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ABSTRACT

The stopping power of ^{107}Ag, ^{109}Ag and ^{150}Sm in nickel and gold was measured as a preliminary test of a new technique for measuring energy loss based on the γ-ray Doppler shift. The analysis of the data was based on the theories of Lindhard, Scharff and Schiott for nuclear and electronic stopping. The results are compared with the semi-empirical predictions of Northcliffe and Schilling.

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I - INTRODUCTION

Several experiments[1,2] have pointed out that the mechanism of slowing down of charged particles in matter depends in an oscillatory fashion on Z_{ion} and Z_{foil}. The amplitude of the oscillations is especially important in the low recoil velocity region. A significant consequence of this fact is related to the DSAM determination of nuclear life-times. Since there are not much data for the stopping of heavy ions at low velocity, DSAM generally uses a theoretical approach for finding dE/dx, like that of Lindhard et al.[3] (LSS) in order to extract life times. Those theories do not account for the Z_{ion}, Z_{foil} oscillations and the DSAM results are found to be Z_{foil} dependent[4].

We measured the stopping powers of heavy ions at low velocity ($v/c \sim 0.5 - 1.0\,\%$) using a method similar to that of Shane and Seaman[5]. A few measurements have been carried out for testing and developing the method.

II - THE METHOD

An ^{16}O beam (see fig. 1) was used to produce Coulomb - excited target nuclei in flight. The Doppler-shifted energy of the γ-rays emitted in the decay of the nuclear state is used to measure the ion velocity. Beam projectiles scattered near 180^{o} detected in coincidence with the γ-rays select target ions recoiling in a cone near the 0^{o} direction.

The recoiling nucleus will decay before or after passing through the stopping material where it loses a fraction of its energy. Choosing the target-foil distance $d \sim vT_{1/2}$ where v is the initial ion velocity and $T_{1/2}$ the half-life of the nuclear state, about half of the recoiling nuclei will decay before and half after passing through the stopping foil. The γ-ray coincidence spectrum shows two peaks corresponding to Doppler-shifted γ-rays emitted from nuclei recoiling at two different velocities (v_f, v_s see fig. 2). A Gaussian peak-fitting routine is used for finding peak positions, allowing the determination of the initial (v_f) and final (v_s) velocity of the recoiling ion.

The stopping foil thickness was measured with standard techniques: energy loss of α-particles and direct surface density determination by weighing a ~0.5 cm^2 foil sample.

III - EXPERIMENTAL SET-UP

A beam of 35 - 45 MeV ^{16}O ions accelerated by the Universidade de São Paulo 8UD tandem Pelletron was used in all measurements. Standard fast-slow coincidence electronics were used for the signals from the annular detector (near 180^o) and the true coaxial (56 cm^3) Ge(Li) detector at 0^o. The spectra were collected in approximately 6 hours of exposure to 20-40nA of $^{16}O^{5+}$ or $^{16}O^{6+}$.

The targets of ^{150}Sm, ^{107}Ag and natural silver were prepared by vacuum evaporation onto Ni foil backings. Target thicknesses were about 0.3 mg/cm^2 and the Ni backings were 1.2 mg/cm^2 thick for the ^{150}Sm and ^{107}Ag and 0.25 mg/cm^2 thick for the natural silver.

IV - DATA ANALYSIS

The recoil velocities (v_f, v_s) were extracted from the shifted γ-ray energies with a method developed[6] for the Reçoil Distance Method of life-time measurements. Since an appreciable fraction of the initial recoil energy (E_f) is lost in the foil and in the low velocity region dE/dx is expected to be highly non-linear with E, the simplest approach for extracting dE/dx,

$$\frac{dE}{dx}(\bar{E}) = \frac{\Delta E}{\Delta x}$$

with

$$\bar{E} = E_f - \frac{\Delta E}{2}$$

may not be correct.

