η production in proton-nucleus collisions near threshold*

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Abstract The η-meson production in proton-nucleus (pA) collisions near threshold is studied within a relativistic meson-exchange model. The primary production amplitude is presented in the distorted-wave impulse approximation for the nucleus with isospin 0 or 1 by assuming that $N^*(1535)$ is excited via a meson exchange and then decays into η and nucleon pair(ηN). Taking ^{18}O and ^{12}C nuclei as examples, we evaluate the production cross sections as a function of the incident proton energy, and analyze the effects of nuclear medium and various meson-exchange contributions. Finally we discuss implications for further experimental studies at the Cooling Storage Ring (CSR) in Lanzhou.

Key words η meson, proton-nucleus collision, $N^*(1535)$

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1 Introduction

There has been considerable interest in studying meson production off nucleons and nuclei[1]. The primary motivations of these studies are to investigate the structure and dynamical properties of the nucleon resonances. As far as nucleon-nucleon (NN) collisions are concerned, there is already a wealth of information on the π-meson production in the near-threshold energy region. The experimental information on η production in NN collisions is much less complete than for π production. In analogy with π production via Δ(1232) excitation, it is believed that η-meson production in NN collisions proceeds via excitation of nucleon isobars. Because of isospin conservation, only the N^* isobar of isospin-$\frac{1}{2}$ which decays into a ηN pair is important. Indeed, there is already strong evidence that near threshold, the $N^*(1535)$ resonance of spin 1/2 and odd parity dominates η production in pion- and photo-induced reactions. In fact this can be expected in the view of the proximity of its mass to that of the ηN pair and its remarkably large ηN branching ratio[2]. The couplings to other resonances are weak and seem to play a minor role in the near-threshold energy region.

Much effort has been devoted to the analysis of η-meson production in NN collisions in the threshold region within the relativistic meson-exchange model[3—6]. The predictions of these model calculations depend heavily on the coupling of mesons to the $N^*(1535)$ resonance. The coupling of π and η is known from the decay width of this resonance but not so well the coupling of other mesons. Thus it is not clear which of the exchanged nmesons dominates η production. Therefore, more accurate data of η meson productions are needed to answer the above issues. Recently the η production in p-deuton collisions[7, 8] become interesting in the light of a possible attractive η-nucleus interaction. It is interesting to use the η production amplitude as an effective impulse operator to study η-meson production off nuclei. In virtue of different properties of nuclei, various reaction channels can be opened. One can expect that new information can be obtained by observing a selected reaction channel.

The aim of the present work is to investigate the η-meson production in $pA \rightarrow p'A'\eta$ reactions for nuclear target A with isospin 0 or 1 within the relativistic meosn-exchange model, where the $N^*(1535)$ is excited via meson exchange and then decays into a ηN pair. As examples, numerical results for ^{12}C

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and ^{18}O are given and their implications for future experimental studies at CSR are discussed.

2 Model for $pA \rightarrow p'A'\eta$

As analyzed in NN collisions near threshold[5], we assume that in the η production process $pA \rightarrow p'A'\eta$ a $N^*(1535)$ is excited via σ, π and ρ meson exchange which then decays into the ηN pair. The Feynman diagrams describing this reaction mechanism are shown in Fig. 1. However, there are some differences between NN and pA collisions. According to the isospin conservation in strong interactions, only the isoscalar σ meson exchange is allowed for nuclear targets of isospin T=0, while π, ρ and σ meson exchange is possible for nuclear targets of isospin $T \neq 0$. Thus, information about different meson exchanges may be extracted by measuring the total cross section of the η production in proton-induced reactions on nuclear targets A with different isospins.

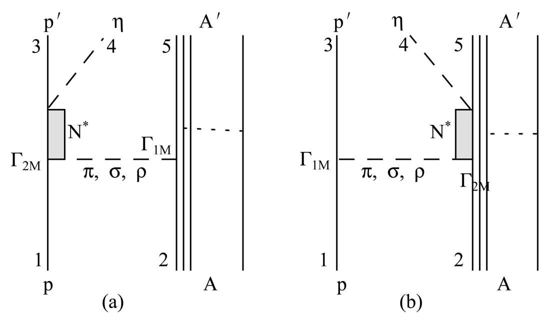

Fig. 1. Feynman diagrams for $pA \rightarrow p'A'\eta$ reactions, the $N^*(1535)$ is excited via meson exchange in the incoming proton (a) and in the target nucleus (b).

