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DEVELOPMENT OF OPTICALLY PUMPED POLARIZED JET TARGETS FOR USE IN HEAVY-ION REACTION STUDIES*

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DEVELOPMENT OF OPTICALLY PUMPED POLARIZED JET TARGETS FOR USE IN HEAVY-ION REACTION STUDIES*

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The development of a laser optically pumped nuclear spin aligned target of ^{151,153}Eu is outlined. The current status of this project, together with the unique "macroscopic" heavy-ion reaction physics that may be addressed using this target, is given.

I. INTRODUCTION

Polarized beams and/or targets can provide sensitive tests of heavy-ion reaction mechanisms, and as demonstrated with polarized ^{6}Li and ^{7}Li beams,[1,2] the polarization observables are dominated by quadrupole effects. The most dramatic polarization effects involve entrance-channel phenomena which are connected to the change in spatial overlap between target and projectile as a function of alignment for a given impact parameter or trajectory. Although not performed with polarized targets/projectiles, subbarrier and near-barrier heavy-ion reaction studies have clearly demonstrated the influence of target static quadrupole deformation on fusion cross sections[3,4] and on fusion-fission cross sections.[5] These particular experimental examples (Refs. 3-5) used near-spherical heavy-ion projectiles (^{16}O, ^{32}S, ^{40}Ar) and targets of the Sm isotopes, which range from spherical ^{144}Sm to deformed ^{154}Sm, to investigate the effects. Near-barrier fusion reactions depend upon the subtle interplay between the repulsive point Coulomb interaction and the attractive nuclear interactions which, in turn, depend on the spatial overlap of the target and projectile nuclear density distributions. For fixed projectile energy, thus fixed distance of closest approach from Coulomb interactions, the spatial overlap, averaged over all target orientations, is largest for the more deformed target. This simple classical idea explains to first order the larger fusion cross sections observed for the more deformed target (^{154}Sm), as illustrated in Fig. 1. Stokstad and Gross[6] have performed an analysis of the ^{16}O + Sm results and have estimated the large increase in sensitivity that would be realized if the ^{16}O + ^{154}Sm experiment could be performed at fixed energy, but as a function of target orientation. This dramatic example, shown in Fig. 2, illustrates one of the advantages in "macroscopic" heavy-ion reaction studies if polarized targets could be used. Subbarrier fusion cross section calculations for the $^{16}O + {}^{165}Ho$ reaction, which is similar to the $^{16}O + {}^{154}Sm$ reaction, have recently been performed by Jacobs and Smilansky[7] as a function of polarization. The effects predicted by Jacobs and Smilansky are smaller than those predicted by Stokstad and Gross, although approximations were made in both calculations. Further theoretical work is required. Effects, such as those illustrated in Fig. 2, have prompted us to develop a polarized target for use in the heavy-ion physics program at ORNL. Design considerations, laser development, mechanical construction, and implementation, together with some of the additional physics addressable when polarized targets are used, are given below.

II. THE ORNL SUPERSONIC GAS-JET TARGET

The polarized target developmental efforts are based on a windowless supersonic gas-jet target which had previously been constructed to facilitate high resolution heavy-ion physics experiments with gaseous targets.[8,9] This target assembly has been completed and installed as a replaceable unit of the scattering chamber of the Enge split-pole magnetic spectrometer located on one of the tandem accelerator beam lines at the Holifield Heavy Ion Research Facility (HHIRF) at ORNL. The target incorporates four stages of differential pumping which allows tandem beam line pressures to be maintained below 3×10^{-8} torr under experimental conditions, while the pressure in the target region is ~50 torr. For gaseous targets (N_2, Ar, Xe, etc.), target thicknesses ranging from fractions of a $\mu g/cm^2$ to ~30 $\mu g/cm^2$ have been achieved in high resolution heavy-ion reaction experiments at HHIRF.[10] Sliding seals on the inner and outer sections allow the target exit aperture and the Enge split-pole spectrometer entrance slits to be positioned within the angular range $0° = \theta \lesssim 35°$. Schematic views of this gas-jet target are shown in Figs. 3 and 4. Additional details may be found in Refs. 8 and 9.

