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A possible experimental observable for the determination of neutron skin thickness*

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The dependence between neutron skin thickness and neutron abrasion cross section ($\sigma_{\rm nabr}$) for neutron-rich nuclei is investigated within the framework of the statistical abrasion ablation model. Assuming that the density distributions for proton and neutron are of Fermi-type, and adjusting the diffuseness parameter of neutron density distribution in the droplet model, we find out the good linear correlation between the neutron skin thickness and the abrasion cross section $\sigma_{\rm nabr}$ for neutron-rich nuclei. The uncertainty of neutron skin thickness determined from $\sigma_{\rm nabr}$ is very small. It is suggested that $\sigma_{\rm nabr}$ can be used as a new experimental observable to extract the neutron skin thickness for neutron-rich nucleus. The scaling behaviours between neutron skin thickness and $\sigma_{\rm nabr}$, separately, for isotopes of $^{26-35}$Na, $^{44-56}$Ar, $^{48-60}$Ca, $^{67-78}$Ni are also investigated.

Keywords: neutron skin thickness, neutron abrasion cross section, statistical abrasion ablation model

PACC: 2500, 2570, 3130G

One of the most fundamental properties of the nucleus is its size or proton (neutron) density distribution. The proton root-mean-square (RMS) radius of nucleus can be determined within a very high accuracy through the charge radius measurement.[1] However, the accuracy of neutron radius is low compared with that of the proton radius so far.

Measurement of neutron density is very important for studying nuclear structures of neutron-rich nuclei, atomic parity non-conservation (PNC), isovector interactions, neutron-rich matter in astrophysics, etc. It is remarkable that a single measurement has lots of applications in atomic physics, nuclear physics and astrophysics.[2,3] Neutron skin thickness (defined as the difference between the neutron and proton RMS radii: $\delta_{\rm np} \equiv \langle r_{\rm n}^2 \rangle^{1/2} - \langle r_{\rm p}^2 \rangle^{1/2}$) is found to be related to a constraint on the neutron equation of state (EOS). This constraint is important for extrapolating the EOS to a high density case, and thereby finding its use for the properties of neutron stars.[4−7] Neutron skin thickness can yield a lot of information on the derivation of volume and surface symmetry energy, as well as nuclear incompressibility with respective to density. Neutron skin thickness is significant for studying EOSs in different theoretical models such as Skyrme Hartree–Fock (SHF),[2−6] relativistic mean-field (RMF),[6,8] Boltzmann–Uehling–Uhlenbeck (BUU) model[9] and droplet model.[10] Furthermore, neutron skin thickness can facilitate the identifying of a nucleus with an exotic structure.

Several attempts have been made to determine the neutron density distribution or neutron skin thickness, such as parity violating measurement[2,6] and the method of using the relationship between the nuclear matter radius and the interaction or reaction cross section.[9,11−19] In this paper, by studying the relationship between the neutron skin thickness and the neutron abrasion cross section ($\sigma_{\rm nabr}$) within the framework of statistical abrasion ablation (SAA) model, we propose to use $\sigma_{\rm nabr}$ as a possible experimental observable to extract $\delta_{\rm np}$.

The SAA model was developed by Brohm *et al* to

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describe peripheral nuclear collisions at high energies in a picture of quasi-free nucleon-nucleon collisions.[20] This model takes independent nucleon-nucleon collisions in an overlap zone of colliding nuclei and determines the distributions of abraded neutrons and protons. The probability of abrading zero nucleons is calculated and the resulting energy-dependent total reaction cross section turns out to be equivalent to the successful microscopic Glauber-type calculation. The SAA model can reproduce the experimental data well[21,22] and has been found to be useful for studying the isoscaling behaviour of projectile-like fragments[23−26] in heavy ions reactions. Here we give a brief description of the SAA model, and its details can be found in Ref.[20] and the references therein.

