GAMMA-RAY ANGULAR DISTRIBUTION IN COULOMB EXCITATION EXPERIMENTS AT INTERMEDIATE ENERGIES AS A SIGNATURE OF ELECTROMAGNETIC AND NUCLEAR FORCES IN PERIPHERAL COLLISIONS*

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In Coulex experiments at intermediate beam energies besides electromagnetic forces the nuclear interaction may occur. These two excitation mechanisms result in emission of γ-rays with a characteristic angular distribution $W(\theta)$. Measurement of $W(\theta)$ was performed at the RISING fast beam set-up to probe the electromagnetic-nuclear interface. Unexpectedly large hadronic-like contribution was observed when high Z projectiles were used.

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1. Introduction

At intermediate beam energies ranging from a few tens to about 150 AMeV, the Coulomb excitation method is particularly useful in γ-spectroscopy studies aiming at evaluation of properties of the first 2^+ level

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in even–even exotic nuclei, such as excitation energies or reduced electric quadrupole transition probabilities B(E2). Successful measurements of this type were performed so far at GSI, GANIL, MSU and RIKEN [1]. In a forward scattering reaction at those energies, mainly long range electromagnetic forces lead to excitation of nuclear states both in the projectile and the target nucleus. In this process, the strong-nuclear interaction is expected to play a minor role. Indeed, it may only contribute to the inelastic cross-section at the touching spheres distance, comparable with the nuclear force range. Projectiles with smaller impact parameters disappear from the inelastic scattering reaction channel because of fragmentation. The probability of electromagnetic excitation of the 2^+ nuclear state at intermediate energies is proportional to $B(\mathrm{E2})Z^2$ [2]. Thus, in a nucleus with a homogenous ellipsoidal charge distribution the Coulex cross-section may be linked to the charge deformation parameter β_C. On the other hand, a part of the inelastic cross-section due to the nuclear force is often scaled by the deformation length $\delta = \beta_\mathrm{N} R$, where β_N is the nuclear deformation parameter. It has been demonstrated in scattering experiments that for light deformed nuclei with $Z < 20$ the nuclear and the charge deformations are equal [3].

It is expected that at intermediate energies in the Coulomb excitation of a low-lying nuclear state, a complete prolate alignment of magnetic substates occurs, whereas reactions driven by the nuclear interaction result rather in an oblate spin alignment [4]. In consequence, the competition of the electromagnetic and the nuclear excitation modes will result in a characteristic γ-ray angular distribution $W(\theta)$ (*cf.* inset in Fig. 1(B). Although no experimental information is available, it is of general consent that in the case of the inelastic forward scattering of heavier nuclei, the Coulex is "safe", *i.e.* it is not affected by the nuclear contribution [1]. Investigation of the γ-ray angular distribution function in nuclei with different atomic numbers may be, therefore, helpful in probing limits of the "safe Coulex" principle.

2. $W(\theta)$ measurements at RISING

Measurements of the γ-ray angular distribution were performed at the RISING fast beam set-up [5]. Incoming ^{54}Cr fragments, chosen in the FRS fragment separator, impinged on a ^{197}Au target. The projectile exit velocity corresponded to $v/c = 42\%$. Inelastic scattering events were selected by γ-^{54}Cr coincidences [6]. The position sensitive Si-CsI telescope CATE allowed for restriction of the projectile scattering angles to less than the grazing one of 2.5°. This ensured that only peripheral collisions were chosen [7]. The $2^+ \rightarrow 0^+$, 834 keV γ-rays from ^{54}Cr were detected in the 15 EUROBALL Ge-clusters. In the RISING set-up, the cluster detectors were arranged around the target at: 16°, 33° and 36° with respect to the beam axis. Such a geometry was rather insensitive to the γ-ray angular distribution due to the large composite detectors size and their angular overlap. However, as it is illustrated in Fig. 1(A), one may group individual crystals in four distinct shells. The resulting $W(\theta)$ function measured for the 834 keV transition is shown in Fig. 1(B).