III. THE ORNL OPTICALLY PUMPED POLARIZED TARGET

Based on the supersonic gas-jet target described briefly above in Sec. II, plans to implement a polarized version at ORNL were developed in 1982. Only two experiments have ever been performed with polarized targets,[11] other than for hydrogen, in low-energy nuclear and heavy-ion physics with charged-particle beams. Charged-particle beams, especially heavy-ion beams, have large stopping powers in target matter, and the relatively large energy deposit poses severe limitations for polarized targets oriented by cryogenic methods. As an illustration, ^{3}He-^{4}He dilution refrigerators have typical "refrigeration powers" of ~1 μW at 7 mK; this is equivalent "in heating power" to the passage of ~70-pA beam of 100-MeV ^{16}O ions through a self-supported 10-μg/cm^2 rare-earth target. Polarized gas-jet targets, with nuclear orientation achieved dynamically via laser optical pumping, overcome the beam-heating problems associated with targets oriented by low-temperature methods.

Europium was chosen as the target species for development of the optically pumped polarized target and is a particularly favorable case for optical pumping[12] since the atomic ground state, $^8S_{7/2}$, has near-spherical symmetry. This tends to reduce the relaxation and, hence, a loss of alignment due to collisions. Other attractive features of Eu are the presence of only a few low-lying excited atomic states and the small hyperfine splitting of the ground state. Our intent is to pump the entire hyperfine structure multiplet of the $^8S_{7/2}$-y $^8P_{5/2}$ resonance transition in Eu at 466.3 nm ($\tau \sim 5$ nsec) with linearly (π) polarized light. Nuclear orientation is achieved via "depopulation pumping." We choose the quantization axis, upon which the orientation is measured, to be in "photon frame" and is the polarization vector ($\vec{E}$) in the case of optical pumping with linearly polarized (π) light. In our experimental geometry (see Figs. 5 and 6), the polarization vector $\vec{E}$ lies in the horizontal nuclear reaction plane. Rotation of the polarization $\vec{E}$ vector in this plane, and hence the quantization axis for the nuclear spin alignment, is easily accomplished using a half-wave polarization rotator appropriate for 466 nm photons.

The nuclear spin alignment is conveniently described by orientation parameters,[13] $B_K(I)$, which are related to the the populations $W(M_I)$ of the nuclear magnetic substates by:

$$B_K = \sum_{M_I} W(M_I)(-1)^{I-M_I} (2I + 1)^{1/2} \langle I \; I \; M_I \; - M_I | K0 \rangle \; .$$

These parameters are the Q = 0 components of the normalized statistical tensors or state multipoles, $B_{KQ}(I)$, commonly used to specify alignment in the general case. In our coordinate system and pumping geometry, only the Q = 0 components are nonvanishing. For both stable isotopes of Eu, ^{151}Eu and ^{153}Eu, the nuclear spin, I, is 5/2; only the even rank orientation parameters B_2 and B_4 are needed to completely describe the alignment ($K_{max} = 2I$), since the system is axially symmetric and invariant to the reversal of the quantization axis.