In the SAA model, nuclei are described in a picture of interacting tubes in high-energy interactions. The colliding nuclei are considered to be composed of parallel tubes orientating along the beam direction. Neglecting the transverse motion, the collision is described by independent interactions of tube pairs. In the collision of projectile tube i containing $A_i = N_i + Z_i$ nucleons and a target tube j with $A_j = N_j + Z_j$ nucleons, the probability with which an incident nucleon of type k (k=n for neutron, k=p for proton) transmits through the target tube without being abraded may be written as

$$t_{j,k} = \exp\left(\frac{-1}{F}(N_j\sigma_{\mathrm{n}k} + Z_j\sigma_{\mathrm{p}k})\right), \tag{1}$$

where F is the section area of tubes and $\sigma_{kk'}$ is the free nucleon-nucleon cross section. For a specific pair of tubes (i, j), the number of absorbed projectile neutrons, ΔN_i, and the number of absorbed protons, ΔZ_i, are assumed to be two different binomial distributions. The two distributions each are determined by the number of incident nucleons and the transmission probability $t_{j,k}$ given above. The distribution of the total number of abraded neutrons $\Delta N{=}\Sigma_i\Delta N_i$, or protons $\Delta Z{=}\Sigma_i\Delta Z_i$, is a superposition of different binomial distributions having different parameters. The average mass loss of the projectile is given by the sum of all tube pairs as follows:

$$\begin{aligned}\langle\Delta A\rangle &= \sum_i \left(\langle\Delta N_i\rangle + \langle\Delta Z_i\rangle\right)\\ &= \sum_{i,j}\left[N_i(1-t_{j,\mathrm{n}}) + Z_i(1-t_{j,\mathrm{p}})\right].\end{aligned} \tag{2}$$

In the limit to infinitesimal tubes, the transmission probability with which a neutron (proton) stays at a given impact parameter b is

$$\begin{aligned}t_k(s-b) =& \exp\{-[D^{\mathrm{T}}_{\mathrm{n}}(s-b)\sigma_{\mathrm{n}k}\\ &+ D^{\mathrm{T}}_{\mathrm{p}}(s-b)\sigma_{\mathrm{p}k}]\},\end{aligned} \tag{3}$$

with D^{T} being the nuclear-density distribution of target integrated along the beam direction and normalized by $\int \mathrm{d}^2sD^{\mathrm{T}}_{\mathrm{n}} = N^{\mathrm{T}}$ and $\int \mathrm{d}^2sD^{\mathrm{T}}_{\mathrm{p}} = Z^{\mathrm{T}}$. So the average absorbed mass in the limit to infinitesimal tubes, again at a given b, is

$$\begin{aligned}<y\Delta A(b)\rangle =& \int \mathrm{d}^2sD^{\mathrm{T}}_{\mathrm{n}}(s)[1-t_{\mathrm{n}}(s-b)]\\ &+ \int \mathrm{d}^2sD^{\mathrm{P}}_{\mathrm{p}}(s)[1-t_{\mathrm{p}}(s-b)],\end{aligned} \tag{4}$$

The integrals extend over the plane perpendicular to the beam direction. In a similar way, the variance of ΔA can be determined by summing the variances of all the binomial distributions for the tube pairs, and in the limit to infinitesimal tubes one finds

$$\begin{aligned}&\langle(\Delta A(b) - \langle\Delta A(b)\rangle)^2 > y\\ &= \int \mathrm{d}^2sD^{\mathrm{T}}_{\mathrm{n}}(s)[1-t_{\mathrm{n}}(s-b)]t_{\mathrm{n}}(s-b)\\ &\quad + \int \mathrm{d}^2sD^{\mathrm{P}}_{\mathrm{p}}(s)[1-t_{\mathrm{p}}(s-b)]t_{\mathrm{p}}(s-b).\end{aligned} \tag{5}$$

The same procedure may be applied to obtaining higher moments of the distributions of abraded neutrons and protons. However, for the present purpose sufficient information is provided by their fist and second moments. In addition, the probability for zero nucleon loss is important because it is related to the total reaction cross section.

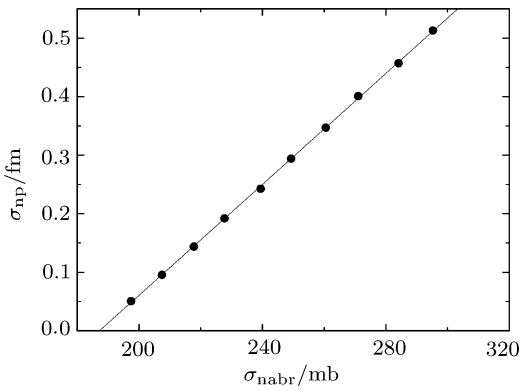


Fig.1. Correlation between δ_{np} and σ_{nabr} for ^{48}Ca in ^{48}Ca+^{12}C at 60A MeV. The solid circles denote the results calculated by the SAA model. The solid line is for the linear fitting of the calculated results.

