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# Fusion probability of massive nuclei in reactions leading to heavy composite nuclear systems

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**Abstract.** Reactions between massive nuclei show a considerable reduction in fusion-evaporation cross-sections at the Coulomb barrier according to the comparison of experimental values with those calculated by barrier passing (BP) and statistical model (SM) approximations. Reduced fusion cross-sections corresponding to fusion probability $P_{\mathrm{CN}}<1$ are accompanied by a high probability of deep-inelastic and quasi-fission processes arising on the way to fusion. At the same time, the excitation functions for evaporation residues (ERs) obtained in very mass-asymmetric projectile-target combinations are well described in the framework of the BP model (assuming $P_{\mathrm{CN}}=1$) and SM approximations. In the framework of SM, the survivability of produced heavy nuclei can be described with the use of adjusted macroscopic fission barriers. Fusion suppression appears in less asymmetric combinations, for which $P_{\mathrm{CN}}$ values can be estimated using survivability obtained for very asymmetric ones leading to the same CN. An attempt was made to systemize the $P_{\mathrm{CN}}$ data derived from different projectile-target combinations leading to ERs in the range from Pb to the most heavies, which are compared with $P_{\mathrm{CN}}$ values obtained in fission experiments.

## 1 Motivation and approach

Reactions with massive nuclei show a considerable reduction in fusion at the Coulomb barrier. It follows from the comparison of experimental cross-sections with those calculated using a barrier passing (BP) model. Reduced fusion cross sections are accompanied by a high probability of deep-inelastic and quasi-fission (QF) processes arising on the way to fusion. The detection of evaporation residues (ERs) resulting from a compound nucleus (CN) formation is an unambiguous sign of the complete fusion of projectile and target nuclei, whereas detected fission (fission-like) events do not specify the CN formation since CN-fission strongly interferes with the QF process. Theoretical models describing ER cross-sections $\sigma_{\mathrm{ER}}$ treat them as the product of i) capture cross-section $\sigma_{\mathrm{cap}}$ relating to the formation of a composite (di-nuclear) system, ii) fusion probability $P_{\mathrm{CN}}$ corresponding to the CN formation from the composite system, and iii) survivability against fission $W_{\mathrm{sv}}$ while the CN decays. Most of the models reproduce measured $\sigma_{\mathrm{ER}}$ quite well, but they give $P_{\mathrm{CN}}$ values differed from each other within several orders of the magnitude [1]. Such a difference implies a similar distinction in $W_{\mathrm{sv}}$.

At the same time, available cross-section data on the fusion, fission and ER production, which are obtained in very mass-asymmetric projectile-target combinations, can be well described in the framework of the BP and statistical model (SM) approximations realized in the HIVAP code [2] (see examples in [3]). In that case, the BP cross-section is associated with $\sigma_{\mathrm{cap}}$ equaled to the fusion cross-section with a reasonable assumption that $P_{\mathrm{CN}}=1$. In the calculations of $\sigma_{\mathrm{cap}}$ at sub-barrier energies, the effect of coupling the entrance channel to other reaction channels is taken into account via fluctuations of radius-parameter $r_0$. These fluctuations are generated around average value $r_0=1.12$ fm with a Gaussian distribution and barrier fluctuation parameter $\sigma(r_0)$ [4]. Variations of strength $V_0$ and fluctuation parameter $\sigma(r_0)/r_0$ in the exponential nuclear potential [4] allow one to reproduce the experimental cross-section data for the capture (fusion), CN-fission and ER production in calculations for very asymmetric systems.

The survivability is calculated in the framework of SM approximations with the Reisdorf's expression for calculations of macroscopic level-density parameters in fission and evaporation channels [2]. The macroscopic components of fission barriers adjusted with scaling factor $k_f$ at rotating liquid-drop (LD) fission barriers $B_f^{LD}(L)$ [5] are used in the expression for fission barrier height $B_f(L) = k_f B_f^{LD}(L) - \Delta W_{gs}$. The empirical masses [6] are used to calculate shell correction energies $\Delta W_{gs}$ (determined as the difference between the empirical and LD masses), as well as for the calculations of excitation and separation energies.

Fitting thus calculated excitation functions to the measured ones obtained in very asymmetric projectile-target combinations by adjusting fission barriers, one can get estimates of $W_{\mathrm{sv}}$. Fusion suppression corresponding to $P_{\mathrm{CN}}<1$ appears in less asymmetric combinations. It can be derived using $W_{\mathrm{sv}}$ obtained for very asymmetric combinations leading to the same CN and $\sigma_{\mathrm{cap}}$ measured or obtained with the BP model calculations.

