CHIN. PHYS. LETT. Vol. 34, No. 7 (2017) 072401

A Photonuclear Reaction Model Based on IQMD in Intermediate-Energy Region *

Bo-Song Huang(黄勃松)[1,2], Yu-Gang Ma(马余刚)[1**]

[1] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800*
[2] *University of Chinese Academy of Sciences, Beijing 100049*

(Received 12 April 2017)

A photonuclear reaction transport model based on an isospin-dependent quantum molecular dynamics model (IQMD) is presented in the intermediate energy region, which is named as GiQMD in this study. Methodology to simulate the course of the photonuclear reaction within the IQMD frame is described to study the photoabsorption cross section and π meson production, and the simulation results are compared with some available experimental data as well as the Giessen Boltzmann–Uehling–Uhlenbeck model.

PACS: 24.10.−i, 25.20.−x, 25.20.Dc, 25.20.Lj DOI: 10.1088/0256-307X/34/7/072401

With the development of the photon beam technique in the nuclear physics community, high-quality quasi-monochromatic photons are available, and therefore photonuclear reaction is attracting more attention nowadays.[1−7] The photon beam is an elementary and non-hadronic probe and therefore allows us in principle to obtain clean information about the internal structure and correlation of nuclear matter. For photonuclear interaction, it can be considered as an important process and a clean probe for the understanding of the nuclear structure and the fundamental dynamics of the nucleon system. It has been studied for several decades using high-energy photon beams to understand the structure of the nucleon and the fundamental dynamics of the nucleon system because of the availability of high-quality monochromatic photon beams up to 10 GeV generated by the tagged photon technique.[8−10] In lower photon energy domain, many research studies focused mainly on low photon energy around 15–40 MeV where the giant dipole resonance (GDR) is dominated.[11−13] In the intermediate energy region of photons from several hundreds of MeV to GeV, the study is relatively less. Recently, in the quasideuteron region[14] at the photon energy of 70–140 MeV, we have investigated photonuclear interaction based on an extended quantum molecular dynamics (EQMD) model[15] to discuss the α-clustering effects of light nuclei, such as ^{12}C and ^{16}O.[16,17] In the present work, we present a photonuclear transport model within an isospin-dependent quantum molecular dynamics (IQMD) frame in intermediate energy. With the model, the calculation of the cross section of pion photo-production can be performed in the energy range from 300 MeV to 600 MeV.

The QMD model is a very successful many-body theory to simulate heavy ion reactions at intermediate energies.[18−26] It contains several major parts: the initialization of projectile and target nucleons, the transport of nucleons in the effective potential, the collisions between the nucleons, and the Pauli-blocking effect. There are various versions of QMD which are best used in different energy regions.[20,21] The isospin-dependent QMD model is based on the QMD model and takes the isospin effects into account in various aspects: a different density distribution for neutrons and protons, the asymmetric potential term of the mean field, and the use of experimental cross sections for nucleon–nucleon collisions and Pauli-blocking effects, respectively. In IQMD, each nucleon is represented by a Gaussian wave packet with a width such as $L = 8.66\,\mathrm{fm}^2$, with its center around the mean position $\boldsymbol{r}_i(t)$ and mean momentum $\boldsymbol{p}_i(t)$,

$$\phi_i = \frac{1}{(2\pi L)^{3/4}} \exp\Big[-\frac{[\boldsymbol{r}-\boldsymbol{r}_i(t)]}{4L}\Big]. \tag{1}$$

The time evolution of each nucleon is governed by Hamilton's equations of motion,

$$p_i' = \frac{\partial\langle H\rangle}{\partial r_i},\ r_i' = \frac{\partial\langle H\rangle}{\partial p_i}. \tag{2}$$

