NUCLEON TRANSFER REACTIONS AND THE ELECTRON-POSITRON PUZZLE

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1. INTRODUCTION

Since more than 10 years positron production has been the subject of extensive experimental and theoretical work. The positrons are emitted from heavy-ion collisions like $^{238}U + ^{181}Ta$ at projectile energies slightly above the Coulomb barrier. The surprising and unexpected discovery are the sharp lines observed in the energy spectra of positrons. These peaks have been observed in two distinct experiments, all carried out at the UNILAC accelerator of the Gesellschaft für Schwerionenforschung (GSI) [Sch83,Cle84,Cow85,Tse85]. The observed width of the positron peaks is typically $\Delta E \sim 80$ keV corresponding to emitter velocity values of $v_{em} \sim 0.05$ c, i.e. in the order of the heavy-ion center-of-mass velocity. The narrowness of the observed peaks indicates that the associated time scale is much longer than the average collision time ($\sim 10^{-22}$ sec). The fact that similar peaks appear in a number of different beam-target combinations suggests a fundamental process, independent of the structure of target and projectile.

Subsequent experiments have shown the existence of similar peaks in the energy spectrum of electrons measured in coincidence with peak positrons [Cow86,Koe89,Sal90] This correlation between the positron and electron energies produces peaks in the sum-energy of the two. The three most prominent coincidence peaks are observed at sum-energies of $E_\Sigma \sim 610$, 750 and 815 keV. These mean sum-energies match nicely with the measured positron singles line energies at essentially half the sum-line energies. The line widths, ΔE_Σ amount to values of ≤ 40 keV which are much narrower than those in the singles spectra. This experimental result together with the nearly equal energies of positron and electron has been taken as possible evidence for the two-body decay of an isolated, slowly-moving neutral object as the origin of the peaks.

The situation became more complex since in various collision systems, investigated with higher experimental sensitivity, several e^+e^- sum-energy lines were found, exhibiting a rather complex pattern of angular and energy correlations. Fig. 1 displays the impact parameter dependence of the production probability of the 748-keV line of $^{238}U + ^{181}Ta$. The pair emission probability is plotted as a function of the distance of closest approach D. Obviously, the line production probability is strongly correlated with this kinematic parameter and is maximal for values of D around 19 fm, i.e. close to the nuclear interaction radius for this system. An exponential increase with decreasing radial separation between the two heavy ions appears to characterize the data. Such an exponential behaviour of the probability are also typical for nuclear reactions in peripheral collision.

For the 748-keV sum-energy line an excitation function was also measured in the energy range between 5.3 MeV/u and 6.8 MeV/u (fig.1). This line has been observed in five separate measurements with beam energies between 5.93-6.16 MeV/u. For beam energies below and above this energy region no narrow e^+e^- sum-energy line was found. The observed resonance or threshold like energy dependence does not fit into any conventional nuclear transfer process.

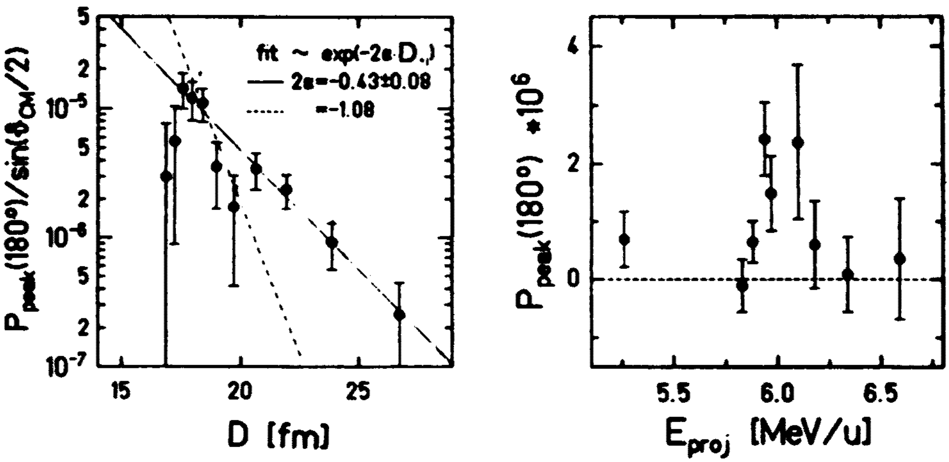

Fig. 1: Kinematic dependence of the 748 keV sum-energy line of $^{238}U + {}^{181}Ta$. (Left): Dependence of the production probability on the distance of closest approach. (Right): Observed yield of line events per collision versus beam energy.

