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Global triton optical model potential

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Abstract

Based on the existing experimental data of elastic scattering angular distributions, we obtain a set of global optical model potential (OMP) parameters for triton (t) as projectile, which can basically reproduce the experimental data for target nuclei from ^{48}Ca to ^{232}Th, as well as ^{27}Al and ^{19}F in the energy region below 40 MeV.

1. Introduction

When triton with incident energy below 300 MeV interact with target nuclei, two processes take place: one is the elastic scattering and the other is absorption or reaction. The angular distributions of elastic scattering and the total reaction cross sections are usually calculated with optical model (OM). The importance of OM has been shown in Ref. [1]. OM is the basis and starting point for all the nuclear model calculations, which gives us much important information about spectroscopic, nuclear shapes, nuclear structure and so on. The optical model potential (OMP) is the main part in OM, and the knowledge of the OMP plays an essential role in the description of many nuclear reactions, e.g. inelastic scattering processes, transfer or the direct reactions, and in nuclear structure studies. The transmission coefficients and the inverse cross sections used in statistical theory are also calculated with optical model.

Up to now, there are many excellent local and global optical potentials for nucleons [2,3], deuteron (d) [4–6], ^{3}He [7,8] and alpha (α) [9,10]. For triton (t), besides some local potentials [11,12], there is only one global potential established by C.M. Perey and F.G. Perey [13] in 1976, which was in popular used for the outgoing channel in nuclear model calculations. As

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triton is an artificial radiative isotope of hydrogen element with short life, it is more difficult to do experiments for triton as projectile in the nuclear reaction than for the other light particles (n, p, d, ^{3}He, α). So the analysis of global triton OMP is significant in guiding the experiments for t-nucleus reactions.

J. Nuriynshi [14] used four- and six-parameter OMP with surface absorption to study the elastic (t, t) scattering at 20 MeV for target nuclei with mass number $40 \leqslant A \leqslant 207$. P.P. Urone et al. [11] discussed the isospin dependence of the mass-3 optical potential and compared the triton and ^{3}He elastic scattering for target nuclei from ^{40}Ca to ^{118}Sn at incident energy 20 MeV and 21 MeV, respectively. J.B.A. England et al. [12] had a further study on the isospin dependence of mass-3 optical potential by adding the effect of spin-orbital coupling to the optical potential, in which the elastic scattering at 33 MeV was presented. In this work, we used the code APMN [15] and took the ^{3}He global optical potential parameters in Ref. [17] as the starting points to obtain a set of optical potential parameters for triton as projectile. The form of optical potential we adopted is the modified Becchetti and Greenlees (BG) [3] form potential which will be displayed in the following section.

This paper is arranged as follows. In Section 2, we provide a description of the optical model and the form of optical potential. Section 3 gives the results, Section 4 is devoted the discussion. Finally, a summary is given in Section 5.

2. Optical model and the form of optical potential

APMN [15] is a code to automatically search for a set of optical potential parameters with smallest χ^2 in $E \leqslant 300$ MeV energy region by means of the improved steepest descent algorithm [18], which is suitable for non-fissile medium-heavy nuclei with the light projectiles, such as neutron, proton, deuteron, triton, ^{3}He, and α. The optical potential in APMN [15] is modified based on the standard BG form [3], i.e. Woods–Saxon form for the real part potential V and the imaginary part potential of volume absorption W_v; derivative Woods–Saxon form for the imaginary part potential of surface absorption W_s; and Thomas form for the spin-orbital coupling potential V_{so} and W_{so}. The Coulomb potential V_C is also included. All the radius and diffusiveness parameters in the standard BG optical potential form are constant, not varying with the mass of target nuclei. In this work, they were modified as functions of the mass of target nuclei according to the work of Haixia An et al. [6]. Then 31 adjustable parameters are involved in the code APMN [15]. The modified BG optical potential form is presented as follows:

