Submitted to Physical
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RADIATIVE PION CAPTURE IN ^{4}He †

James A. Bistirlich, Kenneth M. Crowe, Anthony S. L. Parsons,*
Paul Skarek,‡ and Peter Truoel††

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

and

Carl Werntz**

California Institute of Technology
Pasadena, California 91109

August 1970

The spectrum of high-energy γ rays following the absorption of negative pions in ^{4}He has been investigated. The observed shape of the spectrum and the measured total capture rate $[(0.704 \pm 0.066) \times 10^{15}\ \mathrm{sec}^{-1}]$ agree well with theoretical predictions, assuming that the pions proceed through excitation of states in ^{4}H with $J^\pi = 2^-$ at 3.4, $J^\pi = 1^-$ at 5.1, and $J^\pi = 1^-$ at 7.4 MeV relative to the ^{3}H + n threshold, and taking an operator $\approx \tau^{(-)}\sigma e^{i\vec{k}\cdot\vec{r}}$ for the calculation of the nuclear matrix elements.

A study of the process $\pi^- + {}^4\mathrm{He} \rightarrow {}^4\mathrm{H}^* + \gamma$ provides useful information in two areas, which have received considerable attention from the theorists in recent years--the reaction mechanisms involved when the absorption of π^- in a nucleus results in the emission of a high-energy γ ray, and the excited states of the A = 4 system. Our previous results for the same process from a carbon target[1] revealed that it proceeds partly via the excitation of collective states in the residual nucleus,

as was predicted theoretically for doubly closed nuclei such as ^{12}C and ^{16}O.[2,3] These states are the members of the 15-dimensional representation of the spin-isospin group SU(4). The SU(4) formalism was also applied to the A = 4 system, and led to the prediction of a group of negative parity states with excitation energies between 20 and 30 MeV.[4,5] These levels were observed[6] in the reactions conventionally studied, such as $^3He(n,n)$, $^3H(p,p)$, $^3H(p,n)$, and $^3H(n,n)$. Since these states are in general quite wide, a rather involved phase-shift analysis of scattering and polarization data is required, which is further complicated by the presence of T = 0 states, so that sometimes several solutions consistent with the data are obtained. For radiative pion capture the matrix elements for 1s capture are given by the operator $\tau^{(-)}\sigma e^{i\vec{k}\cdot\vec{r}}$, as can be shown either in the impulse approximation or by using PCAC.[7-10] Only T = 1 states (the $\Delta T_z = -1$ analogues of the ^4He states) occur, which makes an analysis of the reaction very straightforward.

Our experimental setup is shown in Fig. 1. The details of the high-resolution pair spectrometer employed to measure the γ-ray spectrum have been described elsewhere.[1] The energy resolution as determined from a calibration experiment with a hydrogen target was 2 MeV fwhm at E_γ = 129 MeV, and the maximum acceptance 2.2×10^{-5} at E_γ = 120 MeV.

The π^- beam of the 184-inch cyclotron at the Lawrence Radiation Laboratory in Berkeley was stopped in a 120-liter liquid helium Dewar with a 43-cm-diam flask. In order to compute the yield of γ rays per pion stopped in the helium a number of corrections were applied. The muon and electron contamination of the beam were measured by time-

of-flight techniques. The number of pions stopped in the walls was computed from the range curves and from runs with an empty Dewar. In addition, the absolute rate had to be corrected for the loss due to the conversion and scattering of the emitted γ rays in the helium and in the walls of the target. Since the same Dewar filled with hydrogen was used in the calibration experiment, the accuracy of the corrections could be checked independently by comparison with the known capture for hydrogen. The experimental spectrum after 40% background from the container has been subtracted is shown in Fig. 2. It has not been corrected for the energy-dependent efficiency. The total number of events obtained in about 90 hours of beam time is 4240, corresponding to 1.8×10^{10} pions stopped in the target. The observed ratio of the radiative to the total pion capture rate is $(1.28\pm0.13)\times10^{-2}$. Neglecting pion capture from the 2p state and using the value[11] 5.5×10^{16} sec^{-1} for the total nuclear capture rate from the 1s state, we obtain a value for the radiative pion capture rate of $(7.04\pm0.66)\times10^{14}$ sec^{-1}.

