Residual Nucleus Excitation Energy in $(e, e'p)$- Reaction

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The propagation of the struck proton through the nuclear medium is studied in the semi-classical multicollisional internuclear cascade approach. The probability of formation of various residual nucleus configurations and the corresponding excitation energies were obtained as a function of the energy ω transferred to the proton by the knockout.

This study is a part of our investigation on decay channels of single hole states in the residual nucleus, created as a result of the quasifree scattering of high energy electrons on nuclei ($(e, e'p)$-reaction).

Pure quasifree knockout of protons in the plane wave impulse aproximation (PWIA) results in hole excited states which serve as a doorway state for decay, with excitation energy given by:

$$E^* = -E_\alpha + E_F \quad (E_\alpha, E_F < 0) \tag{1}$$

where E_α and E_F are the nucleon binding energy for the shell α and the Fermi level, respectively.

A proton propagating inside the residual nucleus deposits additional energy ΔT as a result of the final state interaction(FSI) associated with the propagation , thus increasing the excitation energy of the doorway state for decay. FSI may also result in the proton not exiting the nucleus, or more than one nucleon exiting, thereby creating more possibilities of excited nuclei than in the simple case of just one nucleon knockout.

In our earlier work we investigated the single particle nature of the quasi-free knockout reaction, wherein the momentum distributions of the proton bound states were studied in the macroscopic-microscopic approach with an axially deformed single particle potential [1][2] and within the Skyrme formalism [3].

In our present work we studied the propagation of proton in nuclear matter after the knockout impulse from the incident electron to allow for additional excitations from FSI. The analysis was performed within the framework of the Fermi Gas Model to provide for a description of nucleon motion in the target just at the instant of the knockout impulse.

The Quasi-Free(QF) knockout is an inelastic process and occurs when an incoming energetic electron transfers energy ω and high momentum $\vec{q}$ to one of the nucleons of the target nucleus. In the impulse approximation, ω and $\vec{q}$ are transferred only to one nucleon with internal momemtum $\vec{P}_{in}$ which is opposite to the momentum of the rest of the nucleus, i.e. $\vec{p}_{in} = -\vec{p}_{A-1}$. The impulse approximation may only be applied under conditions of higher energies, i.e when the energy of the incident electron exceeds $300MeV$, the proton recoil energy is above $50MeV$ and that the momentum transferred to the nucleus is beyond $1fm^{-1}$.

Because QF is an inelastic process, and neglecting the recoil energy of the residual nucleus, we may write:

$$E_p = \omega + E_\alpha, \quad (E_\alpha < 0), \tag{2}$$

and its momentum:

$$p_p = \sqrt{E_p^2 - m_p^2}, \tag{3}$$

where m_p is the free proton mass. As can be seen from Eqs. 2 and 3 , p_p is a function of ω and E_α and is independent of $\vec{q}$.

Figure 1 shows the momentum diagram for QF (impulse approximation) for a fixed ω and two values of $\vec{q}$. Since ω is fixed, the sum $\|\vec{q} + \vec{p}_{in}\|$ will be set to the value of $\sqrt{E_p^2 - m_p^2}$, thereby defining the vector $\vec{p}_{in}$ in this kinematics. A different $\vec{q}$ results in a different $\vec{p}_{in}$ involved in the process, and thus different QF cross-sections.

In the impulse approximation, the FSI after the knockout depends solely on p_p . This means we may study the average effect of FSI on the outgoing nucleon just by transferring an energy ω to a nucleon of the Fermi gas (regardless of $\vec{q}$ and $\vec{p_{in}}$), hence giving rise to the exact same final-state configuration as in the case for QF.

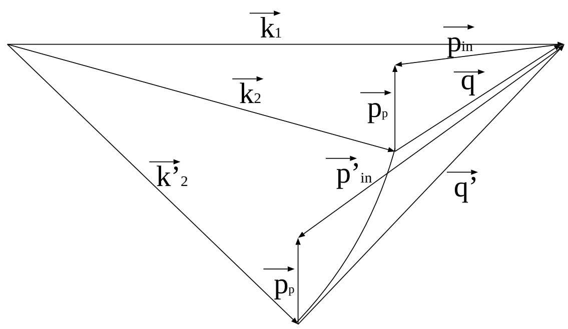

Figure 1. Momentum diagram in the impulse approximation. The fixed final momentum $\vec{p}_p$, defined by ω and E_α, is unaltered by changing the scattered electron momentum $\vec{k_2}$ to $\vec{k_2'}$, the transfered momentum $\vec{q}$ to $\vec{q'}$ and the internal momentum $\vec{p_{in}}$ to $\vec{p_{in}'}$. Note that $\|\vec{k_2}\| = \|\vec{k_2'}\|$.

