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Recoil-momentum spectrum of $^{12}C^*$ from π^- capture on ^{14}N

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Negative pions were stopped in $LiNH_2$ and the nuclear deexcitation γ rays were observed. The Doppler-broadened line shape of the decay γ rays from the 2^+ state of ^{12}C at 4439 keV was analyzed to obtain the momentum distribution of the recoiling ^{12}C nuclei. This distribution is compared with the prediction of a simple model which assumes one-step quasifree π^- absorption on a quasideuteron pair.

[NUCLEAR REACTIONS $^{14}N(\pi^-, X\gamma)$, $E=0$; measured E_γ and Doppler broadening.]

I. INTRODUCTION

Pion absorption is a relatively unique process in that it involves a large excitation (140 MeV) of the absorbing nucleus, or portion thereof, with no corresponding momentum transfer. The concomitant dynamical restrictions may give it potential value in the study of short-range correlations within nuclei.[1]

Measurement of the Doppler broadening of nuclear γ rays arising from π^- absorption as a means of determining pair-momentum spectra in nuclei originated with such a study of the γ rays from the $\pi^- + {}^{16}O$ absorption process by Kossler *et al.*[2] This followed a suggestion by Ericson,[3] who pointed out that the observed momentum distribution should be related to the Fourier transform of the wave function of the center-of-mass coordinate of the absorbing pair.

This technique involves observation of the spectra of γ rays produced in prompt coincidence with π^- mesons stopping in the target. Yields to particular states of daughter nuclei are measured, and for those with lifetimes short enough to display Doppler broadening, the line shapes are unfolded to obtain the recoil-momentum spectra. Although this technique generates information equivalent in principle to that obtainable from charged-particle measurements such as $(\pi^+, 2p)$,[4] (d, α), $(p, {}^3He)$, or $(\alpha, {}^6Li)$, it has the advantage of excellent energy resolution [about 3 keV for Ge(Li) detectors] and virtually zero momentum transfer from the incident particle.

Kossler *et al.*[2] found a mean recoil momentum of 145 MeV/c for the 3945-keV $J^P = 1^+$ state of ^{14}N produced by π^- absorption on ^{16}O. This is in good agreement with the 126 MeV/c predicted by a calculation which assumes one-step quasifree (OSQF) absorption on an $n = l = 0$ np cluster.

Engelhardt, Lewis, and Ullrich[5] have used this technique to measure recoil-momentum distributions for daughter nuclei from π^- absorption reactions on ^{16}O, ^{31}P, and ^{40}Ca. They obtained a mean recoil momentum of 150 MeV/c for the 3945-keV level of ^{14}N from $\pi^- + {}^{16}O$, in good agreement with the results of Kossler *et al.*[2]

In addition, photonuclear reactions at medium energy also have the potential for measuring short-range two-nucleon correlations because of the photon energy-momentum imbalance,[6] and several (γ, np) experiments, such as that by Berman *et al.*,[7] are suggestive of the presence of deuteron clusters in nuclei.

In this experiment we wished to see if the momentum distribution observed for π^- capture on ^{14}N were consistent with what would be expected from a model which assumed OSQF π^- absorption on two $p_{1/2}$ nucleons outside an inert core of ^{12}C in the 2^+ first excited state.

Because of the short (60 fsec) lifetime of the 2^+ level of ^{12}C,[8] there is little slowing down before emission of the γ ray (the characteristic slowing-down time α for ^{12}C in $LiNH_2$ is 915 fsec), and hence the shape of the line in the γ-ray spectrum implicitly contains the momentum spectrum of the recoiling daughter nucleus. Since the absorbing π^- imparts virtually zero momentum to the nucleus, this recoil momentum spectrum is identical to the sum momentum of the absorbing pair, provided that the π^- absorption and subsequent pair ejection is a one-step process free of complicating initial- and final-state interactions.[9]

II. EXPERIMENTAL PROCEDURE

The apparatus is shown schematically in Fig. 1, and the procedure, apart from minor details, was the same as that of Kossler *et al.*[2] The pions were provided by the meson channel of the Space Radiation Effects Laboratory (SREL) synchrocyclotron,[10] and entered the initial energy degraders of the experimental apparatus with a mean momentum of about 200 MeV/c.

γ rays were detected with a 40-cm^3 Princeton Gamma-Tech Ge(Li) detector, with 3.5-keV resolution at 1332 keV. Two spectra were taken in a Kicksort 4096-channel analyzer, one of γ rays in prompt coincidence with π^- stop signatures from the beam telescope, the other of γ rays occurring in a time range of about 100 to 200 nsec prior to the π^- stops. This second spectrum was used to identify peaks not associated with π^- absorption events. The time between the π^- stop logic signal and the γ-ray logic signal was digitized in a Nuclear Data 512-channel analyzer. Prompt coincidences produced a peak of 40 nsec full width at half maximum (FWHM) and a 7-to-1 peak-to-background ratio. 8.27×10^8 π^- stop events were observed. The Kicksort analyzer gain was 3.88 keV/channel.