To find $dE/dx(\bar{E})$, we introduced a multiplicative parameter (α) in the LSS electronic stoping power formula and solved numerically the following integral to calculate α.

$$\Delta x = \int_{E_f - \Delta E}^{E_f} \frac{d\bar{E}}{\left(\frac{dE}{dx}\right)_{nuc.} + \alpha \left(K E^{1/2}\right)_{LSS}} \qquad \text{Eq. 1}$$

A value for α was obtained and it was assumed that $\Delta E/\Delta x$ represents dE/dx at the mean energy $\bar{E}$ defined by:

$$\left.\frac{dE}{dx}(\dot{E})\right|_{\substack{LSS \\ corrected}} = \frac{\Delta E}{\Delta x}$$

This assumption was tested by introducing a modified LSS expression in eq. 1,

$$\frac{dE}{dx} = \eta \left(\frac{dE}{dx}\right)_{nuc} + \alpha \left(k E^{p}\right)$$

and repeating the above procedure with various pairs of (η,p) in the neighborhood of the LSS values (1.0, 0.5). The $\bar{E}$ values were found to be insensitive to the choice of (η,p).

V - RESULTS AND DISCUSSION

The electronic stopping powers from the present work are presented in the sixth column of Table 1 and in the seventh and eighth columns are given the semi-empirical estimates of Northcliffe and Schilling and the LSS predictions, respectively. As the interpolations of Northcliffe and Schilling give only the electronic stopping, the present data have been corrected by subtracting the LSS nuclear stopping power.

As can be seen in Table 1 the measured stopping powers are in general lower than the LSS predictions (except for the case of silver stopping in nickel) as would be expected if the Z_{ion} and the Z_{foil} dependences exhibit minima at atomic numbers 30, 46 and 79[2]. Closer agreement would be expected for the NS interpolation as the data are normalized to several widely used stopping materials such as nickel or gold, which are both at minima in the Z_{foil} dependence. Thus, the present data are consistent with the previously seen[4] oscillations in the Z dependences of the stopping power but they do not constitute a sufficient set for drawing general conclusions. However, this method, with suitable choices for target materials and foils, could generate data to help clarify the (Z_{ion}, Z_{foil}) dependence of heavy ion stopping in regions at present not easily reached by other techniques.

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FIGURE CAPTIONS

Fig. 1 - Chamber and detector diagrams showing the foil-target system in detail.