In our analysis we studied the effect of transferring an energy ω to a proton residing in an energy level of α of the Fermi gas. Here,we chose α randomly but weighted in accordance with the occupation number. The following elementary interactions were taken into consideration[4]:

1. elastic nucleon-nucleon scattering $(NN \to NN)$,
2. formation of Δ-resonance $(NN \to N\Delta)$,
3. recombination of Δ-resonance $(N\Delta \to NN)$,
4. decay of Δ-resonance $(\Delta \to \pi N)$,
5. pion absorption $(\pi N \to \Delta)$.

We invoked Pauli blocking to inhibit the final nucleon from occupying a filled energy level and after the knockout, the proton emerges in a Fermi gas of protons and neutrons. The proton then travels within a characteristic depth $V_0 = -45.7MeV$ for both, protons and neutrons in this Fermi gas (see [5] for details).

To bind these otherwise free nucleons, we defined an effective mass $m_r = m_N - V_0$, wherein the energy and momentum of the bound nucleon is defined by

$$E_N^2 = p_N^2 + m_r^2 \tag{4}$$

Here, m_N is the mass of the free nucleon.

This is to say, we calculate the knockout cross section in the macroscopic-microscopic formalism with PWIA.We then put back the outgoing (without FSI) free proton into a new potential, adding to its energy the initial separation energy E_α and consider it as a proton with reduced mass and momentum:

$$p_p = \sqrt{E_p^2 - m_r^2} = \sqrt{(m_p + E_\alpha + \omega)^2 - m_r^2}, \quad (E_\alpha < 0) \tag{5}$$

where ω is the energy transferred by the knockout and m_p is the free proton mass.

In the initial configuration, the Monte Carlo code chooses a Fermi gas proton, and then substitutes its original momentum by this momentum p_p (see eq.5), considering the proton position randomly and uniformly distributed in the sphere of Fermi sea of bound nucleons, and its momentum direction distributed randomly and isotropically.

This primary proton, propagating inside the residual nucleus, may interact with one of the bound nucleons and change its energy and direction. As a result of this interaction, this nucleon in the target may receive sufficient energy to exit the nucleus or it may undergo another interaction with another bound nucleon, thereby resulting in a nuclear cascade. Hence a primary nucleon may produce several nucleons in secondary reactions. And these nucleons, in turn, may or may not exit the target nucleus.

We applied our formalism to the reaction $(e, e'p)$ for the ^{238}U target. In Fig. 2 we plot the probability of formation the following configurations as a function of the transferred energy ω:

(N, Z)-no nucleons exit the nucleus, $(Z-1, N)$-one proton exits, $(Z, N-1)$-one neutron exits, etc.

And in Fig. 3 is plotted the corresponding excitation energies for the above listed configurations of the resultant nucleus.

We see that the fragmentation of the residual nuclei increases with the increasing energy of the outgoing nucleon.

In Fig. 4 we plot the probability of the residual nucleus $(Z-1, N)$ for the case when there are no FSI and when the outgoing proton may experience any interaction. Fig. 5 shows the respective excitation energies. In the case of no interaction, the excitation of the residual nucleus will directly reflect the hole energy (see (1)). The probability of no interaction first decreases with increasing incident electron energy and then turns over slowly. This behavior reflects the competition between the cross-sectional energy dependence of the elementary processes with that from Pauli blocking.

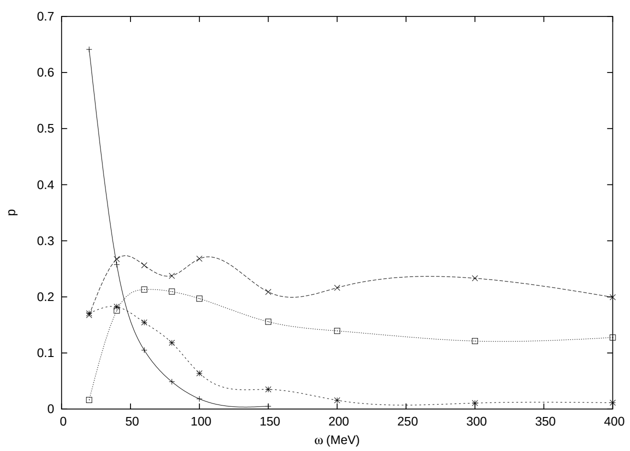

Figure 2. Probability of formation as a function of the energy ω transfered by the knockout for various configurations of the residual nucleus: Z,N (+);Z-1,N (x); Z,N-1 ($*$) and Z-1,N-1 (Squares).

