Search for the Production of Pionium Atoms near Threshold

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We propose a model-independent method to extract a linear combination of the s-wave π-π scattering lengths by measuring the $\gamma\gamma$ decay branching ratio for a tagged sample of $\pi^+\pi^-$ atoms (pionium). In the first experimental search for an appropriate tagging reaction, we observed $\sigma_{\text{tot}} = 76 \pm 21 \pm 11$ pb for *free* pion pair production in $pd \to {}^3\text{He}\,\pi^+\pi^-$ 1.0 MeV above threshold. This result suggests a pionium production cross section $\lesssim 1$ pb.   [S0031-9007(96)01416-0]

"Pionium," an atom formed from a positive and a negative pion, would provide a unique laboratory for study of the low-energy strong interaction between two pions. This interaction is a fundamental process in QCD, where pions play a special role as Goldstone bosons associated with the spontaneous breaking of chiral symmetry. If this were a perfect symmetry of the Lagrangian, the s-wave π-π scattering lengths—$a_0^{I=0}$ and $a_0^{I=2}$ for the two possible isospin (I) channels—would vanish [1,2]. Their deviations from zero thus measure the extent of chiral symmetry breaking (ChSB) introduced by nonvanishing quark masses; they are predictable in lattice QCD [3] or models of nonperturbative QCD [4]. In the context of chiral perturbation theory [5], the values of $a_0^{0,2}$ also bear on the mode of spontaneous symmetry breaking [2].

Unfortunately, a_0^0 and a_0^2 are difficult to measure precisely. Past determinations were based on data for the suppressed decay mode $K^+ \to \pi^+\pi^- e^+\nu_e$ [6], or for $\pi N \to \pi\pi N$ reactions in peripheral [7] or near-threshold [8] kinematics. The former method is insensitive to a_0^2, and has provided limited statistical precision ($\sim \pm 20\%$) on a_0^0. The pion production results are subject to serious model dependence; e.g., the parametrization of ChSB in standard soft-pion analyses is incompatible with QCD [9]. Existing scattering length measurements are thus of insufficient quality to distinguish clearly among competing approaches to nonperturbative QCD [10].

An experiment to study the formation and decay of pionium to provide an alternative, less model-dependent, determination of $|a_0^0 - a_0^2|$ was first suggested by Nemenov [11] and later pursued at Serpukhov. This work led to the first reported evidence for pionium [12] and to a proposal for improved high-energy experiments at CERN [13]. In the present Letter, we suggest a complementary approach, with distinct theoretical advantages for determining $|a_0^0 - a_0^2|$ from pionium decay. We then report the first search for pionium production under experimental conditions appropriate to our proposed technique.

The gross properties of pionium wave functions are dominated by the Coulomb interaction [14]: the predicted binding energy is 1.9 keV and the Bohr radius is 387 fm. The s states are $I = 0 - I = 2$ mixtures, which decay primarily by the strong interaction to $2\pi^0$, with a transition rate expressible in terms of a_0^0 and a_0^2 [14],

$$W(2\pi^0) = \frac{8\pi}{9}\left(\frac{2\Delta m}{\mu_\pi}\right)^{1/2}\frac{(a_0^0 - a_0^2)^2|\Psi_{ns}(0)|^2}{1 + \frac{2}{9}\mu_\pi\Delta m(a_0^0 + 2a_0^2)^2}$$
$$\simeq 1.43(a_0^0 - a_0^2)^2|\Psi_{ns}(0)|^2, \qquad (1)$$

where μ_π is the reduced mass, Δm the decay Q value, and $\Psi_{ns}(0)$ the atomic wave function at zero separation for the s state of quantum number n. Equation (1) suggests a ground-state lifetime $\tau \gtrsim$ few $\times 10^{-15}$ s. The most competitive electromagnetic decay is to 2γ, with

$$W(2\gamma) = \frac{2\pi\alpha^2}{m_{\pi^\pm}^2}|\Psi_{ns}(0)|^2, \qquad (2)$$

where α is the fine structure constant and $m_{\pi^\pm}$ the charged-pion mass [15]. The *relative* branching ratio $W(2\gamma)/W(2\pi^0)$ is proportional to $(a_0^0 - a_0^2)^{-2}$, and is independent of n and of possible strong-interaction corrections to $\Psi_{ns}(0)$. Moreover, this same ratio characterizes the decay of *all* atomic states, in the sense that $\ell > 0$ states deexcite (with $\tau \sim 10^{-11}$ s) almost entirely by x-ray emission, leading eventually to an ns level. In particular, odd-ℓ states cannot decay directly to $2\pi^0$ (boson symmetry) or 2γ (charge conjugation), while the centrifugal barrier causes $\Psi_{n\ell}(0) \to 0$ for all $\ell > 0$.