$$\begin{aligned} V(r) = {} & -V f_r(r) - i W_v f_v(r) + i4a_s W_s \frac{df_s(r)}{dr} \\ & + \lambda\!\!\!^{-}{}_\pi^2 \frac{V_{so} + iW_{so}}{r} \frac{df_{so}(r)}{dr} 2\vec{S}\cdot\vec{l} + V_c(r), \end{aligned} \tag{1}$$

where

$$f_i(r) = \left[1 + \exp\left(\left(r - r_i A^{1/3}\right)/a_i\right)\right]^{-1} \quad \text{with } i = r, v, s, so, \tag{2}$$

$$V = V_0 + V_1 E_T + V_2 E_T^2 + V_3 (N - Z)/A + V_4 Z/A^{1/3}, \tag{3}$$

$$W_s = W_{s0} + W_{s1} E_T + W_{s2}(N - Z)/A, \tag{4}$$

$$W_v = W_{v0} + W_{v1} E_T + W_{v2} E_T^2 + W_{v3} A^{1/3}, \tag{5}$$

$$R_i = r_i A^{1/3} \quad \text{with } i = r, v, s, so, c, \tag{6}$$

$$r_i = r_{i0} + r_{i1} A^{-1/3} \quad \text{with } i = r, v, s, so, \tag{7}$$

$$a_i = a_{i0} + a_{i1} A^{1/3} \quad \text{with } i = r, v, s, so, \tag{8}$$

where Z, N and A are the numbers of protons, neutrons, and the nucleons of the target nucleus, respectively. E_T is the incident triton energy in the laboratory frame. V is the real part potential, W_s and W_v are the surface and volume absorption of the imaginary part potential, respectively, $V_C(r)$ is the coulomb potential and is taken as a potential of uniformly charged sphere with radius R_C. V_{so} and W_{so} are the real and imaginary part of spin-orbital coupling potential, respectively. λ_π^2 is the Compton wave length of pion, usually $\lambda_\pi^2 = 2.0\ \mathrm{fm}^2$.

3. Results

Our theoretical calculation is carried out in the non-relativistic frame, no consideration is given to the relativistic kinetics corrections because they are usually very small when $E_T \leqslant 300$ MeV (see Ref. [6]). Some experimental data used in this work are taken from EXFOR (web address: http://www.nndc.bnl.gov/), others are gained by scanning the figures in the references. The incident energies are always below 40 MeV for all existing experimental data. As for data errors, usually we take the values given in EXFOR; in the case that the data errors are not provided in EXFOR, we take them as 10% of the corresponding experimental data; in the case that data are obtained from figures in other references we also take 10% for the data error. In this work, we choose 18 nuclei shown in Table 1 as the data base for searching global triton optical potential parameters.

Considering triton is the isospin partner of ^{3}He particle, we use the parameters of ^{3}He [17] as starting point.

During our study, we noticed that the value of W_{v3} is very small. Then we tried to let $W_{v3} = 0$ and found that the results had almost no change. For the incident energies for all experimental data are below 40 MeV, so we need not consider the imaginary part of spin-orbital coupling potential, and let $W_{so} = 0$. So we delete these two parameters from our global triton potential, in which there are 29 parameters as following:

$$V = 137.6 - 0.1456 E_T + 0.0436 E_T^2 + 4.3751(N - Z)/A + 1.0474 A/Z^{1/3}, \tag{9}$$

$$W_s = 37.06 - 0.6451 E_T - 47.19(N - Z)/A, \tag{10}$$

$$W_v = 7.383 + 0.5025 E_T - 0.0097 E_T^2, \tag{11}$$

$$a_r = 0.6833 + 0.0191 A^{1/3}, \qquad a_s = 0.8114 + 0.01159 A^{1/3}, \tag{12}$$

$$a_v = 1.119 + 0.01913 A^{1/3}, \qquad a_{so} = 0.3545 - 0.0522 A^{1/3}, \tag{13}$$