The experimental spectrum does not exhibit any structure due to isolated resonances, which is not surprising, since the known T = 1 states are wide and overlap each other. (It should be noted that a calculation with noninteracting ^{3}Hnγ final state does produce a peak in the spectrum, but much broader than that observed; for example, a simple pole model assuming proton exchange[12] produces the dot-dashed curve shown in Fig. 2. The energy at which maximum yield is observed corresponds to an excitation energy measured relative to the ^{3}H + n threshold, $\approx$ 3.7 MeV, close to the $J^\pi = 2^-$ level at 3.4 MeV deduced from phase-shift analysis.[13] This suggests that the shape of the spectrum of radiative pion capture is

dominated by transitions to this level. Assuming that only the 2^- and the two 1^- levels around 5.1 and 7.4 MeV contribute to the capture rate, we can compute the shape of the spectrum from R-matrix expressions and correct for experimental resolution. The method of calculation used is as follows: Integrated over all possible directions of the outgoing particles, the rate for radiative pion capture from a 1s state is given by

$$\frac{d\Lambda}{dE_\gamma} = 16\pi Z^3\alpha^4 \frac{f^2}{4\pi} \omega R \sum_{\bar{s}} \sum_{ijJ_f} \frac{1}{2\pi} \left| \sum_{\lambda\lambda'} (\Gamma^{J_f}_{\lambda,nsl})^{1/2} A^{J_f}_{\lambda\lambda'} \langle J_{f,\lambda'} || A_j || J_i \rangle \right|^2. \tag{1}$$

Here we have removed the pion wave function from the matrix element, taking an average value of

$$\phi = (1/\sqrt{\pi})\,(Z\alpha m_\pi)^{3/2} R^{1/2}, \quad \text{with } R = 0.77.^{14} \tag{2}$$

The width $\Gamma^{J_f}_{\lambda,nsl}$ gives the strength of the coupling of the neutron to the resonance $J_{f,\lambda'}$ and is defined in terms of the reduced width

$$(\Gamma^{J_f}_{\lambda,nsl})^{1/2} = [2P_l(ka)]^{1/2} \gamma^{J_f}_{ns}. \tag{3}$$

The propagator of the resonances is defined in the usual manner[15] as

$$(A^{-1})_{\lambda\lambda'} = \delta_{\lambda\lambda'}(E_\lambda - E) + \Delta_{\lambda\lambda'} - \frac{i\Gamma_{\lambda\lambda'}}{2}. \tag{4}$$

Formula (1) is derived from the R-matrix expressions for the expansion of the scattered wave function within the range of nuclear forces, and its validity is limited by the necessity for the ground-state wave function to cut off the integration within this range. For the sake of consistency with Refs. 13 and 16, the d + nn channel with a threshold at E_λ = 110.4 MeV has been ignored.

The axial vector reduced matrix elements are given by

$$\langle J_f M_f | A^{el}_{JM} | J_i M_i \rangle = (1/q) \int d\vec{r} (\vec{\nabla} \cdot j_J(q_r) Y^M_{JJ}) \langle J_f M_f | \vec{j}_A(\vec{r}) | J_i M_i \rangle ,$$

$$\langle J_f M_f | A^{mag}_{JM} | J_i M_i \rangle = \int d\vec{r}\, j_J(q_r) Y^M_{JJ} \langle J_f M_f | \vec{j}_A(\vec{r}) | J_i M_i \rangle ,$$

$$\langle J_f M_f | \vec{j}_A(\vec{r}) | J_i M_i \rangle \equiv \int \Pi_i \, \delta \vec{r}_i \, \psi^*_f \, \Sigma_i \delta(\vec{r} - \vec{r}_i) \, \tau^{(-)}_i \sigma_i \psi_i . \tag{5}$$