These observations lead to our proposal: a model-independent determination of $|a_0^0 - a_0^2|$ can be made by measuring $W(2\gamma)/W(2\pi^0)$ for pionium produced in any combination of bound or low-lying continuum states. The expected value of the ratio is $\sim 5 \times 10^{-3}$. It is not strictly necessary to detect the $2\pi^0(\to 4\gamma)$ decay for this purpose. If the atoms are produced in a target of low electron density, and their production "tagged" by

detecting an associated recoil particle, then the observed tagging rate essentially determines the $2\pi^0$ rate, since the $2\pi^0$ branching ratio must be $\gtrsim 99\%$ for bound states. (For this argument to be extended to the continuum, the tag must include an efficient veto of events containing charged pions.) The restriction to low target electron density minimizes the role of collision-induced breakup of pionium, and so guarantees that its natural decay dominates. This makes the proposed technique orthogonal to that used in high-energy experiments [12,13], which *rely* on collision-induced breakup, inferring the formation of pionium from an excess yield of $\pi^+ \pi^-$ pairs at very low relative momenta. Extraction of $|a_0^0 - a_0^2|$ from the latter data [16] depends critically on atomic collision calculations and neglects possible strong-interaction corrections to the pionium wave functions [17].

For pionium produced with relativistic $\beta\gamma \lesssim 1$, the mean free path for electronic collisions far exceeds the natural decay length in a target with electron density below 10^{19} cm^{-3}. Despite this low density, one must produce pionium at a rate $\gtrsim 1000$/day, in order to determine the $\gamma\gamma$ decay branch to $\pm 10\%$, and hence $|a_0^0 - a_0^2|$ to $\pm 5\%$. The need for high luminosity with a very thin target makes this technique well suited to a storage ring with internal targets. We have utilized the stored, electron-cooled proton beam in the Indiana University Cyclotron Facility's Cooler ring [18] to carry out the first experimental search for tagged pionium production, to assess the feasibility of a decay experiment. The production reaction studied was $pd \rightarrow {}^3\text{He}\pi^+\pi^-$ at bombarding energies very near the 430.5 MeV threshold. A luminosity $\sim 1 \times 10^{31}$ cm^{-2} s^{-1} was attained with 2×10^9 stored protons bombarding a pure D$_2$ gas jet target of thickness 3×10^{15} atoms/cm^2. ^{3}He ejectiles were detected near 0° to tag $\pi^+\pi^-$ production. The system was calibrated by studying *single* π^0 production in $pd \rightarrow {}^3\text{He}\pi^0$ within 1 MeV of its threshold, where the total cross section is known [19] to be sizable (~ 1 μb).

The near-threshold kinematics and the experimental environment offer several advantages: (1) both the ^{3}He recoils and the $\pi^\pm$ from *free* pair production are confined to far forward laboratory angles, facilitating their detection with nearly 100% acceptance to provide a tag and a veto, respectively, for pionium; (2) an appreciable fraction of the phase space corresponds to π^+-π^- relative momenta where the Coulomb final-state interaction may enhance pionium formation; (3) the cooled beam and thin target allow sufficient ^{3}He energy and angle resolution to suppress three-body (e.g., ^{3}He $\pi^0\pi^0$) background substantially; (4) the purity of the windowless D$_2$ target severely limits other ^{3}He background sources. On the other hand, the small *total* reaction phase space so close to threshold and the large momentum transfer to the ^{3}He both act to reduce the pionium yield.

The experiment layout is shown in Fig. 1. The target was mounted just upstream of a dipole magnet that bent the stored proton beam by 6° and the ^{3}He ejectiles by 13.2°. The ^{3}He were analyzed in a 5.6 m long magnetic channel, with detectors at the entrance (a small drift chamber and a thin plastic scintillator S1) and exit (a position-sensitive silicon detector PSD, a second plastic scintillator S2, and a stopping intrinsic germanium detector). The total angular acceptance of the channel was 1.8° vertically and 4.0° horizontally. The trigger was a threefold coincidence among S1, S2, and PSD.

