Excitation of the isobaric analog state of ^{165}Ho by pion single-charge exchange

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Forward-angle differential cross sections for the ^{165}Ho$(\pi^+,\pi^0)^{165}$Er(IAS) reaction have been measured at $T_\pi=98.0$, 163.2, and 228.3 MeV in the angular range $2^\circ \lesssim \theta_{\pi^0} \lesssim 14^\circ$. The shapes of the angular distributions at 98.0 and 163.2 MeV are compared to predictions arising from the strong absorption model of pion single-charge exchange scattering. Extrapolated 0° cross sections are compared with trends previously established with mostly spherical and near-spherical nuclei. The measurement demonstrates the possibility of using the (π^+,π^0) reaction for studying neutron density deformations in oriented ^{165}Ho.

I. INTRODUCTION

Excitation of isobaric analog states (IAS's) is a prominent process in forward-angle pion single-charge-exchange (SCE) reactions near and above the (3,3) resonance. These reactions have been extensively studied both experimentally[1–7] and theoretically[8,9] for a number of target nuclei, mostly spherical or near spherical, ranging from ^{7}Li to ^{208}Pb. The general behavior of the 0° cross sections is relatively well understood in simple geometrical terms within the framework of the strong absorption model, treated semiclassically in an eikonal approximation.[4,9]

A further study of on- and near-resonance pion SCE excitation of the IAS's on very deformed nuclei is of interest for two reasons: (i) to test our understanding of the reaction mechanism in a significantly different region of the nuclear surface density, and (ii) as a possible means of investigating the shape of the neutron matter density in a relatively direct way. These questions are relevant in light of two dominant features of the on-resonance (π^+,π^0) reaction: (a) the reaction takes place on the excess neutrons, and (b) the reaction is strongest on the nuclear surface, at a radius typically corresponding to where the nuclear density is $\sim 15\%$ of its central value. Clearly, such a selective probe of the nuclear surface is a potentially useful tool in neutron deformation studies. This possibility is all the more interesting since the existing information[10–14] on neutron deformations, largely deduced in model-dependent calculations from inelastic hadron scattering data, is unreliable and ambiguous. It is of fundamental interest in nuclear physics to study and understand any differences between the charge and neutron density distributions.

Chiang and Johnson have recently suggested[15,16] that measurements of the asymmetry for IAS excitation

$$A_s = \frac{\dfrac{d\sigma^{\perp}}{d\Omega} - \dfrac{d\sigma^{\parallel}}{d\Omega}}{\dfrac{d\sigma^{\perp}}{d\Omega} + \dfrac{d\sigma^{\parallel}}{d\Omega}} \tag{1}$$

leads to a determination of the neutron deformation parameter β_2^n of the target nucleus. Here $d\sigma^{\perp}/d\Omega$ ($d\sigma^{\parallel}/d\Omega$) is the cross section at 0° for the (π^+,π^0) reaction on a target whose nuclei are aligned in a direction perpendicular (parallel) to the incoming beam. The relation between A_s and β_2^n is approximately model-independent since the model-dependent uncertainties in the overall normalization of the calculated cross sections cancel in the asymmetry ratio. Deformed, easily oriented nuclei, such as ^{165}Ho, are prime candidates for such a study.

As a starting point in addressing the above questions, we have undertaken a study of the energy and forward-angle dependence of the reaction ^{165}Ho$(\pi^+,\pi^0)^{165}$Er(IAS) on an unoriented target at energies bracketing the (3,3) resonance. The aim of the experiment was to compare the measured cross sections and angular distributions with predictions of the strong absorption model, and to investigate whether the observed signal-to-noise ratio is adequate for a reliable determination of the asymmetry A_s.

II. EXPERIMENTAL SETUP

The experiment was performed at the Clinton P. Anderson Meson Physics Facility of the Los Alamos National Laboratory (LAMPF) with pi mesons produced in the low energy pion beam line. Neutral pions created by the SCE reaction were detected with the LAMPF π^0 spectrometer[17] in its two-post configuration. The spectrometer consists of two identical arms, each containing three planes of lead-glass converters and wire chambers, followed by a lead-glass total energy calorimeter. Photons created by the decay of a π^0 into two gamma rays are converted into charged-particle showers in the lead-glass planes. The opening angle between the decay photons, calculated from the wire chamber information, is used to deduce the total energy of the π^0.

