# Low-Energy Enhancement in the Photon Strength of $^{95}$Mo

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(Received 10 January 2012; published 19 April 2012)

A new experimental technique is presented using proton-$\gamma$-$\gamma$ correlations from $^{94}$Mo$(d, p)^{95}$Mo reactions which allows for the model-independent extraction of the photon strength function at various excitation energies using primary $\gamma$-ray decay from the quasicontinuum to individual low-lying levels. Detected particle energies provide the entrance excitation energies into the residual nucleus while $\gamma$-ray transitions from low-lying levels specify the discrete states being fed. Results strongly support the existence of the previously reported low-energy enhancement in the photon strength function.

DOI: 10.1103/PhysRevLett.108.162503 PACS numbers: 21.10.Pc, 25.45.Hi, 27.60.+j, 29.30.Ep

The density and width of nuclear excited states increase with excitation energy towards the particle separation energies creating a quasicontinuum of levels in heavier nuclei. Nuclear properties in this excitation-energy region are believed to be best characterized using statistical quantities such as nuclear level density and the photon strength function $f(E_\gamma)$ which is the ability of atomic nuclei to emit and absorb photons with energy $E_\gamma$. Usually it is assumed—according to the Brink hypothesis [1]—that $f(E_\gamma)$ is a function of $E_\gamma$ only. As critical input in statistical reaction models, a full understanding of $f(E_\gamma)$ is of central importance for advanced fuel cycles [2] and astrophysical element formation [3,4]. For the latter, these reaction models are used to calculate cross sections in astrophysical settings for neutron-capture reactions that are believed to be responsible for the formation of virtually all elements heavier than iron. The impact of $f(E_\gamma)$, with an even slight modification due to pygmy resonances, on calculated astrophysical reaction rates has been discussed [5]. Recently, the influence of $f(E_\gamma)$ with a modest low-energy enhancement on the neutron-capture reaction rate calculations in the $r$ process has been investigated for Fe, Mo, and Cd isotopes [6]. It was demonstrated that the low-energy enhancement can cause order of magnitude changes in the astrophysical relevant energy region of these neutron-capture cross sections with the potential to significantly influence elemental and isotopic production.

Studies of $f(E_\gamma)$ have benefited from a wealth of data collected in neutron-capture [7], charged-particle induced reactions [8], and from photon scattering facilities [9,10]. The majority of available experimental methods, however, rely on the use of models because measured $\gamma$-ray spectra are simultaneously sensitive to both the nuclear level density and $f(E_\gamma)$. Additionally, data from different reactions are often incompatible [11] which causes difficulties in fully understanding $f(E_\gamma)$. In the last decade a significant disagreement between different measurements of $f(E_\gamma)$ has emerged in the form of an unexpected increase in $f(E_\gamma)$ at low $\gamma$-ray energies (below $\approx 3$ MeV) as reported in many light-to-medium mass nuclei from charged-particle induced reactions [12–17]. However, analyses of data from radiative neutron-capture experiments do not support its presence [18] or are inconclusive [19]. Further complicating this debate is the lack of any theoretical mechanism for such an enhancement despite its implications on fundamental processes.

In light of its importance and experimental disagreements, a new model-independent experimental technique is required to address questions regarding the existence of this low-energy enhancement in $f(E_\gamma)$. In this Letter such an approach is presented for determining the shape of $f(E_\gamma)$ over a wide range of energies free of model dependencies. The method involves the use of coupled high-resolution particle and $\gamma$-ray spectroscopy to determine the $\gamma$-ray emission probabilities from the quasicontinuum to discrete low-lying levels of known spins and parities. The power of the new technique lies in the ability to positively identify $\gamma$ decay from a defined excitation-energy region to individual well-resolved states (referred to as primary transitions) and was used to study the shape of $f(E_\gamma)$ in $^{95}$Mo. The result independently verifies the existence of the enhancement in $f(E_\gamma)$ for low $\gamma$-ray energies as reported in Ref. [13].