Five plastic scintillators were arrayed around the entrance and to either side of the 6° dipole, to detect low-energy charged pions (typically bent by $\sim 100°$) or their daughter muons. Signals from these scintillators were used in software either as a logical veto, in search of a pionium signal, or as a coincidence requirement to tag *free* pion pair production. At 431.5 MeV, the overall probability to detect at least one of a charged-pion pair was $(74 \pm 10)\%$, as determined from Monte Carlo simulations and experimental calibrations. The calibrations compared simulated to measured ratios of threefold ^{3}He$\pi^+\pi^-$ to
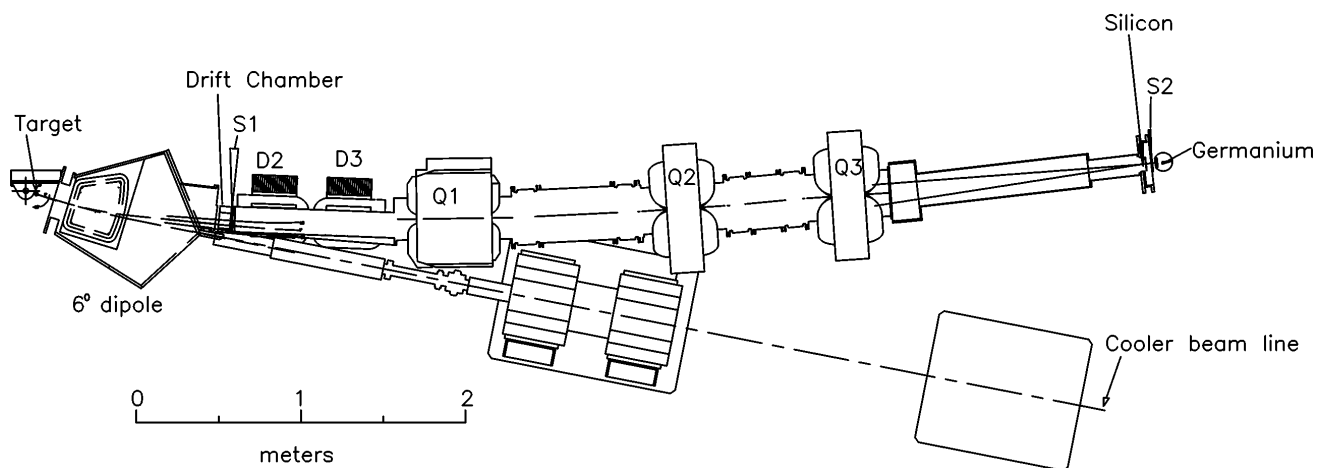

FIG. 1. Plan view of the magnetic channel and ^{3}He detectors. The channel contains two dipole and three quadrupole magnets, following the 6° dipole that separates ^{3}He's from beam protons.

twofold ^{3}He (π^+ or π^-) coincidences, and in runs with a ^{3}He target, of ^{4}Heπ^+ coincidences to ^{4}He singles for $p\,^3$He $\rightarrow$ ^{4}Heπ^+ near its threshold.

Separate detectors were used to monitor the luminosity, via pd elastic scattering events, with the forward proton ($6° \leq \theta_p^{\mathrm{lab}} \leq 15°$) and recoil deuterons detected in coincidence. The pd elastic cross section was in turn calibrated against pp elastic scattering in separate runs utilizing a jet target of molecular HD gas.

Results obtained with this apparatus 0.7 MeV above the single π^0 production threshold are shown in Fig. 2. The ^{3}He group, already prominent in the *raw* S1–S2 time-of-flight (TOF) spectrum, is cleanly isolated [see Fig. 2(a)] by a particle identification gate placed on the energy loss in S1 and S2. The drift chamber position spectrum for the ^{3}He's [Fig. 2(b)] reveals the entire kinematic cone for $pd \rightarrow$ ^{3}Heπ^0, with only small ($\sim$15%) acceptance losses imposed by channel magnets at the top and bottom of the locus. The total cross section we extract agrees, within our absolute normalization uncertainty of $\pm$10%, with the published value $\sigma_{\mathrm{tot}} = 0.88$ μb [19].
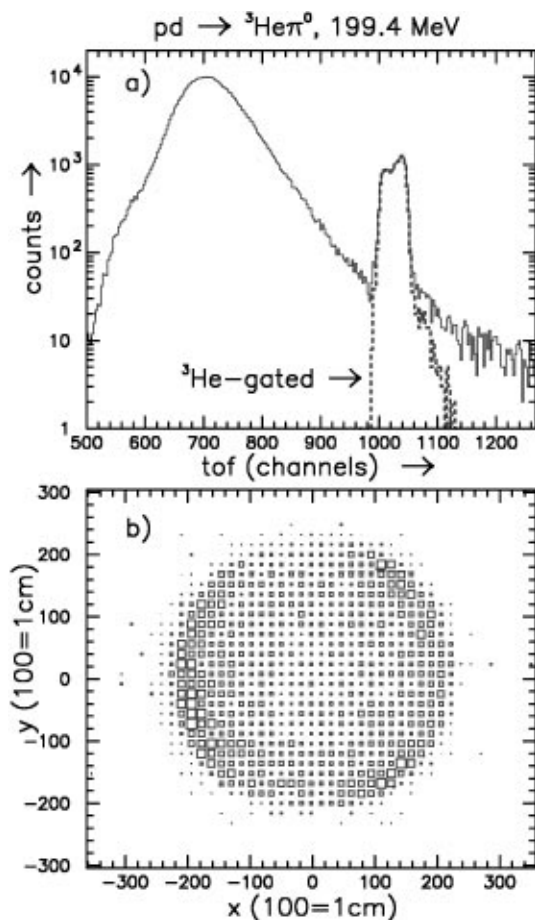