The nucleons interact with each other by means of the nuclear mean field and nucleon–nucleon collisions. The nuclear mean field is written as

$$U(\rho,\tau_z) = \alpha\Big(\frac{\rho}{\rho_0}\Big) + \beta\Big(\frac{\rho}{\rho_0}\Big)^{\sigma} + \frac{1}{2}(1-\tau_Z)V_{\mathrm{c}} + C_{\mathrm{sym}}\frac{(\rho_{\mathrm{n}}-\rho_{\mathrm{p}})}{\rho_0}\tau_z + U^{\mathrm{Yuk}},$$

where ρ_0 is the normal nuclear matter density with the value of $0.17\,\mathrm{fm}^{-3}$, ρ, ρ_{n} and ρ_{p} are the total density, neutron and proton densities, respectively, τ_z is the zth component of the isospin degree of freedom, which equals 1 for neutrons or −1 for protons. The coefficients α, β and σ are the Skyrme parameters, and their values are −124 MeV, 70.5 MeV and 2.0, respectively, which connect closely with the hard nuclear

*Supported by the National Natural Science Foundation of China under Grant Nos 11421505 and 11220101005, the National Basic Research Program of China under Grant No 2014CB845401, and the Strategic Priority Research Program of the Chinese Academy of Sciences under Grant No XDB16.

**Corresponding author. Email: ygma@sinap.ac.cn

© 2017 Chinese Physical Society and IOP Publishing Ltd

equation of state (EOS) of bulk nuclear matter. Two of them are fixed by the constraints that the total energy is a minimum at the saturation density $\rho = \rho_0$ with a value of $E/A = -16\,\mathrm{MeV}$ which corresponds to the volume energy in the Bethe–Weizsacker mass formula and the free particle without binding energy. Here V_c is the Coulomb potential, U^{Yuk} is the Yukawa potential, and C_{sym} is the symmetry energy coefficient with the value of 25 MeV. In this work, we utilize the local Fermi distribution for nucleon momentum distribution in the initialization of the IQMD. The local Fermi momentum is defined as

$$P_{\mathrm{Fermi}} = \hbar[3\pi^2\rho_{n,p}(r)]^{1/3}. \tag{3}$$

For the coordinate of the nucleon, the centroid of each Gaussian of nucleon is randomly distributed in a phase space sphere with $R = 1.12\,\mathrm{A}^{1/3}\mathrm{fm}$ corresponding to a ground-state density. Because nucleons are fermion, they have to obey Pauli principle, i.e., for each collision of two nucleons, if there is not enough phase space for the momentum and coordinate of the two nucleons after collision, then this collision will be blocked.

Now we describe the method of photonuclear reaction used in the IQMD frame in details. In distinguishing the IQMD model, here we call the photonuclear IQMD model γ-induced QMD (GiQMD). It is noted that there is the Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model which can also treat photon induced reaction in the BUU framework.[27] However, in contrast with the QMD model, BUU is an one-body transport model.[28–30] In our model, there are two steps in the overall process; the first is the initial step, i.e., we obtain the initial information of the phase space of nucleons after the kinetic process of photon–nucleon interaction. Through the added differential cross-section of photon–nucleon interaction, we use the bias sampling of Monte Carlo to obtain the weight which is proportional to probability of reaction events in the part of initialization. For the second step, the outgoing nucleons and pions propagate in nuclear medium through the transport process.[31]

For the initial step, we just consider that a photon collides with only one of the nucleons which is chosen randomly in the target nucleus in each event. The coordinates and momenta of this nucleon are sampled based on spherical distribution and the local Fermi momentum distribution depicted in Eq. (3), respectively. The 4-momenta of outgoing nucleons and π-mesons satisfy the conservation of 4-momentum. We add the elementary cross sections of photon–nucleon interaction, which include single and two-pion photon-production[32] by a Bias Monte Carlo method and obtain the total occurring event numbers of photonuclear reactions. For simplicity, we consider the situation that a photon hits a nucleon first. According to the basic scattering formula, the total events of the reactions can be expressed as

$$\begin{aligned} N &= \int I_0(x', y', E_\gamma)\sigma(E_\gamma, \boldsymbol{p})\delta(x' - x) \\ &\quad \cdot \delta(y' - y)\delta(z' - z)dx'dy'dz' \\ &= \int I_0(x, y, E_\gamma)\sigma(E_\gamma)dE_\gamma, \end{aligned} \tag{4}$$