 

The measurement was carried out at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory. Excited $^{95}$Mo nuclei were produced by the $^{94}$Mo($d$, $p$) reaction at a beam energy of 11 MeV incident on a 1 cm diameter target of thickness 250(6) $\mu$g/cm$^2$. The average beam current during the 3-day experiment was ~5.5 nA. The STARS-LiBerACE detector array [20], consisting of Compton suppressed high-purity germanium clover-type detectors [21,22] and large area segmented annular silicon detectors (assembled to $\Delta E$-$E$ telescopes) [23], was used to detect coincident $\gamma$ radiation and charged particles, respectively. (LiBerACE stands for Livermore Berkeley Array for Collaborative Experiments; STARS stands for Silicon Telescope Array for Reaction Studies.) Five clover detectors were placed at a distance of 20 cm from the target. Two identical $\Delta E$-$E$ telescopes were placed on opposite sides of the target with 150 $\mu$m $\Delta E$ and 1000 $\mu$m $E$ detectors. The telescopes were mounted downstream and upstream of the target with the $\Delta E$ detectors covering an angular range of 28° to 56° and 118° to 145°. Gamma events of multiplicity one or greater were recorded if they were associated with a particle detected in one of the $\Delta E$-$E$ telescopes within a 550 ns coincidence window. For offline analysis the coincidence windows were further reduced to 100 ns.

From well-resolved low-lying levels in the particle spectra, the total uncertainty in the particle energy, due to beam-energy spread and energy resolutions of the $\Delta E$-$E$ telescopes, was measured as ~200 − keV FWHM. Energy and efficiency calibrations of high-purity germanium detectors for low-energy $\gamma$ rays were performed using a $^{152}$Eu $\gamma$-ray source while for higher-energy $\gamma$ rays the $^{12}$C($d$, $p$)$^{13}$C and $^{13}$C($d$, $p$)$^{14}$C reactions were used. The 204-keV transition from the first-excited state in $^{95}$Mo is of particular importance to this work. An efficiency of 2.4(1)% for this transition was determined separately from $p$-$\gamma$ and $p$-$\gamma$-$\gamma$ coincidence data using the 204 and 582 keV transitions. The $\gamma$-ray efficiency in add-back mode for a 1 MeV transition is 1.03(4)% and decreases to 0.26(3)% for the 6.90 MeV $^{14}$C line.

The experiment was designed to investigate statistical feeding from the quasicontinuum to individual low-lying levels $L_j$ with energies $E_{L_j}$ in $^{95}$Mo. The excitation energy $E_i$ in the residual nucleus is obtained from measured proton energies in the $\Delta E$-$E$ telescopes and only $p$-$\gamma$-$\gamma$ events fulfilling two conditions are considered: (i) a known $\gamma$-ray transition deexcites a well-resolved low-lying level of energy $E_{L_j}$, (ii) the energy of the second $\gamma$ ray—referred to as the primary $\gamma$ ray—is equal to $(E_i - E_{L_j})$ with 200 keV precision due to the resolution of the $\Delta E$-$E$ telescopes. Any $p$-$\gamma$-$\gamma$ event satisfying these conditions provides an unambiguous determination of the origin and destination of the observed primary transition in $^{95}$Mo, assuming that the emission of primary transitions with energies $\leq$ 400 keV in the quasicontinuum is negligible. Figure 1 illustrates the procedure to extract events of interest. From various initial energies $E_i$, the efficiency-corrected intensities of primary transitions $N_{L_j}(E_i)$ to several levels $L_j$ (corrected for branching ratios) are extracted on an event-by-event basis, and for statistical reasons, collected in 1-MeV wide bins.

The strength $f(E_\gamma)$ of the primary $\gamma$ rays between the gated quasicontinuum region $E_i$ and discrete level with energy $E_{L_j}$ is extracted according to the expression [24]

$$f(E_\gamma) \equiv f_{J^\pi}(E_\gamma) = \frac{\bar{\Gamma}_{J^\pi}(E_i, E_\gamma)\rho_{J^\pi}(E_i)}{E_\gamma^{2\lambda+1}} \qquad (1)$$

where $\bar{\Gamma}_{J^\pi}(E_i, E_\gamma)$ is the average width of primary $\gamma$ rays with energy $E_\gamma$ from levels with spin and parity $J^\pi$ at excitation energy $E_i$, $\rho_{J^\pi}(E_i)$ is the level density at $E_i$, and $\lambda$ is the multipolarity of the transitions. The first equivalence in Eq. (1) is based on the Brink hypothesis.