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## 2 $P_{CN}$ from fission study

In heavy ion (HI) experiments, $P_{CN}$ values can be derived with the detection of fission (fission-like) fragments (FFs) and subsequent comparison of a total FF yield including deep-inelastic events with the FF yield assigned to true CN-fission. The events relating to CN-fission are extracted with an appropriate decomposition of the obtained FF angular distributions [7] and with the decomposition of the measured total kinetic energy and mass distributions for FFs [8]. In Fig. 1 $P_{CN}$ values derived from fission studies in reactions with W, Au, and Pb targets [8] are shown as a function of an excess of the interaction energy over the Bass barrier [9]. As one can see, the $^{28}$Si+$^{208}$Pb and $^{30}$Si+$^{197}$Au data, corresponding to nearly the same mass-asymmetry in the entrance channel, are in sharp disagreement with each other. The same is for the $^{32}$S+$^{197}$Au and $^{36}$S+$^{197}$Au data. So as a result, $P_{CN}$ values obtained in the $^{30}$Si, $^{36}$S+$^{197}$Au study were omitted in subsequent analysis (see below).

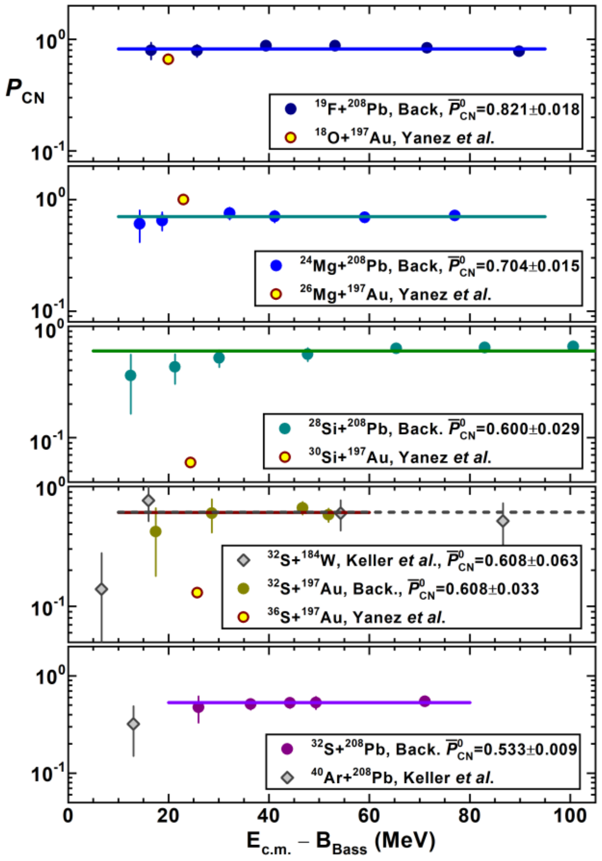

**Fig. 1.** $P_{CN}$ values (symbols) derived from fission studies in reactions with W, Au, and Pb targets [8] are shown as a function of an excess of the interaction energy over the Bass barrier [10]. A constant fit to the data (lines) and appropriate mean values are also indicated.

In Fig. 2 $P_{CN}$ values derived from fission studies in the interaction of $^{238}$U with the Mg to Ca target nuclei and obtained in the $^{40,48}$Ca+$^{238}$U and $^{26}$Mg+$^{248}$Cm reactions [8] are shown as the same function of the energy as shown in Fig. 1. Inconsistency of the data in the vicinity of the barrier [9] only allows one to consider $P_{CN}$ values at energies well above the barrier.