Table 1
The data base for searching global optical potential parameters

Nucleus	Energy (MeV)	Refs.	Nucleus	Energy (MeV)	Refs.
^{232}Th	33	[12]	^{87}Rb	15	[26]
^{208}Pb	17–33	[12,19,20]	^{82}Se	15	[27]
^{207}Pb	8.5–20	[20,21]	^{68}Zn	17	[19]
^{182}W	20	[20]	^{58}Ni	9–33	[12,19,28,29]
^{140}Ce	15–17	[19,22]	^{54}Fe	17–20	[19,20]
^{116}Sn	17–20	[19,20]	^{52}Cr	15–20	[23]
^{90}Zr	15–20	[19,23,24]	^{51}V	11–33	[12,29]
^{89}Y	33	[12]	^{48}Ti	2–17	[19,31]
^{86}Sr	15	[25]	^{46}Ti	17	[19]

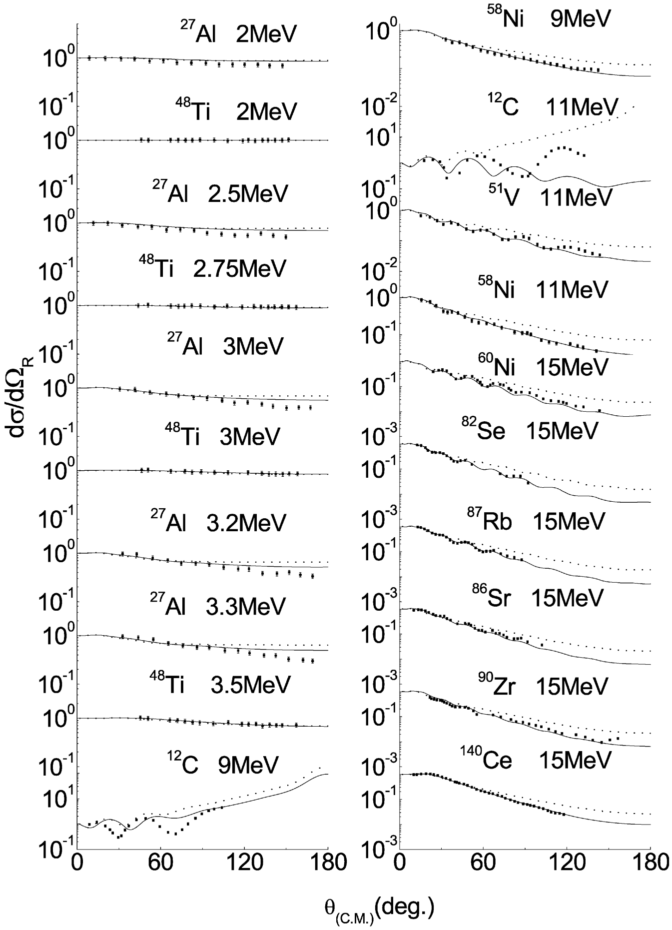

Fig. 1. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the center of mass frame, the incident energies are from 2 MeV to 15 MeV, the experimental data are taken from Refs. [22,24–27,29,31,36]. The dots denote the experimental data, the solid lines represent the values calculated with our global parameters, the dashed lines represent the values calculated with the parameters of C.M. Perey and F.G. Perey; the same symbols are used in all figures.

$$r_r = 1.1201 - 0.1504A^{-1/3}, \qquad r_s = 1.251 - 0.4622A^{-1/3}, \tag{14}$$

$$r_v = 1.3202 - 0.1776A^{-1/3}, \qquad r_{so} = 0.46991 + 0.1294A^{-1/3}, \tag{15}$$

$$r_c = 1.4219, \tag{16}$$

$$V_{so} = 1.9029. \tag{17}$$

With above optical potential parameters, we calculate the angular distributions of elastic scattering for many nuclei with triton as projectile. And the calculated values and experimental data of elastic scattering angular distributions are shown in Figs. 1–6.