The target, 500 g of lithium amide ($LiNH_2$) solid powder in a plastic bag, was suspended in the π^- beam. No attempt was made to measure absolute γ-ray yields because the possible existence of mesoatomic processes and large mesic molecules[11] would alter the capture ratios of the molecular constituents and hence invalidate predictions made from, say, the Fermi-Teller Z law.[12] A rough estimate, however, indicated a yield for the 4439-keV state of ^{12}C of about $(10 \pm 5)\%$. π^- absorption on lithium or hydrogen nuclei does not, of course, contribute any nuclear γ rays to the spectrum.

III. DATA ANALYSIS

The only lines in the spectrum which could be associated with π^- absorption on ^{14}N were the photopeak and the single- and double-escape peaks of the 4439-keV transition of ^{12}C. These were not present in the off-time spectrum. The double-escape peak was used for fitting because of its better statistics and the presence of several accidentally zeroed channels in the photopeak region. In Fig. 2 we show a Gaussian function fitted to this peak which gave a FWHM of (134.7 ± 4.6) keV. The system was estimated to have a double-escape resolution of (8.5 ± 2.0) keV.

Doppler broadening

It has been shown[13] that the intensity of a Doppler-broadened peak at an energy $\Delta E'$ from its center is given by

$$N(\Delta E') \propto \int_{K'}^{\infty} \frac{1}{K} \frac{dn}{dK} dK, \tag{1}$$

where K is the momentum, K' is given by

$$K' = \frac{Mc\Delta E'}{E_\gamma}, \tag{2}$$

and dn/dk is the momentum distribution. If one assumes a momentum distribution

$$\frac{dn}{dK} \propto K^2 e^{-K^2/Q^2} \tag{3}$$

(see Sec. IV), one obtains

$$N(\Delta E') \propto e^{-K'^2/Q^2} \tag{4}$$

and a mean momentum of

$$\bar{p} = \frac{Mc(\text{FWHM})}{2E_\gamma}, \tag{5}$$

which is $\sqrt{\ln 2}$ times the value of Q. Inserting our measurement of the FWHM into Eq. (5) gave a mean recoil momentum of 169 ± 6 MeV/c.

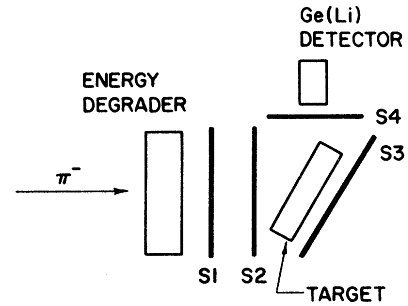

FIG. 1. Experimental apparatus. $S1$, $S2$, $S3$, and $S4$ are 0.64-cm-thick square plastic scintillators.

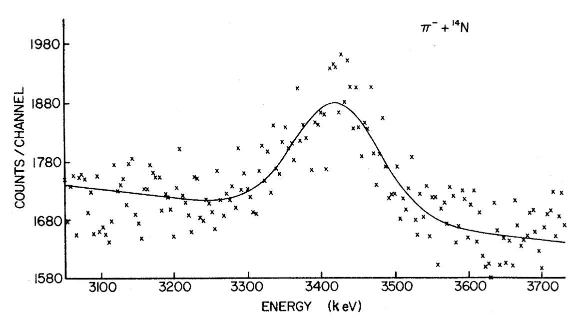

FIG. 2. The Doppler-broadened double-escape peak of the first 2^+ level of ^{12}C. The fit is a Gaussian function with normalized $\chi^2 = 1.128$.

IV. MODELS

In the paper of Kossler *et al.*[2] a Born-approximation microscopic model for the pion absorption was used which gave agreement with the $^{16}O(\pi^-, 2n\gamma)^{14}N$ recoil-momentum distribution. We apply this same scheme here. The pion is assumed to be in a p-state atomic orbital and interacting with $H \propto \vec{\sigma} \cdot \vec{\nabla}_\pi$.[2,14] Nuclear wave functions are chosen from Cohen and Kurath,[15] and the two outgoing neutrons are plane waves.