taking single pion photon-production as an example, $\sigma(E_\gamma)$ is the differential cross section of single pion photon-production in the nucleon rest frame, E_γ and $\boldsymbol{p}$ are the 4-momentum of the photon, x, y and z are the three-dimensional coordinates of the nucleon, and $I_0(x', y', E_\gamma)$ is the flux of the photons, which is considered as a constant in this work. Now we consider the nucleus case. According to the scattering formula, we obtain the events as follows:

$$\begin{aligned} N = &\int I_0(x, y, E_\gamma) \int \sigma(E_\gamma, \boldsymbol{p}) \\ &\cdot \rho_N(\boldsymbol{r}, \boldsymbol{p})d^3rd^3pd\cos\theta_{\mathrm{Lab}}d\phi_{\mathrm{Lab}}dE_\gamma, \end{aligned} \tag{5}$$

where $\frac{d\sigma(E,\boldsymbol{p},\theta_{\mathrm{Lab}},\phi_{\mathrm{Lab}})}{d\Omega}$ is the differential cross-section of θ_{Lab} and ϕ_{Lab}, and θ_{Lab} and ϕ_{Lab} are the polar angle and azimuth angle of the outgoing π meson in the lab frame, respectively. The absolute momenta of π are obtained based on the condition of 4-momentum conservation

$$p^{\mathrm{out}} = p^{\mathrm{in}} + q - p_k, \tag{6}$$

where p^{in} and q are the incident energies of the nucleon and photon, respectively, p_k and p^{out} is the 4-momenta of outing π and nucleon, respectively, and $f(\boldsymbol{r}, \boldsymbol{p})$ is the phase space density of the nucleus in the initial state. Using a discrete integral of the variables in Eq. (5), we obtain the form as follows:

$$\begin{aligned} N = &\sum_j^\infty \sum_k^\infty \sum_l^\infty \sum_m^\infty \sum_n^\infty \sum_q^\infty \sum_p^\infty \sum_o^\infty I_0(x^l, y^m, E_\gamma) \\ &\times \frac{d\sigma(E_\gamma, \theta_{\mathrm{Lab}}, \phi_{\mathrm{Lab}})}{d\Omega_{\mathrm{rest}}} \frac{m_N|(1 - |\frac{\boldsymbol{p}}{E_N^i}|)E_\gamma|}{|\boldsymbol{p}E_\gamma - E_N E_\gamma \boldsymbol{z}|} \\ &\times \left|\frac{d\Omega_{\mathrm{rest}}}{d\Omega_{\mathrm{Lab}}}\right| f(\boldsymbol{r}, \boldsymbol{p})\Delta E_\gamma \Delta x^l \Delta y^m \Delta z^n \\ &\cdot \Delta p_x^q \Delta p_y^p \Delta p_z^o \Delta\cos\theta_{\mathrm{Lab}}^j \Delta\phi_{\mathrm{Lab}}^k, \end{aligned} \tag{7}$$

where $|\frac{d\Omega_{\mathrm{Lab}}}{d\Omega_{\mathrm{rest}}}|$ is the Jacobi conversion between the rest frame of nucleon and the lab frame. The superscripts of j and k mean the integral variable of index indicated the outing π meson polar angle and azimuth angle, respectively, l to o represent the index for six integral variables of phase space. We just sample the integration variables θ_{Lab} and ϕ_{Lab},

$$\begin{aligned} \cos\theta_{\mathrm{Lab}} &= 2\varepsilon_1 - 1,\ \phi_{\mathrm{Lab}} = 2\pi\varepsilon_1; \\ \Delta\cos\theta_{\mathrm{Lab}} &= 2\Delta\varepsilon_1,\ \Delta\phi_{\mathrm{Lab}} = 2\pi\Delta\varepsilon_2, \end{aligned} \tag{8}$$