The deduced $T(b)$ and the total reaction cross sec-

tion in Ref.[20] respectively are

$$T(b) = \exp\Big(- \int \mathrm{d}^2 s \{ D_{\mathrm{n}}^{\mathrm{P}}(s) D_{\mathrm{n}}^{\mathrm{T}}(s-b)\sigma_{\mathrm{nn}} + D_{\mathrm{p}}^{\mathrm{P}}(s) D_{\mathrm{p}}^{\mathrm{T}}(s-b)\sigma_{\mathrm{pp}} + [D_{\mathrm{n}}^{\mathrm{P}}(s) D_{\mathrm{p}}^{\mathrm{T}}(s-b) + D_{\mathrm{p}}^{\mathrm{P}}(s) D_{\mathrm{n}}^{\mathrm{T}}(s-b)]\sigma_{\mathrm{np}} \} \Big), \quad (6)$$

and

$$\sigma_{\mathrm{tot}} = \int \mathrm{d}^2 b [1 - T(b)]. \quad (7)$$

The production cross section for a specific isotope can be calculated from

$$\sigma(\Delta N, \Delta Z) = \int \mathrm{d}^2 b P(\Delta N, b) P(\Delta Z, b), \quad (8)$$

where $P(\Delta N, b)$ and $P(\Delta Z, b)$ are the probability distributions for the abraded neutrons and protons at a given impact parameter b, respectively. These probability distributions each are a superposition of different binomial distributions.

Heavy-ion reactions at relativistic energies can be described as a two-step process. The initial stage can be described by a Glauber-type model as 'participants' and 'spectators'. The participants in an overlapping region between the projectile and the target interact strongly while the spectators are left to move almost without being disturbed.[27] The second stage of the reaction is characterized by the evaporation of particles. This deexcitation process is described by the conventional statistical model under the assumption of thermal equilibrium in the excited prefragment. The excitation energy for the projectile-like prefragment is determined according to the method in Ref.[28]. The statistical hole-energy model gives an average excitation energy of 13.3 MeV per hole. After the calculation of deexcitation, we can obtain the final fragment distributions comparable with the experimental data.

As to the density distributions of the projectile D_i^{P} and target D_i^{T} (i=n, p) used in the SAA model, harmonic-oscillator(HO)-type density distributions are suitable for light nuclei but it is more reasonable to use the Fermi-type distribution for heavier mass system.[29] In our calculations, the Fermi-type distributions are used for neutron and proton, separately, and they are

$$\rho_i(r) = \frac{\rho_i^0}{1 + \exp\left(\dfrac{r - C_i}{f_i t_i / 4 \cdot 4} \right)}, \quad i = \mathrm{n}, \mathrm{p}, \quad (9)$$

where ρ_i^0 is the normalization constant which ensures that the integration of the density distribution equals the number of neutrons (i=n) or protons (i=p); t_i is the diffuseness parameter; C_i is half the density radius of neutron or proton and determined by droplet model[30]

$$C_i = R_i[1 - (b_i/R_i)^2], \quad i = \mathrm{n} \text{ or } \mathrm{p}, \quad (10)$$

with $b_i = 0.413 f_i t_i$, R_i being the equivalent sharp surface radius of neutron or proton, R_i and t_i being given by the droplet model; a factor f_i is introduced by us to change the diffuseness parameter. In a standard droplet model, f_i is equal to 1 for the density distribution in expressions (9) and (10) and can well describe the stable nuclei.[31] In Ref.[32], Trzcińska *et al* found that half the density radii for neutrons and protons in heavy nuclei were almost the same, but the diffuseness parameter for the neutrons was larger than that for the protons. So we introduce the factor f_i to adjust the diffuseness parameter for neutron.