We use

$$\frac{dN}{dK} \propto |\langle f|H|i\rangle|^2 qK^2 d\Omega_q d\Omega_k, \tag{6}$$

where dN/dK is the recoil-momentum distribution and q is the relative momentum of the outgoing pair. We obtain, dropping negligible terms,

$$\frac{dN}{dK} \propto qK^2 \left\{ 0.879 \left[R_{00}(\sqrt{2}q) R_{10}\left(\frac{K}{\sqrt{2}}\right) - R_{10}(\sqrt{2}q) R_{00}\left(\frac{K}{\sqrt{2}}\right) \right]^2 + 0.121 R_{00}{}^2(\sqrt{2}q) R_{02}{}^2\left(\frac{K}{\sqrt{2}}\right) \right\}, \tag{7}$$

where the R_{nl} are harmonic-oscillator radial wave functions.[16] The magnitude of q is forced to be large from energy conservation requirements, and so Eq. (7) becomes

$$\frac{dN}{dK} \propto K^2 R_{00}{}^2\left(\frac{K}{\sqrt{2}}\right) \propto K^2 e^{-K^2/2} \tag{8}$$

or

$$\frac{d^3N}{dK^3} = \frac{1}{K^2}\frac{dN}{dK} \propto e^{-K^2/2}. \tag{9}$$

K is in units of 126 MeV/c. Thus we find an identical form to that obtained for $\pi^- + {}^{16}O$ by Kossler *et al.* in Eq. (9) of Ref. 2. Of course, because of the larger rms radius of ^{16}O, their natural unit for K was 107 MeV/c. It should be emphasized that this calculation does not inherently give a Gaussian form for the momentum distribution. Had the two-particle coefficients of fractional parentage[15] been markedly different, the result could have been clearly non-Gaussian.

Another approach to this problem is to assume a quasideuteron cluster model for the pair of absorbing nucleons. With the cluster in an $n = 0, l = 0$ state this also results in the expressions of Eqs. (8) and (9).

V. CONCLUSIONS

Equations (8) and (9) predict a mean recoil momentum of 148 MeV/c, compared with the experimental result of (169 ± 6) MeV/c, a difference of

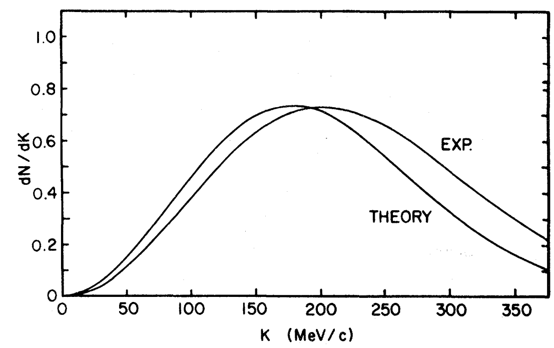

FIG. 3. The momentum distributions dN/dK derived from our data and from our model. K is in units of 125.6 MeV/c.

12%, which we think is a good agreement in light of the various approximations made in these calculations. The calculated shapes of dN/dK and d^3N/dK^3, along with the experimental results, are shown in Figs. 3 and 4, respectively.

This calculation was done without introducing a correlation function, and the result is identical to that obtained by assuming the quasideuteron cluster model. This result is similar to that of Kossler *et al.*,[2] who measured a mean recoil momentum of 145 MeV/c for $\pi^- + {}^{16}O$. Their analogous calculation predicted a mean recoil momentum of 126 MeV/c, which similarly differs from their measurement by 13%. Thus both of these experimental results are in good agreement with either model.

This is the only pion reaction with ^{14}N for which the shape of the ^{12}C 2^+ line has been analyzed, so there are no direct comparisons available. This peak has been observed, however, in two studies of π^- reactions with ^{16}O, and the comparison is

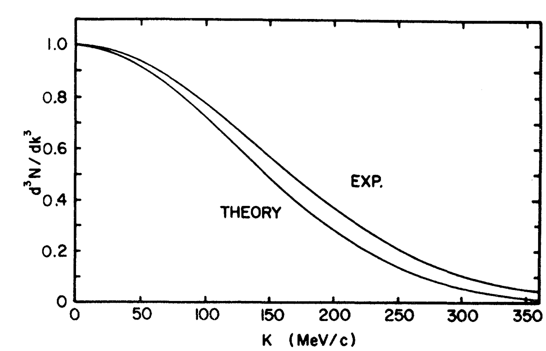

FIG. 4. The momentum distributions d^3N/dK^3 derived from our data and the model.

noteworthy. Engelhardt *et al.*[5] studied π^- absorption at rest and obtained a FWHM of (137 ± 15) keV, which gave them a mean recoil momentum of (183 ± 21) MeV/c. This has been interpreted as a measure of the momentum distribution of an α cluster in the ^{16}O nucleus.[17] Lieb and Funsten,[18] using the $^{12}C^*$ 4439-keV γ rays produced by 230-MeV π^- incident on ^{16}O (with no stopping requirement), obtained a momentum transfer of 139 MeV/c. They also note that their relatively large cross section $(16.1 \pm 6.4$ mb) for this channel is consistent with a quasifree α knockout (the spectroscopic factor for this level is about five times that for the ^{12}C ground state). A comparison of these results suggests that in-flight pion reactions may possibly be associated with lower momentum transfer, even though the initial and final nuclear states are the same.

Finally, though it is possible that the good agreement obtained between experiment and model is accidental, and that initial- and final-state processes may not be negligible, the result is consistent with the calculations which assume capture on the two $p_{1/2}$ nucleons outside an inert $^{12}C^*$ core.

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