$$M = \frac{1}{\Delta\varepsilon_1}\frac{1}{\Delta\varepsilon_2}, \tag{9}$$

where ε and η are the random variables. Making these

substitutions in Eq. (7), we can find

$$N = \sum_{j}^{\infty}\sum_{k}^{\infty}\sum_{l}^{\infty}\sum_{m}^{\infty}\sum_{n}^{\infty}\sum_{q}^{\infty}\sum_{p}^{\infty}\sum_{o}^{\infty} I_0(x^l, y^m, E_\gamma) \times \frac{d\sigma(E_\gamma, \theta_{\rm Lab}, \phi_{\rm Lab})}{d\Omega} \frac{m_N|(1-|\frac{\boldsymbol{p}}{E_N^i}|)E_\gamma|}{|\boldsymbol{p}E_\gamma - E_N^i E_\gamma \boldsymbol{z}|} \times \left|\frac{d\Omega_{\rm rest}}{d\Omega_{\rm Lab}}\right| 8\pi\rho_N(\boldsymbol{r}, \boldsymbol{p})\Delta x^l \Delta y^m \Delta z^n \cdot \Delta p_x^q \Delta p_y^p \Delta p_z^o \Delta\varepsilon_1^j \Delta\varepsilon_2^k. \quad (10)$$

Introducing the quantity of weight, the equation reads

$$N = \sum_{i}^{N_3} 1 \times W(i), \quad (11)$$

where the weight for each event is

$$W(i) = I_0(x^i, y^i, E_\gamma)\frac{d\sigma(E_\gamma, \boldsymbol{p}^i, \theta_{\rm Lab}, \phi_{\rm Lab})}{d\Omega} \times \frac{m_N|(1-|\frac{\boldsymbol{p}}{E_N^i}|)E_\gamma|}{|\boldsymbol{p}^i E_\gamma - E_N E_\gamma^l \boldsymbol{z}|}\left|\frac{d\Omega_{\rm rest}}{d\Omega_{\rm Lab}}\right| f(\boldsymbol{r}^i, \boldsymbol{p}^i)/M, \quad (12)$$

where N_3 is actual number of simulation. Then, the angular distribution of produced pions can be obtained by the added cross-section through the weight for each events, and weight $W(i)$ means equivalently the occurrence events of the photon-absorption process. In the second step, the produced nucleons and the particles will transport inside the nucleus. They go through rescattering and absorption in a long time evolution until the excited nucleus tends to equilibrium finally.

Based on the weight $W(i)$, we can use weight to calculate the yield of the particles in the first step,

$$y = \sum_{i}^{N}\sum_{j}^{W(i)} \beta(i, j), \quad (13)$$

where $\beta(i, j)$ is the number of each outgoing particle after elementary photon–nucleon reaction, i is the event index, and j is the index of run for each event. For one π and two π channels, $\beta(i, j)$ equals to 1 and 2, respectively. We calculate the outgoing particles after the whole transportation process and eventually obtain the yield of particles by multiplying a coefficient.

The Pauli-blocking effect is also considered for the outing nucleons after the process of elementary interaction before its transportation in nucleus. The photonuclear reaction will be abandoned in the run if the momentum and coordinate of the outgoing nucleons are checked to reach the Pauli-blocking condition. Meanwhile, to obtain a relatively stable nucleus, we consider the coordinates of initial nucleons with a spherical distribution and momentum with a local Fermi distribution. Actually, we have used more stable ground state with the EQMD model[11,15] to discuss the α-clustering effect of light nuclei in the low photon energy of quasi-deuteron region.[16] In the further work we plan to use this model to reach a more precise description of the photonuclear reaction process in this medium energy region of photon.

In our model, the first step is that we need to add the cross section to calculate the weight as described above. Since the elastic scattering and the Compton scattering cross section are very low in intermediate energy (above 200 MeV) and can be ignored,[27] we only consider the absorption cross section for the elementary photon-nucleon channel. There are two elementary channels in our model, the single π, which is significant in the low photon energy, and the two-π production channel. We also assume the cross-section of photon–neutron the same as the photon–proton,

