would doubt that they could be easily neglected in other transfer reactions on deformed nuclei. Work is in progress at this laboratory to assess the importance of inelastic effects in single-nucleon transfer reactions.

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Effects of Isobaric-Analog Resonances on the Mean Lifetimes of Compound-Nucleus Fine Structure by Crystal Blocking in Germanium*

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The crystal-blocking method for protons along a ⟨110⟩ axis of a 30-keV-thick Ge crystal has been used to show sizable effects on mean compound-nuclear lifetimes of (1) the enhancement of an isobaric-analog resonance, and (2) the spin of the final state excited by inelastic scattering.

We have been able to demonstrate that the presence of an isobaric-analog resonance (IAR) shortens the mean lifetime of the many compound-nuclear fine-structure resonances contributing to the inelastic scattering of protons from Ge isotopes. Furthermore, we have observed that the *final-state* spins affect the effective lifetimes in a manner which can be understood on the basis of angular-momentum considerations.

We used the technique of blocking in a thin single crystal of Ge, pioneered by Maruyama *et al.*,[1] and confirmed since by Gibson *et al.*[2] and Clark *et al.*[3] Briefly, this technique consists in carefully comparing the *suppression* of elastic with inelastic scattering yields along a crystallographic axis or plane; since the elastic scattering is "prompt" (i.e., almost entirely Rutherford) for 5-MeV protons on Ge, while the inelastically scattered protons to various final states may be delayed in the compound nucleus, the angular distributions, e.g., near an axis, for the inelastic protons will display shallower dips than the elastic protons. The detailed shapes of these "dips" can be interpreted, in principle, by performing elaborate computer calculations, taking into account lattice vibrations of emitting and blocking atoms, multiple scattering, recoil time of flight, etc.[4] In this way, a connection between lifetime and dip shape can be established. Much remains to be done theoretically to make this connection in a unique, noncontroversial manner. While the absolute lifetime values reported here should be considered as preliminary evaluations, we feel the *relative* values for different bombarding energies and final states reveal new and significant nuclear information at this stage.

Since we wanted to ask questions concerning IAR having natural widths of about 30–50 keV, we required thinner crystals than those used by previous workers,[1,3] namely, 1.5 μm thickness, corresponding to about 30 keV energy loss by the incident proton beam. Conditions which allowed the accumulation of sufficient statistics without serious crystal-distortion effects[5] were found to occur when the crystal was heated to 450°C during bombardment, and the beam current was kept below 100 nA. Crystal quality was monitored continuously by observing a blocking (star) pat-

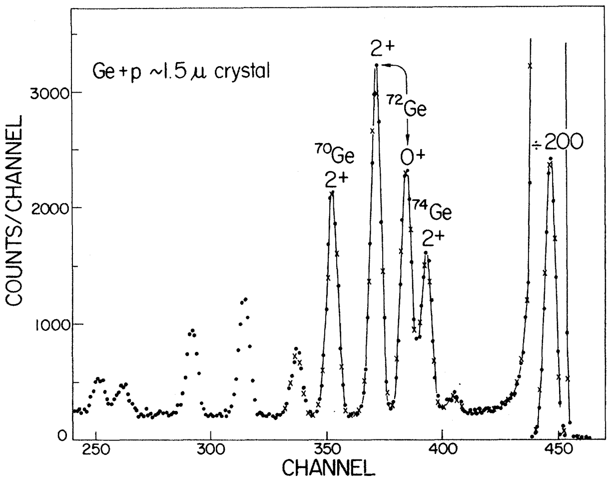

FIG. 1. Accumulated proton spectrum for 5.110-MeV protons on a ~30-keV-thick Ge crystal, observed at $\theta_{lab}=90°$, showing the four peaks for which lifetime information is obtained. Elastic peak at extreme right reduced 200 fold.