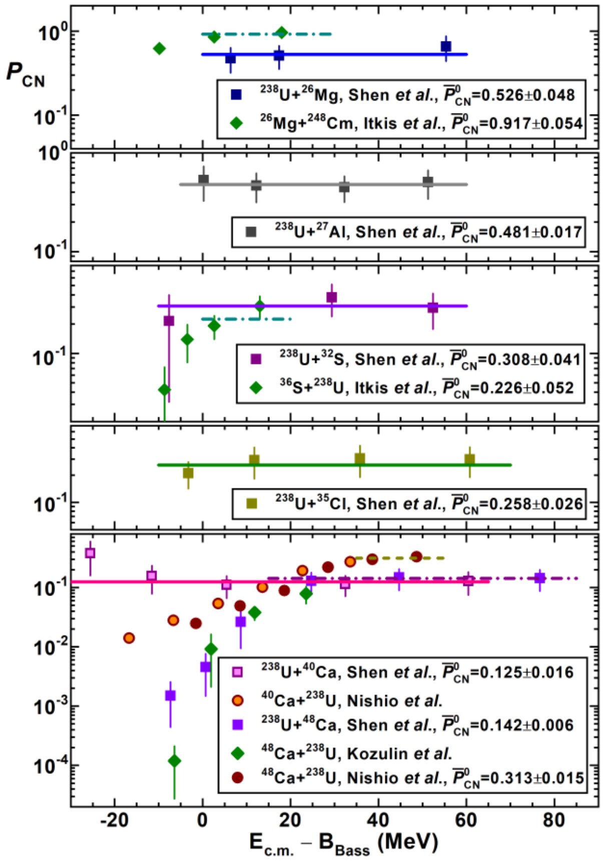

**Fig. 2.** The same as in Fig. 1 but in the cases of the interaction of $^{238}$U with the Mg to Ca target nuclei and for the $^{40,48}$Ca+$^{238}$U and $^{26}$Mg+$^{248}$Cm reactions [8].

## 3 $P_{CN}$ from ER cross sections

The analysis described in Section 1, was applied for the first time to the data obtained in $^{12}$C and $^{48}$Ca reactions leading to $^{216,218}$Ra$^*$ compound nuclei [10]. Then it was used to estimate of $P_{CN}$ using ER cross-section data obtained in some selected very asymmetric and less asymmetric (up to nearly symmetric) projectile-target combinations leading to $^{202}$Pb$^*$, $^{220}$Th$^*$, $^{248}$Fm$^*$ and trans-fermium compound nuclei [11]. These results have been used for further $P_{CN}$ data systemizing (see below).

In Figs. 3 and 4 ER cross-section data obtained recently in reactions induced by $^{44,48}$Ca and $^{50}$Ti on rare-earth elements [12] are compared with the ER and fission excitation functions obtained in very asymmetric reactions [13] leading to the same compound nuclei $^{202}$Po$^*$ and $^{210}$Rn$^*$, respectively. As one can see in Fig. 3, ER and fission cross sections obtained in reactions induced by $^{16}$O and $^{34}$S are well described using the same macroscopic component of fission barriers (the same $k_f$ at the LD values). At the same time, in order to reproduce the excitation functions for the sum of $xn$ evaporation channels $\sum\sigma_{xn}$ obtained in $^{44,48}$Ca reactions, the magnitude of $P_{CN}$=0.27 has to be introduced. A similar situation is observed for the $^{48}$Ca induced reaction leading to $^{210}$Rn$^*$ (see Fig. 4). Despite nearly the same excitation energies at the fusion (Bass) barriers for the reactions with $^{48}$Ca and $^{50}$Ti, $\sum\sigma_{xn}$ drops by an order of magnitude for the latter that corresponds to $P_{CN}$=0.03.