$$\gamma + N \to N + \pi, \quad (14)$$

$$\gamma + N \to N + \pi + \pi. \quad (15)$$

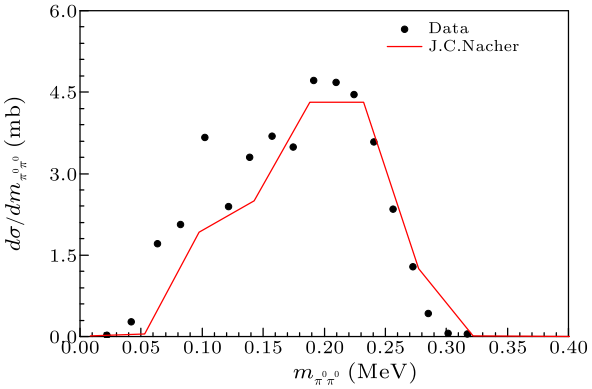

Fig. 1. (Color online) Differential cross section of two-pion invariant mass distributions for incident photon energy in the range of 400–460 MeV. The data is obtained from Ref. [35]. The red solid line depicts the calculation with the model by Nacher *et al.*[34]

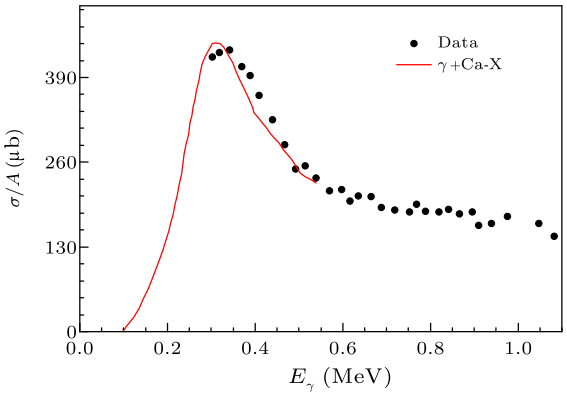

Fig. 2. (Color online) Total cross section for (γ, Ca). The data come from Ref. [36].

For the single pion channel shown in Eq. (6), we use the MAID model for this elementary differential cross section.[33] For the two-pion channel in Eq. (7), we use the model of Gomez *et al.*[32] and Nacher *et al.*[34] to calculate the differential cross section. The calculation of the cross sections consists of 27 Feynman diagrams which include Δ, $N^*(1440)$ and $N^*(1520)$ as

intermediate baryonic states and the ρ meson as an intermediate two-pion resonance. It gives a good description in comparison with the experimental data. However, the differential cross section calculated by the model is in the region between the two thresholds to 800 MeV,[32] therefore we select the maximum of the incident photon energy below 800 MeV in our model. Figure 1 shows the differential cross section as a function of the produced two-pion invariant mass for photon–proton interaction with incident photon energy in the range of 400–460 MeV,[34,35] and Fig. 2 shows the total cross section of (γ, ^{40}Ca) as a function of incident photon energy together with the experimental data, from which we can find that the added elementary channels are reasonable.

For final state interaction, the sequence of collision has been considered in the transport process, which is written as

$$N + N \to N + \pi, \tag{16}$$

$$N + \Delta \to N + N, \tag{17}$$

$$\Delta \to N + \pi. \tag{18}$$

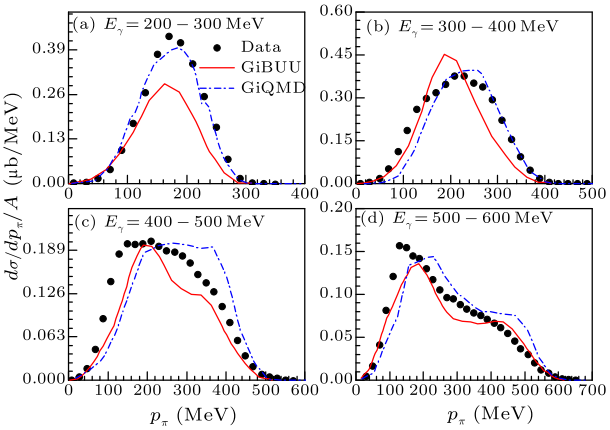

Fig. 3. (Color online) Momentum distribution of pions produced from γ+^{40}Ca in different energy regions.