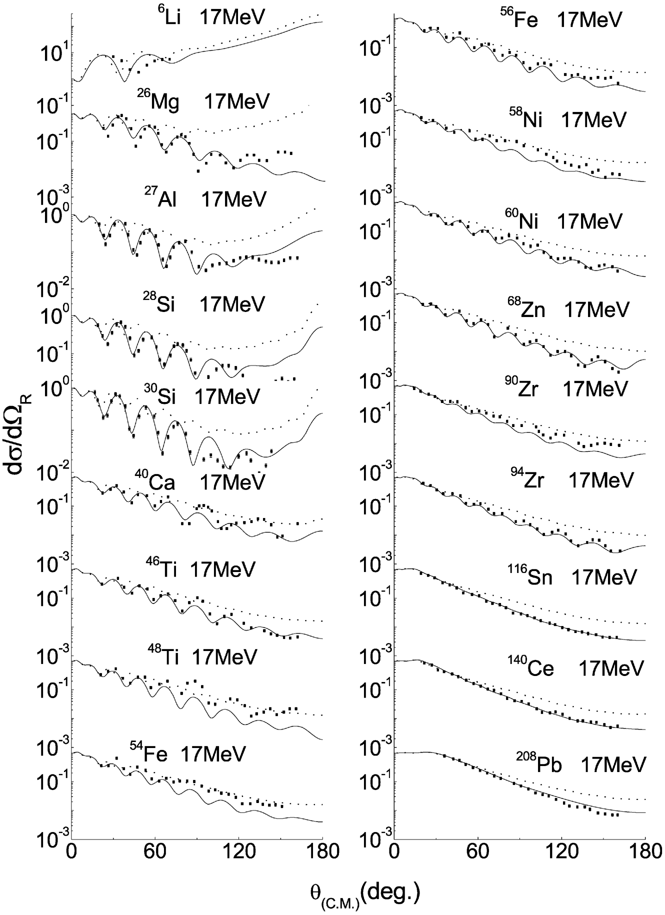

Fig. 2. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the center of mass frame, the incident energy is 17 MeV, the experimental data are taken from Refs. [19,34,35,41].

4. Discussion

The χ^2 represents the deviation of the calculated values from the experimental data, in this work, which is defined as follows:

$$\chi^2 = \frac{1}{N}\sum_{n=1}^{N}\chi_n^2, \tag{18}$$

$$\chi_n^2 = \frac{1}{N_{n,\mathrm{el}}}\sum_{i=1}^{N_{n,\mathrm{el}}}\frac{1}{N_{n,i}}\sum_{j=1}^{N_{n,i}}\left(\frac{\sigma_{\mathrm{el}}^{\mathrm{th}}(i,j)-\sigma_{\mathrm{el}}^{\mathrm{exp}}(i,j)}{\Delta\sigma_{\mathrm{el}}^{\mathrm{exp}}(i,j)}\right)^2, \tag{19}$$

where χ_n^2 is for a single nucleus, and n is the nucleus sequence number. χ^2 is the average values of N nuclei, and N denotes the numbers of nuclei included in global parameters search. $\sigma_{\mathrm{el}}^{\mathrm{th}}(i,j)$ and $\sigma_{\mathrm{el}}^{\mathrm{exp}}(i,j)$ are the theoretical and experimental differential cross sections at the jth angle