The intensity of primary transitions $N_{L_j}(E_i)$ is proportional to the sum of the partial radiation width from energy $E_i$. Exploiting Eq. (1) and assuming that dipole transitions strongly dominate, the intensity can be expressed

$$\begin{aligned} N_{L_j}(E_i) &\propto \sum_{J^\pi} \sigma_{J^\pi}(E_i)\bar{\Gamma}_{J^\pi}(E_i, E_i - E_{L_j})\rho_{J^\pi}(E_i) \\ &= f(E_i - E_{L_j})E^3_{(E_i - E_{L_j})}\sum_{J^\pi}\sigma_{J^\pi}(E_i) \qquad (2) \end{aligned}$$

where $\sigma_{J^\pi}(E_i)$ is the cross section for populating the levels with given spin and parity at excitation energy $E_i$. From Eq. (2) the energy dependence of $f(E_\gamma)$ is obtained entirely from experimentally measured quantities (for final low-lying levels of the same $J^\pi$) completely free of any model dependencies. The absolute value of $f(E_\gamma)$ cannot be obtained using this present approach.

Intensities of primary transitions to the following 13 low-lying levels were measured (energies in keV): 204 ($3/2^+$), 766 ($7/2^+$), 786 ($1/2^+$), 821 ($3/2^+$), 948

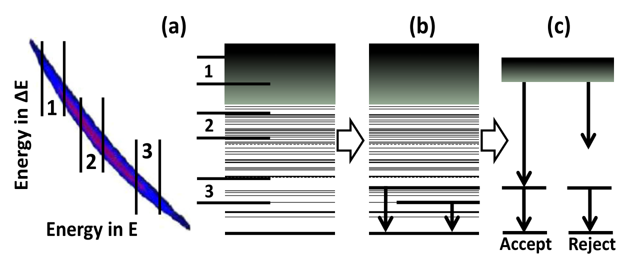


FIG. 1 (color online). Procedure to extract primary $\gamma$-ray transitions: (a) Tagging on proton energies determines the excitation energy of the residual nucleus. High (low) proton energies yield low (high) excitation energies. (b) Low-lying levels are selected by tagging on emitted $\gamma$ rays. (c) Applying the condition that the sum of discrete and primary $\gamma$-ray energies must be equivalent to the excitation energy (e.g., region 1) provides acceptable events of unambiguous origin and destination. Transitions not satisfying the requirements are rejected.

$(9/2^+)$, 1039 $(1/2^+)$, 1074 $(7/2^+)$, 1370 $(3/2^+)$, 1426 $(3/2^+)$, 1552 $(9/2^+)$, 1620 $(3/2^+)$, 1660 $(3/2^+)$, and 3043 $(3/2^+)$. Previously published level and transition energies as well as spin assignments [25] for all 13 levels were verified using $p$-$\gamma$ and $p$-$\gamma$-$\gamma$ coincidence events [26]. Only four minor discrepancies with respect to Ref. [25] were identified: (i) for the 1370 keV level the $3/2^+$ assignment was reported in an early $(d, p)$ measurement [27] in agreement with the present spin assignment. The positive-parity character was verified in a $(\vec{p}, d)$ reaction [28], (ii) the level at 1426 keV has been reported as $3/2^+$ [27,28] in agreement with a 3/2 spin assignment from the present analysis, (iii) the level at 1660 keV exhibits spin 3/2 characteristics, consistent with $\leq 5/2$ [25]. For this state the assumption of positive parity is made here, (iv) the reported excitation energy for the 3037 keV level [25] has been remeasured and corrected to 3043 keV.

