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Systematic dependence of the slowing-down environment on nuclear lifetime measurements by the Doppler-shift attenuation method

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The mean life of the ^{22}Ne 3.34 MeV level measured by Doppler-shift attenuation method at an average recoil velocity of $0.009c$, shows large fluctuations with different slowing-down materials ranging from Li to Pb. These fluctuations are correlated with a linear dependence of the "apparent" mean life τ on the electronic slowing-down time α.

[NUCLEAR REACTIONS ^{19}F(α,p), E=5.31 MeV; measured Doppler-shift attenuation. ^{22}Ne level deduced $T_{1/2}$ as a function of Z_2.]

I. INTRODUCTION

It has been shown by Broude *et al.*[1,2] and Haas *et al.*[3] that the "apparent" mean lives for different levels in ^{22}Ne, ^{27}Al, and ^{22}Na measured by the Doppler-shift attenuation method (DSAM) at $v/c \lesssim 1\%$ exhibit similar fluctuations. In the present work we tried to find a correlation between these fluctuations and physical parameters related to the slowing-down process. For this purpose, we measured by DSAM the mean life of the ^{22}Ne 3.34 MeV level for which Broude *et al.*[1] have already done an extensive study. In our experiment, we repeated the measurements for 12 slowing-down materials (C, Mg, Si, Ca, Ti, Ni, Ag, Sn, Ba, Ta, Au, and Pb) and, in addition, we completed the study by using three new backing materials (Li, Na, and Sr).

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ^{22}Ne 3.34 MeV level was excited via the ^{19}F(α,p)^{22}Ne reaction at E_α= 5.31 MeV. The targets consisted of a layer of CaF_2 (thickness: 20 μg/cm^2) evaporated on different backing materials. These backing materials were either solid ingots or evaporated layers. To prevent oxidation, the Li, Na, Ca, Sr, and Ba backings were covered with a thin layer of gold (thickness: 20 μg/cm^2) and were transported under dry inert atmosphere to the target chamber. For each backing, a γ-ray spectrum was recorded with a 80 cm^3 Ge(Li) detector placed at $\theta_\gamma = 0°$. The energy calibration was obtained from the known energies of the γ rays emitted by a ^{56}Co source for which spectra were taken between two measurements with different backings. The energy resolution of the detector was 4.1 keV for the ^{56}Co 2035 keV γ ray. Using the centroid method, the energy E_γ of the 2.08 MeV γ ray from the ^{22}Ne 3.34 → 1.26 MeV transition under study, was deduced for each backing. Two more γ-ray spectra were taken. For the first one, the Ge(Li) detector was placed at θ_γ = 90° and the γ rays from the ^{19}F + α reaction were recorded at the same times as those from a ThC'' source which was used to calibrate the γ-ray energy scale. For the ^{22}Ne 3.34 → 1.26 MeV transition a γ-ray energy of E_{γ_0} = 2082.1 ± 0.3 keV was determined in good agreement with recent values quoted in the two papers of Ref. 4. For the second one, the Ge(Li) detector was placed at θ_γ= 0° and the target consisted of a layer of CaF_2 (20 μg/cm^2) evaporated on a thin film of carbon (15 μg/cm^2). The α beam passed first through the carbon support before reaching the CaF_2 foil and the beam energy was slightly increased to correct for the energy loss in the support. Based on this measurement, we determined the energy E_{γ_m} corresponding to the full γ-ray shift of the transition under study and also the mean initial velocity of the ^{22}Ne recoils. The energy E_{γ_m} = 2100.9 ± 0.3 keV was exactly equal to the energy calculated from the reaction kinematics assuming an isotropic center of mass distribution of the outgoing ^{22}Ne nuclei and taking into account the γ-ray energy attenuation due to a finite size effect of Q_1 = 0.98 for the Ge(Li) detector. The γ-ray line shape observed with the "unbacked" target was consistent with the hypothesis of an isotropic angular distribution. The attenuation factor $F(\tau)$ has been extracted, for each backing, from the measured γ-ray energies using the relation: $F(\tau) = (E_\gamma - E_{\gamma_0})/(E_{\gamma_m} - E_{\gamma_0})$. The corresponding mean life τ has been obtained using the Lindhard *et al.*[5] estimates for the electronic and nuclear stopping cross sections with the treatment of Blaugrund[6] for the mean scattering angle. The mathematical approximation for the universal curve representing $(d\epsilon/d\rho)_n$ has been described elsewhere.[7]

The experimental values of $F(\tau)$ and the resulting

TABLE I. DSAM mean life results for the ^{22}Ne 3.34 MeV level with different stopping materials of atomic number Z_2.

