Differential isomeric ratios following two-proton knockout from ^{208}Pb

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A theoretical analysis of experimental results [Phys. Rev. C **80**, 064608 (2009)] for isomeric ratios of ^{206}Hg residues, following direct two-proton knockout from ^{208}Pb , is extended to consider their dependence on the longitudinal momentum of the residues. Despite the significant degree of experimental (thick target) momentum broadening, the isomeric ratio retains a significant sensitivity to this momentum. The measured distribution is well reproduced by calculations that assume the direct two-proton removal mechanism. Adjustments to the isomeric residue momentum distribution due to possible additional (unobserved) prompt feeding of the 5^- isomeric state are also discussed.

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Introduction—Earlier work on the $^{46}\text{Ti}(-\text{nnp})$ reaction channel indicated that the measured isomeric ratio of high-spin isomeric states was strongly dependent on the residue linear momentum [1]. Numerous isomers populated via the fragmentation of ^{92}Mo showed a similar sensitivity [2]. Studies on lighter projectiles have also clarified the sensitivity of the residue momenta to the angular momentum of the removed nucleon(s) in fast nucleon knockout reactions (e.g., Refs. [3,4]). As an addition to our previous work of Ref. [5], in which the population of isomeric states via direct two-proton removal was considered, we have now extracted such differential information for ^{206}Hg residues from the recent relativistic ^{208}Pb beam experiment of Ref. [6].

Our previous analysis considered isomeric population ratios following two-proton removal from ^{208}Pb , obtaining reasonable agreement with the experimental measurements. In particular, the experimental isomeric ratio ($21.9^{+1.2}_{-2.9}\%$) for the $2.09\text{ }\mu\text{s}$ 5^- isomer in ^{206}Hg was well described by the yield from the direct two-proton removal mechanism, after due consideration of the observed feeding from the higher-lying 7^- , 8^+ , and (isomeric) 10^+ states. A theoretical value of 18.8% was obtained. Here we compare new data for residue momentum distributions and isomeric production ratios as a function of the residue momentum, with the theoretical expectations based on the direct two-proton removal mechanism. In addition, we consider the effects of experimental cuts on the residue momentum distribution imposed by slits in the fragment separator.

Differential Isomeric Ratios—We first state some definitions. The isomeric ratio R is defined as the ratio of the cross section for populating the isomeric state σ_I to the inclusive cross section for the population of all final states σ_T . Decomposing, with respect to momentum,

$$R = \frac{\sigma_I}{\sigma_T} = \frac{\int dK_A \sigma_I(K_A)}{\int dK_A \sigma_T(K_A)}, \quad (1)$$

where $\sigma(K_A) = d\sigma/dK_A$ and K_A is the residue momentum in the laboratory frame. To compare with the measurements, the range of the K_A integrals must be that of the appropriate experimental setup.

For the 5^- isomer case of interest here the measured isomer cross section will also include contributions due to the direct population of the three higher-lying states (the 7^- , 8^+ , and 10^+ states) that are observed to feed the 5^- isomer and contributions from additional, unobserved transitions. Our primary consideration here is the isomeric ratio as a function of the momentum K_A . We define

$$Q(K_A) = \sigma_I(K_A)/\sigma_T(K_A), \quad (2)$$

which is thus related to the isomeric ratio R by

$$R = \frac{1}{\sigma_T} \int dK_A Q(K_A) \sigma_T(K_A). \quad (3)$$

This form is helpful when considering the effects of possible unobserved 5^- state feeding, to be discussed in the following.

Experimental Considerations—As was discussed in detail in Ref. [6], the ^{208}Pb fragmentation experiment was performed at the GSI (Helmholtzzentrum für Schwerionenforschung GmbH), Darmstadt, Germany at 1 GeV/u incident energy. As the heavy ^{206}Hg reaction residues are so close in mass and charge to the ^{208}Pb primary beam, slits were placed in the spectrometer, following the 2.526 g/cm^2 ^9Be reaction target, to best eliminate the unreacted beam and to protect the downstream detectors. The physical slits are placed after the first dipole, at position S1, of the fragment separator (FRS) [6].