Here we describe the calculation of photonuclear reaction within the GiQMD model and give the momentum distribution of π production of the photon induced ^{40}Ca at serval energies. Figure 3 shows the momentum spectrum result of (γ, ^{40}Ca) for average photon energy from 200 MeV to 600 MeV. In this figure, the black solid circle is the data from the TAPS,[37,38] the red solid line is calculated by the GiBUU model,[27] and the blue dashed line is our calculation. From the figure, our GiQMD calculations give reasonable description in the four photon energy regions. However, in the higher photon energy, the peak at about 200 MeV slightly moves to higher pion momentum. The reason for the inconsistence with both data and the GiBUU calculation might be that we have not introduced the vector mesons since the two-pion production shows that the inclusion of the vector meson for the outgoing particles is dominant at high energy of incident photons, which leaves us an improvement space for the GiQMD model.

Figure 4 shows the comparison of momentum distribution of (γ, ^{12}C) and (γ, ^{40}Ca) in photon energy interval between 500 MeV and 600 MeV together with the data of (γ, ^{12}C).[38] The single pion production cross section is significant in the total absorption process. From the comparison with the case with the less final state interaction (FSI) (^{12}C), we find a great reduction in the larger FSI case (^{40}Ca) for π^0 production, which is an important probe for nuclear structure such as the neutron skin and symmetry energy. In Fig. 5, we give the comparison of our calculation with the GiBUU's result as well as the experimental data which comes from Ref. [38], where the coherent or incoherent π-photoproduction channels are considered.[39] Overall, our GiQMD model gives a right trend with the data, but it is not so good as GiBUU below 300 MeV, which deserves a further improvement for our present model.

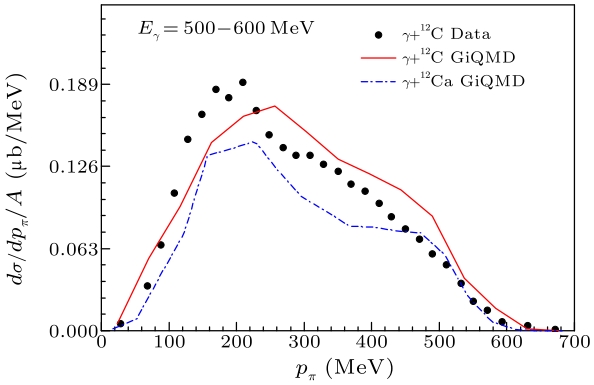

Fig. 4. (Color online) Momentum distribution of pion from ^{12}C and ^{40}Ca for $E_\gamma = 500$–600 MeV.

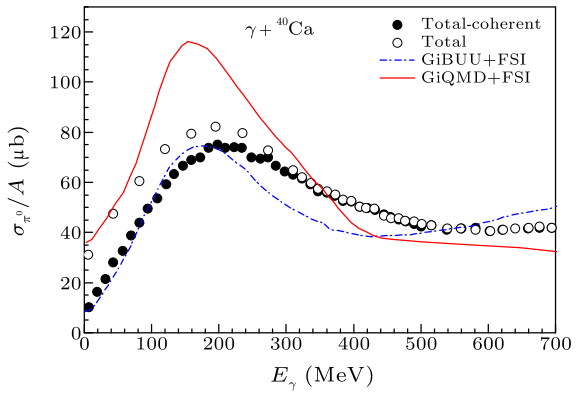

Fig. 5. (Color online) Excitation function of the cross section of single π^0 for γ+^{40}Ca. The open or solid dotted lines represent the data for considering the coherence (solid circles) or not (open circle), respectively.[38] Blue and red dashed lines represent the GiBUU and GiQMD results with FSI, respectively.

In summary, we have presented an extended transport model (GiQMD) for intermediate energy photonuclear reaction based on the IQMD model, and calculated the yield of pions and its cross section. An overall good agreement with experimental data as well as other models is reached, and therefore it shows that

this model is feasible to study photonuclear reactions in the energy region from about 200 MeV to 600 MeV. Using this GiQMD model, our calculation result is similar to the GiBUU model, which indicates that the calculations are model independent. In comparison with the BUU type model, the QMD model can well describe the fluctuation and fragmentation, therefore we will use the GiQMD model to describe the photon-induced fragmentation in the near future.