The parameters that specify the spectrometer setup are listed in Table I. The spectrometer arms were set symmetrically around 0° for the entire data set. The distance between the target and the first photon conversion plane in each arm, and the opening angle between the two arms depended on the beam energy. The peak of the spectrometer acceptance was chosen to be near the expected location of the IAS.

Pion beams of 98.0, 163.2, and 228.3 MeV kinetic energy (at the center of the target) were used during the experiment. The fractional momentum spread $\Delta p/p$ of these beams was typically 0.25%. The target consisted of three disks of holmium metal with thicknesses 0.89, 0.80, and 1.09 g/cm^2, respectively, for a total of 2.78±0.14 g/cm^2. The disks were separated to take advantage of the compensation between the ionization energy loss of the incident charged pions in the target and the error in reconstructing the π^0 opening angle from an event taking place downstream of the presumed location of the interaction, viz., the upstream face of the target. This finite-thickness target effect is fully described elsewhere.[18] Disk-to-disk separations were 0.96, 0.79, and 0.51 cm for incident beam energies of 100, 165, and 230 MeV, respectively. The observed π^0 energy resolution (FWHM) ranged from 3.2 to 3.5 MeV.

III. DATA ANALYSIS

The data were sorted into spectra of reconstructed π^0 kinetic energy. The angular acceptance of the spectrometer allowed a further sorting of the data into three scattering angle bins of roughly equal acceptance for the 98.0 and 163.2 MeV data. At 228.3 MeV, the limited amount of data taken permitted only a single angle bin encompassing the entire acceptance. Measured forward-angle π^0 kinetic energy spectra are shown in Fig. 1, plotted as a function of excitation in the residual nucleus. All of these

TABLE I. Geometry of the π^0 spectrometer.

Nominal T_π (MeV)	Target-converter radius (cm)	Spectrometer opening angle (deg)	Acceptance peak (MeV)
100	100	77.78	80.0
165	120	57.64	145.0
230	120	46.06	210.0

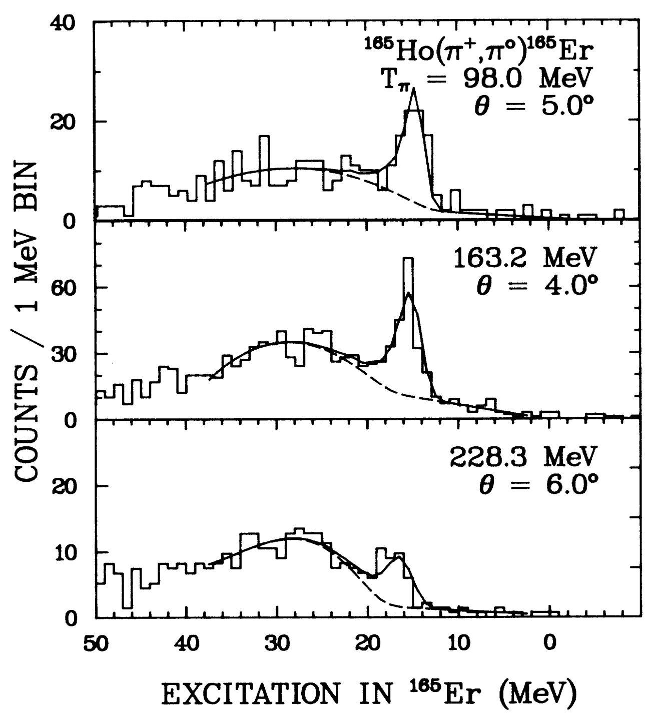

FIG. 1. Forward-angle spectra of π^0 yield as a function of excitation in the residual nucleus ^{165}Er. The solid curves represent typical fits to the spectra. The dashed lines indicate the background levels.

TABLE II. Calculated differential cross sections for ^{165}Ho(π^+,π^0)^{165}Er(IAS) and the reanalyzed ^{120}Sn(π^+,π^0)^{120}In(IAS).