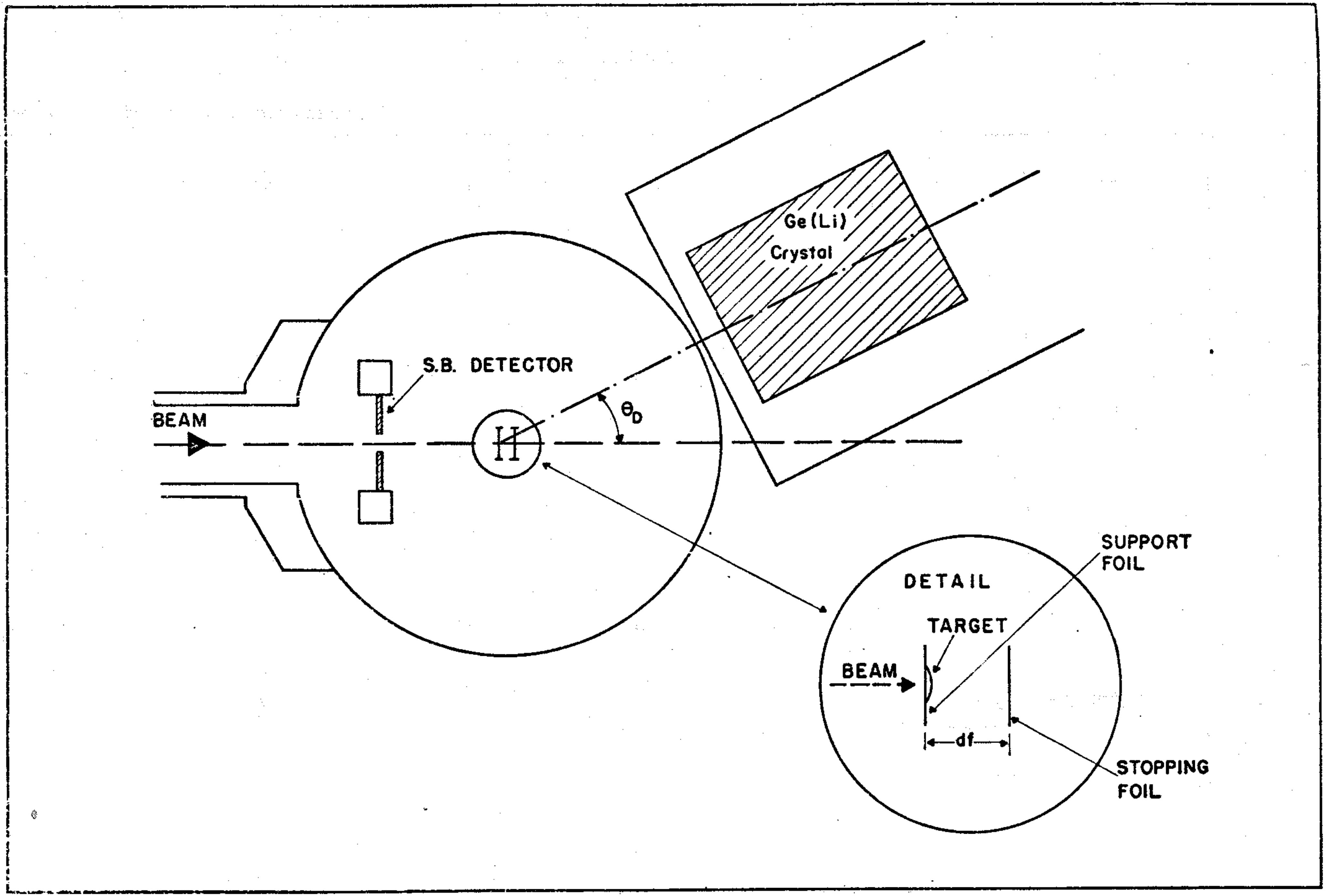
Fig. 2 - Spectrum of partially and fully shifted γ-rays from natural silver target (^{109}Ag(414keV) and ^{107}Ag(423keV) in coincidence with backscattered ^{16}O.

