent of the resolution and the transmission of the spectrometer. We determined this ratio both with a Monte Carlo computer program and analytically; we find a value of 0.52 for ^{10}B and ^{6}Li and 0.72 for ^{14}N.

The pure $M1$ isovector transition in ^{6}Li sets stringent limits on any isovector couplings of the axion. Since the excited state is 0^+ it cannot be spin aligned. Consequently, from the values $R_{\rm expt}=0.092\pm0.002$,[10] $R_{120}=0.091\pm0.003$,[13] and $\epsilon_a/\epsilon_\pi=0.52$, we find from (1) that $\Gamma_a/\Gamma_\pi<0.10$ (90% C.L.). We note that we have allowed for an additional 3% systematic uncertainty in the determination of R_{120} in this case, since this transition was one of eleven used to calibrate the apparatus.[13]

The transition from the ^{10}B 3.58-MeV state ($J^\pi=2^+$) to the 3^+ ground state is mixed $M1$ and $E2$. The ratio of $E2$ to $M1$ amplitudes, termed δ, is measured to be 1.5 ± 0.6.[14] This complicates the analysis because the expected ratio for R_{120} is a function of δ. In addition, if the 3.58-MeV state is aligned, the number of pairs emitted into the acceptance of the spectrometer is affected. Warburton *et al.*[10] describe in detail how to compensate for both effects. Allowing for the mixed multipolarity and spin alignment we find, for the axion to $M1$ pair-intensity ratio,

$$\frac{\Gamma_a}{\Gamma_{\pi M1}}=\left(\frac{R_{120}(\delta,F_2,F_4)}{R'_{120}}-1\right)\left(\frac{\epsilon_{\pi M1}}{\epsilon_a}\right)\left(\frac{1+(\epsilon_{E2}\Gamma_{\pi E2})/(\epsilon_{M1}\Gamma_{\pi M1})+N_{12,180}}{(1-\alpha F_2)}\right),$$

where F_2, F_4, and $N_{12,180}$ are alignment parameters described by Warburton *et al.*; $\epsilon_{\pi M1}$, $\epsilon_{\pi E2}$, and ϵ_a are the efficiencies for detecting pairs from pure $M1$, pure $E2$, and axion transitions, respectively; and α contains the effect of alignment on the axion angular distribution. For ^{10}B, $\alpha=0.11$. Since the alignment is not well known, we have done the analysis assuming the alignment parameter F_2 that minimizes the experimental sensitivity to axions. (This corresponds to $F_2=1.0$, $F_4=0.07\pm0.29$.) We have used the value $\delta=2.70$ for the $E2/M1$ mixing ratio, which is the value within the 99.9% C.L. that minimizes the sensitivity. The resulting upper limit for axion emission is $\Gamma_a/\Gamma_{\pi M1}<10.8$, at 90% confidence.

A second isoscalar transition, that of the transition in ^{14}N from the 2^+ 7.03-MeV excited state to the 1^+ ground state, was also analyzed. The measured value of δ is 0.74 ± 0.09[15]; we used $\delta=1.02$ (99.9% C.L.). F_2 and F_4 were again taken to minimize the sensitivity to axions. We find that $\Gamma_a/\Gamma_{\pi M1}<2.2$ (90% C.L.).

A comparison of the experimental limits for Γ_a/Γ_π and the predictions of the conventional axion theory and the new theories of Krauss and Wilczek[8] and of Peccei, Wu, and Yanagida[7] is given in Table I. For the conventional axion we use the current given by Donnelly *et al.*[16]:

$$J_\mu^{\rm eff}=-\tfrac{1}{2}(N-1)(\chi+1/\chi)A_\mu^s+\{\tfrac{1}{2}\chi[1-N(1-Z)/(1+Z)]-(2\chi)^{-1}[1+N(1-Z)/(1+Z)]\}A_\mu^3,$$

where A_μ^s and A_μ^3 are the isoscalar and isovector currents, respectively. N is the number of quark families, and Z is the ratio of the up and down quark masses. For Peccei-Wu-Yanagida models I and III, these formulas are directly applicable with the modification that $N=1$ and 2, respectively. In the case of model II, we find from the procedure of Bardeen and Tye[17] that

$$J_\mu^{\rm eff}=-\tfrac{1}{2}(\chi+1/\chi)A_\mu^s-\tfrac{1}{2}\{\chi(1-Z)/(1+Z)+\chi^{-1}(3+Z)/(1+Z)\}A_\mu^3.$$

The current in the case of Krauss and Wilczek is the same as in Peccei's model I. The only free parameter in any of these models is χ, which can be fixed by setting the axion mass equal to 1.7 MeV in the appropriate mass for-

TABLE I. The expected branching ratios from several theories and the experimental limits on the axion branch for the ^{10}B and ^{14}N isoscalar and the ^{6}Li isovector decays.

Theory	Isovector $\Gamma_a/\Gamma_{\pi M1}$ ^{6}Li	Isoscalar $\Gamma_a/\Gamma_{\pi M1}$ ^{10}B	^{14}N
Conventional ($\chi=0.044$)	5.3	470	310
Krauss and Wilczek[a] ($\chi=68$)	7.2	0	0
Peccei, Wu, and Yanagida[b]			
I ($\chi=68$)	7.2	0	0
II ($\chi=68$)	1.1	1000	680
III ($\chi=34$)	0.66	260	170
Experiment (90% C.L.)	≤ 0.104	≤ 10.8	≤ 2.2

[a]Reference 8. [b]Reference 7.

mula.