T_π [a] (MeV)	$\langle\theta_{c.m.}\rangle$ (deg)	$\Delta\theta$ (deg)	Uncorrected $(d\sigma/d\Omega)_{c.m.}$ (±systematic±statistical) (mb/sr)	Solid angle correction	Corrected $(d\sigma/d\Omega)_{c.m.}$ (mb/sr)
			^{165}Ho		
98.0	5.03	2.81	0.594±0.023±0.083	1.08	0.641±0.093
	7.97	3.05	0.525±0.047±0.071	1.03	0.541±0.088
	12.54	3.06	0.309±0.072±0.079	0.987	0.305±0.105
163.2	3.97	1.99	1.69±0.08±0.16	1.07	1.81±0.19
	6.62	1.99	1.03±0.19±0.19	0.988	1.02±0.27
	9.90	3.15	0.652±0.226±0.106	0.833	0.543±0.250
228.3	6.09	2.93	1.33±0.42±0.25	0.892	1.19±0.44
			^{120}Sn		
165	4.5	1.1	1.40±0.30±0.06	1.01	1.41±0.31
	6.9	0.9	1.23±0.08±0.05	1.00	1.23±0.09
	11.0	2.0	0.60±0.15±0.04	0.972	0.58±0.15

[a]The laboratory kinetic energy at the center of the target.

spectra show a peak corresponding to the expected location of the isobaric analog transition.

The differential cross sections are given by the expression

$$\left[\frac{d\sigma}{d\Omega}\right]_{c.m.}=\frac{YJ}{\Phi\tau t\epsilon c_{att}\Delta\Omega}, \qquad (2)$$

where Y is the yield of events leading to the isobaric analog state, J is the Jacobian of the center-of-mass to laboratory transformation, Φ is the integrated pion flux through the target, τ is the data acquisition livetime, t is the target thickness, ϵ is the overall spectrometer efficiency, c_{att} is the photon attenuation in the target and in 2.5 cm thick polyethylene absorbers mounted on each arm of the spectrometer, and $\Delta\Omega$ is the spectrometer Monte Carlo calculated solid angle.

The yields Y were taken to be the areas extracted from the IAS peaks in the π^0 kinetic energy spectra. The extraction was done with a fitting routine that utilized the method of maximum likelihood based on Poisson statistics.[17] All spectra were fit in a consistent manner to a function in which the continuum and regions of accidentals were represented by polynomials, with the peak shape taken from a monoenergetic π^0 line shape described below. The background and signal were fit simultaneously; the only peak parameter allowed to vary was the peak amplitude. Typical fits to the data are shown in Fig. 1.

The pion beam fluxes were determined by calibrating the number of pions at the target against the amount of primary beam incident on the pion production target. At 98.0 and 163.2 MeV, pions are counted by activating disks of plastic scintillation material in the pion beam and measuring the ^{11}C decay arising from the reaction ^{12}C(π^+,x)^{11}C, whose cross sections are known.[19] At 228.3 MeV, no activation was made; however, data were acquired from the reaction ^{7}Li(π^+,π^0)^{7}Be(IAS), whose cross section at 0° is known[2] at this energy. Analysis of the π^0 spectrum from ^{7}Li SCE permitted the number of pions incident on the target per unit of primary beam to be inferred. This technique was also employed with the 100 and 165 MeV pion beams, where it was found to agree with the activation results to within experimental errors.

The spectrometer efficiency ϵ is taken to be the product of the probability of converting the π^0 decay photons in both arms of the spectrometer,[17] the efficiency of the spectrometer multiwire proportional chambers, and the ~90% efficiency in reconstructing valid charged-particle tracks in the chambers.

The geometric solid angle for each angle bin, $\Delta\Omega$, was calculated by a Monte Carlo simulation program[17] that incorporated the beam and target geometry, the energy spread of the beam, the ionization energy loss and straggling in the target, the photon-detector geometry, the photon position and energy resolutions, and the constraints applied in sorting the raw data. The program also determines a line shape corresponding to monoenergetic π^0's and the average π^0 scattering angle for each of the angle bins. The calculated π^0 line shapes were then used in the peak fitting described above. The widths of the Monte Carlo line shapes were in good agreement with the observed energy resolutions. The average scattering angles and their one-standard-deviation uncertainties are given in Table II.