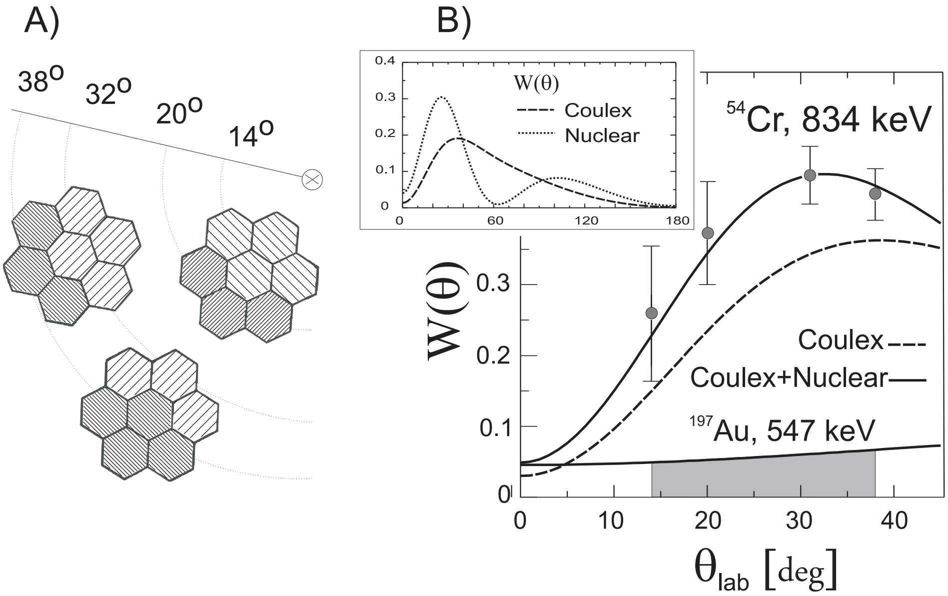

Fig. 1. (A) Sketch of the HPGe shell arrangement in four rings at the RISING set-up. For simplicity only three clusters at different angles are drawn. (B) $W(\theta)$ measured for the 834 keV line in ^{54}Cr ($v/c = 42\%$) compared to the calculated distribution plots. The curves and the experimental points were related through the intensity of the ^{197}Au 547 keV line integrated over the detection solid angle, as indicated in grey. To illustrate the difference in shape of the γ-ray angular distributions, the normalized $W(\theta)$ for nuclear and electromagnetic interactions in the full angular range are shown in the inset.

As described with details in [8], at projectile energies $E > 50$ AMeV and deflection angles close to or smaller than the grazing angle, the coupled-channels computer code DWEIKO can be used to calculate multi-pole electromagnetic and nuclear excitation amplitudes in the projectile and the target nuclei. Scattering on a fully parameterized optical potential is assumed at the contact distance, whereas collisions with smaller impact parameters are accounted for by a strong absorption model. The model calculation was performed for the discussed case of scattering of ^{54}Cr on ^{197}Au. The standard set of the optical model parameters: $W = V = -60$ MeV, $R_0 = 1.3$ fm and $a = 0.62$ fm was used. The imposed minimum impact parameter of

13.5 fm reproduced the measured grazing angle of 2.5° [7]. The B(E2) values of 0.0870 e^2b^2 and 0.44 e^2b^2 for ^{54}Cr and ^{197}Au, respectively, were applied. The calculation provided, among others, the target and the projectile excitation cross-sections: $\sigma_{\rm T}$, $\sigma_{\rm P}$ and γ-ray angular distribution functions $W(\theta)$ for the both reaction partners. In the ^{197}Au case, $W(\theta)$ integrated over the detection solid angle was referred to the total measured intensity of the 547 keV line. This, together with the $\sigma_{\rm P}$ and $\sigma_{\rm T}$ cross-sections ratio provided a scaling factor that was used to relate the calculated and the measured $W(\theta)$ in ^{54}Cr. In Fig. 1(B), $W(\theta)$ for the ^{54}Cr 834 keV line calculated for the Coulex process is compared with the experimental points. One clearly sees an excess of counts at the forward detection angles with respect to the theoretical curve. Indeed, according to the calculation more than 10% of the inelastic scattering cross-section is due to the nuclear interaction in ^{54}Cr when assuming the deformation $\beta_{\rm N}$=$\beta_{\rm C}$ = 0.25 derived from the B(E2) value. In contrast, those calculations show that for the $E_{\rm ex}$ = 547 keV, $3/2^+ \rightarrow 7/2^+$ excitation in gold the nuclear component is negligible due to a dependence of the E2 nuclear matrix element on the ground state spin [8]. As one may see in Fig. 1(B), a very good agreement is achieved between the experimental points and the model predictions when the nuclear force is included.

Studies of the Coulomb excitation at intermediate energies performed so far were limited to relatively low Z projectiles. Only a few recently reported experiments performed at GSI and MSU [1] concerned heavier Kr and Sn isotopes. In all these measurements the "safe Coulex" was postulated. The method described here, was applied in order to verify this assumption.