With two levels each of spins 1/2, 7/2, and 9/2 and seven levels with spin 3/2 the dependence of $f(E_\gamma)$, subsequently referred to as $f_{(d,p)}(E_\gamma)$, on $E_\gamma$ is investigated. Unfortunately, a direct comparison of intensities for different $E_i$ and/or $J^\pi$ is very difficult because the term $\sum_{J^\pi} \sigma_{J^\pi}(E_i)$ is not reliably known. When exploiting intensities of primary transitions from the same initial excitation energy $E_i$ to different low-lying discrete levels of the same $J^\pi$ any ambiguity in the spin and energy dependence of the $(d, p)$ reaction cross section can be avoided because $\sum_{J^\pi} \sigma_{J^\pi}(E_i)$ is the same for all these intensities. With this the $^{95}$Mo results of $f_{(d,p)}(E_\gamma)$ are compared to data from the $^{96}$Mo($^3$He, $\alpha$)$^{95}$Mo reaction from the CACTUS array [13], denoted as $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ which were analyzed using the Oslo method [29]. For the purpose of comparison, data of $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ were fitted using a quadratic polynomial in the $\gamma$-ray energy range of 1 to 6.5 MeV, as shown in Fig. 2. The same figure also compares values of $f_{(d,p)}(E_\gamma)$ deduced from the seven 3/2 levels with $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$. From $f_{(d,p)}(E_\gamma)$ only the $E_\gamma$ dependence can be obtained and the data from different $E_i$ are independently normalized to the quadratic polynominal fit of $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ based on a $\chi^2$ minimization.

Visually, the agreement between the two sets of data in Fig. 2 for the entire range of $E_\gamma$, including the region of the low-energy enhancement, is very good. A more quantitative description of the agreement can be made using a standard $\chi^2$ criterion. These $\chi^2$ values have to be calculated separately for each $E_i$ and final $J^\pi$. It should be noted that uncertainties of $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ are only estimates (based on the quadratic fits) which may influence the values of $\chi^2$ somewhat. In addition, any uncertainty connected to expected Porter-Thomas fluctuations [30] of partial radiation widths is not considered separately. The influence of these fluctuations are expected to be smaller than the experimental uncertainties—estimates based on the statistical model indicate fluctuations to be 10% to 15% at most and to

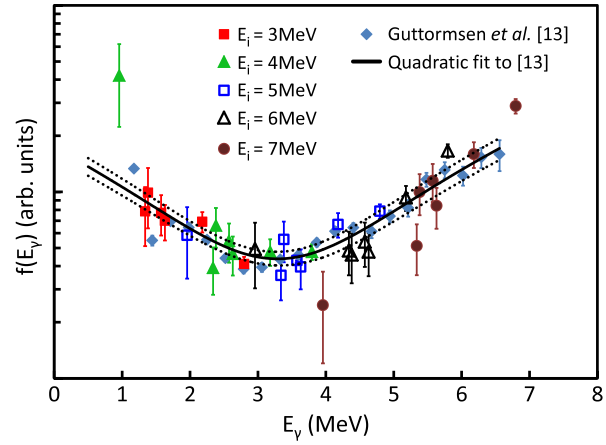


FIG. 2 (color online). Comparison of $f_{(d,p)}(E_\gamma)$ from this work with $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ (filled blue diamonds) from Guttormsen *et al.* [13]. The quadratic polynominal fit to $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ is shown as a solid black line while fitted upper and lower error bars are shown as dotted black curves. Values of $f_{(d,p)}(E_\gamma)$ are extracted from intensities $N_{L_j}(E_i)$ to $3/2^+$ levels using Eq. (2). The absolute normalization of $f_{(d,p)}(E_\gamma)$ is based on an independent $\chi^2$ minimization between the data of this work for each excitation-energy region $E_i$ and the quadratic fit.

decrease with $E_i$—and are partly masked by the estimate in uncertainties of $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$.

In any case, all $\chi^2$ values are fully consistent with the assumption that the results of $f_{(d,p)}(E_\gamma)$ from this work and $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ are in agreement with each other. Specifically, there are no cases which can be excluded on a $\approx 3\sigma$ confidence level.