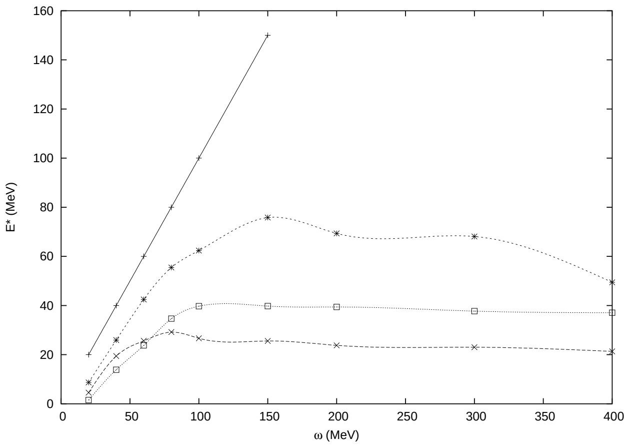

Figure 3. Excitation energy as a function of the energy ω transfered by the knockout for various configurations of the residual nucleus: Z,N (+);Z-1,N (x); Z,N-1 ($*$) and Z-1,N-1 (squares).

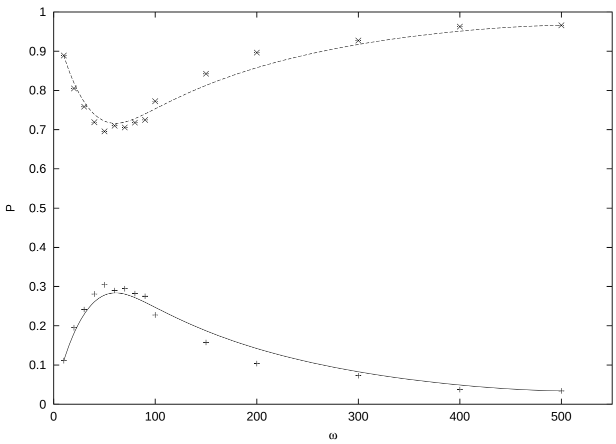

Figure 4. Probability as a function of ω for the $(Z-1,N)$ residual nucleus configuration. The upper curve (x) is the probability that the proton exits the nucleus without any interaction, and the lower curve (+) the probability of any interaction.

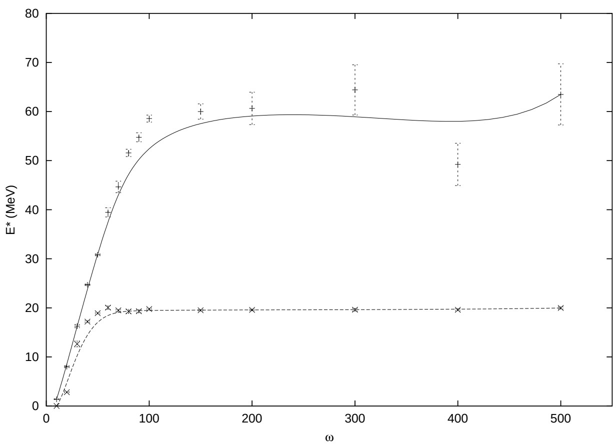

Figure 5. Excitation energy $E*$ as a function of the energy ω transfered by the knockout for the $(Z-1,N)$ residual nucleus configuration. The lower curve (x) is without any interaction, and the upper curve (+) with any interaction.

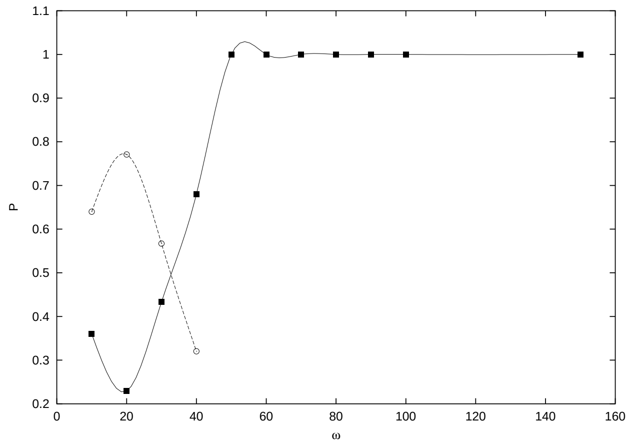

Figure 6. Probability as a function of ω for the (Z,N) residual nucleus configuration. The curve with circles is the probability that the proton suffers no interaction, and the one with squares the probability with any interaction.

In Fig. 6 we plot for the case of the (Z,N) residual nucleus, the probability that the proton undergoes no FSI and the probability that this proton may experience any interactions. In the latter case, the excitation energy is always equal to ω.

1 Conclusions

The likelihood that the struck proton may not exit from the target nucleus decreases with increasing trasferred energy ω. Above $150MeV$, this probalility is negligible. The probability that the proton exits the target nucleus without any interaction is constant ($\cong 0.25$) for $\omega > 50MeV$. Fragmentation (number of fragments after the FSI) of the residual nucleus increases with increasing energy ω. The average residual nucleus excitation energy increases with increasing fragmentation.

Acknowlegements

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