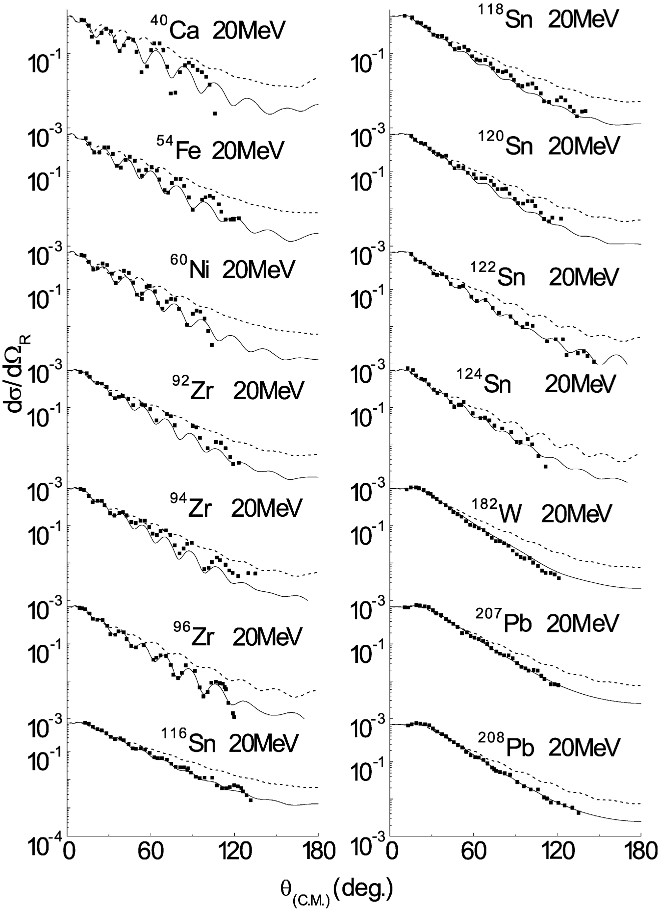

Fig. 3. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the center of mass frame, the incident energy is 20 MeV, the experimental data are taken from Refs. [20,28].

with the ith incidence energy, respectively. $\Delta\sigma_{\rm el}^{\rm exp}(i, j)$ is the corresponding experimental data error. $N_{n,i}$ is the number of angles for the nth nucleus and the ith incidence energy. $N_{n,\rm el}$ is the number of incident energy points of elastic scattering angular distribution for the nth nucleus.

Through minimizing the average χ^2 value of 18 nuclei in Table 1 with the modified code APMN, we find an optimal set of global triton potential parameters, which are given in Eqs. (9)–(17).

With the obtained parameters above, we get the average value of $\chi^2 = 11.21$ for these 18 nuclei. Using the parameters of C.M. Perey et al. [13], we obtain the average value of $\chi^2 = 876.8$ for the same 18 nuclei. We also use the parameters of ours and C.M. Perey et al. to calculate the χ_n^2 for every single nucleus, which include above 18 nuclei in Table 1 and also some other nuclei not in Table 1, and denote ours with χ_{n1}^2, C.M. Perey et al. with χ_{n2}^2, respectively. And the results are shown in Table 2.

From Table 2, we can see that for the nuclei in Table 1, except ^{54}Fe(33.36), ^{52}Cr(18.99), ^{89}Y(19.49), all χ_{n1}^2 are less than 15.0 and most of them are less than 10.0. For those nuclei not

Table 2
χ_n^2 of a single nucleus. χ_{n1}^2 for our global potential parameters, χ_{n2}^2 for those of C.M. Perey and F.G. Perey

Nucleus	χ_{n1}^2	χ_{n2}^2	Nucleus	χ_{n1}^2	χ_{n2}^2
^{232}Th	4.568	10 840	^{58}Ni	8.355	496.3
^{208}Pb	3.296	431.3	^{57}Fe	12.74	236.6
^{207}Pb	0.2815	23.18	^{56}Fe	12.77	789.1
^{182}W	4.719	262.8	^{54}Fe	33.36	135.0
^{140}Ce	0.7425	83.81	^{52}Cr	18.99	225.0
^{124}Sn	5.125	208.5	^{51}V	11.88	860.2
^{122}Sn	4.948	492.5	^{48}Ti	7.457	5.032
^{120}Sn	6.155	82.60	^{46}Ti	9.147	359.2
^{118}Sn	5.386	154.1	^{48}Ca	9.263	834.2
^{116}Sn	1.914	230.2	^{40}Ca	64.54	2639
^{112}Sn	1.910	253.7	^{32}S	320.6	15 690
^{96}Zr	7.170	551.6	^{30}Si	40.48	556.5
^{94}Zr	8.074	153.4	^{28}Si	64.15	1516
^{92}Zr	8.092	105.2	^{27}Al	14.98	138.7
^{90}Zr	8.055	63.13	^{26}Mg	119.2	396.8
^{89}Y	19.49	814.1	^{24}Mg	165.0	1017
^{86}Sr	1.977	14.06	^{19}F	11.62	716.9
^{87}Rb	0.6183	19.95	^{16}O	37.12	499.8
^{82}Se	0.7510	33.03	^{13}C	494.3	2477
^{68}Zn	7.598	501.9	^{12}C	184.3	44 870
^{64}Ni	6.627	402.6	^{9}Be	59.72	1632
^{62}Ni	3.026	316.2	^{7}Li	37.25	30.55
^{60}Ni	7.286	213.0	^{6}Li	19.98	63.71