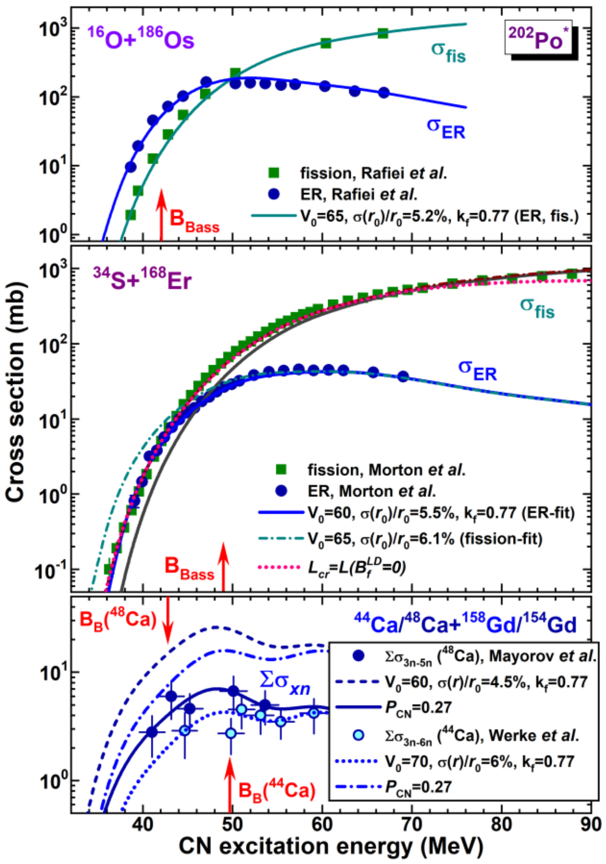

**Fig. 3.** ER, and fission cross sections obtained in reactions induced by $^{16}$O, $^{34}$S [13] and $^{44,48}$Ca [12] that lead to the $^{202}$Po$^*$ CN (symbols) are compared with the calculations [4] using the same scaling parameter $k_f$ = 0.77 at the LD fission barriers (lines). In the cases of $^{44,48}$Ca, the magnitude of $P_{CN}$=0.27 has to be introduced to reproduce the ER cross-section data [13].

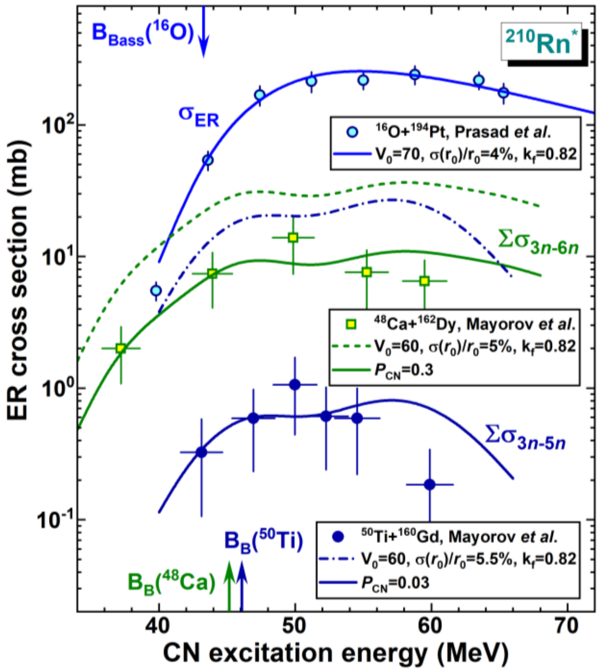

**Fig. 4.** The same as in Fig. 3 but for ER cross sections obtained in reactions leading to the $^{210}$Rn$^*$ CN [12, 13] and calculations with $k_f$=0.82. In the cases of $^{48}$Ca and $^{50}$Ti, $P_{CN}$=0.3 and 0.03, respectively, have to be introduced to describe the data.

It was revealed, according to the analysis of ER excitation functions, that the decay of compound nuclei from Fm$^*$ to Rf$^*$ formed in very asymmetric reactions could be described with $k_f$=1.2 [11]. That is in contrast to $k_f$<1, with which the decay of compound nuclei with $Z\leq98$ can be described. Applying this finding to the description of the survivability of even heavier compound nuclei $^{268}$Sg$^*$ and $^{274}$Hs$^*$ formed in asymmetric reactions with $^{30}$Si and $^{26}$Mg, respectively, one can arrive at $P_{CN}$<1 for both the reactions, as shown in Fig. 5.

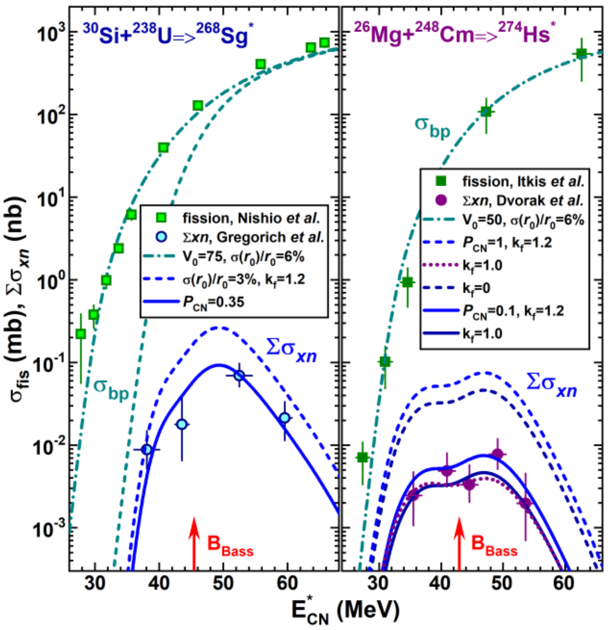

**Fig. 5.** The same as in Figs. 3 and 4 but for the cross sections obtained in reactions leading to the $^{268}$Sg$^*$ and $^{274}$Hs$^*$ compound nuclei [14, 15]. Calculations with $P_{CN}$=0.35 and $k_f$= 1.2, and with the values indicated in the right panel were used to describe the $^{30}$Si+$^{228}$U and $^{26}$Mg+$^{248}$Cm data, respectively.