Extensive optical pumping calculations have been done for the Eu system using the computer program RATES.[14] The complete set of coupled differential equations is solved to obtain the detailed time evolution of the coupled ($\vec{F} = \vec{I} + \vec{J}$) density matrix. The rate equations include the effects due to both ground- and excited-state relaxation, laser linewidth, and a realistic atomic absorption profile. The nuclear density matrix can be projected from the coupled matrix at any time. Although the effects of the beam plasma due to the passage of the heavy-ion beam remain unaddressed, ground-state relaxation effects are expected to be unimportant in the near-collisionless domain expected in the gas jet. The time evolution of the nuclear orientation in the target is shown in Fig. 7, for optical pumping of the y $^8P_{5/2}$ level with both linearly (π) and circularly (σ) polarized laser light, to illustrate the effects. The orientation parameters, B_2 and B_4, have been projected from the alignment tensors of the coupled nuclear-electronic system (done by RATES). One notes from Fig. 7 that nearly ideal alignment conditions are reached in about 15 μs for optical pumping of the $^8S_{7/2} \rightarrow$ y $^8P_{5/2}$ transition with linearly polarized (π) laser photons for our choice of pumping conditions. Figure 8 shows the associated expected steady state populations of the magnetic substates in the F = 6 ground-state hyperfine level, the absolute population of which has also been indicated. Again, the quantization axis is chosen in the "photon frame," i.e., the polarization vector ($\vec{E}$) in the case of optical pumping with linearly (π) polarized light and the propagation direction ($\vec{k}$) of the laser in the case of optical pumping with circularly (σ) polarized light.

Considerable laser development to efficiently pump the relatively broad hyperfine structure manifold for both isotopes ($\Delta f \approx 5$ GHz) with one broadband CW laser has been completed. These developments include tailoring the laser output bandwidth to match the approximately Gaussian absorption profile for the transition without "holes" in the output spectrum. A magneto-opto galvanic lock and stabilization technique is used to provide laser stability at the center of the absorption profile.

Most polarized target hardware has been designed and constructed, and our developmental efforts are currently centered on the construction of the high-temperature components of the gas-jet target that are required for vapor Eu.

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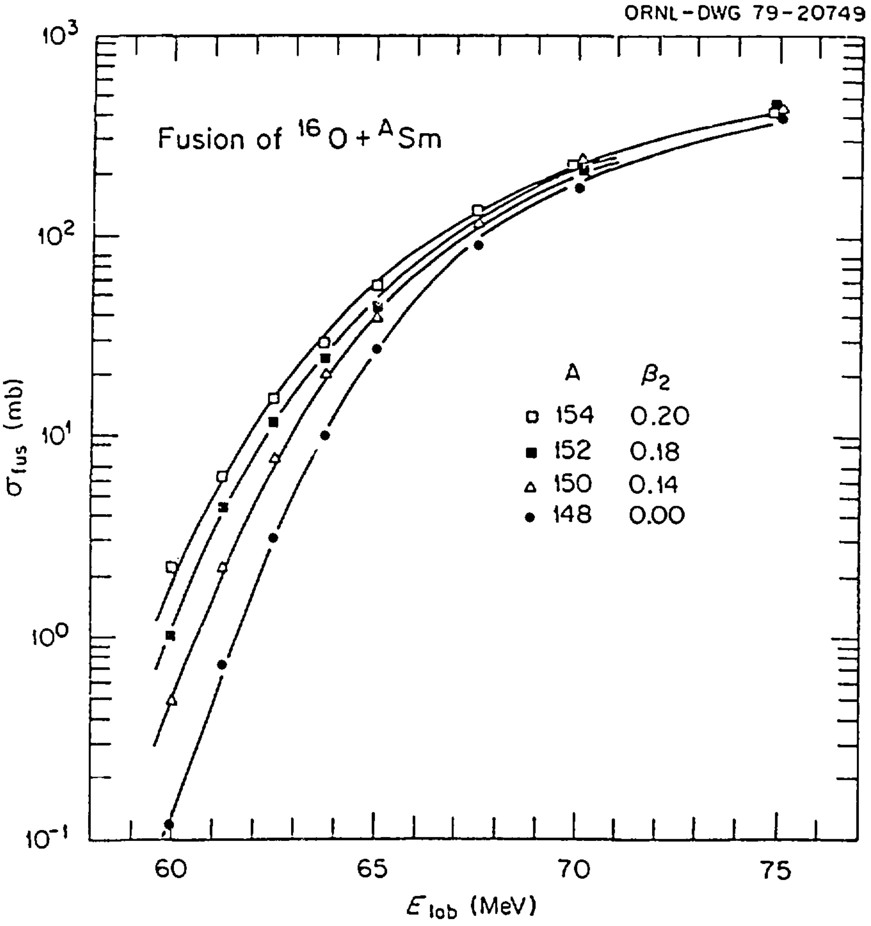