IV. RESULTS

The cross sections calculated with the foregoing prescription are listed in the fourth column of Table II. The systematic uncertainties reflect the ambiguities in assigning the background levels beneath the peaks. We estimate an overall normalization uncertainty of 12% for the 98.0- and 163.2-MeV data arising from a 5% uncertainty in the target thickness, a 10% uncertainty in the spectrometer efficiency, and a 5% uncertainty in the determination of the beam flux. These same uncertainties for target and efficiency, along with a 16% uncertainty in the beam flux, contribute to an overall normalization uncer-

TABLE III. Results of fitting angular distributions to the form $f(\theta)=a\{J_0^2(qR)+\frac{1}{2}(\overline{\Delta\theta})^2(d^2/d\theta^2)[J_0^2(qR)]\}$.

Nucleus	T_π (MeV)	$\overline{\Delta\theta}$ (deg)	a (mb/sr)	R (fm)	Density radii[a] 50% (fm)	15% (fm)
^{165}Ho	163.2	3.0	2.31±0.51	7.11±1.91	6.18	7.17
	98.0	3.0	0.71±0.13	5.66±1.55		
^{120}Sn	165	1.5	1.81±0.28	5.22±0.81	5.32	6.32

[a]Reference 20.

tainty of 20% for the 228.3 MeV data.

Fits were made to the angular distributions shown in Table II to provide information regarding the magnitude and shape of the distributions, relative to both the previously established[4] systematics of the SCE reaction and to the strong absorption model of SCE.[8] The fitting function is based on the presumed[8] Bessel-function shape of the angular distribution, $J_0^2(qR)$, and includes a term that accounts for changes of the true angular distribution over the range of the angular acceptance of the spectrometer. The function used was

$$f(\theta)=a\{J_0^2(qR)+\tfrac{1}{2}(\Delta\theta)^2\frac{d^2}{d\theta^2}[J_0^2(qR)]\}\ , \tag{3}$$

where $q=2k\sin(\theta/2)$, k is the beam momentum, R is an effective nuclear radius at which the interaction takes place, θ is the scattering angle, and $\Delta\theta$ is the one-standard-deviation spread in the angular acceptance. The fitting routine permits only the normalization a and the radius R to vary. The results for the ^{165}Ho data, shown in Table III, are in agreement with the 15%-density radius for ^{165}Ho tabulated by deJager, deVries, and deVries,[20] with pion elastic scattering,[21] and with the giant resonance data of Erell *et al.*[22]

A correction to the measured cross sections, due to the effects of the finite solid angle of the spectrometer, was determined separately. The correction was made by estimating the smearing of the "true" angular distribution by the angular acceptance of the spectrometer. For the purposes of the calculation, the shape of the "true" angular distribution was taken to be $J_0^2(qR)$, where R is now the nuclear radius found by the fitting procedure described above. The form of the correction for the ith angular bin was

$$c_i=\frac{J_0^2(q_iR)}{\langle J_0^2\rangle_i}\ , \tag{4}$$

where q_i is evaluated at the mean scattering angle θ_i as determined by the Monte Carlo calculation, and

$$\langle J_0^2\rangle_i=\frac{\int J_0^2[2kR\sin(\theta/2)]f(\theta)d\theta}{\int f(\theta)d\theta}\ . \tag{5}$$

The function $f(\theta)$ in Eq. (5) represents the angular acceptance for the ith angular bin, and was taken to be a Gaussian distribution with mean θ_i and standard deviation $\Delta\theta_i$. The latter parameter is also determined by the Monte Carlo calculation. The corrections c_i are shown in Table II, along with the widths $\Delta\theta_i$.

Comparisons between nuclei are made on the basis of the magnitudes of the zero-degree scattering cross sections. The systematics of 0° pion SCE scattering between 100 and 295 MeV have been established[1,4] for a wide range of nuclear masses. The zero-degree cross sections follow[4] the form

$$\frac{d\sigma}{d\Omega}(0^\circ)=g(E)(N-Z)A^{-\alpha(E)}\ . \tag{6}$$

At 165 MeV, $\alpha(E)$ is consistent with the value[8] $\frac{4}{3}$, in agreement with the predictions[8] based on strong absorption. Figure 3 shows the previously reported 0° cross sections[1,4] (divided by neutron excess) as a function of the nuclear mass A. The solid lines represent the results[4] of fitting these earlier data to the form given in Eq. (6). The open circles in Fig. 3 represent the present work, where we have extrapolated the 98.0 and 163.2 MeV data to zero degrees by evaluating Eq. (3) at $\theta=0$, using the parameters given in Table III. At 228.3 MeV, where only one point on the angular distribution was available, the 0° cross section was taken to be $[J_0^2(qR)]^{-1}$ times the measured cross section, where $R=1.4A^{1/3}$ fm, and q was evaluated at the average scattering angle. The results of these 0° extrapolations are given in Table IV.