Since the initially suggested simple two-body scenario no longer offers a viable explanation for the major part of these data, the origin of this phenomenon remains a puzzle.

In this paper the results of the electron-positron puzzle will be compared with measured excitation functions and angular distributions for the one-neutron transfer reaction in the nearly identical heavy-ion system $^{238}U + {}^{197}Au$. A short review of the elastic scattering is given in the following chapter. The new correlation between elastic scattering and nucleon transfer reaction will be presented in the third chapter. Finally, nucleon transfer reactions between heavy ions will be discussed for which the positron lines have been discovered.

2. ELASTIC AND INELASTIC SCATTERING OF TWO HEAVY NUCLEI

The most straightforward way to the understanding of scattering of two heavy nuclei is obtained in the semiclassical approach. For large values of the Sommerfeld parameter η and large values of the wave number k_∞ the motion of the centers of the colliding nuclei can be described by classical orbits. In the following the results of the elastic scattering and one-neutron transfer reaction will be presented in dependence of the distance of closest approach D associated with classical orbits.

$$D = \eta / k_{\infty}(1 + 1/\sin\frac{1}{2}\theta_{cm}) \quad (1)$$

In such a representation, effects due to the nuclear interaction become nearly independent of dynamical quantities such as the bombarding energy. This can be understood because of the short range of the nuclear force which is strongest at the distance of closest approach.

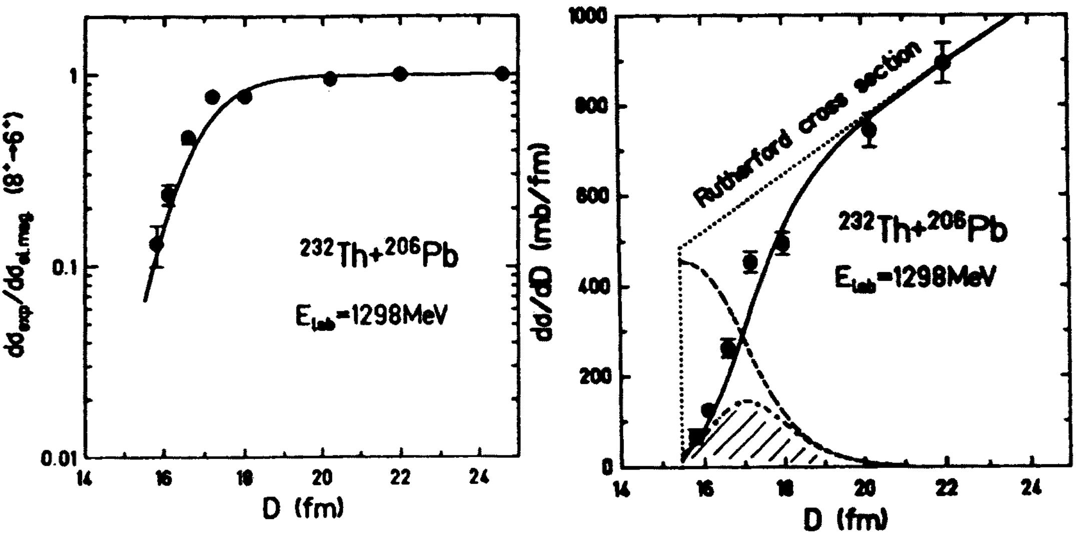

Fig. 2: Cross section for populating the 8^+ level divided by a calculated cross section versus the distance of closest approach D for the $^{232}Th + {}^{206}Pb$ at 1298 MeV (left). Right: Absolute cross sections for the inelastic scattering as a function of D. The dashed line represents the total reaction cross section.

Figure 2 shows the experimental cross section for the 8^+ level divided by a theoretically calculated cross section versus the distance of closest approach D for ^{232}Th bombarded with ^{206}Pb projectiles at an incident energy of 1298 MeV [Boe86]. Particle-γ coincidence techniques were used to identify excited states of reaction products populated through inelastic scattering and in nucleon transfer reactions. It should be noted, that the experimental cross section includes both the direct population through the reaction as well as the indirect population through feeding from higher lying levels during the deexcitation process. Since the cross section saturates for $I \leq 8$ and a direct population of the lower lying states is only a negligible portion of the total yield, the experimental $(8^+ \rightarrow 6^+)$ yield can be considered to be the total probability for producing an elastic + inelastic collision. The theoretical cross sections are based on semiclassical Coulomb excitation calculations using $B(E2,0^+ \rightarrow 2^+) = 9.21\ e^2b^2$ [Bem73] and the rigid rotor model for the other relevant E2 matrix elements within the ground band. For bombarding energies well below the Coulomb barrier ($V_C = 648$ MeV for the $^{232}Th + ^{208}Pb$ system) the cross section can be calculated by the Rutherford formula