in Table 1 but with $A > 40$, the χ_{n1}^2 are always less than 15.0 and most of them are less than 10.0, too. For the lighter nuclei between ^{19}F and ^{40}Ca, only ^{19}F and ^{27}Al are with χ_{n1}^2 less than 15.0, all other nuclei with rather larger χ_{n1}^2, three of them larger than 100.0, the rest two larger than 40.0. Our global parameters are not well suited for 1p nuclei with $Z < 9$ which, with a few exceptions, usually show large χ_{n1}^2.

The χ_{n2}^2 of C.M. Perey et al. [13] are usually much larger than those of ours, except for ^{48}Ti and ^{7}Li. For the parameters of C.M. Perey et al., the χ_{n2}^2 are usually very large, and most of them larger than 100. This shows that our set of global triton optical potential parameters are much better than those of C.M. Perey et al. to reproduce the existing experimental data of elastic angular distributions in general. And our set of optical potential parameters provides a direction for the nuclear experiments in the future. The global parameters of C.M. Perey et al. are not suited for the calculation of the angular distributions in elastic scattering of tritons, they can only be used to calculate transmission factors and inverse cross sections of ejected tritons.

The elastic scattering angular distributions calculated with our global parameters and with those of C.M. Perey et al. as well as the experimental data are plotted in Figs. 1–6. The solid lines represent the values calculated with our parameters, the dashed lines represent the results with the parameters of C.M. Perey et al., and the points represent the experimental data. Figs. 1–4 show the Rutherford ratio of the differential cross sections in the center of mass (C.M.) system. Fig. 5 shows the Rutherford ratio of the differential cross sections in the laboratory (Lab) system. And Fig. 6 displays the differential cross sections in C.M. system.

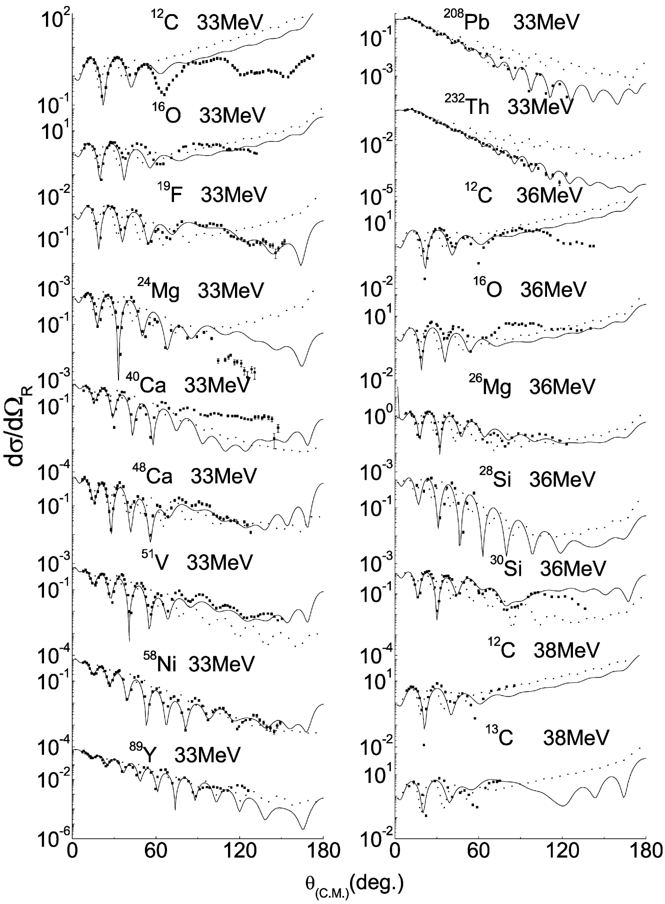

Fig. 4. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the center of mass frame, the incident energies are from 33 MeV to 38 MeV, the experimental data are taken from Refs. [12,32,37,38].