Neutron abrasion cross section (σ_{nabr}) is defined as the sum of production cross sections for fragments with the same charges as that of the projectile, but less neutron number than that of the projectile, i.e. one or more neutrons are removed from the projectile in collision

$$\sigma_{\mathrm{nabr}} = \sum_{i=1}^{N} \sigma(i, 0), \quad (11)$$

where N is the neutron number of the projectile. In the SAA model, $\sigma(i, 0)$ is the fragment production cross section given by expression (8). It should be pointed out that $\sigma(i, 0)$ decreases very quickly as i increases. The value of $\sigma(N, 0)$ will be very close to zero for most projectiles. That means peripheral reactions contribute to σ_{nabr} dominantly. Thus σ_{nabr} may be sensitive to the neutron distribution in the surface. Since reaction cross section (σ_{R}) and interaction cross section (σ_{I}) reflect the information about the overall size of a nucleus, it is not very accurate to determine the neutron skin thickness in a nucleus by using σ_{R} or σ_{I}. In fact δ_{np} determined by them has an error on order of ± 0.1fm when the error of σ_{I} is not larger than 5%.[11] Below we will demonstrate that measuring σ_{nabr} may be favourable to determining δ_{np}.

In the calculation for neutron-rich nucleus, f_{p} in expression (9) of proton density distribution retained a value of 1.0 as the usual droplet model, while f_{n} in expression (9) of neutron density distribution is changed. Different values of δ_{np} will be deduced from expression (9) for different values of f_{n}. Similarly, different values of σ_{nabr} are obtained in the SAA calculation with

different density distributions for the projectile. Thus we can obtain the correlation between $\sigma_{\rm nabr}$ and $\delta_{\rm np}$.

As an example, we investigate the dependence between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ for ^{48}Ca through the reaction of ^{48}Ca+^{12}C at 60A MeV. From the results shown in Fig.1, when $f_{\rm n}$ varies from 1 to 1.45, we can see that $\delta_{\rm np}$ increases as $\sigma_{\rm nabr}$ increases. A linear fitting ($\delta_{\rm np}$=$b_{\rm S}\sigma_{\rm nabr}$+$a_{\rm S}$) can well describe the correlation between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$. The fitted result is $\delta_{\rm np}$=0.00474$\sigma_{\rm nabr}$–0.88646. From this linear relation, $\delta_{\rm np}$ can be extracted if $\sigma_{\rm nabr}$ is measured experimentally. For errors about 1% and 5% of $\sigma_{\rm nabr}$ at 250 mb, the deduced $\delta_{\rm np}$ has errors of ±0.012 fm and ±0.059 fm, respectively. The error of $\delta_{\rm np}$ deduced from $\sigma_{\rm nabr}$ is much smaller than that deduced from $\sigma_{\rm R}$ or $\sigma_{\rm I}$.