Treating the η production in the distorted wave impulse approximation[9, 10] is sufficient to calculate the primary amplitude for the $pA \rightarrow p'A'\eta$ reactions because the N-N interaction is short-ranged compared with the extension of the nuclear wave function. For the meson-nucleon couplings, we use the covariant Lagrangian[5, 11],

$$\begin{cases} \mathscr{L}_{\eta NN^*} = g_{\eta NN^*}\overline{\psi}_N \psi_{N^*}\phi_\eta, \\ \mathscr{L}_{\sigma NN^*} = \mathrm{i} g_{\sigma NN^*}\overline{\psi}_{N^*}\gamma^5\phi_\sigma\psi_N, \\ \mathscr{L}_{\sigma NN} = g_{\sigma NN}\overline{\psi}_N\psi_N\phi_\sigma, \\ \mathscr{L}_{\rho NN} = g_{\rho NN}\bar{\psi}_N\left(\gamma^\mu \boldsymbol{\rho}_\mu + \frac{\kappa_\rho}{2m_N}\sigma^{\mu\tau}\partial_\mu\boldsymbol{\rho}_\tau\right)\cdot\boldsymbol{\tau}\psi_N, \\ \mathscr{L}_{\rho NN^*} = \mathrm{i} g_{\rho NN^*}\bar{\psi}_{N^*}\gamma^5\gamma^\mu\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\psi_N, \\ \mathscr{L}_{\pi NN} = -\mathrm{i} g_{\pi NN}\bar{\psi}_N\gamma^5\boldsymbol{\tau}\cdot\boldsymbol{\phi}_\pi\psi_N, \\ \mathscr{L}_{\pi NN^*} = g_{\pi NN^*}\bar{\psi}_{N^*}\boldsymbol{\tau}\cdot\boldsymbol{\phi}_\pi\psi_N, \end{cases} \tag{1}$$

where g_{MNN} and g_{MNN^*} ($M=\pi,\rho,\sigma$) stand for the coupling constants. ψ_N, ψ_{N^*}, ϕ_η, ϕ_π, ϕ_σ and $\boldsymbol{\rho}$ denote the fields of the nucleon, $N^*(1535)$, η, π, σ and ρ mesons, respectively. $\boldsymbol{\tau}$ is the isospin vector with the usual Pauli spin matrices as components and $\sigma^{\mu\nu} = \mathrm{i}[\gamma^\mu,\gamma^\nu]/2$ with γ^μ the Dirac gamma matrices. κ_ρ is the tensor coupling coefficient.

The η production amplitude in $pA \rightarrow p'A'\eta$ reactions can then be written in the form,

$$T_{fi}^{pA\rightarrow p'A'\eta}(p_{p'},p_{A'},p_\eta;p_p,p_A) = F_{fi}(p_{p'},p_\eta;p_p)\cdot t_{pp\rightarrow pp\eta}\,, \tag{2}$$

where $t_{pp\rightarrow pp\eta}$ stands for the basic amplitude of the η production in p-p collisions,

$$t_{pp\rightarrow pp\eta} = \sum_{M=\pi,\rho,\sigma} F_M^2(q^2)\bar{u}(p_5,s_5)\Gamma_{1M}u(p_2,s_2)\times G_M(q^2)\bar{u}(p_3,s_3)g_{\eta NN^*}G_{N^*}(s)\Gamma_{2M}u(p_1,s_1) + \text{(exchange terms)}. \tag{3}$$

Here all contributions from π, ρ and σ mesons are summed up. Γ_{1M} and Γ_{2M} are the Meson-N-N and Meson-N-N* interaction vertexes. $u(p_i,s_i)$ and $\bar{u}(p_i,s_i)$ are the Dirac spinors of the initial and final state protons, respectively. p_i and s_i denote the momentum and spin of proton i. $G_{N^*}(s)$ is the propagator of the N* defined as

$$G_{N^*}(s) = \frac{\not{p}_{N^*} + m_{N^*}}{m_{N^*}^2 - s - \mathrm{i}m_{N^*}\Gamma_{N^*}(s)}\,. \tag{4}$$