In the simplest shell-model picture, there is one state with T = 1, $J^\pi = 2^-$, two states with T = 1, $J^\pi = 1^-$.[4,5] Introducing the parameter x for the configuration mixing for $^3P_1$ and $^1P_1$ for the two 1^- states as in Ref. 16, we have

$$|2^-, 1\rangle = |^3P_2\rangle ; \quad |1^-, 1\rangle = (x|^1P_1\rangle + |^3P_1\rangle)/(1+x^2)^{1/2},$$

$$|1^-, 2\rangle = (-|^1P_1\rangle + x|^3P_1\rangle)/(1+x^2)^{1/2} . \tag{6}$$

Harmonic oscillator wave functions give

$$\langle {}^3P_2 || A^{el}_2 || 0 \rangle = \frac{\omega a}{\sqrt{2\pi}} F_{el}(\omega^2) \quad \langle {}^3P_1 || A^{mag}_1 || 0 \rangle = \frac{\omega a}{\sqrt{2\pi}} F_{el}(\omega^2),$$

$$\langle {}^1P_1 || A^{mag}_1 || 0 \rangle = 0. \tag{7}$$

We take $a = 1/\sqrt{m\omega_{osc}} \equiv 1.38$ F, as suggested by the ^{4}He charge radius. For a channel radius 4 F the Wigner limit for the reduced neutron width of a single resonance is 5.5 MeV. Shell-model calculations suggest a value of $x \approx -1.25$,[5,17,18] whereas analysis of ^{3}He + p scattering[19] implies $x = -0.3$. The reduced widths for the individual states are then obtained from the appropriate formulas in Ref. 16, and only

the actual resonance energy remains to be fixed. The position of the peak depends primarily on the energy of the 2^- level, and we get a good fit for $E_R = 3.4$ MeV, in good agreement with results from the analysis of neutron scattering on tritons.[13] This corresponds to an energy of excitation ≈ 24 MeV in ^{4}He, somewhat lower than the 2^- energy from the charge-independent analysis of the $^3H(p,n)^3He$ reaction (≈ 24.8 MeV). We used $E_R = 5.1$ MeV for the lower 1^- state[13] and $E_R = 7.5$ MeV for the upper.[16] The results of this calculation are represented by the dashed ($x = -0.3$) and the solid ($x = -1.25$) curves in Fig. 2.

After folding the theoretical curve with experimental resolution and efficiency and normalizing to the data, we obtain, for the best fit (for 99 deg of freedom, since we take $70 \leq E_\gamma \leq 120$), $\chi^2 = 96$ for $x = -1.25$ and $\chi^2 = 109$ for $x = -0.3$. The accuracy of our data does not allow one to rule out either of the two choices for x. Even more striking than the close prediction of the shape of the spectrum is the fact that the absolute rates, 0.718×10^{15} sec^{-1} for $x = -1.25$ and 0.693×10^{15} sec^{-1} for $x = -0.3$, agree with the measured one within the experimental errors. The uncertainty in the experimental value for the radiative capture rate has a contribution from the total absorption rate, since it is not a measured but is an extrapolated value from higher elements. This contribution is not included in our quoted error.

The Lawrence Radiation Laboratory members of this collaboration express their thanks to Carl Werntz for joining them in the interpretation of their data by contributing his theoretical calculations. The industrious efforts of our scanning crew and the help of the Cyclotron crew under James Vale are gratefully acknowledged.

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†This work was supported by the Atomic Energy Commission, the National Science Foundation [GP-9114, EP-19887], and the Office of Naval Research [Nonr-220(47)].

*Now at Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

‡Permanent address: CERN, Geneva, Switzerland.