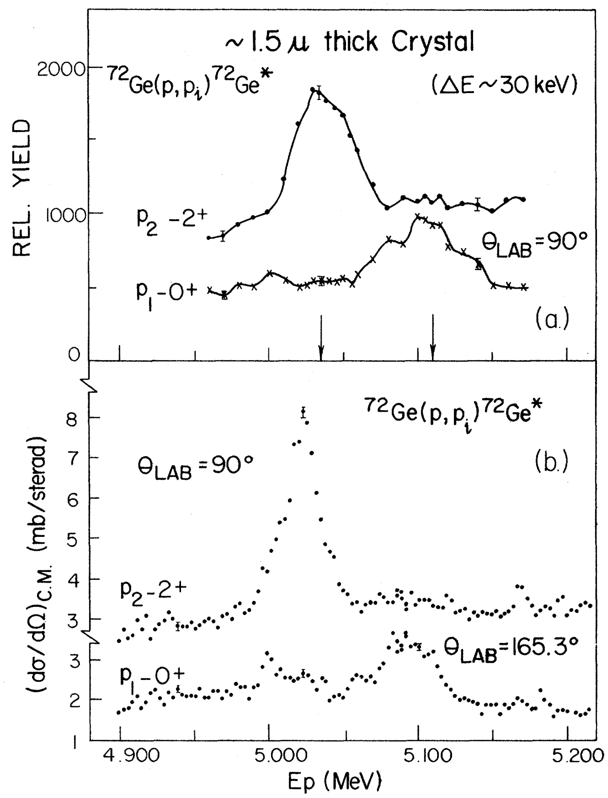

FIG. 2. (a) Excitation curve for 90° inelastic proton scattering on ^{72}Ge to first-excited 0^+ and second-excited 2^+ states for ~30-keV-thick crystal used. Arrows denote on- and off-resonance positions described in text. (b) Thin-target (3-keV) excitation curves for same states in (a). $l=2$ IAR in ^{73}As at 5.022 MeV; $l=0$ IAR at 5.094 MeV.

tern near the forward direction on a quartz screen in the Faraday cup. The actual blocking experiment was performed at a scattering angle of 90 deg around a ⟨110⟩ axis, using a cooled, 4.5-mm-long×1.5-mm-wide, position-sensitive Si detector[6] located at 130 cm from the target. Figure 1 shows the accumulated proton spectrum observed in this detector. The elastic peak, and inelastic peaks from ^{74}Ge (0.596 MeV, 2^+), ^{72}Ge (0.690 MeV, 0^+; 0.830 MeV, 2^+), and ^{70}Ge (1.04 MeV, 2^+) were monitored by the detector via our online computer in a two-dimensional mode, displaying both energy and angular distribution dip. The inelastic peaks have typically about 1% of the elastic peak intensity; the latter at all times served to monitor the "prompt" dip shape for possible crystal deterioration (found to be negligible under the above conditions).

Our measurements consisted of runs at two different bombarding energies: $E_p=5.035$ MeV, chosen so as to be *on* resonance for ^{72}Ge $+p$ leading to the 830-keV 2^+ state, and simultaneously *off* resonance for inelastic scattering to the 0^+ first-excited state at 690 keV; and $E_p=5.110$ MeV, where the *on-* and *off*-resonance conditions are reversed for the two states. Their excitation curves for the actual crystal thickness used are shown in Fig. 2(a); the inelastic scattering excitation curves for a 3-keV-thick (amorphous) target are given in Fig. 2(b). No particular resonant features in ^{70}Ge and ^{74}Ge were pursued because of the special complications due to intermediate structure in the former,[7] and the fact that the (p,n) threshold for the latter lies at 3.40 MeV. As was previously demonstrated,[1] the effect of the neutron threshold is to broaden compound resonances to such an extent as to restore the full, "prompt" dip depth in the blocking pattern ($\bar{\tau}\lesssim 10^{-17}$ sec, or $\bar{\Gamma}\gtrsim 100$ eV). The resonance in ^{73}As at 5.035 MeV was determined to have $l=2$; polarization measurements are in progress in our laboratory to decide between $J=\frac{3}{2}^+$ and $\frac{5}{2}^+$.[8] The resonance at 5.110 MeV was found to be $l=0$, hence $J=\frac{1}{2}^+$. Both of these energies lie below the ^{72}Ge(p,n) threshold at 5.21 MeV.