$$\frac{d\sigma_{Ruth}}{dD} = 2\pi(D - a) \tag{2}$$

where $a = \eta/k_\infty$ is half the distance of closest approach for head-on collisions.
For energies above the Coulomb barrier angular distributions of the elastic and inelastic channels typically exhibit a Fresnel-type diffraction pattern with comparatively little structure and a sharp drop in the ratio of elastic scattering to Rutherford scattering as soon as the two nuclei penetrate to distances less than the nuclear interaction radius R_{int}. The transition from Coulomb scattering to nuclear absorption within a narrow and well-defined region of distances near R_{int} (fig.2) leads to simple relationships for elastic scattering and reaction cross sections, which are of an essentially geometrical nature and do not depend on details of nuclear structure. A particularly simple parameterization of elastic scattering data is the semiclassical method suggested by Broglia et al [Bro72]. This allows the use of the following formula:

$$\frac{d\sigma_{el}}{dD} = [1 - P_{abs}(D)]\,\frac{d\sigma_{Ruth}}{dD} \tag{3}$$

for elastic scattering, where $[1 - P_{abs}(D)]$ is an attenuation factor' of the Rutherford cross section. The missing flux is going into different reaction channels and the reaction cross section is therefore given by

$$\frac{d\sigma_{Reac}}{dD} = P_{abs}(D)\,\frac{d\sigma_{Ruth}}{dD} \tag{4}$$

The 'attenuation factor' $[1 - P_{abs}(D)]$ used to fit the elastic scattering data can be written as

$$[1 - P_{abs}(D)] = \exp\left\{ -\frac{2}{\hbar}\int_{-\infty}^{\infty} W[r(t)]dt \right\} \tag{5}$$

where W is identified with the imaginary part of the optical model potential [Bas80]. For the potential W one can use the proximity potential, which depends only on the distance $r(t) - C_1 - C_2$ between the surfaces of the nuclei.

$$W[r(t)] = W_0 \exp\left[-\frac{r(t) - C_1 - C_2}{a_W} \right] \tag{6}$$

where a_W denotes the diffuseness of the potential. Assuming an undisturbed Rutherford trajectory, the integral can be given analytically since the absorption from the elastic channel takes place in the vicinity of the turning point [r(t) = D].

$$[1 - P_{abs}(D)] = \exp\left\{ -\frac{2}{\hbar} W_0 \exp\left[-\frac{D - C_1 - C_2}{a_W} \right] \frac{D}{v} \right\} \tag{7}$$

where v is the initial beam velocity. For all heavy ion systems the nuclear radii C_1, C_2 for projectile and target nucleus can be calculated from an empirical formula [Wil80], while the parameter W_0 is fixed by quarter-point condition $\frac{d\sigma_{el}}{d\sigma_{Ruth}}(R_{int}) = 1/4$. The only free parameter a_W is fitted to the elastic scattering which varies from the Ni + Ni system to the Th + Pb system only between 0.6-0.8 fm.

In fig. 2 (right) the experimental data for the $8^+ \rightarrow 6^+$ transition of the ground band of ^{232}Th are compared to the classical calculations of eq.7. For comparison the Rutherford cross section and the calculated reaction cross section (eq.4) are indicated by the dotted and dashed line, respectively.

3. RELATIONSHIP BETWEEN ELASTIC SCATTERING AND NUCLEON TRANSFER REACTIONS

Nucleon transfer reactions with light and medium heavy ions have proven to be a selective probe for the understanding of single particle and collective nuclear properties. In contrast to light projectiles heavy ions offer the possibility to study new phenomena which originate in the much larger Coulomb contribution to the total interaction. In particular, heavy deformed nuclei will be Coulomb excited by the strong electromagnetic field to high spin states already at the time when they start interacting through the nuclear forces. In order to explore these aspects an estimate of the absolute transfer cross section is of great interest.