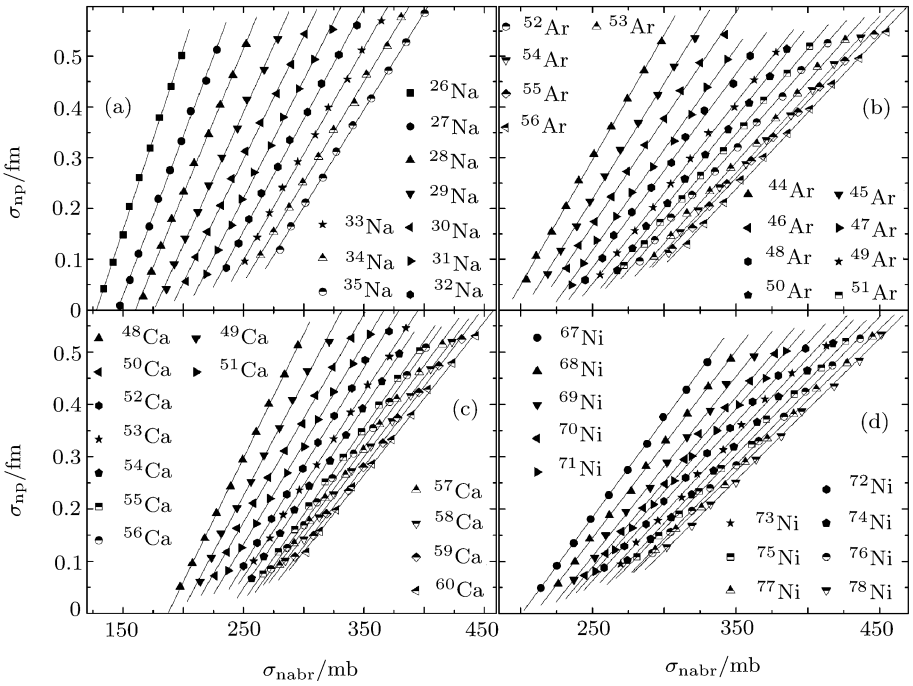


Fig.2. Correlations between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ for isotopes of $^{26-35}$Na (a), $^{44-56}$Ar (b), $^{48-60}$Ca (c), and $^{66-78}$Ni (d). These data are calculated using reactions of $^{\rm A}$Na+^{12}C, $^{\rm A}$Ar+^{12}C, $^{\rm A}$Ca+^{12}C, and $^{\rm A}$Ni+^{12}C at 60A MeV. The lines denote the linear fitting results for each nucleus.

Furthermore, we investigate the dependences of $\delta_{\rm np}$ on $\sigma_{\rm nabr}$ for isotopes of neutron-rich Na, Ar, Ca and Ni in reactions of $^{26-35}$Na+^{12}C, $^{44-56}$Ar+^{12}C, $^{48-60}$Ca+^{12}C, and $^{67-78}$Ni+^{12}C at 60A MeV by using the same method. When $f_{\rm n}$ changes from 1.0 to 1.45 (or from 0.95 to 1.40 for some nuclei which have relatively large $N-Z$), we find good linear correlations between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ for each nucleus as shown in Fig.2. But the slopes for different nuclei are different. Here we use $b_{\rm S}$ and $a_{\rm S}$ to denote the slope and intercept of the linear fitting results for each nucleus from Fig.2. $b_{\rm S}$ decreases as $N-Z$ increases as shown in Fig.3. We estimate the error of $\delta_{\rm np}$ for ^{78}Ni ($b_{\rm S}$=0.00271). If $\sigma_{\rm nabr}$ has errors of 1% and 5% at 400mb, the deduced errors of $\delta_{\rm np}$ are less than ±0.011 fm and ±0.054 fm, respectively. We still can obtain $\delta_{\rm np}$ with a small uncertainty. So, we can conclude that it is a general phenomenon that $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ have a linear correlation for neutron-rich nuclei. Owing to a small uncertainty of $\delta_{\rm np}$ extracted from $\sigma_{\rm nabr}$, if we can measure $\sigma_{\rm nabr}$ within an error less than 5%, it can be used as a very good observable to determine $\delta_{\rm np}$. So we propose to use $\sigma_{\rm nabr}$ as a new observable to extract $\delta_{\rm np}$ experimentally.

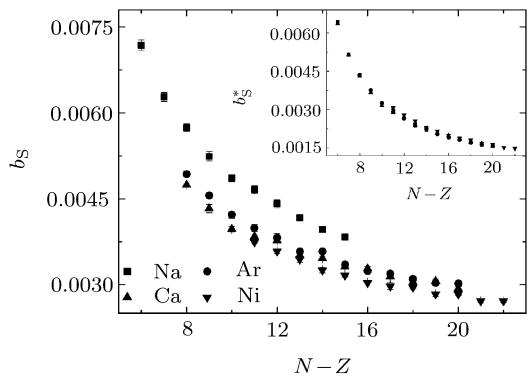


Fig.3. The curves for slope value ($b_{\rm S}$) of linear fitting result in Fig.2 versus neutron excess ($N-Z$), where the inset shows $b^*_{\rm S} = b_{\rm S}A^{1/3}/(N-Z)^{2/3}$ versus ($N-Z$).

Table 1. Results of fitting parameters P, $b_{\rm M}$(slope), $a_{\rm M}$(intercept) in Fig.4 of $^{26-35}$Na, $^{44-56}$Ar, $^{48-60}$Ca and $^{67-78}$Ni.