From these figures, we can clearly see that our theoretical results can reproduce the experimental data much better than C.M. Perey et al. We can also see that our calculated results are not in good accordance with experimental data for ^{12}C at 9, 11 MeV in Fig. 1, for ^{58}Ni, ^{54}Fe, ^{48}Ti, ^{40}Ca and ^{6}Li at 17 MeV in Fig. 2, for ^{12}C, ^{16}O at 33, 36 MeV, and ^{24}Mg, ^{40}Ca at 33 MeV for large angles in Fig. 4. Except for above mentioned target nuclei at some incoming energies, our calculated angular distributions are usually in rather good agreement with the experimental data.

For ^{12}C, the disagreement may be caused by elastic scattering strong coupling with inelastic scattering, as pointed out by Buck [33]. ^{16}O and ^{40}Ca are double magic nuclei with strong effect of inner structure, which cannot be considered in optical model. As for ^{58}Ni, ^{54}Fe, ^{48}Ti and ^{24}Mg at some incident energies for large angles, the reasons are not yet very clear for the discrepancy between our theoretical results and experimental data. Anyhow, one cannot find a set of global OM parameters to make the calculated results in good accordance with experimental data for all target nuclei at all incoming energies.

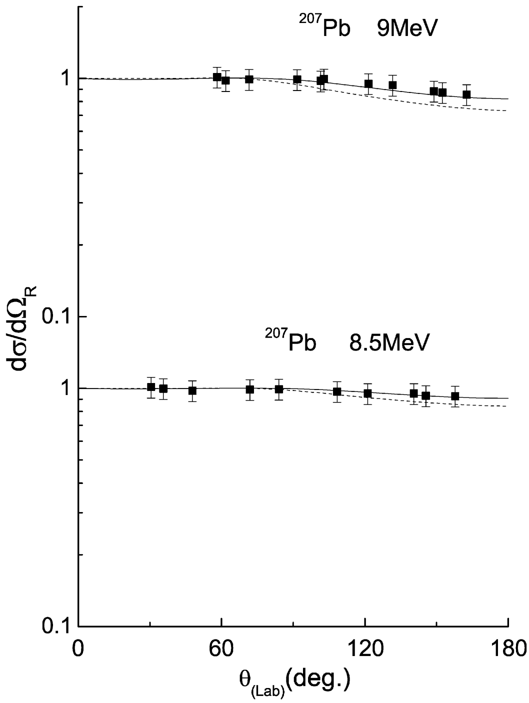

Fig. 5. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the Laboratory frame, the incident energies are from 8.5 MeV to 9 MeV, the experimental data are taken from Ref. [21].

In the code APMN [15], the compound nucleus elastic scattering is calculated with the Hauser–Feshbach statistic theory with Lane–Lynn width fluctuation correction [16] (WHF), which is designed for medium-heavy target nuclei. For these nuclei, the spaces between levels are usually small, the concepts of continuous levels and level density can be properly used for description of higher levels, say, their excited energies are higher than the combined energy of the emitting particle in compound nucleus. In the code APMN, the Hauser–Feshbach theory supposed that after the compound nucleus emits one of the six particles—n, p, d, t, α and ^{3}He, or a γ photon, all discrete levels of the residual nucleus de-excite only through emission of γ photons, not permitting emission of any particles. For medium-heavy target nuclei, when the incident energy increase to about 5–7 MeV, the cross sections of the compound nucleus elastic scattering usually will drop to very small values in comparison with the shape elastic scattering; so there is no need for considering pre-equilibrium particle emission.