Fig. 1. Fusion cross sections for the ^{16}O + ^{148,150,152,154}Sm reactions as a function of ^{16}O bombarding energy (from Stokstad et al., Refs. 3, 4, and 6). For fixed bombarding energy (distance of closest approach), cross sections for ^{154}Sm are largest due to the larger nuclear density spatial overlap between target and projectile due to quadrupole deformation.

ORNL-DWG 79-20755R

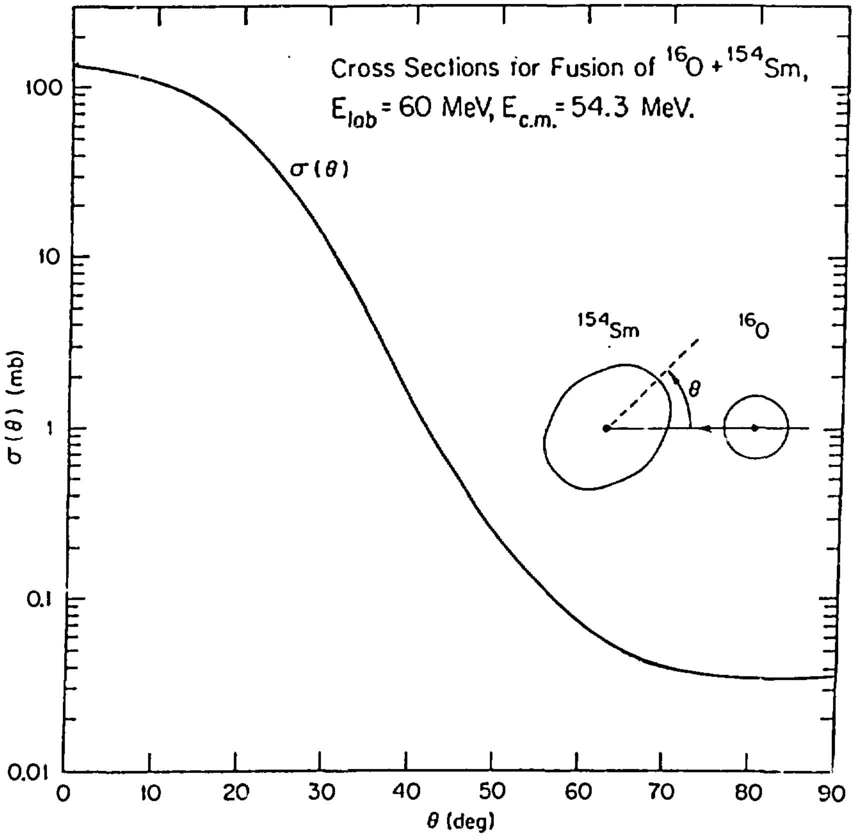

Fig. 2. Calculated fusion cross sections for ^{16}O + ^{154}Sm at fixed ^{16}O energy (E_{lab} = 60 MeV) as a function of the orientation of the symmetry axis of the nuclear density distribution for ^{154}Sm (Ref. 6).