Stopping material	Z_2	$F(\tau)$	τ (ps)
Li	3	0.72 ± 0.03	0.69 ± 0.10
C	6	0.61 ± 0.02	0.44 ± 0.03
Na	11	0.65 ± 0.03	0.69 ± 0.09
Mg	12	0.65 ± 0.02	0.43 ± 0.03
Si	14	0.56 ± 0.02	0.45 ± 0.03
Ca	20	0.64 ± 0.02	0.56 ± 0.05
Ti	22	0.51 ± 0.02	0.39 ± 0.03
Ni	28	0.40 ± 0.02	0.30 ± 0.03
Sr	38	0.65 ± 0.02	0.48 ± 0.05
Ag	47	0.40 ± 0.02	0.33 ± 0.03
Sn	50	0.50 ± 0.02	0.36 ± 0.03
Ba	56	0.62 ± 0.02	0.50 ± 0.05
Ta	73	0.37 ± 0.02	0.31 ± 0.03
Au	79	0.33 ± 0.03	0.32 ± 0.03
Pb	82	0.46 ± 0.02	0.36 ± 0.03

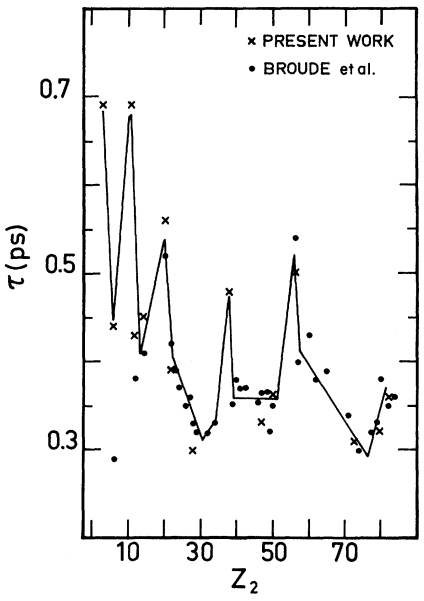

FIG. 1. Values of the "apparent" mean life τ plotted against the atomic number Z_2 of the stopping material.

"apparent" mean lives are given in Table I. For the alkaline backing materials, the thickness of the protecting gold layer was taken into account and has introduced an additional uncertainty on the mean life values. These values are represented on Fig. 1 as a function of the atomic number Z_2 of the backing material and from this representation it is evident that τ depends on Z_2. The values indicated by dots are from the work of Broude *et al.*[1] which are in good agreement with the values from the present experiment except for the case $Z_2 = 6$. In our measurement, the carbon backing was a thick piece of graphite for which the density, given by the manufacturer and checked in our laboratory, was 1.573 g/cm^3. However, the important new results on Fig. 1 is that the three backings (Li, Na, and Sr) used in the present work correspond, in addition to the already known results obtained for the Ca and Ba backings, to maxima in the variation of τ versus Z_2.

III. DISCUSSION

To find a correlation between these data and physical parameters, we consider the phenomenological representation of the stopping power proposed by Warburton, Alburger, and Wilkinson.[8] These authors have defined a slowing time α given by $\alpha = M_1 v_0 / K\rho$, where M_1 is the incident ion atomic mass, $v_0 = c/137$, ρ is the density of the slowing down material, and the parameter K is related to the different components of the slowing-down process by: $K^2 = K_e^2 - 4K_n K_3$. The parameter K_n is related to the nuclear part of the stopping power and the parameters K_e and K_3 to the electronic part. At the initial recoil velocity of the present work, i.e., $v/c \simeq 0.9\%$, the parameter K_3 can be neglected, α depends only on K_e and is defined as the electronic slowing down time. Taking the Lindhard *et al.*[5] estimate for K_e and expressing the density ρ as a function of the number of stopping atoms per cm^3 N_2, one obtains

$$\alpha(s) = 1.2 \times 10^{10} \frac{M_1 (Z_1^{2/3} + Z_2^{2/3})^{3/2}}{Z_1^{1/6} Z_1 Z_2 N_2} .$$