FIG. 2. Spectra for pd collisions 0.7 MeV above the $pd \rightarrow$ ^{3}Heπ^0 threshold: (a) time of flight between scintillators S1 and S2, ungated (solid curve) and gated (dashed curve) by ^{3}He particle identification; (b) drift chamber position, showing the small lab-frame kinematic cone and edge-peaking characteristic of a near-threshold two-body reaction.

In a run 1 MeV *below* the π^0 threshold, we found the cross section times acceptance for ^{3}He background to be <100 pb, a remarkable result for a 0° spectrum, emphasizing the cleanliness of the cooled beam, internal target environment.

Higher-energy data were acquired (see Table I) at four energies straddling the production thresholds for $\pi^0\pi^0$ (415.4 MeV) and $\pi^+\pi^-$ (430.5 MeV). The raw TOF spectrum obtained at 431.5 MeV is shown in Fig. 3(a). The two dominant groups are continuum protons and deuterons (the latter from $pd \rightarrow pd\pi^0$, $nd\pi^+$ reactions); the expected location of the ^{3}He's falls between them. ^{3}He products are readily identified by energy depositions in the silicon (ΔE) and germanium (E) detectors [see Fig. 3(b)]. However, the observation of a "forbidden" ^{4}He group in this spectrum indicates background, now somewhat above the 100 pb level, arising from interactions of beam halo, or of particles scattered out of the beam by the D$_2$ target, with matter outside the gas jet. Analogous ^{3}He contributions are suggested by the nonvanishing yield observed at 412.0 MeV.

The ^{3}He-gated TOF peak at 431.5 MeV [solid curve in Fig. 3(a)] must therefore comprise contributions from nontarget background and $2\pi^0$ production, as well as from pionium and free $\pi^+\pi^-$ production. The latter contribution is determined by demanding a prompt coincidence with one or more of the five charged-pion scintillators, while the first two contributions can be inferred from the yield measured just below $\pi^+\pi^-$ threshold with the pion scintillators in anticoincidence. The charged-pion coincidence gives the shaded spectrum in Fig. 3(a), where we now observe a narrow peak within the ^{3}He energy range expected kinematically for $\pi^+\pi^-$ production. The yields observed at the various bombarding energies, within the latter ^{3}He energy gate (or its equivalent at 433.5 MeV) and with the pion scintillators placed in coincidence or in anticoincidence, are converted to cross section times channel acceptance (σ_{eff}) in Table I.

The results in column 2 of Table I show clear evidence for *free* $\pi^+\pi^-$ production very near threshold. After subtraction of below-threshold background (yielding column 3) and correction for overall pion scintillator

TABLE I. Total cross section times acceptance (σ_{eff}) for ^{3}He products near the $2\pi^0$ (415.4 MeV) and $\pi^+\pi^-$ (430.5 MeV) thresholds. Only statistical errors are specified.