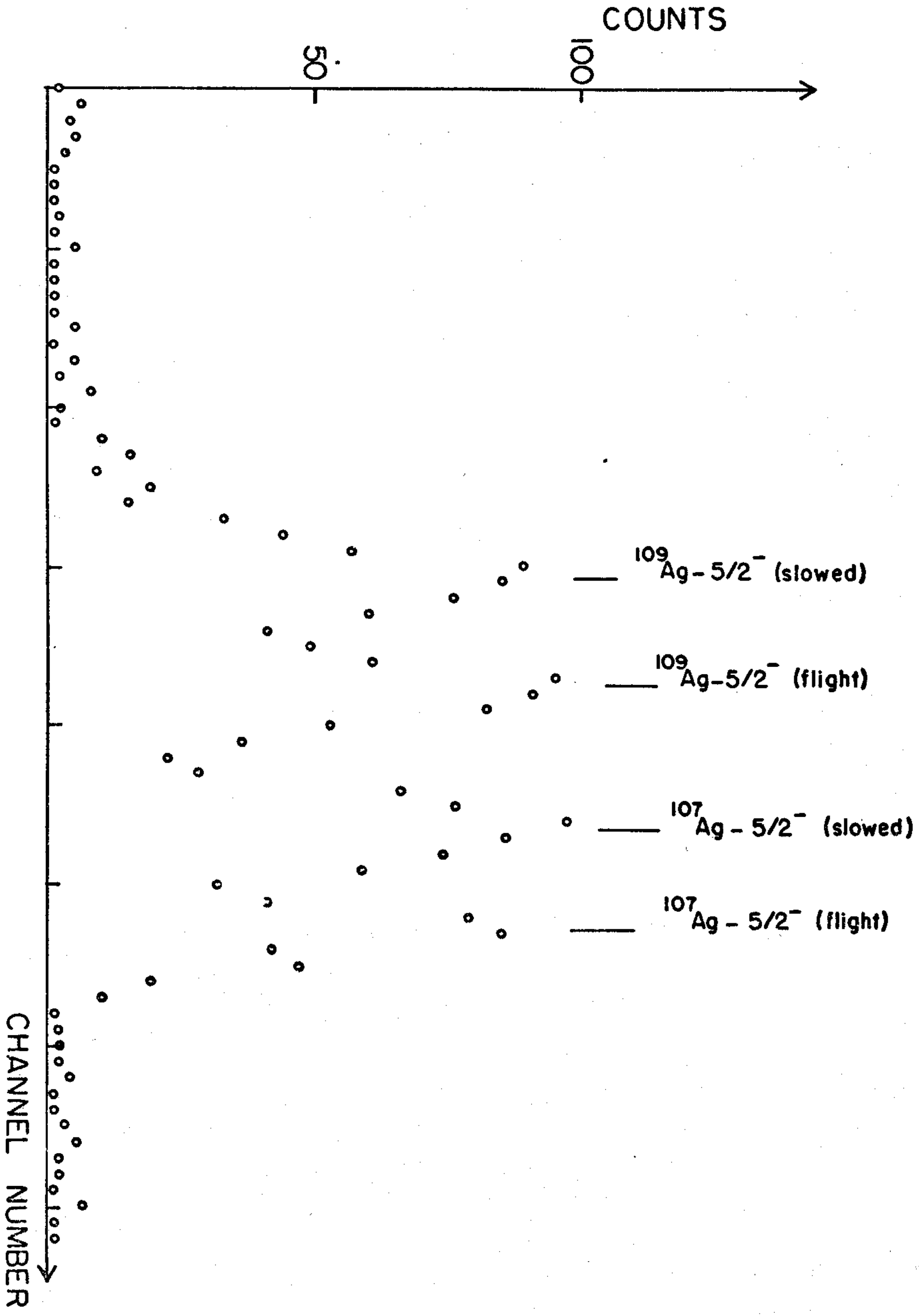
Table I - Measured stopping powers and corresponding theoretical predictions of N.S. and L.S.S. (the LSS nuclear stopping was subtracted from the exp. points to obtain dE/dx) el.

ion, stopping medium	initial ion energy E: (MeV)	ion energy loss ΔE (MeV)	thickness stopping medium Δx mg/cm^2	$\bar{E}$ MeV	$\frac{dE}{dx}$ elect. MeV /mg/cm^2	N.S.elect. MeV /mg/cm^2	L.S.S.elect. MeV /mg/cm^2
^{150}Sm , Au	11.3 (.5)	10.9 (.5)	2.43 (.06)	5.3 (.3)	2.3 (.2)	2.0	3.4
^{150}Sm , Ni	10.6 (.6)	9.9 (.5)	1.19 (.06)	5.3 (.3)	4.3 (.3)	5.1	6.6
^{107}Ag , Au	11.5 (.6)	8.4 (.4)	2.43 (.06)	7.1 (.6)	2.5 (.2)	2.6	3.9
^{107}Ag , Ni	12.6 (.5)	11.2 (.5)	1.19 (.06)	5.9 (.3)	7.4 (.4)	5.9	7.0
^{107}Ag , Ni	19.3 (.6)	13.2 (.4)	1.19 (.06)	12.0(.4)	10.1 (.5)	9.2	10.0
^{109}Ag , Ni	18.9 (.5)	13.3 (.4)	1.19 (.06)	11.4(.3)	10.2 (.5)	8.8	9.7

Numbers in parentheses are errors

TABLE I


Ge (Li)
Crystal
S.B. DETECTOR
BEAM
θD
DETAIL
TARGET
SUPPORT FOIL
BEAM
df
STOPPING FOIL



COUNTS
50
100
CHANNEL NUMBER
109Ag-5/2⁻ (slowed)
109Ag-5/2⁻ (flight)
107Ag-5/2⁻ (slowed)
107Ag-5/2⁻ (flight)