	P	$b_{\rm M}/10^{-5}$	$a_{\rm M}$	$b_{\rm M}Z^{0.31}$
Na	8.68 ± 0.22	629 ± 3	-1.037 ± 0.007	0.0132
Ar	42.46 ± 0.14	557 ± 3	-1.420 ± 0.010	0.0136
Ca	52.0 ± 0.23	526 ± 3	-1.461 ± 0.011	0.0133
Ni	57.15 ± 0.21	471 ± 2	-1.392 ± 0.008	0.0132

We try to find whether there are scaling behaviours for the dependences of $\delta_{\rm np}$ on $\sigma_{\rm nabr}$ for all these nuclei in different isotopes. From Fig.3 we can see the values of $b_{\rm S}$ are similar to those for isotopes of Ar, Ca and Ni and tend to be saturated as the values of $(N-Z)$ becomes larger. Analysis shows that $\rm b_S$ can be scaled by being multiplied with $A^{1/3}/(N-Z)^{2/3}$, i.e. $b^*_{\rm S} = b_{\rm S}A^{1/3}/(N-Z)^{2/3}$, and its value is almost the same for all nuclei with the same value of $(N-Z)$ as shown in the inset of Fig.3. To study the correlation between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ for nuclei with the same charge numbers, we define a one-parameter function $M(P)$ related to $\sigma_{\rm nabr}$, mass number A and neutron excess $(N-Z)$ of a nucleus as follows:

$$M(P) = \frac{\sigma_{\rm nabr}A^{1/3}}{(N-Z)^{2/3}} + P(N-Z)^{1/3}, \qquad (12)$$

where P is the parameter related to Z. Good linear correlations between $\delta_{\rm np}$ and $M(P)$ are found for isotopes of Na, Ar, Ca and Ni. Figure 4 shows the correlation between $\delta_{\rm np}$ and $M(P)$ and also the linear fittings using $\delta_{\rm np} = b_{\rm M}M(P) + a_{\rm M}$. P is determined when the error of the linear fitting between $\delta_{\rm np}$ and $M(P)$ is the smallest, parameters $b_{\rm M}$ and $a_{\rm M}$ are also determined at the same time. The linear fitting results of Fig.4 and P for each isotope are listed in Table 1. P increases as Z increases and can be fitted by using the first-order exponential decay function $P = -287.87341\exp(-Z/6.51256) + 61.69174$ with χ^2 =312. The value of $b_{\rm M}$ decreases as Z increases and can be fitted by a function $b_{\rm M} = 0.0133Z^{-0.31}$ with χ^2=10.5, and we find that the values of $b_{\rm M}*Z^{0.31}$ for these isotopes with different values of Z have little difference as shown in Table 1.