Here p_{N^*}, m_{N^*} are the four momenta and the mass of the N*, and s is the square of the c.m. energy of the N* system. $\Gamma_{N^*}(s)$ is the energy-dependent decay width of the N* resonance. Chiang et al.[12] calculated the N* self-energy considering three decay channels $N^*\rightarrow N\eta$, $N^*\rightarrow N\pi$, $N^*\rightarrow N\pi\pi$. The decay width corrected for the N* self-energy is

$$\Gamma_{N^*}(s) = \Gamma(s=M_{N^*})\frac{\bar{q}(s)}{\bar{q}(m_{N^*})}\,, \tag{5}$$

where $\Gamma(s=M_{N^*})$=150 MeV is the on-shell width of the $N^*(1535)$. $\bar{q}(s)$ is the η momentum in the center of mass frame of the ηN system. In Eq. (3), $G_M(q^2)$ is the propagator of the exchanged meson M. For scalar and pseudoscalar mesons the propagators are defined as

$$G_M(q^2) = \frac{\mathrm{i}}{q^2 - m_M^2 + \mathrm{i}\varepsilon}\,. \tag{6}$$

The propagator of a vector meson is defined as

$$G_{\mu\nu}^M(q^2) = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m_M^2}\right)\frac{\mathrm{i}}{q^2 - m_M^2 + \mathrm{i}\varepsilon}\,, \tag{7}$$

where $g_{\mu\nu}$ is the metric tensor, m_M and q are the mass and four momenta of the exchanged meson M, respectively. In this work, a covariant monopole form factor[5] is added at each vertex,

$$F_{\rm M}(q^2)=\frac{\Lambda_{\rm M}^2-m_{\rm M}^2}{\Lambda_{\rm M}^2-q^2}\,, \tag{8}$$

where q is the momentum transfer between two protons, $m_{\rm M}$ denotes the mass of the exchanged meson and $\Lambda_{\rm M}$ is a cutoff parameter for each exchanged meson.

The distorted waves of incoming and outgoing particles and the wave functions of the nucleon in the nucleus are taken into account in the nuclear transition form factor $F_{\rm fi}(\boldsymbol{p}_{\rm p'},\boldsymbol{p}_\eta;\boldsymbol{p}_{\rm p})$ of Eq. (2). For the $\rm pA\to p'A'\eta$ reactions one may write

$$F_{\rm fi}(\boldsymbol{p}_{\rm p'},\boldsymbol{p}_\eta;\boldsymbol{p}_{\rm p})=\int{\rm d}^3r\psi_{\rm p'}^{(-)*}(\boldsymbol{r})\phi_\eta^{(-)*}(\boldsymbol{r})\rho_{\rm A}(r)\psi_{\rm p}^{(+)}(\boldsymbol{r}), \tag{9}$$

where $\rho_{\rm A}(r)$ is the nuclear density normalized to the number of nucleons in the nucleus. $\psi_{\rm p'}^{-*}(\boldsymbol{r})$, $\phi_\eta^{-*}(\boldsymbol{r})$ and $\psi_{\rm p}^{+}(\boldsymbol{r})$ are the distorted wave functions of the outgoing proton, η meson and incoming proton, respectively. It is well known that the eikonal form of the distorted wave function is a very good approximation at higher energies[13, 14]. Therefore, we use in present work the eikonal approximation to calculate the distorted waves. If only first-order optical potentials are used for the distortion and the real part of the p-p amplitude is neglected, one finds

$$\psi_{\rm p'}^{(-)*}(\boldsymbol{r})={\rm e}^{-{\rm i}\boldsymbol{p}_{\rm p}\cdot\boldsymbol{r}}\exp\left[-\frac{1}{2}\sigma_{\rm NN}\int_z^\infty{\rm d}z'\rho_{\rm A}(b,z')\right], \tag{10}$$

$$\phi_\eta^{(-)*}(\boldsymbol{r})={\rm e}^{-{\rm i}\boldsymbol{p}_\eta\cdot\boldsymbol{r}}\exp\left[-\frac{1}{2}\sigma_{\eta\rm N}\int_z^\infty{\rm d}z'\rho_{\rm A}(b,z')\right], \tag{11}$$

$$\psi_{\rm p}^{(+)}(\boldsymbol{r})={\rm e}^{{\rm i}\boldsymbol{p}_{\rm p}\cdot\boldsymbol{r}}\exp\left[-\frac{1}{2}\sigma_{\rm NN}\int_{-\infty}^z{\rm d}z'\rho_{\rm A}(b,z')\right]. \tag{12}$$