Fig. 2 (right) shows the calculated reaction cross section for the $^{232}Th + {}^{206}Pb$ system at 6.3 MeV/u. For large internuclear distances ($D > 18\ fm$) the reaction cross section is completely exhausted by the transfer cross section. In order to separate the transfer reactions from more violent collisions at smaller distances D we estimate the differential transfer cross section in first order by

$$\frac{d\sigma_{tr}}{dD} = [1 - P_{abs}(D)]\ P_{abs}(D) \frac{d\sigma_{Ruth}}{dD} \tag{8}$$

assuming the same 'attenuation factor' $[1 - P_{abs}(D)]$ as measured for the elastic channel. With this new semiclassical relation one can calculate absolute cross sections for transfer reactions with positive Q-values from the measured elastic scattering data. For the $^{232}Th + {}^{206}Pb$ at 6.3 MeV/u the absolute transfer cross sections are shown in fig.2 (dashed-dotted line) and fig.3 which are in good agreement with experimental cross sections of the dominant transfer channel. The angular distribution is peaked at a distance slightly larger than the nuclear interaction radius $R_{int} = 16.3\ fm$.

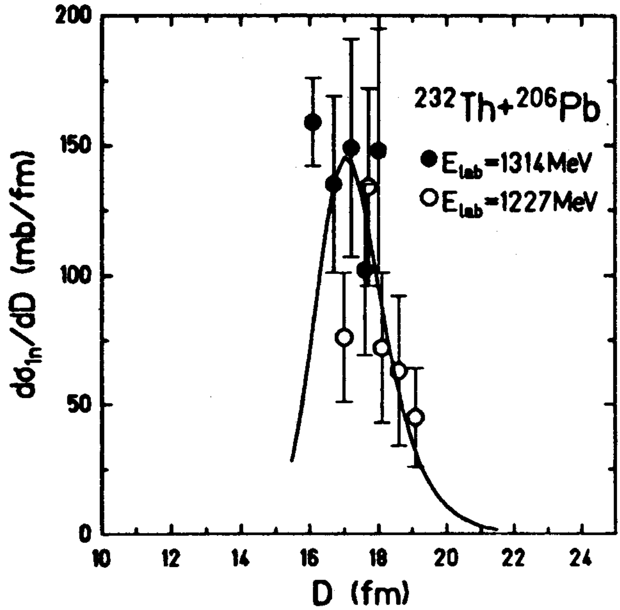

Fig. 3: 1n-transfer cross sections for the $^{232}Th+^{206}Pb$ at 6.3 MeV/u versus the distance of closest approach D.

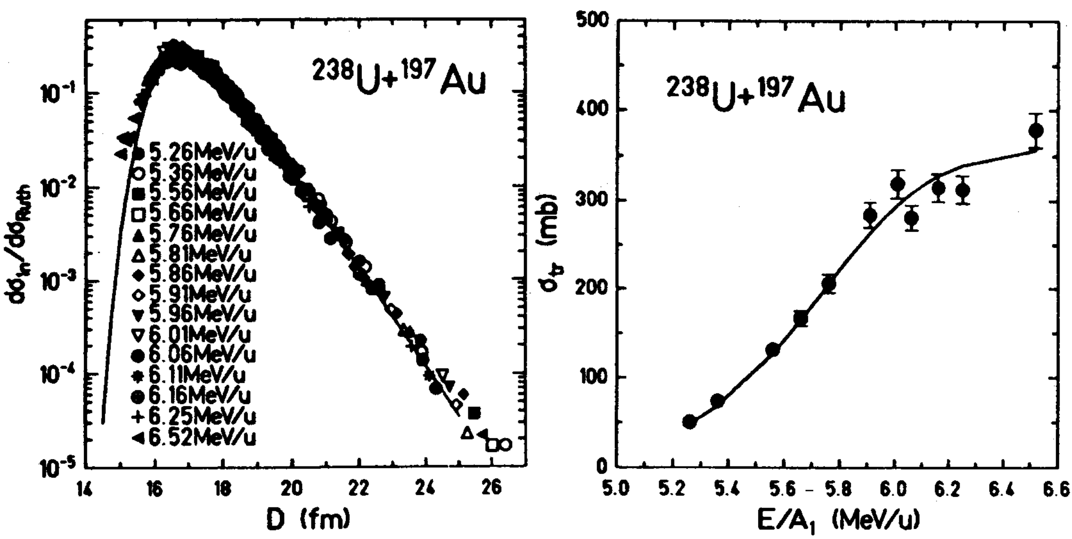

Fig. 4: (Left): Ratio of the 1n-transfer cross section to the Rutherford cross section for the $^{238}U+^{197}Au$ system as a function of the distance of closest approach D. (Right): Excitation function of the 1n-transfer reaction.