As one can see in Fig. 5, small variations in the macroscopic component of fission barriers have a small effect on the production cross sections for the heaviest nuclei. It is the result of a small value of this component (~0.4 MeV) for Hs fission barriers used in calculations. Neglecting this component leads to $P_{CN}$=1, but this assumption is in contradiction to a smooth drop of the macroscopic fission barriers to zero with an increase in the CN fissility and to a trend implying a general reduction in $P_{CN}$ with the same change (see below).

## 4 $P_{CN}$ systematics and summary

Several approaches to the $P_{CN}$ data scaling were tested with argument $x$ corresponding to Coulomb factor $Z_pZ_t/(A_p^{\frac{1}{3}}+A_t^{\frac{1}{3}})$, equilibrated mean fissility $X_{mean}^{eq}$ and effective fissility $X_{eff}$ (the last two were proposed earlier, within the application of the extra-push model [16] to data analysis). $P_{CN}$ values obtained with fission and ER data were separately fitted using $f(x)=1/\{1+exp[k(x-x_c)]\}$ function, with $k$ and $x_c$ as fitted parameters. As in the case of fission data, some ER $P_{CN}$

data had been in a significant deviation from a general trend. These data corresponding to the formation of $^{202}$Po$^*$, $^{210}$Rn$^*$, $^{248}$Fm$^*$ and $^{274}$Hs$^*$ in reactions with $^{34}$S, $^{50}$Ti and $^{26}$Mg (see Figs. 3–5 and [11]) were omitted in all fitting procedures. The least $\chi^2$ value was obtained with the equilibrated mean fissility as the argument of $x$. The result of the fitting of both the fission and ER $P_{CN}$ data considered in this work are shown in Fig. 6.

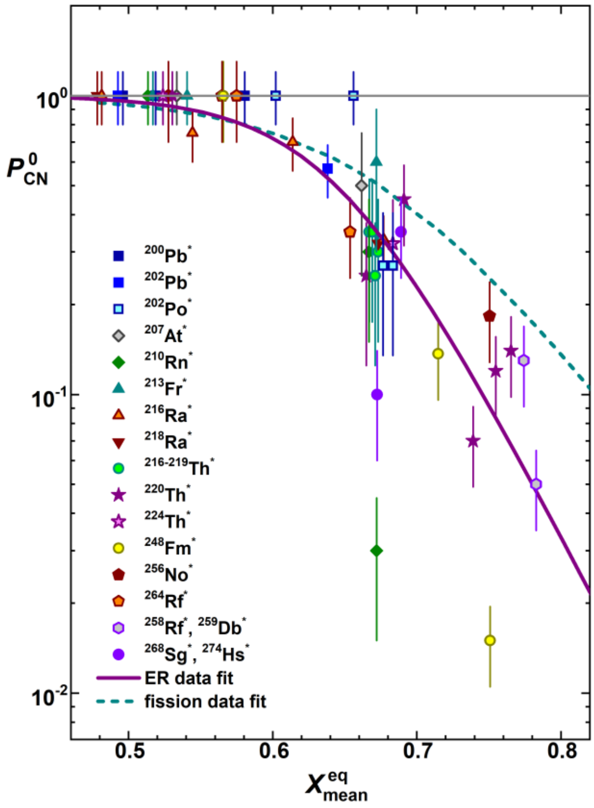

**Fig. 6.** The $P_{CN}$ data derived from the analysis of ER cross sections obtained in complete fusion reactions with the different mass-asymmetry in the entrance channel and leading to the same CN (designated by the corresponding symbol) are fitted with a function of the equilibrated mean fissility (a solid line). The result of the same function fit to the $P_{CN}$ data obtained in fission studies (see Figs. 1 and 2) is shown by a dashed line. See the text for more details.