ORNL-DWG 83-10642

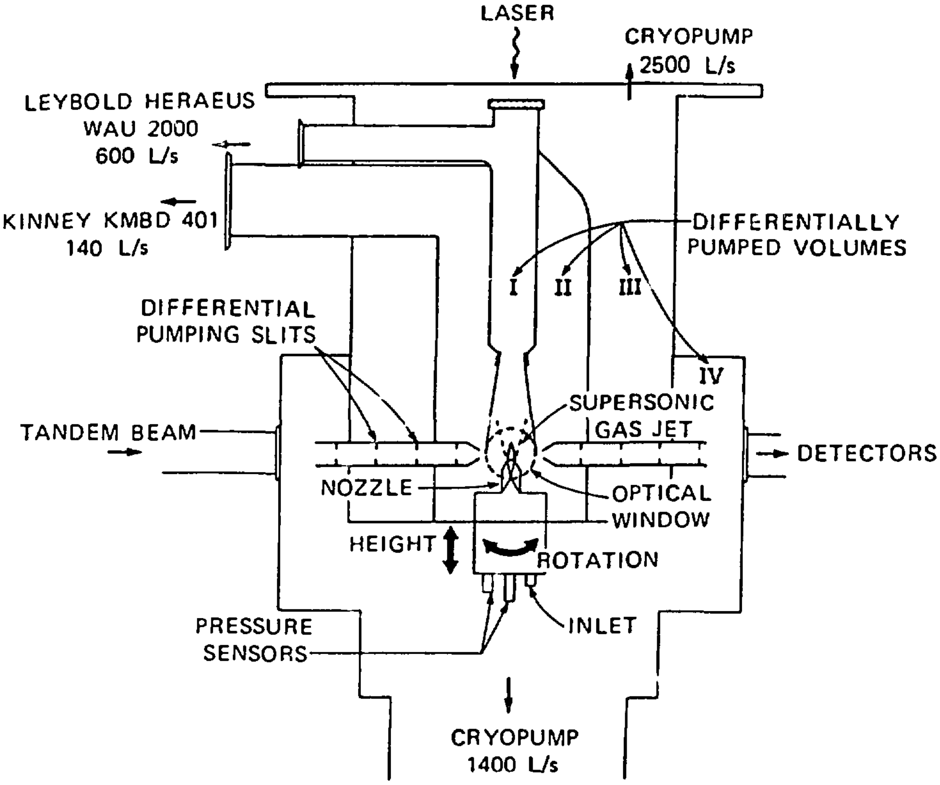

Fig. 3. Schematic side view of the ORNL supersonic gas-jet target.