The resulting blocking patterns for the two bombarding energies are shown in Fig. 3, the quantities R refer to the ratios between minimum values and average shoulder values. To the extreme right, we see the "prompt" patterns for elastic scattering, known to very high precision. An additional such distribution was obtained at 4.20

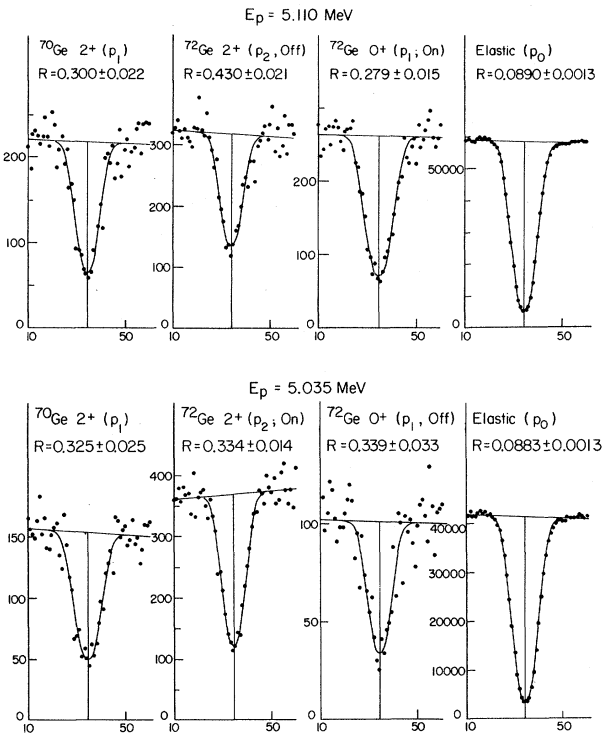

FIG. 3. Blocking "dips" observed at two proton energies, along ⟨110⟩ axis, for ~1.5-μm-thick Ge crystal. Total beam exposure ~0.01 C. At extreme right, prompt dips for elastic scattering (excellent statistics). Other dips are shallower, indicating varying degrees of delay in inelastic scattering. R is the ratio of minimum to shoulder values. Curves through points represent least-squares fits using Gaussian plus sloping background.

MeV, which corresponds to the mean *outgoing* inelastic proton energy after scattering, and was found to have an identical R value, within the uncertainties, to either of the elastic curves shown. We see that there are large, significant differences, not only between elastic and inelastic R values, but among the various inelastic R values themselves. The preliminary lifetime values deduced therefrom, using a simplified formula[9] with a cutoff radius $r_c = 3a_{TF}$, the latter being the Thomas-Fermi screening radius, are listed in Table I.

Before discussing these values, it is well to point out that the mean lifetimes extracted here, even if evaluated correctly, are the result of a number of averaging processes: We recall that we are examining a slice about 30 keV wide (target thickness) at about 11 MeV excitation energy in ^{73}As. This slice contains several hundred resonances with spins J varying from $\frac{1}{2}$ to perhaps $\frac{11}{2}$ (both parities). Remember also that the levels

TABLE I. Blocking lifetime results for Ge + p along ⟨110⟩ axis.