Beam energy (MeV)	^{3}He $\pi^\pm$ (pb)	^{3}He $\pi^\pm$ − bkgd (pb)	^{3}He $\overline{\pi^\pm}$ (pb)
412.0[a]	32 ± 12		135 ± 5.5
429.5[a]	16 ± 8		419 ± 41
431.5[a]	67 ± 11	51 ± 14	367 ± 26
429.5[b]	20 ± 9		541 ± 47
433.5[b]	124 ± 19	104 ± 21	566 ± 40

[a]Yields extracted with ^{3}He energy gate appropriate to $\pi^+\pi^-$ production at 431.5 MeV.
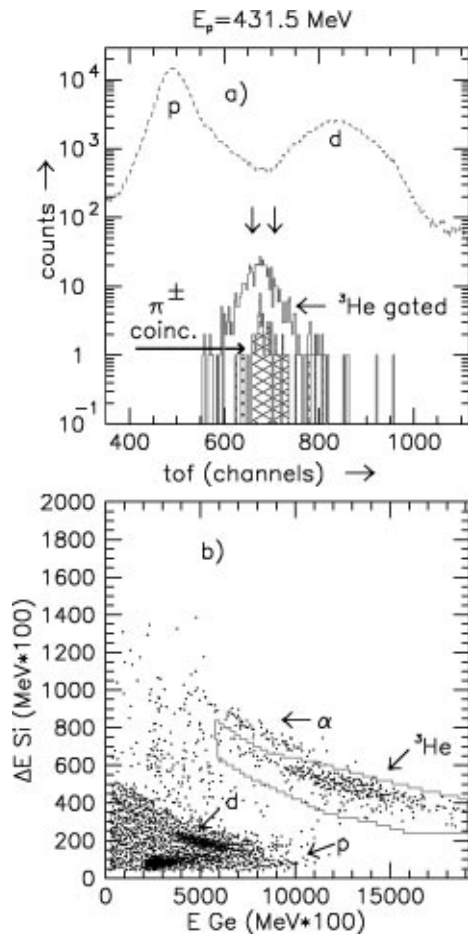[b]Yields extracted with ^{3}He energy gate appropriate to 433.5 MeV.

FIG. 3. Spectra obtained 1.0 MeV above the $pd \rightarrow$ ^{3}He$\pi^+\pi^-$ threshold: (a) S1–S2 time, ungated (dashed), gated (solid) by ^{3}He particle identification, and gated in coincidence with one or more pion scintillators (cross-hatched); (b) particle identification from silicon and germanium detector pulse heights, showing the ^{3}He gate used in (a). The vertical arrows in (a) indicate the allowed ^{3}He energy range accompanying charged-pion pair or pionium production.

efficiency $[(74 \pm 10)\%]$ and channel acceptance times efficiency $[(91 \pm 5)\%$, according to simulations assuming a uniform phase space density for the three-body final state], we find $\sigma_{tot} = 76 \pm 21(\text{stat}) \pm 11(\text{syst})$ pb for $pd \rightarrow$ ^{3}He$\pi^+\pi^-$ at an energy 1.0 ± 0.2 MeV above threshold. The systematic error in σ_{tot} includes uncertainties in luminosity, acceptance, and efficiency. The value of σ_{eff} is a factor of 2 larger 3.0 MeV above threshold, despite a substantial ($>20\%$) loss in acceptance.

In contrast, we see *no evidence for pionium production*. The ^{3}He yield in *anticoincidence* with $\pi^\pm$ (column 4 of Table I) changes negligibly as we cross the pionium threshold, allowing us to place a direct upper limit (90% confidence level) σ_{tot}(pionium) ≤ 70 pb, 1.0 MeV above threshold, while $\sigma_{eff} \leq 79$ pb 3.0 MeV above threshold. More stringent, but model-dependent, limits can be inferred from the *free* pair production by estimating the ratio of phase space relevant to pionium vs free pairs. The pionium signal reported in [12] is confined to relative π^+-π^- momenta $\lesssim 2$ MeV/c, corresponding to $\lesssim 1\%$ of the

reaction phase space in our case, even after correction for the enhancement due to Coulomb attraction [20]. Thus, in the absence of additional enhancements, the pionium cross section is not likely to exceed 1 pb.

In summary, we have proposed a model-independent method to extract a linear combination of the π-π scattering lengths from the 2γ decay of a tagged sample of pionium atoms produced in a target of low electron density. We have studied $pd \rightarrow$ ^{3}He$\pi^+\pi^-$ 1.0 MeV above threshold as a potential tagging reaction, utilizing a system with demonstrably low background sensitivity. The observed yield of *free $\pi^+\pi^-$* pairs suggests a total pionium production cross section below 1 pb under these conditions. At this cross section level, a decay experiment would require a time-averaged luminosity $\gtrsim 10^{34}$ cm^{-2} s^{-1}, beyond the capabilities of present proton storage rings with beam cooling. Alternative production reactions and energies are being explored.

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