As a second example, the angular distributions for one-neutron transfer in $^{238}U + ^{197}Au$ normalized to the Rutherford cross sections and measured at 15 different beam energies near and below the Coulomb barrier are shown in fig. 4 [Wir91]. The solid line is calculated from the elastic scattering of a nearly identical heavy-ion system, $^{232}Th + ^{206}Pb$. For these heavy-ion systems at bombarding energies close to the Coulomb barrier the one-neutron transfer is the main reaction channel. The transfer cross section seems to be independent of the bombarding energy if the data are plotted as a function of the distance of closest approach D. One observes an exponential increase of the transfer probability with decreasing radial separation between the two heavy nuclei which is very similar to the measured pair emission probability for the 748 keV sum-energy line of the almost identical heavy-ion system $^{238}U + ^{181}Ta$ (fig.1). However, the excitation functions for both processes are quite different. While the transfer cross section increases smoothly with the bombarding energy (fig.4), one finds a resonance-like dependence of the electron-positron probability with the beam energy (fig.1).

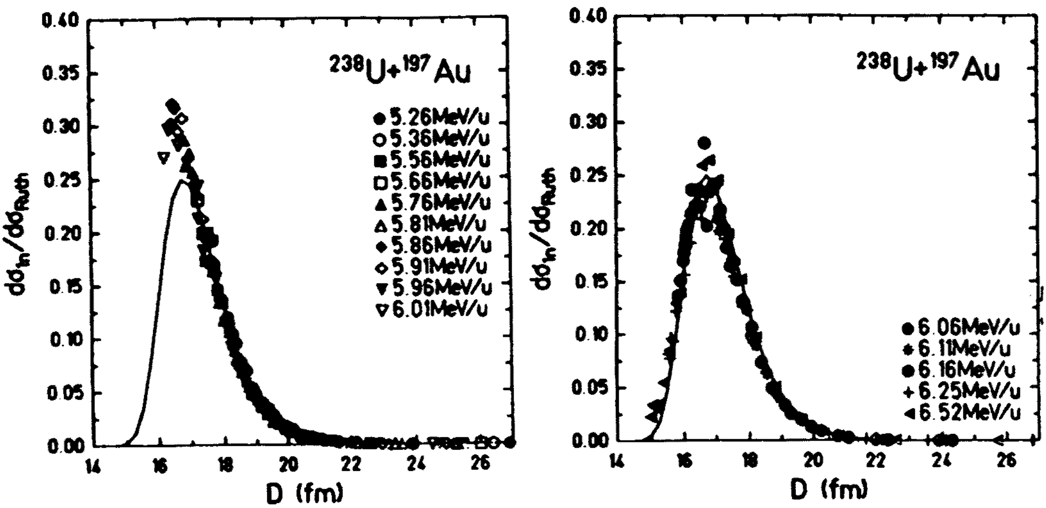

Fig. 5: Linear representation of the same data as shown in fig.1 for incident energies below (left) and above (right) 6.03 MeV/u. The solid line is calculated from a semiclassical relationship between elastic scattering and transfer reactions [eq.8].

However, a closer inspection of the data - as demonstrated by the linear plots in fig.5 - shows a significant excess of cross section for distance of closest approaches D=16-17 fm at low bombarding energies (left) relative to the ones above 6.06 MeV/u (right). The experimental uncertainties of the 1n-transfer cross sections are typically 5% for the close collisions. The observed cross section excess amounts to about 20 mb measured at internuclear distances which can only be reached in reactions with bombarding energies higher than 5.9 MeV/u. It is interesting to note, that the energy window of 5.9-6.06 MeV/u for the detection of the additional 1n-transfer cross section almost coincides with the one of the maximum electron-positron pair emission probability of the 748 keV line in the $^{238}U + ^{181}Ta$ system (fig.1). Since the excitation functions and the angular distributions are very similar, one may raise the question if both observables, nucleon transfer and electron-positron coincidences, study the same physical phenomena.

If the excitation of a nuclear state in the projectile or target nucleus is the physical origin, a cross section of $\simeq 40 \mu b$ for internal pair conversion of a single nuclear transition can be calculated from the additional transfer cross section. This cross section is of the same order of magnitude as the one measured for $e^- e^+$ coincidences although it is difficult to explain the narrow width of the sum lines for a moving emitter. Conversion electron measurements are planned for the $^{238}U + ^{181}Ta$ system in order to clarify this possibility. It might also be possible that longer contact times ($\simeq 10^{-21}$ sec) due to the influence of the nuclear interaction on the trajectory are responsible for the larger transfer cross sections.

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