	R or R_1'	τ(as)[a]
E_p = 4.200 MeV		
Ge(p,p_0)	0.0888 0.0025≡R_1'	
E_p = 5.035 MeV		
Ge(p,p_0)	0.0883±0.0013	
^{70}Ge(2+)p_1	0.325 ±0.025	58.8±4.6
^{72}Ge(2+)p_2	0.334 ±0.014 (On)[b]	62.1±2.6
^{72}Ge(0+)p_1	0.339 ±0.033 (Off)[b]	63.1±6.3
E_p = 5.110 MeV		
Ge(p,p_0)	0.0890±0.0013	
^{70}Ge(2+)p_1	0.300 ±0.022	53.9±3.8
^{72}Ge(2+)p_2	0.430 ±0.021 (Off)[b]	81.2±4.9
^{72}Ge(0+)p_1	0.275 ±0.015 (On)[b]	51.0±2.6
^{74}Ge(2+)p_1	0.161 ±0.017	31.6±3.3

[a]Obtained with the formula of Ref. 9 and $\gamma_c = 3a_{TF} = 0.422$ Å; $as = 10^{-18}$ sec.
[b]Refers to *on* or *off* the appropriate resonance for this channel.

of given J are distributed in their widths according to some law, such as that given by Porter and Thomas,[10] and that the probability of their formation by incoming protons is proportional to their width.

We can obtain some rather reliable level-density information from extrapolation of known density at neutron-capture energies (~7.5 MeV).[11] This yields a value of ~200 eV for the mean spacing of $J = \frac{1}{2}^+$ states at 11 MeV excitation, and shows that, in view of the measured values of $\overline{\Gamma}$, we are still in the régime $\overline{\Gamma} < \overline{D}$. This fact makes it possible to deduce mean lifetime values by assuming a superposition of exponential decays.

All those (unresolved) fine-structure states having the spin and parity of the analog state will be enhanced[12] near the latter; the enhancement factor f is defined by $\Gamma_\lambda \equiv f\Gamma_i$, Γ_λ and Γ_i being the enhanced and unenhanced fine-structure widths, respectively. We note that the effect on the *mean* lifetime observed *on* resonance is only due to the enhancement of the small subpopulation of states of appropriate spin and parity; all other compound states maintain their average *off*-resonance behavior. The observed change between *on*- and *off*-resonance mean lifetimes, as given in Table I must then be interpreted in terms of some level-density distribution $\rho(J, \underline{E})$,[13] to arrive at a mean enhancement factor $\overline{f}_J$. A crude, preliminary estimate of this quantity leads to a value of $\bar{f}_{5/2^+} \cong 2.5$.

Inspection of Table I further reveals that the mean lifetime, at the same (*off*-resonance) bombarding energy, for the proton group feeding the 2^+ state in ^{72}Ge, is about 28% *longer* than the group going to the 0^+ excited state of ^{72}Ge. This is qualitatively as expected on the basis of angular-momentum considerations alone: Strong preference for $l'=0$ over $l'=2$ proton emission this far below the Coulomb barrier ($V_c \sim 7$ MeV) favors, on the average, higher compound J values for an $I=2^+$ final state, and lower J values for a 0^+ final state. Higher-J-value states live longer, yielding shallower blocking dips, as observed. Preliminary width estimates obtained from a complete Hauser-Feshbach calculation for our particular case[14] yield the values 13.6 and 11.0 eV for the 0^+ and 2^+ final states, respectively. This is in excellent agreement with the relative values given in Table I, and shows that penetrabilities completely account for the observed differences. In the future, lifetime differences for different final states of the same spin (e.g., 2^+) might reveal nuclear *structure* differences in the continuum not previously accessible.

In conclusion, we consider the detectability of compound-elastic scattering in the presence of shape-elastic (potential) scattering. In our case, the elastic scattering is mainly Rutherford, plus a small amount of potential nuclear scattering. The elastic-scattering blocking dips at three bombarding energies were found to be identical (cf. Table I). Since inelastic scattering constitutes only about 1% of elastic, we might expect only about 1% of the elastic scattering to be compound elastic. It is challenging to devise situations where the compound-elastic fraction might become detectable. Whereas one has to add scattering *amplitudes* to interpret elastic-scattering interference patterns, it is the *intensities* that add when looking for lifetime effects on blocking patterns. For example, a 60% interference dip reflects only a 9% intensity change in the lifetime effect.

A more detailed account of this work is in preparation.

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