Z_1 and Z_2 are, respectively, the charges of the incident ion and the slowing down material. In other words, this relation which is derived from a simple screening Coulomb potential[5] shows that the electronic slowing-down time α is inversely proportional to the electron density distribution of the two colliding atoms. The correlation between τ and α is shown on Fig. 2 where we have reported the "apparent" mean lives together with the calculated slowing down times α for solids with $Z_2 \leq 28$. The "apparent" mean lives τ are represented as a function of α on Fig. 3 and this representation brings out the linear dependence of τ versus α and, at the same time, demonstrates that τ is directly related to the electron density distribution of the two colliding atoms.

In the present ^{22}Ne case, we have no "absolute" mean life determination for comparison. However, in similar DSAM studies for ^{27}Al (Ref. 2) and ^{22}Na (Ref. 3), it has been demonstrated that the "absolute" lifetime values obtained in these cases with RDM (recoil distance method) were in agreement with lifetimes obtained by DSAM with "slow"

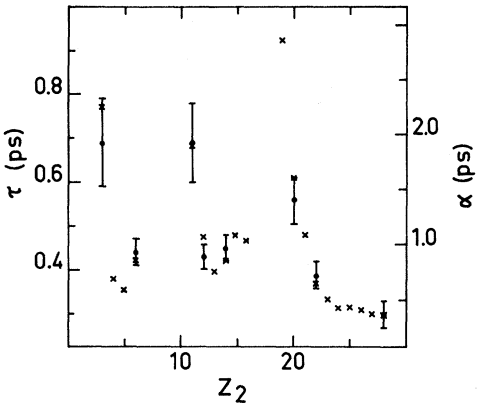

FIG. 2. The "apparent" mean life τ (dots) and the calculated electronic slowing down time α (crosses) versus Z_2 for solid materials with $Z_2 \leq 28$.

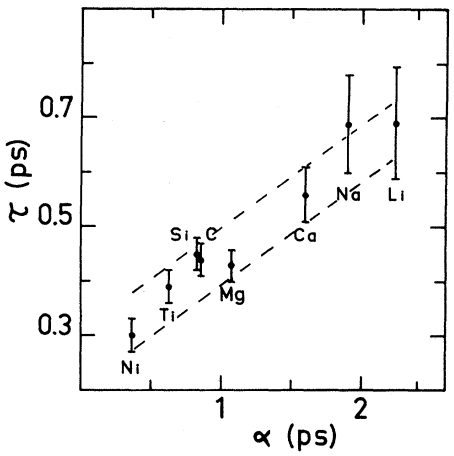

FIG. 3. The "apparent" mean life τ versus α. For the sake of clarity, the experimental data corresponding to $Z_2>28$ have not been included. However, all data points, from the present work and that of Broude *et al.* (Ref. 1) for $3 \leq Z_2 \leq 82$, fall in the region defined by the two parallel lines.

backings (Ca and Ba) while the ones obtained with "fast" backings (Ni, Au, and Ta) were too short by approximately 50% of their values. These observations and the α-τ correlation, demonstrated in the present work indicate that the Lindhard *et al.*[5] stopping power predictions overestimate the electron density distribution of the colliding atoms for "fast" backings and that the corresponding lifetime values, at $v/c \leq 1\%$, are generally too short.

In conclusion, for nuclear lifetime measurements with DSAM at velocities $v/c \leq 1\%$, there is a correlation between the "apparent" lifetime obtained with the Lindhard *et al.*[5] slowing down predictions and the electronic slowing-time α which is related to the electron density distribution of the two colliding atoms. The considerations of the present paper strongly support the efforts made by different groups[9,10] to describe the electronic cross sections using the detailed structure of the atoms electron density. For example, Latta and Scanlon,[10] starting from the Lindhard-Scharff-Winther theory[11] and renormalizing the target-atom electron density distribution, have shown that the variation of the relative stopping powers versus Z_2 presents sharp peaks at Z_2 values of 11, 19, 37, and 55 which can be correlated to the maximum value of the "apparent" mean life for Na, Ca, Sr, and Ba slowing-down materials. The present work shows one more peak corresponding to the Li slowing-down material.

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