In order to illustrate the comparison between a spherical and a deformed nucleus, the 165 MeV ^{120}Sn SCE data of Erell *et al.*[22] were reanalyzed with the methods described above. The results are given in Table II and displayed in Fig. 2, along with the ^{165}Ho angular distribution at 165 MeV. The results of fitting both angular distributions to the fitting function of Eq. (3) are shown as the solid curves in Fig. 2. The fit to the reanalyzed ^{120}Sn data gives an extrapolated 0° cross section of 1.77±0.26 mb/sr. This result is in good agreement with results from both Erell's dissertation[2] (1.80±0.18 mb/sr) and Sennhauser *et al.*[4] (1.86±0.14 mb/sr). The calculated interaction radius for ^{120}Sn is also in agreement with the tabulated[20] value listed in Table III. The Bessel-function form is seen to be in good agreement with both angular

TABLE IV. Extrapolated 0° cross sections for ^{165}Ho$(\pi^+,\pi^0)^{165}$Er(IAS).

T_π (MeV)	$[d\sigma(0^\circ)/d\Omega]_{\mathrm{c.m.}}$ (mb/sr)
98.0	0.676±0.110
163.2	2.00±0.31
228.3	3.41±1.24

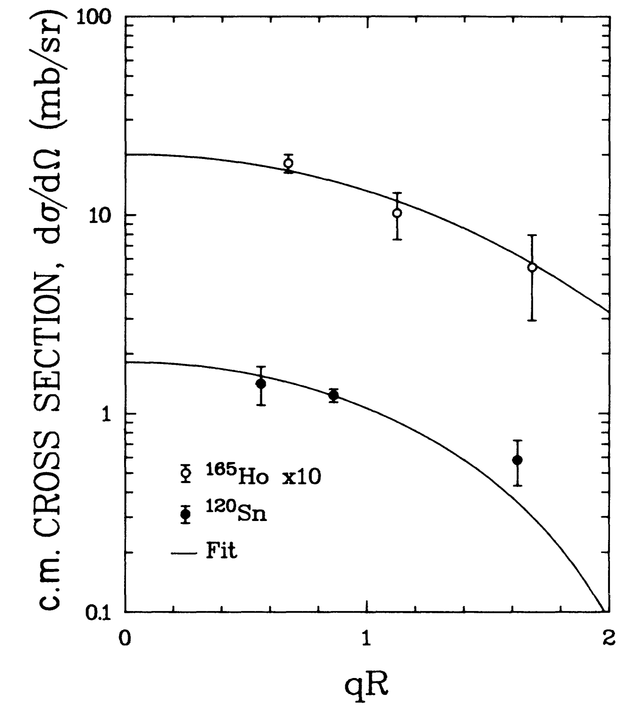

FIG. 2. Comparison of the angular distribution for pion single-charge exchange at 165 MeV on ^{165}Ho and ^{120}Sn. The solid curves show the fit to Eq. (3).