Here $\rho_{\rm A}(b,z')$ is the nuclear density; $\sigma_{\rm NN}$ and $\sigma_{\eta\rm N}$ are the nucleon-nucleon and nucleon-η cross sections in the considered energy region. So far there is no reliable experimental data on $\sigma_{\eta\rm N}$ and it is believed that the ηN interaction is rather weak. $\sigma_{\eta\rm N}$=0 mb is employed in our calculation, namely, the distortion of the η wave function is neglected. $\sigma_{\rm NN}$=40 mb[2] is used in the energy region considered.

The differential cross sections $\sigma(\rm pA\to\eta p'A')$ for these reactions can be written as[2]

$$\begin{aligned}&{\rm d}\sigma\ ({\rm pA}\to\eta{\rm p'A'})=\\&\frac{m_{\rm p}^2}{2\sqrt{(p_{\rm p}\cdot p_{\rm A})^2-(m_{\rm p}m_{\rm A})^2}}\overline{\sum_{s_{\rm i}}}\sum_{s_{\rm f}}|T_{\rm fi}|^2\times\\&(2\pi)^4\delta^4(p_{\rm p}+p_{\rm A}-p_{\rm p'}-p_{\rm A'}-p_\eta)\times\\&\frac{{\rm d}^3p_{\rm p'}}{(2\pi)^3E_{\rm p'}}\frac{{\rm d}^3p_{\rm A'}}{(2\pi)^32E_{\rm A'}}\frac{{\rm d}^3p_\eta}{(2\pi)^32E_\eta}\,,\end{aligned} \tag{13}$$

where $s_{\rm i}$ and $s_{\rm f}$ are the spins of the particles in the initial and final states. $p_{\rm p}$ and $p_{\rm A}$ are the four momenta of the incoming proton and the target nucleus; $m_{\rm p}$ and $m_{\rm A}$ are the masses of the proton and the nucleus, respectively. The η-N invariant mass spectrum and total reaction sections can be obtained from Eq. (13).

3 Numerical results and discussion

In our calculation all the parameters are taken from Refs. [5, 11, 15]. For the sake of completeness all these parameters are included in Table 1. The coupling constants of π, ρ and σ to NN and NN*, together with the cutoff parameters, are taken from the work of Eyser et al[15]. The π and η couplings to N*(1535) are deduced from the partial widths of the N* decay into πN and ηN. $g_{\rho\rm NN^*}$ is deduced from $\gamma\rm N\to N^*$ data[6]. For the σ meson, no direct information can be used to determine its coupling to the N*, so $g_{\sigma\rm NN^*}$ is evaluated from the relation $g_{\sigma\rm NN^*}/g_{\sigma\rm NN}=g_{\pi\rm NN^*}/g_{\pi\rm NN}$[5]. The values $g_{\eta\rm NN^*(1535)}$=2.06 and κ_ρ=6.1 are taken from Chiang et al.[12] and Li et al.[11], respectively. Harmonic-oscillator functions with parameters determined by elastic electron scattering[16] are used for the nuclear densities. Numerical calculations are performed for ^{18}O ($T\neq0$) and ^{12}C ($T=0$) targets at an incoming proton energy of 2.5 GeV.

Table 1. Parameters used in our calculation[5, 11, 15].

meson	$g^2_{\rm MNN}/4\pi$	$\Lambda_{\rm M}$/GeV	$g_{\rm MNN^*(1535)}$
σ	4.076	1.6	0.426
π	14.6	1.3	0.8
ρ	0.95	1.3	1.66