A primary ^{132}Xe beam passing through the FRS scattered on ^{197}Au with the average energy of 60 AMeV. Gammas were measured in the RISING cluster detector array in coincidence with ^{132}Xe ions detected with CATE. In the reaction, the grazing angle was significantly bigger than the CATE angular range of 3°, therefore, only peripheral collisions were chosen. Despite a short measurement time, angular distributions of both the 667 keV, $2^+ \rightarrow 0^+$ and the 547 keV, $7/2^+ \rightarrow 3/2^+$ transitions in ^{132}Xe and ^{197}Au, respectively, could be measured thanks to high excitation cross-sections $\sigma_{\rm T}$ and $\sigma_{\rm P}$. Gamma-ray spectra shown in Fig. 2(A) demonstrate the 547 keV line emitted in rest from ^{197}Au and the Doppler corrected 667 keV γ-line from ^{132}Xe, both registered at the four detection angles.

The experimental and the calculated $W(\theta)$ curves are presented in Fig. 2(B). In the calculation, the electron recombination that may change the spin alignment in large Z ions was taken into account [9]. The calculated $W(\theta)$ function for the 547 keV transition from ^{197}Au (the lower solid line) — not affected by the nuclear interaction — and the measured angular distribution for this line were matched up. This allowed to link the measured and the calculated 667 keV line angular distributions in ^{132}Xe (the dashed line). As one sees from the plot, the ^{132}Xe measured $W(\theta)$ significantly disagrees in amplitude with the calculation performed for $\beta_{\rm N} = 0.14$, arising from $B({\rm E2}) = 0.460\ e^2b^2$. To reproduce the data, the relative excitation cross-section of ^{132}Xe with respect to the ^{197}Au had to be increased in the calculation. This was accomplished by enhancing the nuclear-like interaction component by the amount that corresponds to much larger than expected deformation of $\beta_{\rm N} = 0.7$ (the upper solid line). However, it should be pointed out that the flattering of the two $W(\theta)$ curves due to the spin alignment attenuation, makes difficult any speculation on the excitation character based on their shape.

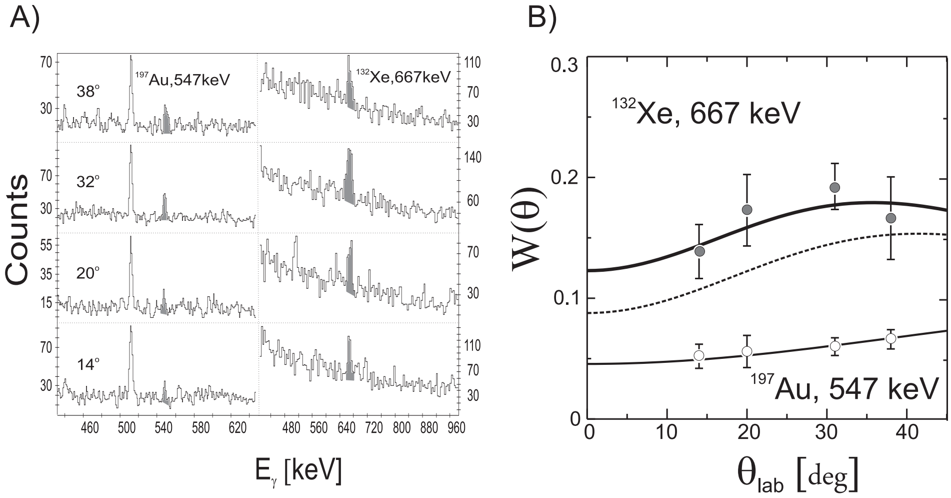

Fig. 2. (A) Gamma-ray spectra detected at the four Ge detector angles, left: the ^{197}Au 547 keV line emitted at rest; right: Doppler corrected ($v/c = 0.35$) 667 keV γ-rays from ^{132}Xe. (B) Measured and calculated $W(\theta)$ for the both lines. The solid and dashed curves correspond to Xe Coulex calculations with the excessive nuclear interaction and with the standard parameters that predicts mainly the electromagnetic excitation, respectively. In the calculations the $G_2 = 0.76$ and $G_4 = 0.2$ attenuation factors due to an electron recombination [9] were assumed.

3. Conclusions

The described experiments show, that at intermediate beam energies the "safe Coulomb" excitation conditions may be difficult to achieve. The presented analysis of γ-ray angular distributions suggests that in excitation of the first 2^+ state in intermediate energy inelastic scattering experiments, despite selecting of very forward scattered projectiles, the nuclear force may still play a non negligible role even for heavier nuclei. The applied Coulomb excitation model well describes the experimental observation in the medium-light deformed nucleus ^{54}Cr. However, it fails in the case of larger Z, nearly spherical ^{132}Xe, where the large excess of the nuclear interaction seems to occur. The result may indicate that in the applied model, the parameterization of the nuclear interaction between colliding nuclei by the nuclear deformation is not fully appropriate.

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