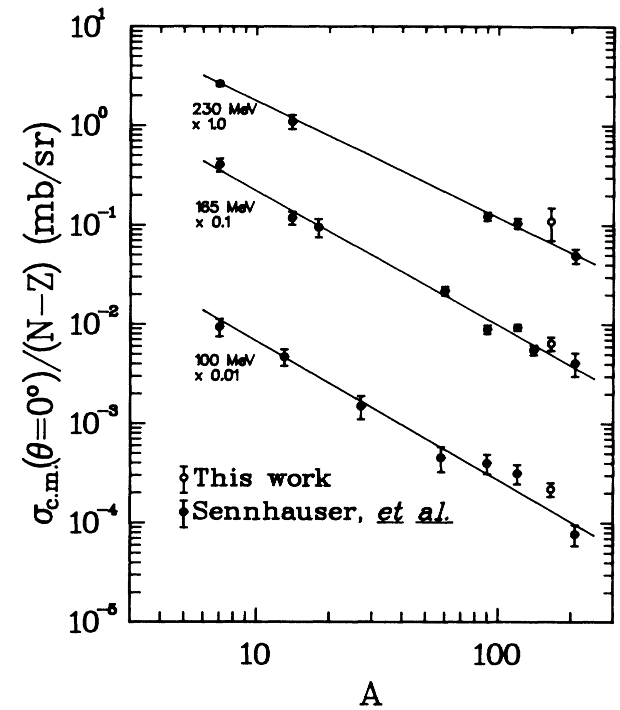

FIG. 3. Systematics of the (π^+,π^0) reaction as a function of nuclear mass. The solid points are data reported by Sennhauser *et al.* (Ref. 8).

distributions, thus indicating the validity of extending the prediction[8] of Johnson from spherical to deformed nuclei.

The differences between the present 0° cross sections and the trend given by Eq. (6) appear to be significant only for the 98.0-MeV point. Taken as a whole, however, the present 0° cross sections average about 1.6 times the value given by Eq. (6). Consistent enhancement of one nucleus relative to the others was not noted by Sennhauser *et al.*[4] in their work; however, these earlier data do exhibit significant nonstatistical fluctuations around the systematic curves which are evident in Fig. 3, even for the best-determined case of 165 MeV. The straightforward geometric model may not be sophisticated enough to be able to account for details, such as shell effects, which may cause deviations of 0° cross sections away from the form given by Eq. (6).

Several explanations to account for the observed enhancement can be ruled out. Noting that the SCE cross section is proportional to the square of the circumference of the nucleus as seen by the incoming beam, one might argue that the deformed ^{165}Ho nucleus may present a larger effective circumference when averaging over all possible orientations of the nuclear symmetry axis with respect to the beam direction. This effect, however, cannot account for more than a few percent of the enhancement, as indicated by the similarity of the perpendicular and parallel orientation cross sections shown by Chiang and Johnson.[16]

A second possible source of an enhancement is an increase in the diffuseness of the neutral density distribution in ^{165}Ho relative to other nuclei. While the diffusenesses of the charged matter densities of deformed nuclei appear to be no different from those of spherical nuclei,[20] there is no information regarding the diffuseness of the neutral density. Thus the observed enhancement in the 0° cross sections may be evidence for an increased overall diffuseness of the neutral density in deformed nuclei.

We made some theoretical calculations of the neutron and proton densities in ^{165}Ho to test this latter hypothesis. The densities were calculated with the program BRACK (Ref. 23) incorporating the Negele[24] density-matrix-expansion effective nucleon-nucleon interaction. The test was to compare the ratio of

$$\frac{\Delta\rho}{\rho}=\frac{\rho_n-\rho_p}{\rho_n+\rho_p} \tag{7}$$

to $(N-Z)/A$ for ^{165}Ho with the established ratios[8] for the spherical nuclei, where ρ_n (ρ_p) is the calculated neutron (proton) density, and $\Delta\rho/\rho$ is evaluated at the interaction radius. Enhanced cross sections would be seen in the event that the ratio

$$r_\rho=\frac{\Delta\rho/\rho}{(N-Z)/A} \tag{8}$$

for ^{165}Ho is larger than that of the spherical nuclei. Our result, $r_\rho=1.2$ at $R=7.1$ fm, is smaller than that for other nuclei, so that density effects appear to be ruled out as a cause of the enhanced ^{165}Ho cross sections.

V. SUMMARY AND CONCLUSIONS

Forward-angle cross sections for $^{165}\mathrm{Ho}(\pi^+,\pi^0)^{165}\mathrm{Er}$ (IAS) have been measured in the region of the (3,3) resonance. The shapes of the differential cross sections are consistent with the form $J_0^2(qR)$ as predicted[8] by Johnson. The extrapolated 0° cross sections for the strongly deformed nucleus ^{165}Ho fall somewhat above the phenomenological systematics established by Sennhauser *et al.*,[4] but the amount of disagreement is not markedly larger than the nonstatistical scatter of data from spherical nuclei. The strong IAS signals observed in (π^+,π^0) reactions suggest that asymmetry measurements, such as those suggested by Chiang and Johnson, are feasible for ^{165}Ho, and possibly for other easily oriented nuclei as well. An experiment incorporating an oriented ^{165}Ho target is in preparation.

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