The corresponding laboratory frame residue momenta K_A can be calculated event by event by measuring the x position after the second dipole, at position S2, of the FRS using

$$K_A = K_A^0 \left(1 + \frac{x}{D}\right), \quad (4)$$

where $x = 0$ corresponds to the a residue momentum of $K_A^0 = 3.0823 \times 10^5\text{ MeV/c}$ and D is the spectrometer dispersion constant. D takes the value -2150 mm at S1 and 6474 mm at S2. Thus, larger values of the S1 position correspond to smaller residue momenta. The S1 slit positions were believed to be $0 < x < 10\text{ mm}$ [5]. The precise slit positions are important for discussion of the total residue transmission and the reduction of isomeric ratios due to preferentially cutting the extremities of the momentum distribution. However, due to the considerable (thick) target broadening effects both of these effects were found to be weak in the present experimental setup.

The theoretical calculations described in the following are performed in the projectile rest frame. These intrinsic reaction-mechanism-induced momentum distributions are then convoluted with the target-broadened residue distribution calculated using LISE++ [7], as was described in Ref. [5].

Direct two-proton removal—The theoretical momentum distribution of the 5^- isomer residues is calculated as the sum of the contributions from direct population of the 5^- state and the 7^- , 8^+ , and 10^+ states that are observed to feed into the 5^- isomer in ^{206}Hg . Residues produced in all of these relatively high-spin states have wide reaction-mechanism-induced momentum distributions $\sigma_I(\kappa_c)$ in the projectile rest-frame compared to the inclusive distribution $\sigma_T(\kappa_c)$. The latter is calculated from the yields to all 52 particle-bound shell-model final states expected to be populated. Further details of the theoretical calculations can be found in Refs. [5,8,9].

The theoretical and experimentally determined residue momentum distributions are compared in the upper part of Fig. 1. Due to the strong target broadening there are relatively

FIG. 1. (Color online) Cross sections $\sigma(K_A)$ and isomeric ratios $Q(K_A)$ as a function of residue momentum in the laboratory frame. The upper panel shows the theoretical inclusive residue momentum distributions for all final states (solid red line) and for those states known to contribute to the 5^- state isomeric ratio ($\times 5$, dashed). The theoretical curve has been offset by -0.0009×10^5 MeV/c. The red points show the experimental position distribution at S2, converted to momentum. The ratio of the theoretical to experimental curves is also shown (green square points and green dashed line) and shows excellent agreement in the center of the transmitted distribution. The lower panel shows the corresponding isomeric ratio $Q(K_A)$ for the raw theoretical calculation (solid), with the constant 3.1% correction (dashed), and from scaling by 21.9/18.8 (open circles). The two correction schemes give very similar results in the center of the distribution where the cross section is largest. The data points show fully stripped (red circles) and hydrogen-like (blue squares) residue events. The vertical dashed lines show the approximate positions of the spectrometer slits at position S1 (see text).

small differences between the theoretical isomeric and total momentum distributions. The theoretical calculations were offset (by -0.0009×10^5 MeV/c) to match the peak of the experimental distribution. Also shown is the ratio of the theoretical and experimental distributions for all ^{206}Hg residues (upper panel, green curve, and filled square symbols), showing excellent agreement in the region $(3.075 - 3.08) \times 10^5$ MeV/c. The ratio curve is symmetric about its center, indicating that the slits are cutting in a similar manner on both sides of the K_A distribution. This comparison also allows us to deduce the approximate position of the slits; placing the estimated slit positions at the points where the experimental transmission is half the theoretical value suggests that the slit positions, indicated by the vertical dashed lines in Fig. 1, were centered at ~ 3.7 mm, transmitting residues in the region $-0.3 < x < 7.7$ mm.

It is clear that the slits do not cut the momentum distribution sharply and a number of events are observed at x positions (and deduced momenta) that should be excluded by the slits. The cuts in the residue position distribution are sharp at the S1 slits, but neither the S1 slits nor the S2 position detectors are placed precisely at the relevant focal plane, giving a diffuse edge to the distribution. Conversion of the x positions to momentum is then imprecise since we assume the slits and detectors are at the focal plane, and in reality, each position at S2 represents a (narrow) range of residue momenta.

The present differential isomeric ratio calculations, $Q(K_A)$, are compared to the experimental data in the lower panel of Fig. 1. The bare theoretical calculation (solid curve) is generally smaller than the data (solid square and circular points), but the K_A dependence is in good agreement. This magnitude mismatch is expected since, as was noted previously, the theoretical momentum integrated isomeric ratio of 18.8% is at the lower limit of the measured value $21.9^{+1.2}_{-2.9}\%$. The measured and theoretical momentum distributions both show an increase in the isomeric ratio with decreasing K_A .