††Present address: Physics Department, University of California – Los Angeles, California 90024.

**On leave from The Catholic University of America, Washington, D. C. 20017.

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FIGURE LEGENDS

Fig. 1. Experimental layout.

Fig. 2. Energy spectra of γ rays from π^- capture in ^{4}He. Solid histogram: data in 0.5-MeV bins.

Solid curve: R-matrix predictions with x = - 1.25.

Dashed curve: R-matrix predictions with x = - 0.3.

Dot-dashed curve: pole-model predictions.

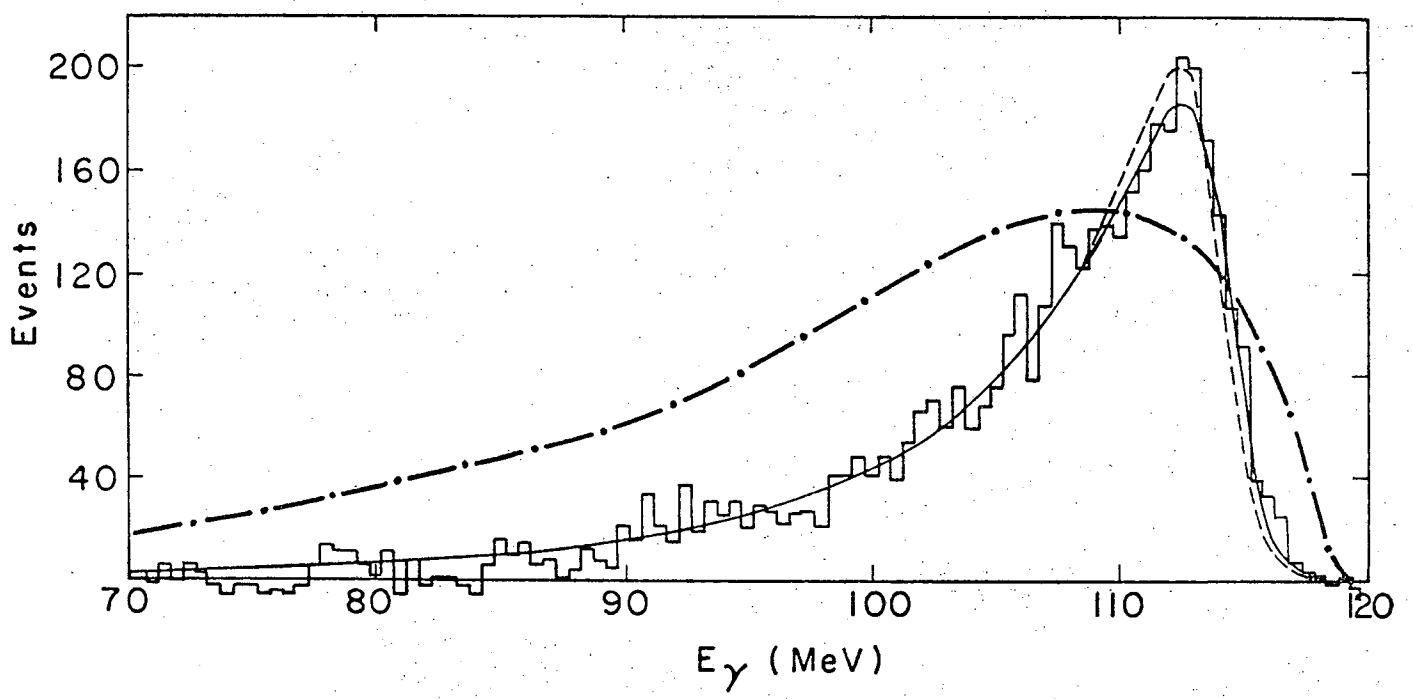

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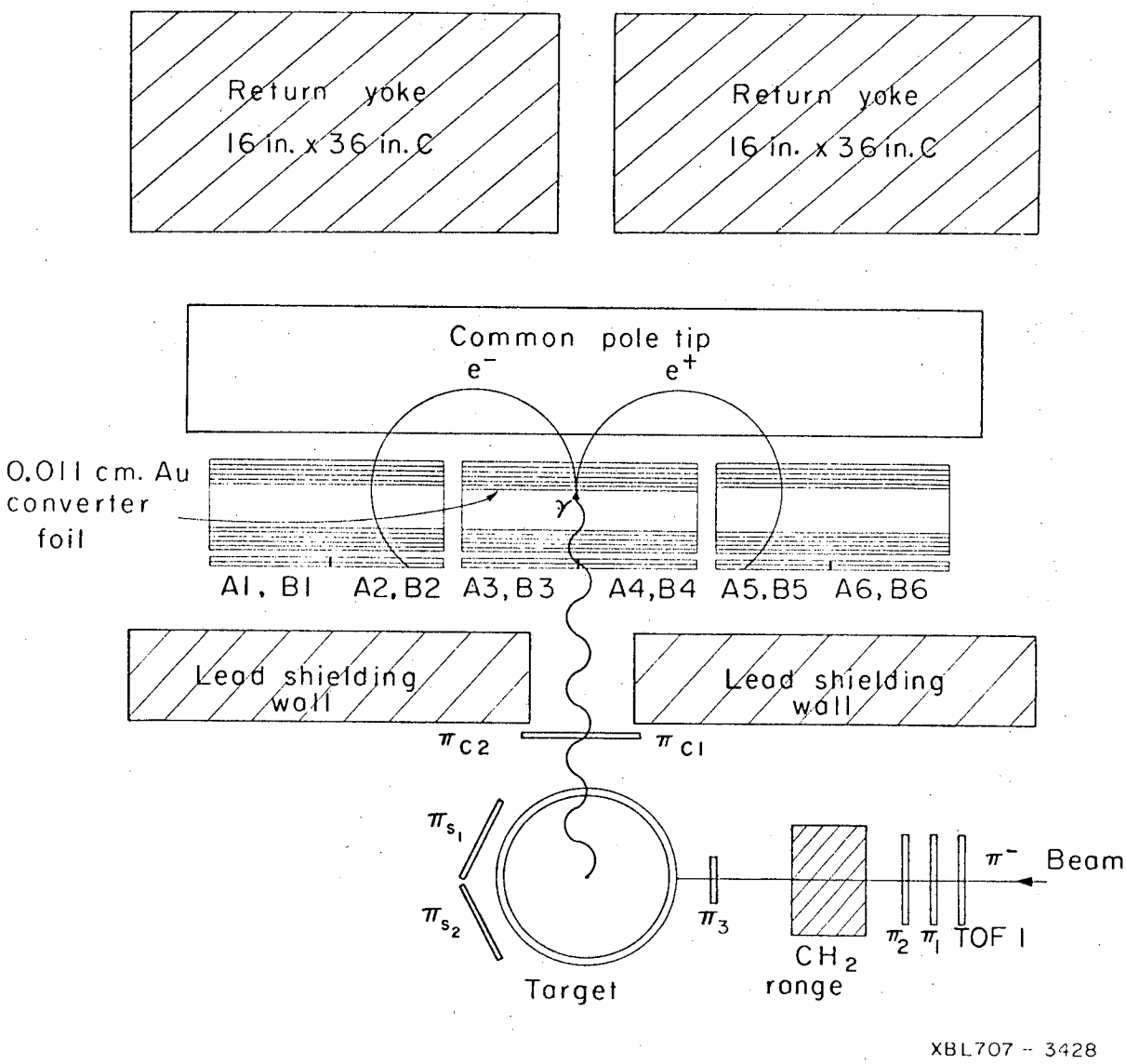
Fig. 1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A2, B2
A3, B3
A4, B4
A5, B5
A6, B6
Lead shielding
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Fig. 2

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