ORNL-DWG 83-10644

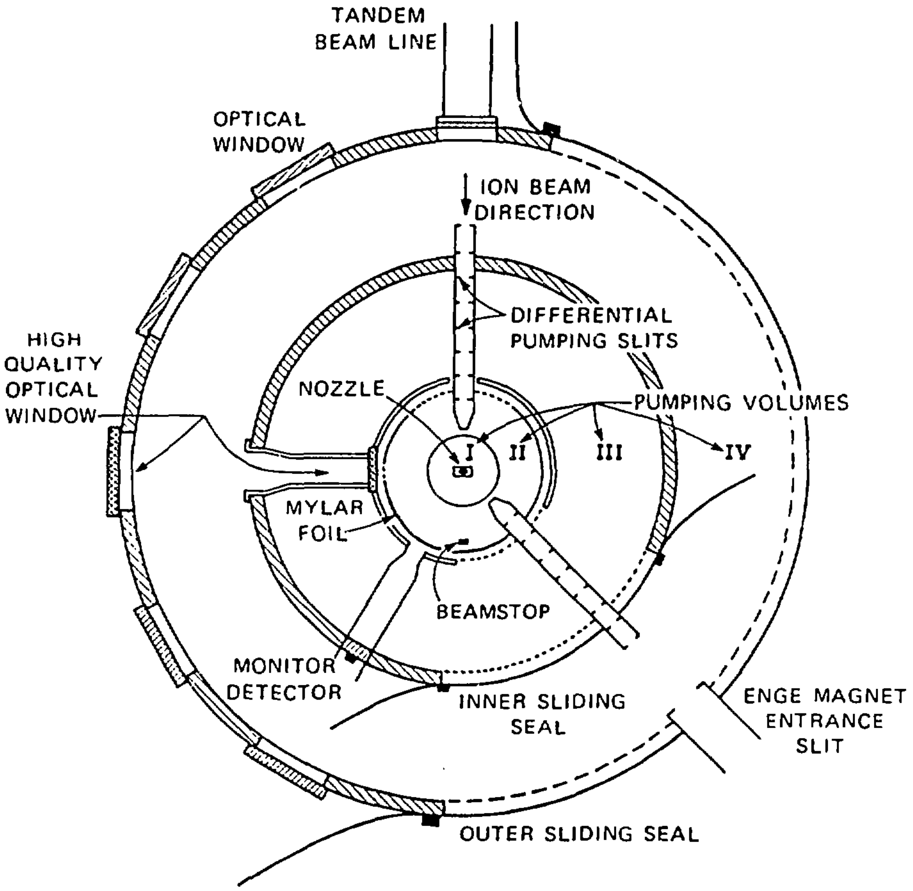

Fig. 4. Schematic top view of the ORNL supersonic gas-jet target.

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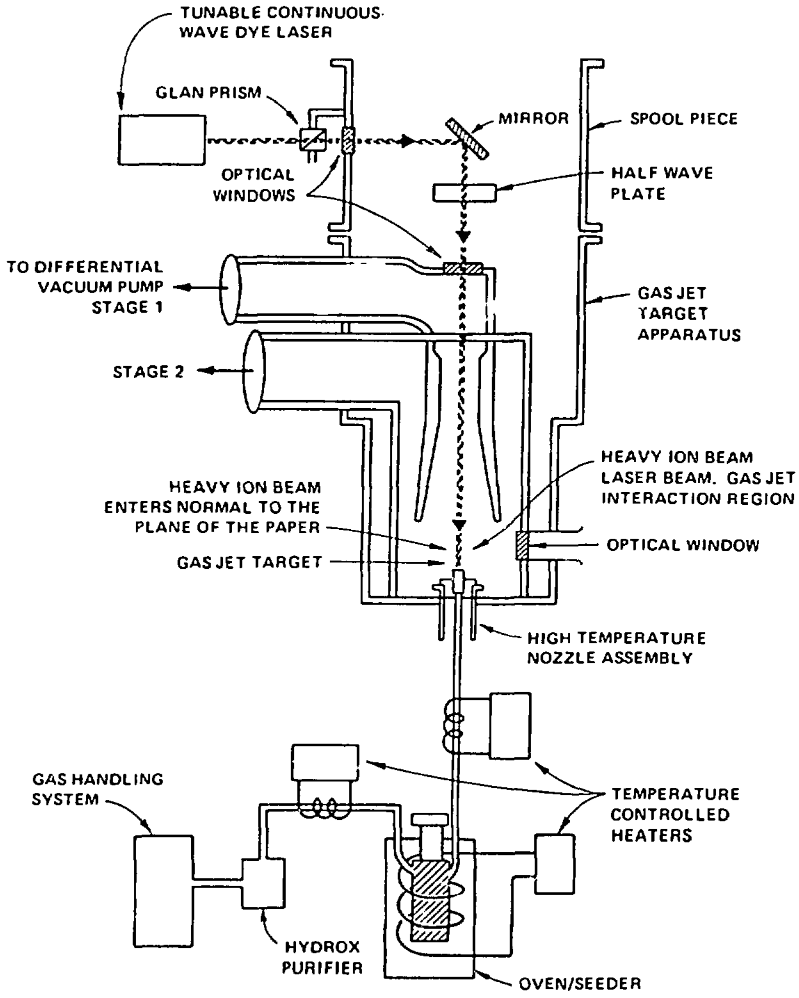


Fig. 5. Experimental arrangement and geometry of the polarized target apparatus.