We now take account of the mismatched magnitudes of the $Q(K_A)$. The theoretical underestimation of R is most likely due to prompt feeding into the 5^- state that is unobserved experimentally and so is unaccounted for in σ_I , though included in the calculation of σ_T . We associate the magnitude of this contribution with the observed deficit $R_{\text{exp}} - R_{\text{th}}$, but have no way of assessing the momentum distribution associated with these contributions. The simplest correction to $Q_{\text{th}}(K_A)$ is to assume that the momentum distribution of the unobserved feeding is the same as due the observed feeding. This is reasonable if the additional states are of high spin. Making this correction, the $Q_{\text{th}}(K_A)$ curve in Fig. 1 is simply scaled by the factor $R_{\text{exp}}/R_{\text{th}}$. The result is shown by the open circles.

Alternatively, the missing 5^- isomer feeding can be assumed to have the same residue momentum distribution as the inclusive cross section $\sigma_T(K_A)$. In this case we must add the deficit as a constant ($R_{\text{exp}} - R_{\text{th}}$) to $Q_{\text{th}}(K_A)$ [see Eq. (2)] with the momentum distribution of $\sigma_T(K_A)$. The result is shown by the dashed curve in Fig. 1. Both (small) corrections give very similar results and agree well with the current data set. With the corrections taken into account, the moderate underestimate of the data for small momenta and

overestimation in the distribution center suggests potential feeding comes from high-spin states.

As was discussed previously, the precise position of the slits is unclear; an estimate is indicated by the vertical dashed lines in Fig. 1. It is evident that there is some cutting of the momentum distribution for the lowest two and highest three points, but there is no immediate reason to suspect the isomeric states should be preferential cut (or transmitted) for a particular K_A . The increase in $Q_{\text{exp}}(K_A)$ for small K_A is consistent with our calculations, but the large decrease at large K_A , for the last two points in particular, is curious. Regardless of the cuts, we will expect the experimental distribution $Q_{\text{exp}}(K_A)$ to be symmetric about the center, but it patently is not. For this reason these points, and accordingly, the lowest momentum points should be treated with caution.

The differential isomeric ratio will evidently be more apparent if a thinner target were to be used. While a thinner target will offer a lower total yield, the narrower momentum distribution will allow for more effective and efficient cuts. Calculations for different momentum bins were presented in Ref. [5] (Fig. 2). Here we present the quantity $Q(\kappa_c)$, the isomeric ratio as a function of the residue momentum in the projectile rest frame, in Fig. 2; in effect we assume a zero-thickness target. The sensitivity to the residue final-state spin is now clear and can potentially be used to identify the spin of specific isomeric states. Certainly the difference between low-spin and high-spin isomers should be clear. Though the isomeric ratio for high-spin states increases dramatically for the extremes of the residue momentum, the cross section falls rapidly also, giving significantly reduced yield.

In principle, cuts on the residue momentum can be used to enhance the proportion of an isomeric state in a secondary beam, which can then be used for reaction studies. An example related to the present case can be the creation of a secondary beam of ^{207}Tl in the $11/2^-$ 1.33 s isomeric state. A second proton knockout reaction will then preferentially populate high-spin states in ^{206}Hg when compared to the yields from the direct two-proton knockout mechanism, discussed here, though the alignment of the isomeric state must also be carefully considered.

Summary—In summary, we extended the results of previous work to confront new data on the $^{206}\text{Hg}(5^-)$ state residue momentum distribution and isomeric ratio as a function of residue momentum. The data, obtained from the fragmentation of a 1 GeV/u ^{208}Pb primary beam, are compared with

FIG. 2. Calculated isomeric ratios, as a function of residue momentum, in the projectile rest frame in the absence of broadening of the distributions by the target. The lines show the individual contributions for the 5^- (dashed), 7^- (solid), 8^+ (dotted), and 10^+ (dot-dashed) states. The total distribution is shown by the solid line and open circles. The distribution expected for the 0^+ ground-state transition is also shown (solid triangles), multiplied by a factor of 5. At large momenta, not only does the total 5^- isomeric ratio increase, but it is also dominated by events populating the 10^+ isomeric state.

direct two-proton removal reaction mechanism expectations and a reasonable agreement is obtained. The residue's spin alignment along the beam direction can also be calculated and is expected to show a strong sensitivity to the residue momentum. Such more complete differential data are beyond the scope of the present experimental capabilities. Further precision measurements using thinner targets, particularly of single-nucleon knockout and absolute cross sections, will allow further verification of the direct reaction mechanism for heavy mass projectiles and for which the present results offer much encouragement.

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