For the light target nuclei, especially for 1p-shell nuclei (from Li to O), the spaces between levels are usually large, the concepts of continuous levels and level density are not suited for them. One has to completely use discrete levels for incoming energy lower than, say, 30 MeV. Furthermore, for light nuclei, only when the incident energy increase to higher 15–20 MeV, the cross sections of the compound nucleus elastic scattering are able to drop to small values in comparison with the shape elastic scattering; so the pre-equilibrium particle emission is also need to be considered. Therefore, the code APMN is not suited for light nuclei in the energy region below 15–20 MeV. Thus it can be understood that the calculated results may be worse in comparison with experimental data for some light nuclei in the low energy region (say, lower

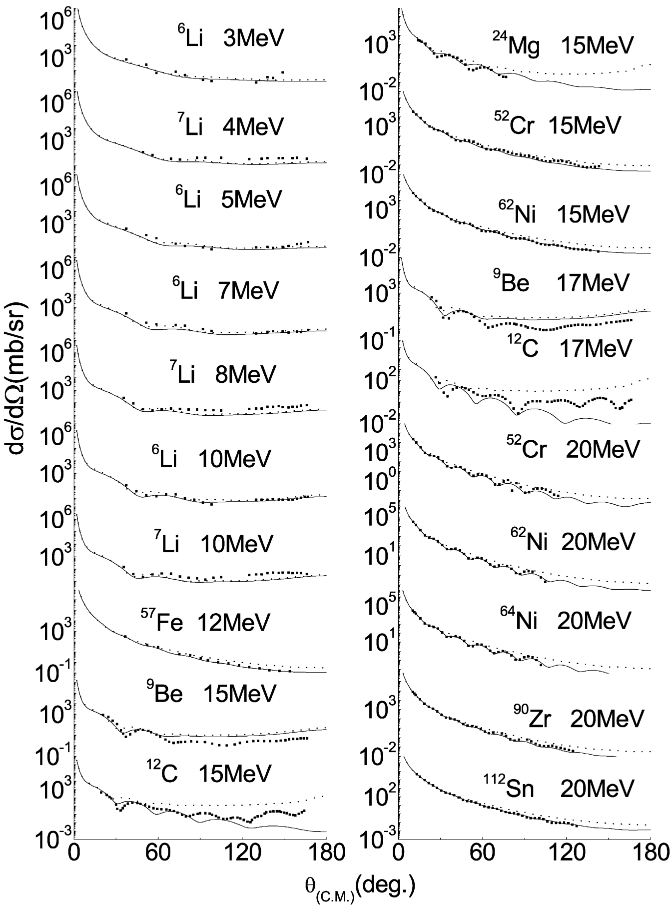

Fig. 6. Comparisons of the experimental angular distributions of elastic scattering with the calculated values from our global potential parameters and those of C.M. Perey and F.G. Perey in the center of mass frame, the incident energies are from 3 MeV to 20 MeV, the experimental data are taken from Refs. [23,30,39,40,42].

than 20 MeV) due to the fact that compound nucleus scattering is an important part of the total elastic scattering.

5. Summary

A set of global triton optical potential parameters are obtained based on the existing experimental data of elastic scattering angular distributions by using the modified code APMN [15], with which the calculated elastic scattering angular distributions can basically fit the corresponding experimental data for many nuclei from ^{48}Ca to ^{232}Th, as well as ^{27}Al and ^{19}F. They can be used directly for many nuclei with experimental data and those nuclei for which experimental data are lacking. For some other nuclei, especially for those nuclei lighter than ^{40}Ca, this set of global parameters maybe not fit the experimental data well. In these cases, it can be taken as the starting point in further searching for the local optimal parameters for this target nucleus. Polarization of the projectile is not considered in this work. Because of the $J = 1/2$ spin, polarized triton beams are important in reaction and nuclear structure studies. We plan to investigate the effect of polarization in a future work.

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