As one can see, the fitted $P_{CN}$ values obtained with the ER data decrease faster than those corresponding to fission data as the equilibrated mean fissility increases. The former could be applied to the estimate of the drop in the $P_{CN}$ value at the transition from $^{48}$Ca to $^{50}$Ti induced reactions leading to the same $^{288}$Fl$^*$ CN. This drop should not exceed a factor of two, implying the same survivability in both reactions.

Summarizing one has to mention that

- $P_{CN}$ and survivability $W_{sv}$ in the complete fusion reactions leading to the heaviest nuclei are correlating values in the calculations of ER cross-sections. Available fission and ER cross-section data were used to consider $P_{CN}$ and $W_{sv}$. ER data could be described in the framework of the barrier passing model for capture and the statistical model (SM) for a CN-decay using $P_{CN}$ as an adjustable parameter.
- $P_{CN}$ values obtained in reactions corresponding to fission of heavy composite system formed in nucleus-nucleus collisions were scaled with the Coulomb factor and fissility parameters proposed in the framework of the extra-push model.
- $P_{CN}$ values were also derived by comparing ER cross-sections obtained in very asymmetric projectile-target combinations (having $P_{CN}$=1) and those obtained in less asymmetric ones, for which $P_{CN}$ must be obtained. The survivability of heavy nuclei produced in very asymmetric reactions was reproduced by adjusting the macroscopic component of fission barriers within SM approximations. These barriers were used for the $P_{CN}$ estimates in more symmetric reactions leading to the same CN.
- $P_{CN}$ values obtained with the ER cross-sections were also scaled in the same way as fission data. A comparison of both dependencies shows that a drop in $P_{CN}$ values deduced with the ER data as functions of the Coulomb factor and fissility occurs faster than the one for similar values obtained with fission data.

## References

1. R.S. Naik *et al.*, Phys. Rev. C **76**, 054604 (2007); W. Loveland, EPJ Web of Conf. **131**, 04003 (2016)
2. W. Reisdorf, Z. Phys. A **300**, 227 (1981); W. Reisdorf, M. Schädel, Z. Phys. A **343**, 47 (1992)
3. L. Corradi *et al.*, Phys. Rev. C **71**, 014609 (2005); R.N. Sagaidak, A.N. Andreyev, Phys. Rev. C **79**, 054613 (2009)
4. W. Reisdorf *et al.*, Nucl. Phys. A **438**, 212 (1985)
5. S. Cohen *et al.*, Ann. Phys. (NY) **82**, 557 (1974)
6. G. Audi *et al.*, Nucl. Phys. A **729**, 337 (2003)
7. B.B. Back, Phys. Rev. C **31**, 2104 (1985); R. Yanez *et al.*, Phys. Rev. C **88**, 014606 (2013)
8. W.Q. Shen *et al.*, Phys. Rev. C **36**, 115 (1987); E.M Kozulin *et al.*, Phys. Lett. B **686**, 227 (2010); I.M. Itkis *et al.*, Phys. Rev. C **83**, 064613 (2011); K. Nishio *et al.*, Phys. Rev. C **86**, 034608 (2012)
9. R. Bass, Lect. Notes Phys. **117**, 281 (1980)
10. R.N. Sagaidak *et al.*, Phys. Rev. C **68**, 014603 (2003)
11. R.N. Sagaidak, Eur. Phys. J. D **45**, 59 (2007); R.N. Sagaidak, EPJ Web of Conf. **21**, 06001 (2012)
12. D.A. Mayorov *et al.*, Phys. Rev. C **90**, 024602 (2014); D.A. Mayorov *et al.*, Phys. Rev. C **92**, 054601 (2015); T.A. Werke *et al.*, Phys. Rev. C **92**, 054617 (2015)
13. R. Rafiei *et al.*, Phys. Rev. C **77**, 024606 (2008); C.R. Morton *et al.*, Phys. Rev. C **62**, 024607 (2000); E. Prasad *et al.*, Phys. Rev. C **84**, 064606 (2011)
14. K. Nishio *et al.*, Eur. Phys. J. A **29**, 281 (2006); K.E. Gregorich *et al.*, Phys. Rev. C **74**, 044611 (2006)
15. J. Dvorak *et al.*, Phys. Rev. Lett. **100**, 132503 (2008); I.M. Itkis *et al.*, Phys. Rev. C **83**, 064613 (2011)
16. H. Gäggeler *et al.*, Z. Phys. A **316**, 291 (1984); J.P. Blocki *et al.*, Nucl. Phys. A **459**, 145(1986)