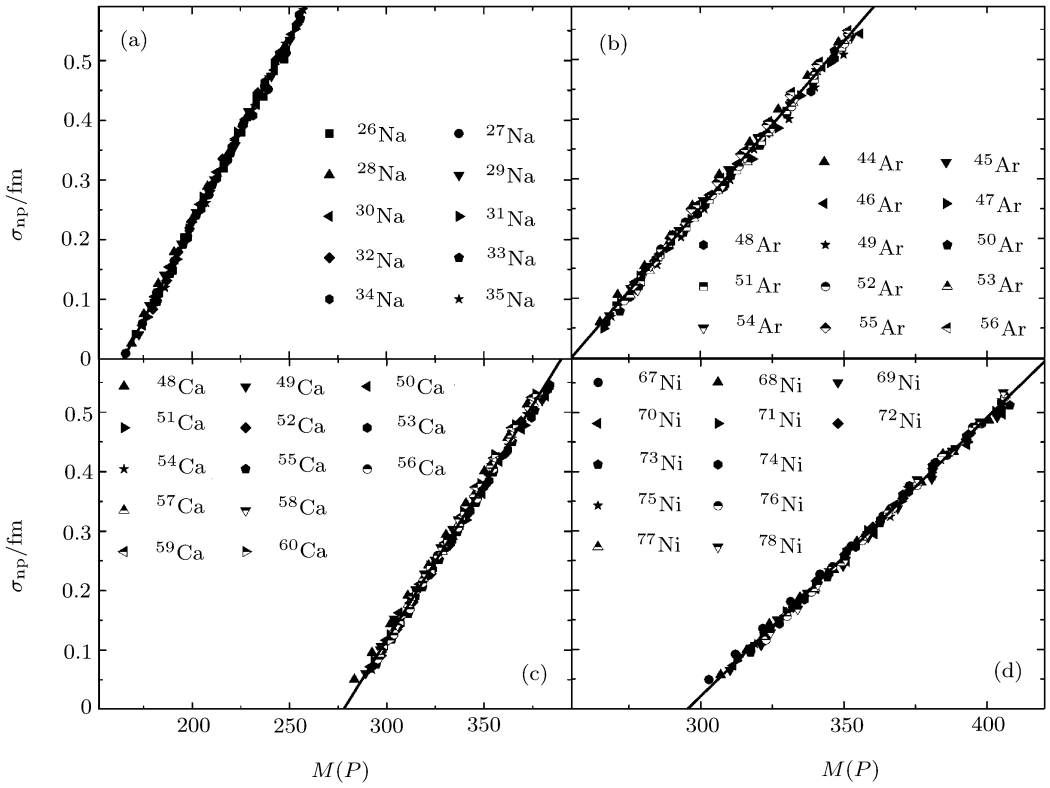


Fig.4. Correlations between $\delta_{\rm np}$ and $M(P)$ for isotopes of $^{26-35}$Na (a), $^{44-56}$Ar (b), $^{48-60}$Ca (c), $^{67-78}$Ni (d). The solid lines are for linear fitting results of $\delta_{\rm np}$ and $M(P)$.

Multiplying $M(P)$ by $Z^{-0.31}$, and adding such a variable P_0 that the intercept is zero, we find that the correlations between $\delta_{\rm np}$ and $M(P)Z^{-0.31}+P_0$ for all these isotopes are scaled together as shown in Fig.5.

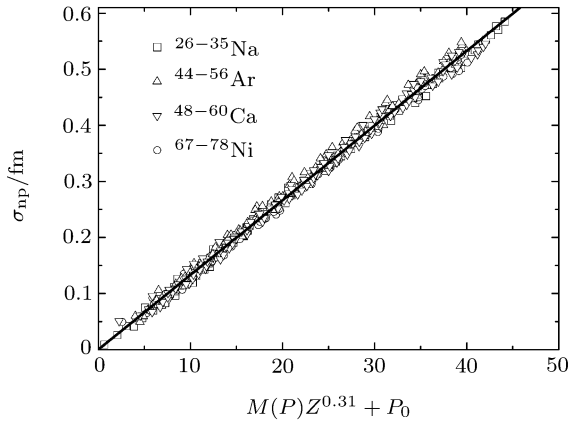


Fig.5. Correlations between $\delta_{\rm np}$ and $M(P)Z^{0.24}+P_0$ for isotopes of $^{26-35}$Na (a), $^{44-56}$Ar (b), $^{48-60}$Ca (c), $^{67-78}$Ni (d), where the solid line is for the linear fitting result.

In summary, assuming the density distributions of proton and neutron to be of Fermi-type, we adjust a diffuseness parameter of neutron density distribution in the droplet model and find good linear correlations between $\delta_{\rm np}$ and $\sigma_{\rm nabr}$ for isotopes of neutron-rich $^{26-35}$Na, $^{44-56}$Ar, $^{48-60}$Ca, $^{67-78}$Ni within the framework of statistical abrasion ablation model. $\sigma_{\rm nabr}$ may be sensitive to the neutron distribution in the surface since the peripheral reaction contributes to it dominantly. Thus measuring $\sigma_{\rm nabr}$ will be a very good tool for studying the neutron distribution and neutron skin thickness. We find that the error of $\delta_{\rm np}$ deduced from $\sigma_{\rm nabr}$ is much smaller than that deduced from $\sigma_{\rm I}$ or $\sigma_{\rm R}$. So we propose to use $\sigma_{\rm nabr}$ as a new experimental observable to extract and investigate the neutron skin thickness in neutron-rich nuclei. By defining a function $M(P)$ related to $\sigma_{\rm nabr}$, A, Z and $N-Z$, the scaling behaviours between $\delta_{\rm np}$ and $M(P)$ are studied in isotopes of neutron-rich Na, Ar, Ca and Ni.

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