References

[1] Weller H R, Mohammad A W, Gao H Y et al 2009 *Prog. Part. Nucl. Phys.* **62** 257
[2] Filipescu D, Anzalone A, Balabanski D L et al 2015 *Eur. Phys. J.* A **51** 185
[3] Wu H L, Chen J H, Liu B et al 2015 *Nucl. Sci. Tech.* **26** 050103
[4] Luo W, Balabanski D L and Filipescu D 2016 *Nucl. Sci. Tech.* **27** 113
[5] Muramatsu N, Chen J Y, Chang W C et al 2009 *Phys. Rev. Lett.* **103** 012001
[6] Shimizu H and Muramatsu N 2017 *Nucl. Phys. News* **27** 19
[7] Utsunomiya H, Hashimoto S and Miyamoto S 2015 *Nucl. Phys. News* **25** 25
[8] Hicks K et al 2009 *Phys. Rev. Lett.* **102** 012501
[9] Nakano T (for the LEPS Collaboration) 2003 *Nucl. Phys.* A **721** 112c
[10] Tavares O A P, Duarte S B, Deppman A et al 2004 *J. Phys.* G **30** 377
[11] He W B, Ma Y G, Cao X G, Cai X Z and Zhang G Q 2014 *Phys. Rev. Lett.* **113** 032506
[12] He W B et al 2014 *Nucl. Tech.* **37** 100511 (in Chinese)
[13] He W B, Ma Y G, Cao X G, Cai X Z and Zhang G Q 2016 *Phys. Rev.* C **94** 014301
[14] Levinger J S 1951 *Phys. Rev.* **84** 43
[15] Maruyama T, Niita K and Iwamoto A 1996 *Phys. Rev.* C **53** 297
[16] Huang B S, Ma Y G and He W B 2017 *Phys. Rev.* C **95** 034606
[17] Huang B S, Ma Y G and He W B 2017 *Eur. Phys. J.* A **53** 119
[18] Aichelin J 1991 *Phys. Rep.* **202** 233
[19] Hartnack Ch, Puri R K et al 1998 *Eur. Phys. J.* A **1** 151
[20] Peilert G, Stöcker H, Rosenhauer A et al 1989 *Phys. Rev.* C **39** 1402
[21] Aichelin J, Rosenhauer A, Peilert G et al 1987 *Phys. Rev. Lett.* **58** 1926
[22] Ma Y G and Shen W Q 1995 *Phys. Rev.* C **51** 710
[23] Ma Y G, Shen W Q and Zhu Z Y 1995 *Phys. Rev.* C **51** 1029
[24] Yan T Z, Ma Y G, Cai X Z et al 2006 *Phys. Lett.* B **638** 50
[25] Wang T T, Lv M, Ma Y G et al 2015 *Chin. Phys. Lett.* **32** 062501
[26] Xing Y Z et al 2016 *Chin. Phys. Lett.* **33** 122501
[27] Buss O, Gaitanos T, Gallmeister K et al 2012 *Phys. Rep.* **513** 1
[28] Bertsch G F and Das Gupta S 1988 *Phys. Rep.* **160** 189
[29] Ma Y G et al 1993 *Phys. Rev.* C **48** R1492
[30] Zhang F 2016 *Chin. Phys. Lett.* **33** 012501
[31] Carrasco R C et al 1997 *Nucl. Phys.* A **616** 575
[32] Gomez T J A et al 1996 *Nucl. Phys.* A **600** 413
[33] Drechsel D and Tiator L 1992 *J. Phys.* G **18** 449
[34] Nacher J C et al 2001 *Nucl. Phys.* A **695** 295
[35] Messchendorp J G et al 2002 *Phys. Rev. Lett.* **89** 222302
[36] Bianchi N et al 1996 *Phys. Rev.* C **54** 1688
[37] Gabler A R et al 1994 *Nucl. Instrum. Methods Phys. Res. Sect.* A **346** 168
[38] Krusche B et al 2004 *Eur. Phys. J.* A **22** 277
[39] Darwish E M 2015 *Chin. Phys. Lett.* **32** 122501