An alternate approach to compare $f_{(d,p)}(E_\gamma)$ with $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$, again independent of any models but also eliminating systematic uncertainties, can be obtained with the ratio $R$ of $f(E_\gamma)$ for two different primary $\gamma$-ray energies from the same initial excitation energy $E_i$ to discrete low-lying levels of the same spin and parity at energies $E_{L_1}$ and $E_{L_2}$ as

$$R = \frac{f(E_i - E_{L_1})}{f(E_i - E_{L_2})} = \frac{N_{L_1}(E_i)(E_i - E_{L_2})^3}{N_{L_2}(E_i)(E_i - E_{L_1})^3}. \quad (3)$$

A total of 24 ratios can be constructed from each $E_i$ and when the energies of the primary transitions are similar $(E_{L_1} \sim E_{L_2})$ the ratios do not exhibit much variation and have values of $\sim$1 across all excitation energies as shown in Fig. 3(a). This is expected from the statistical model of the decay as the two $\gamma$-ray energies are very similar and the changes in $f(E_\gamma)$ should not be dramatic. Observation of ratios in accord with expectation serves as an important consistency check of the method. On the other hand if the difference between $E_{L_1}$ and $E_{L_2}$ is large enough, specific information on $f(E_\gamma)$ can be extracted. When the ratios are $>1$ $(< 1)$ then $f(E_\gamma)$ is an increasing (decreasing)

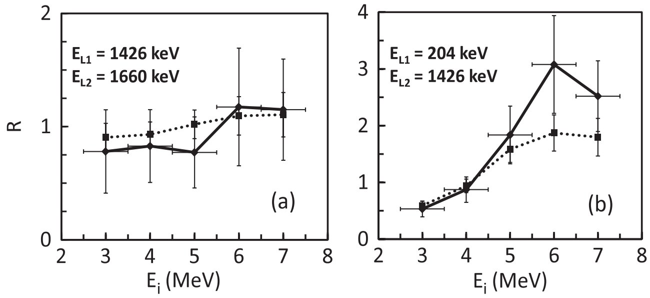


FIG. 3. The ratio $R = f(E_i - E_{L_1})/f(E_i - E_{L_2})$ as a function of excitation energy $E_i$. $E_{L_1}$ and $E_{L_2}$ shown in each panel indicate the low-lying discrete levels being fed by the primary transitions. For each ratio $R$ the numerator includes the higher-energy primary transition. The horizontal error bars are representative of the bin size. The ratios connected by the solid line are experimental results, $R_{(d,p)}$, while those connected by dotted lines are ratios extracted from the fit to the data of Guttormsen *et al.* [13], $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$.

function of $E_\gamma$. For instance, the point at $E_i \sim 3$ MeV in Fig. 3(b) yields $f(E_\gamma \sim 2.8\,\mathrm{MeV})/f(E_\gamma \sim 1.6\,\mathrm{MeV}) \approx 0.5$ while the point at $E_i \sim 7$ MeV in the same panel yields $f(E_\gamma \sim 6.8\ \mathrm{MeV})/f(E_\gamma \sim 5.6\ \mathrm{MeV}) \approx 2.5$. This dependence of $R_{(d,p)}$ on $E_i$ clearly indicates the existence of a minimum near $E_\gamma \sim 3$–4 MeV in $f(E_\gamma)$ (see also Fig. 2). Overall the 24 ratios from all $E_i$ are consistent with the following statement: $f(E_\gamma)$ is an increasing function of $\gamma$-ray energy for $E_\gamma \gtrsim 4$ MeV, a relatively flat function for $E_\gamma \sim 2$–4 MeV, and a decreasing function of $E_\gamma$ for $E_\gamma \lesssim 2$ MeV. The ratios $R_{(d,p)}$ from this work represent a wide primary $\gamma$-ray energy range available for comparison to ratios of $R_{(^3\mathrm{He},\alpha)}$ obtained from the polynominal fit of $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ (solid line in Fig. 2).

The overall comparison between the two data sets is facilitated using residuals, shown in Fig. 4, and defined as

$$\delta = \frac{R_{(^3\mathrm{He},\alpha)} - R_{(d,p)}}{\sqrt{\sigma^2_{(^3\mathrm{He},\alpha)} + \sigma^2_{(d,p)}}}. \tag{4}$$

The deviations ($\delta < 0$) at $E_i = 6$ and 7 MeV indicate that $f_{(d,p)}(E_\gamma)$ is steeper than $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ for $E_\gamma \gtrsim 5$ MeV. At $E_i = 4$ MeV six values (some of them overlap) are found with $\delta > 1.5$ and are due to ratios with the 3043 keV level suggesting an even larger enhancement in $f_{(d,p)}(E_\gamma)$ compared to $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$. Of course, not all $\delta$ values corresponding to a specific $E_i$ and $J^\pi$ are independent.