ORNL-DWG 83-10643

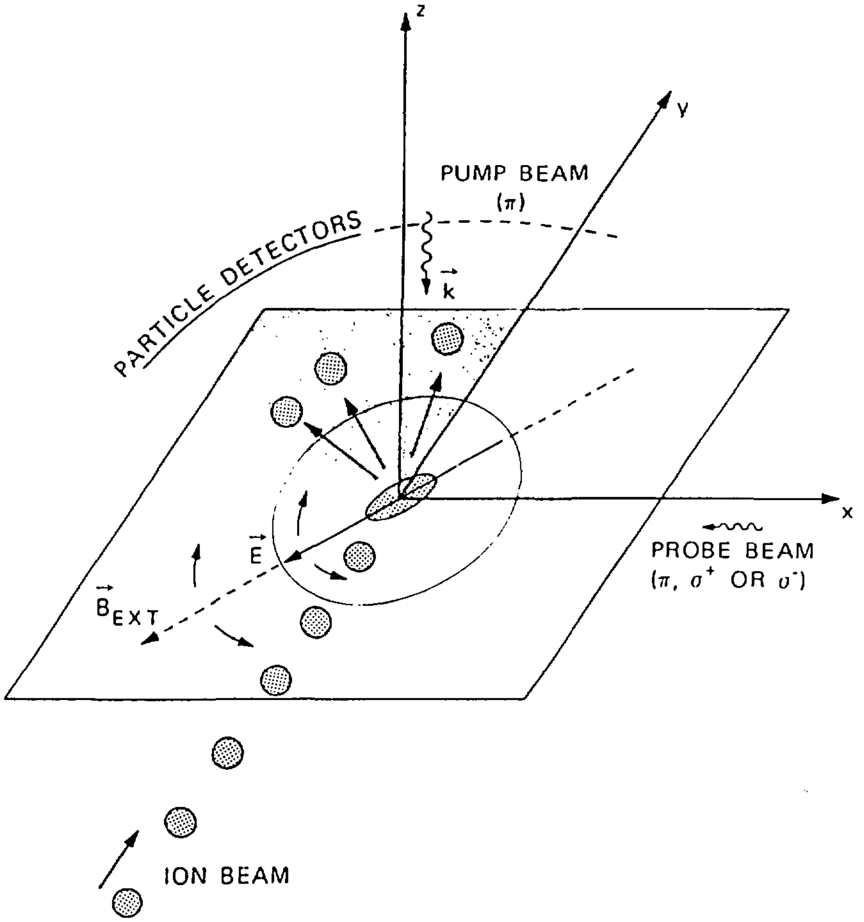
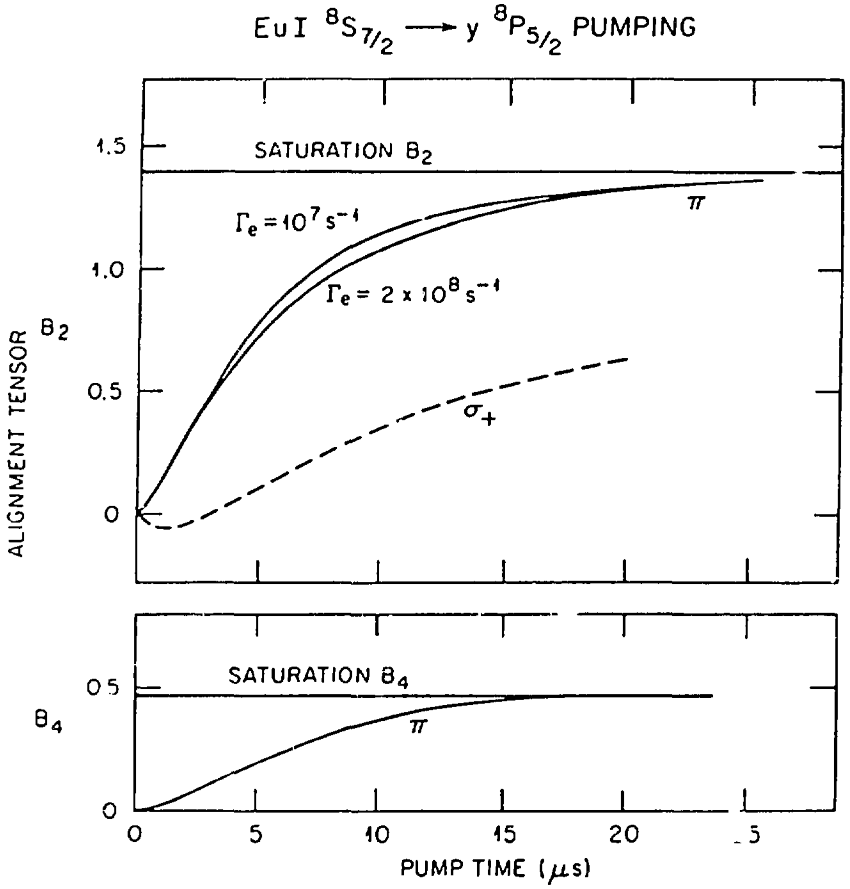