Figure 2(a) and (b) show the ηN invariant mass distribution and the Dalitz plot for the $\rm p+^{18}O\to p+^{18}O+\eta$ reaction. One can see that the ηN invariant mass distribution changes dramatically due to the N*(1535) excitation with respect to the pure phase space, and there is a sharp peak around 1535 MeV. The same thing can be found in the Dalitz plot. In free space the position and the width of the peak only depend on the mass and width of this resonance. Due to the nuclear distortion the position and width of the peak will change slightly. It can easily be shown that the nuclear distortions of the proton reduce the magnitude of the reaction cross sections. As shown in Fig. 1, the N*(1535) can be excited via meson exchange between the incoming proton and the nucleon inside the target. If the N*(1535) is excited in a nucleon inside the nucleus, this N*(1535) will interact with other nucleons inside the target. As discussed by Chiang et al.[12], the mass and the width of the N*(1535) will have many-body corrections due to Pauli blocking, η and π absorption. By taking this many-body modifications into account, we calculate the respective contributions of Fig. 1(a) and (b) to the cross section for the proton-induced reaction on ^{18}O. The obtained results are shown in Fig. 3. We can observe from Fig. 3 that the dominant contribution comes from the N*(1535) excitation in the incoming proton rather than in the target nucleus, which implies that the nuclear medium affects the reaction cross sections only slightly.

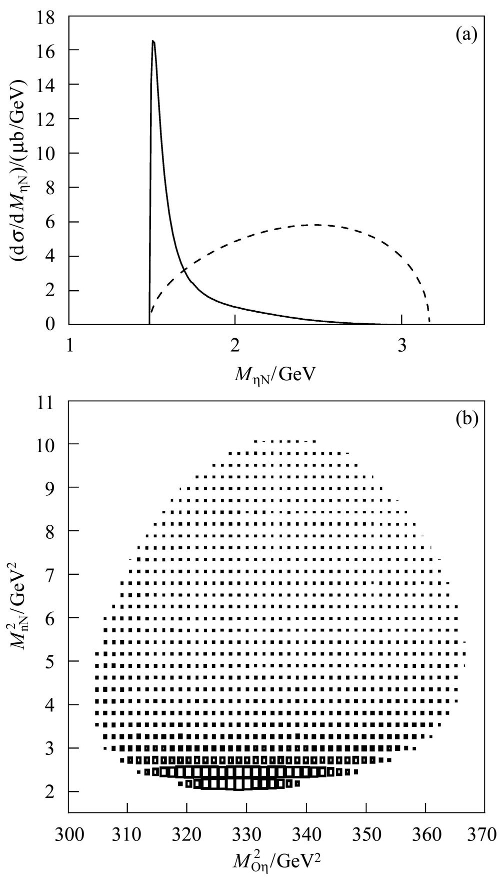

Fig. 2. The ηN invariant mass spectra (a) and the Dalitz plot (b) for the p+^{18}O→p+^{18}O+η reaction. The solid curve is the ηN invariant mass distribution and the dash curve is the pure phase space distribution.

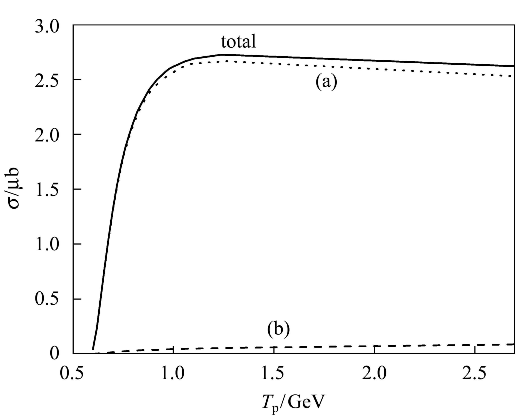

Fig. 3. The total cross section for p+^{18}O → p+^{18}O+η. (a) and (b) indicate the contributions for N* excitation in the incoming proton and in the target nucleus, respectively.

The total cross sections of pA → p′A′η reactions on different nuclear targets with different isospins are calculated as a function of the incoming proton energy. The numerical results for ^{12}C and ^{18}O targets are shown in Fig. 4. It is obvious that the total cross section for the ^{18}O target is much larger than for the ^{12}C target. There are two reasons for these results. Firstly, all the σ, ρ and π meson exchanges are allowed for the interaction between the proton and the ^{18}O target, while only the σ meson-exchange is allowed for the interaction between the proton and the ^{12}C target due to the isospin conservation in strong interactions. Secondly, the ρ meson exchange gives the main contribution to the cross section for the isospin $T\neq 0$ target. In Fig. 5 we show partial cross sections of various meson exchanges for the ^{18}O nuclear target. It can be seen that the contribution of the ρ meson exchange to the cross section is much large with respect to these of other meson exchanges. Therefore, by choosing different nuclear targets in the experiments and comparing various observations, one can extract useful information on the couplings of the mesons exchanged to the nucleus.