For the case of isoscalar decays, we can now determine the expected axion branch using the techniques outlined in Donnelly *et al.*[16] It should be stressed that in the case of isoscalar transitions, the axion and $M1$-gamma transition rates are both proportional to the square of the matrix element of the nucleon spin operator so that the ratio of the rates of axion emission to gamma (or internal pair) emission is independent of nuclear matrix elements. However, one must use the quark-model[18] estimate that $F_A^0=0.6F_A^1$.

For axion emission in the ^{6}Li case, we have used the results of Treiman and Wilczek[19] which give a relationship between the axion emission rate and the measured rate for the analog beta-decay process. This procedure removes all nuclear-wave-function and nucleon strong-interaction uncertainties.

We find that all the above axion theories predict axion intensities that are more than a factor of 50 greater than the 90%-confidence upper limits derived from the data of Warburton *et al.* The theories are therefore inconsistent with these data.

The theories under consideration all predict lifetimes less than 3×10^{-12} s. The limits we have set are valid for all lifetimes less than 2×10^{-11} s. This lifetime is determined by the geometric acceptance of the magnetic spectrometer, which constrains axions to decay within 5 mm of the target. For longer lifetimes, the limits are less stringent, since only a fraction of the axions would decay within the accepted region.

Our measurements of angular distributions of nuclear pairs can also set limits on the axion. In particular, the measurement of Gorodetzky *et al.*[20] on the first excited state in ^{11}B is more sensitive to axions than the Warburton data, although one cannot remove nuclear-model uncertainties. The recent measurement of Savage, McKeown, Filippone, and Mitchell[21] on an isovector transition in ^{14}N, although less sensitive and more dependent on nuclear models, is also incompatible with all the axion theories. A recent analysis[22] of the SINDRUM $\pi^+\rightarrow e^+e^-e^+\nu$ data looking for $\pi^+\rightarrow e^+\nu a$ sets very sensitive limits on possible axions.

The reason that we are able to exclude the above theories is that they enhance nuclear deexcitation by axion emission with either a very large or a very small χ parameter, the size of the χ parameter being fixed in all the models by the mass of the axion. Though not allowed in the above models, we note that if 1.7-MeV particles were emitted at a rate typical of the weak interaction ($\chi\approx1$) there would be a reduction of the expected branch by 3–4 orders of magnitude. Such particles would not be ruled out by present nuclear experiments.

We would like to thank Ian Affleck for help with the calculations, and S. B. Treiman and J. Harvey for discussions during this analysis. This work was supported by the National Science Foundation.

[1]T. Cowan, H. Backe, K. Bethge, H. Bokemeyer, H. Folger, J. S. Greenberg, K. Sakaguchi, D. Schwalm, J. Schweppe, K. E. Stiebing, and P. Vincent, Phys. Rev. Lett. **56**, 444 (1986).

[2]A. B. Balantekin, C. Bottcher, M. R. Strayer, and S. J. Lee, Phys. Rev. Lett. **55**, 461 (1985).

[3]A. Schafer, J. Reinhardt, B. Muller, W. Greiner, and G. Soff, J. Phys. **11**, L69 (1985).

[4]S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[5]F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[6]N. Mukhopadhyay and A. Zehnder, Phys. Rev. Lett. **56**, 206 (1986).

[7]R. D. Peccei, Tai Tsun Wu, and T. Yanagida, Phys. Lett. **172B**, 435 (1986).

[8]L. M. Krauss and F. Wilczek, Phys. Lett. **173B**, 189 (1986).

[9]F. P. Calaprice, R. W. Dunford, R. T. Kouzes, M. Miller, A. Hallin, M. Schneider, and D. Schreiber, Phys. Rev. D **20**, 2708 (1979).

[10]E. K. Warburton and D. E. Alburger, *Nuclear-Spin Parity Assignments* (Academic, New York, 1966), p. 114. Also E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **132**, 776 (1963); E. K. Warburton, D. E. Alburger, A. Gallmann, P. Wagner, and L. F. Chase, Jr., Phys.

Rev. **133**, B42 (1964).
[11]M. E. Rose, Phys. Rev. **76**, 678 (1949).
[12]G. K. Horton and E. Phibbs, Phys. Rev **96**, 1066 (1954).
[13]E. K. Warburton, private communication.
[14]E. K. Warburton, J. W. Olness, S. D. Bloom, and A. R. Poletti, Phys. Rev. **171**, 1178 (1968).
[15]F. Ajzenberg Selove, Nucl. Phys. **A449**, 1 (1986).
[16]T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz, Phys. Rev. D **18**, 1607 (1978).
[17]W. Bardeen and H. Tye, Phys. Lett. **74B**, 229 (1978).
[18]S. L. Adler, E. W. Colglazier, Jr., J. B. Healy, I. Karliner, J. Lieberman, Y. J. Ng, and H. Tsao, Phys. Rev. D **11**, 3309 (1975).
[19]S. B. Treiman and F. Wilczek, Phys. Lett. **74B**, 381 (1978).
[20]S. Gorodetzky, F. Scheibling, P. Chevallier, P. Mennrath, and G. Sutter, Phys. Lett. **1**, 24 (1962).
[21]M. J. Savage, R. D. McKeown, B. W. Filippone, and L. W. Mitchell, Phys. Rev. Lett. **57**, 178 (1986).
[22]R. Eichler, L. Felawka, N. Krams, C. Niebuhr, H. K. Walter, S. Egli, R. Engfer, Ch. Grab, E. A. Hermes, H. S. Pruys, A. Van der Schaaf, D. Vermeulen, W. Bertl, N. Lordong, U. Bellgardt, G. Otter, T. Kozlowski, and J. Martino, Phys. Lett. **175B**, 101 (1986).