The agreement between present and previous data confirms the shape of the photon strength function as reported by Guttormsen *et al.* [13]. It should be noted that the present measurement examines photon strength to individual discrete levels only, while the previous work [13] determined the total strength without specific requirements on the energy of the level that is fed by the primary transitions.

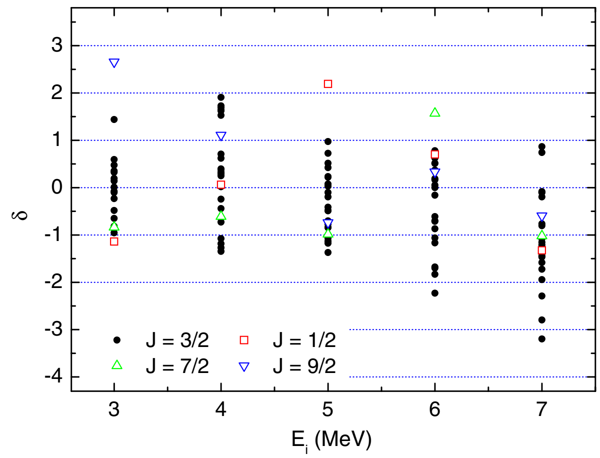


FIG. 4 (color online). Differences between $R_{(d,p)} = f_{(d,p)}(E_i - E_{L_1})/f_{(d,p)}(E_i - E_{L_2})$ and $R_{(^3\mathrm{He},\alpha)} = f_{(^3\mathrm{He},\alpha)}(E_i - E_{L_1})/f_{(^3\mathrm{He},\alpha)}(E_i - E_{L_2})$ [13] expressed in terms of residual $\delta$. Ratios with the 3043 keV level do not contribute to the 3 MeV excitation-energy region.

To be explicit, the gating and energy sum requirements restrict the observation of the low-energy enhancement in $f(E_\gamma)$ to transitions originating from relatively low excitation energies ($E_i < 5$ MeV). The enhancement cannot be studied at higher excitation energies due to the lack of a suitable well-resolved state with $E_{L_j} \gg 3$ MeV. Hence, no statement can be made regarding the possibility of an enhancement from higher excitation-energy regions and any speculation can only be made by invoking the Brink hypothesis. Recently, it has been suggested [29] that the low-energy enhancement may be due to the presence of high-spin initial states which would increase the $\gamma$ multiplicity and the number of low-energy $\gamma$ transitions. This scenario is not supported since only low-spin states have been used in the present work. Furthermore, the neutron pickup reaction to obtain $f_{(^3\mathrm{He},\alpha)}(E_\gamma)$ is different than the neutron-transfer reaction used to measure $f_{(d,p)}(E_\gamma)$. It may be expected that very different initial states are populated in these two reactions, yet the shape of the photon strength functions is very similar.

In summary, a new experimental technique to extract the relative photon strength from the quasicontinuum to individual low-lying levels has been presented. The advantage of this approach lies in its independence to any model input and provides an alternative to other methods. Application of the technique to $^{95}$Mo clearly supports the picture of an increase of the photon strength function at low $\gamma$-ray energies as observed by Guttormsen *et al.* [13]. More precisely, the application of stringent gating requirements allows for observation of the enhancement only from the region of low-excitation energies. Any implication to higher energies is based on the validity of the Brink hypothesis. For astrophysical neutron-capture reaction calculations the mere existence of the low-energy enhancement has implications on reaction rates of some $r$-process nuclei as discussed in Refs. [5,6]. More measurements are desirable, in particular, an experimental campaign populating the same residual nucleus in different reactions may provide valuable insight into the enhancement and its physical origin.

The authors thank the operations staff at the 88-Inch Cyclotron of Lawrence Berkeley National Laboratory for a smooth run. This work is performed under the auspices of the U.S. Department of Energy Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344 and University of Richmond under DE-FG52-06NA26206 and DE-FG02-05ER41379. For Lawrence Berkeley National Laboratory this work was supported by the Director, Office of Science, Office of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. M. W. acknowledges support from the National Research Foundation of South Africa and M. K. from the research plan MSM 0021620859 of the Ministry of Education of the Czech Republic.

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