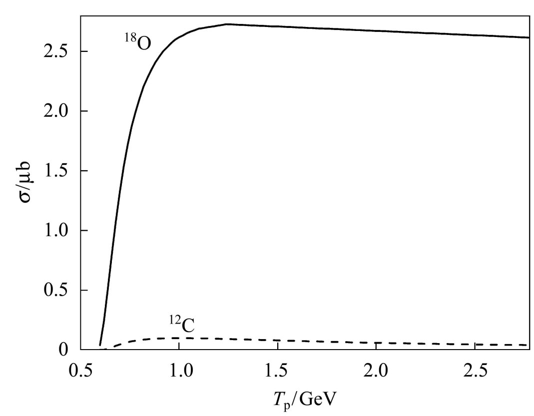

Fig. 4. Total cross sections of pA → p′A′η reactions. The solid curve is for ^{18}O, the dashed curve is for ^{12}C.

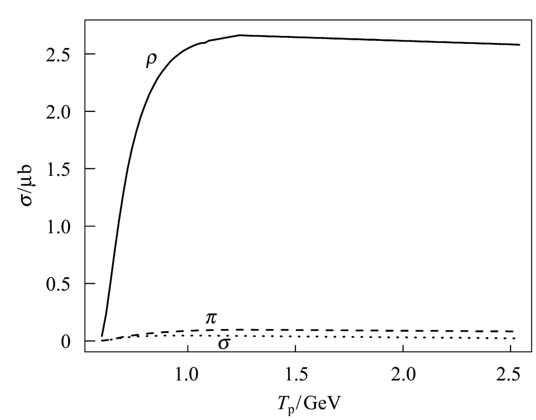

Fig. 5. The partial cross sections of various meson exchanges in the p+^{18}O → p+^{18}O+η reaction.

At present little information is available about the proton-induced η production on nuclear targets. The Cooling Storage Ring (CSR) in Lanzhou will soon be completed and allow for incoming proton beams with kinetic energies of up to 2.8 GeV. This new facility is well suited to study the dynamical properties of nucleon resonances. Our work provides the basis for theoretical analysis, indispensable for the studies of the η-meson production in pA collisions. The total cross sections of the η production in proton-nucleus collisions are the order of μb. Thus, the η-meson production and the dynamical properties of the $N^*(1535)$ can be studied by observing the outgoing η meson in proton-nucleus collisions at CSR.

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References

1 Johansson T. Int. J Mod. Phys. A, 2005, **20**: 1588
2 Particle Data Group. Phys. Lett. B, 2004, **592**: 120
3 Nakayama K, Speth J et al. Phys. Rev. C, 2002, **65**: 045210
4 Peña M T, Garcilazo H, Riska D O. Nucl. Phys. A, 2001, **683**: 322
5 Gedalin E, Moalem A, Razdolskaja L. Nucl. Phys. A, 1998, **634**: 368
6 Germond J F, Wilkin C. Nucl. Phys. A, 1990, **518**: 308
7 Bilger R et al. Phys Rev. C, 2002, **65**: 044608
8 Bilger R et al. Phys Rev. C, 2004, **69**: 014003
9 Kitching P, McDonald W J et al. Adv. Nucl. Phys., 1985, **15**: 43
10 Frankel S, Frati W, Walet N R. Nucl. Phys. A, 1994, **580**: 595
11 LI C H, Ko C M. Nucl. Phys. A, 2002, **712**: 110
12 Chiang H C, Oset E. Phys. Rev. C, 1991, **44**: 738
13 YUAN Hong-Kuan, ZOU Bing-Song, CHEN Hong et al. HEP & NP, 2004, **28**: 961 (in Chinese)
14 Fernández de Córdoba P, Ratis Y, Oset E et al. Nucl. Phys. A, 1995, **586**: 586
15 Eyser K O, Machleidt R, Scobel W. Eur. Phys. J. A, 2004, **22**: 105
16 De Vries H, De Jager C W et al. Atomic Data and Nuclear Data Tables, 1987, **36**: 495