Fig. 6. Schematic illustrating the coordinate system and quantization axis in the "photon frame" for the ORNL polarized target.

ORNL-DWG 81-23495


EuI $^8S_{7/2} \longrightarrow y\ ^8P_{5/2}$ PUMPING

16 W/cm^2 AT 0.5 Å BANDWIDTH = $\Gamma_{up} = 6 \times 10^6\ s^{-1}$

$\Gamma_{down} = 1.8 \times 10^8\ s^{-1}$

Fig. 7. Evolution of the nuclear orientation parameters, B_2 and B_4, for Eu for optical pumping of the $^8S_{7/2} \rightarrow y\ ^8P_{5/2}$ transition at 466 nm for the assumed pumping parameters given in the bottom of the figure. Here, Γ_e is the excited-state relaxation rate; Γ_{up} is the induced transition rate; and Γ_{down} is the spontaneous radiative decay rate for the y $^8P_{5/2}$ state.

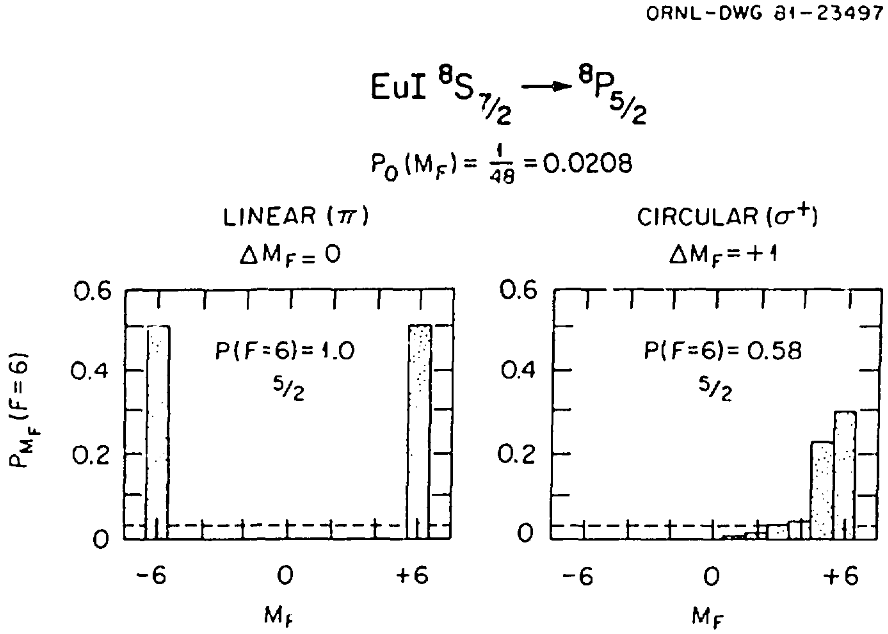


Fig. 8. Steady state magnetic substate (M_F) populations for the hyperfine state F = 6 ($\vec{I} + \vec{J}$) of the Eu ground state, for pumping with π or σ^+ light. Here, M_F is with respect to the quantizatio axis in the "photon frame."